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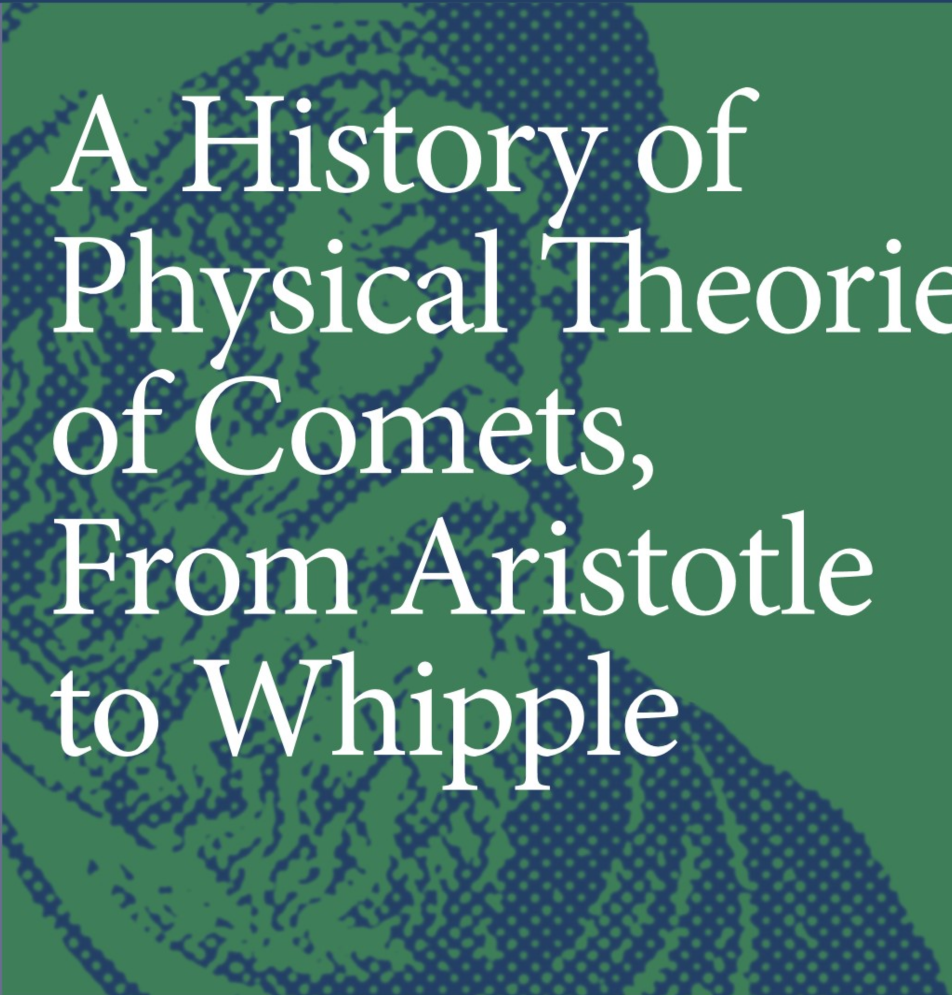
Tofigh Heidarzadeh



A History of Physical Theories of Comets, From Aristotle to Whipple

Springer

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Archimedes

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To Farzaneh and Nikoo
for their endless love
and support

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Tofigh Heidarzadeh
Chino Hills, California
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Introduction

Although the development of ideas about the motion and trajectory of comets has been investigated piecemeal, we lack a comprehensive and detailed survey of physical theories of comets. The available works either illustrate relatively short periods in the history of physical cometology or portray a landscape view without adequate details. The present study is an attempt to review – with more details – the major physical theories of comets in the past two millennia, from Aristotle to Whipple.

My research, however, did not begin with antiquity. The basic question from which this project originated was a simple inquiry about the cosmic identity of comets at the dawn of the astronomical revolution: how did natural philosophers and astronomers define the nature and place of a new category of celestial objects – comets – after Brahe's estimation of cometary distances? It was from this turning point in the history of cometary theories that I expanded my studies in both the pre-modern and modern eras. A study starting merely from Brahe and ending with Newton, without covering classical and medieval thought about comets, would be incomplete and leave the fascinating achievements of post-Newtonian cometology unexplored.

Based on the fundamental physical characteristics attributed to comets, the history of cometology may be divided into four periods: from Aristotle to Brahe, during which comets were assumed to be meteorological phenomena; from Brahe to Newton, when comets were admitted as celestial bodies but with unknown trajectories; from Newton to Laplace, during which they were treated as members of the solar system with more or less the same properties of the planets; and the post-Laplacian period, in which the mass and density of comets was calculated to be much less than that of planets. By estimating the mass of comets in the 1800s, Laplace diverted cometology into a new direction. Comets were now considered among the smallest bodies in the solar system and deprived of the most important properties that had been used to explain their physical constitution during the previous two millennia.

Ideas about the astrological aspects of comets are not considered in this study. Also, topics concerning the motion of comets are considered only to the extent that they are helpful in illustrating their physical properties. The main objective is to demonstrate the foundations of physical theories of comets, and also the interaction between observational and mathematical astronomy, and the physical sciences in defining the properties of comets.

The number of publications containing ideas about the physical properties of comets shows a radical increase in the third and forth periods of our account of cometology. Among the numerous general astronomy texts or treatises devoted to comets in these periods, those were selected for discussion here that either proposed a different theory of comets or criticized physical aspects of contemporary theories. The survey includes only works published in England and France, and a few in German-speaking countries.

Although the present study is mainly focused on the physical theories of comets, its results will be relevant to studies in the history of geology, planetary science, and astrology. On the other hand, these results may suggest new studies about educational practices for physics and astronomy in post-Newtonian Europe, as well as the ways that different parts of Newton's physical, astronomical and cosmological ideas evolved after him. Also, the debates about the constitution and chemical properties of comets in the post-Laplacian era suggest the need for new research about the possible influence of cometary studies on the foundations of astrophysics.

Contents

Chapter 1
Aristotle's Theory of Comets

The pre-modern history of cometary theories, in large part, is the history of Aristotle's theory of comets. Although Aristotle is not the first philosopher who developed a theory on comets, he is the first known to have employed various observational facts to elaborate a consistent theory of comets within a structured cosmology. Aristotle's theory is a physical theory in which the material, mechanism of formation, and motion of the comets are all explained.

The cometary theory of Aristotle is a part of his coherent theory of the cosmos wherein the categorized objects of the universe are arranged in a distinct configuration. To build such a harmonious picture, Aristotle defined some fundamental concepts based on observation and logic. Dividing the entire universe into two distinct regions was the most basic hypothesis. Aristotle separated the heavens from the earth and defined the realm of each. This demarcation of the celestial and terrestrial regions, however, was not merely a determination of borders; it was an introduction of two completely different sets of phenomena, which should be understood by two different sets of physical principles.

As modern astronomers and physicists found that they needed to define the realm of 'outer space' at the threshold of the space age, a typical ancient natural philosopher needed to answer the basic question "Where does the sky begin?" Although lightning, meteors, the moon and sun, comets and stars are perceived at the same distance on the 'celestial sphere', it is clear that some of these phenomena are closer than others. As a matter of fact, human eyes are not ideal measurement tools to estimate depth in the sky. Beyond a certain range, our eyes are not able to evaluate the linear distances of objects accurately. What is perceived is the *relative distance*, which is a judgment about proximity or distance of objects. When one object obscures a part of another, it is perceived closer than the obscured one.[1]

Based on this natural law of perception, long before Aristotle, people arranged some of the upper phenomena according to their distances. For example, from the eclipse of the sun by the moon, it was found that the sun was farther, and from the fact that none of the stars could eclipse the moon it became clear that the moon was

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[1] Robert Sekuler and Randolph Blake, *Perception* (New York: McGraw-Hill, 2002), pp. 312, 331.

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closer to the earth than the stars. In the fifth century B.C., Anaxagoras of Clazomenae correctly suggested that the stars are above the sun and moon, and he ascribed the light of the moon to the sun.[2] By the end of the fourth century B.C., when the homocentric models of Eudoxus and Calippus were developed, it was generally accepted among the Greek scholars that the earth should be located at the center of the universe encompassed by the spheres of the moon, sun, Mercury, Venus, Mars, Jupiter, Saturn and the fixed stars.[3] Aristotle mentions his own observation of the occultation of the planets along with the accounts of Babylonian and Egyptian astronomers in order to support observational evidence for the sequence of the planets:

> We have seen the moon, half-full, pass beneath the planet Mars, which vanished on its shadow side and forth by the bright and shining part. Similar accounts of other stars are given by the Egyptians and Babylonians, whose observations have been kept for very many years past, and from whom much of our evidence about particular stars is derived.[4]

A counterpart of the speculations about heavenly bodies and their arrangement lay in ideas about the materials between the earth and the heavens. Empedocles (ca. 450 B.C.), combining his predecessors' assumptions, suggested that there are four primary elements of fire, air, water and earth.[5] By the time of Plato (427–347 B.C.) it was established that the four elements are configured in concentric spheres in the order of earth, water, air and fire. Plato even gives the relative sizes of these spheres as two radii of the earth for water, five radii of the earth for air and ten radii of the earth for fire. However, it was Aristotle (384–322 B.C.) who described the properties and configuration of the elements in detail and developed theories for the phenomena related to them. In fact, it is the properties of the elements that shape the structure of the Aristotelian universe and divide it into celestial and terrestrial realms.

Aristotle explains his theories concerning celestial and terrestrial phenomena in two main works. In his four books of *On the Heavens*, Aristotle deals with celestial matters and in the four books of *Meteorology* he discusses the phenomena occurring

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[2] Morris R. Cohen, and I. E. Drabkin (eds.), *A Source Book in Greek Science* (Cambridge: Harvard University Press, 1958), p. 93.

[3] J. L. E. Dreyer, *A History of Astronomy from Thales to Kepler* (New York: Dover, 1953), pp. 87–107. Dreyer's first three chapters give a brief account of the history of astronomy to Plato. The fourth chapter (pp. 87–107), which contains the models of Eudoxus and Calippus, shows the mathematical and observational achievements of pre-Aristotelian Greek astronomy. Though for Pythagoreans Venus was prior to Mercury in their cosmic sequence, by the time of Plato the correct sequence was generally accepted. Plato himself in *Timaeus* places Mercury after the sun, but in the *Republic* reckons Venus before Mercury. See also: Olaf Pederson, *Early Physics and Astronomy* (Cambridge: Cambridge University Press, 1993), pp. 21–27, 56–58.

[4] Aristotle, *On the Heavens*, 292^a 1–10, in Aristotle, *The Complete Works of Aristotle*, ed. Jonathan Barnes (Princeton: Princeton University Press, 1995), p. 481. Besides the occultation, the period of revolutions of the planets was a basic criterion to judge about their distance. See ibid., 291^a 25–291^b 10.

[5] Dreyer, *From Thales to Kepler*, p. 23.

in the terrestrial region. Although at first glance it seems that comets would be discussed in *On the Heavens*, they are in fact explained in the *Meteorology*, along with two other phenomena, the Milky Way and shooting stars. Therefore, in Aristotelian cosmology, comets (as well as the Milky Way and shooting stars) belong to the sub-lunar region and they are assumed to be atmospheric phenomena. To understand the reasons why Aristotle relegated comets to the terrestrial region, it is necessary to comprehend his theory of the cosmos and especially his proposals about the celestial region.

In *On the Heavens*, Aristotle describes the distinction between the celestial and terrestrial regions. Among Aristotle's works, *On the Heavens* comes just after the *Physics*, in which he elaborates the concepts of nature, motion, change and cause, and the immovable mover. In his classification of knowledge, physics (which is the science of nature), mathematics, and metaphysics, are the main branches of the theoretical sciences. This classification is based on premises that matter, on the one hand, is either movable or immovable, and on the other hand, is either separate or not separate. Physics is the science of movable but not separate matter; mathematics is the science of immovable and separate matter, and metaphysics is the science of non-separate, immovable matter.[6] The science of physics, therefore, is very broad and encompasses not only non-organic matter, but also the organic world. Aristotle, in four major works, *Physics*, *On the Heavens*, *On Generation and Corruption*, and *Meteorology*, elucidates his theories about some major subjects in the science of nature. These four books, though separately titled, complete each other and create a grand Aristotelian picture covering the cosmos, or all things from the earth to the heavens.

In *On the Heavens*, Aristotle divides the entire universe into two separate realms based on the nature and motion of substances. In this division, the sphere of the Moon marks the border: above the border is the ethereal or celestial region, where the stars and planets are located, and below that is the region of generation and corruption, where the central sphere of the earth is encompassed by three concentric spheres of water, air and fire. The substance of the celestial part is ether (the fifth element) and its natural motion is circular and perpetual. The sub-lunar region, however, is made up of four elements (earth, water, air, and fire), and their natural motion is rectilinear and temporary. The structure of the sub-lunar region is configured by the lightness or heaviness of the elements. Earth, being the heaviest element, is located at the center and surrounded by water, air and fire respectively. The fifth element, on the other hand, is neither heavy nor light. It is ungenerated, indestructible, and immune from increase and alteration.[7] Quite the opposite, the four elements are not eternal and are subject to generation and destruction.[8]

The celestial region, therefore, is unchangeable. This statement not only is based on Aristotle's deductive reasoning, but also it is derived from observational facts:

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[6] Aristotle, *Metaphysics*, trans. J. H. McMahon (New York, 1991), 1026^{a}, pp. 124–125.

[7] Aristotle, *On the Heavens*, 271^{a} 1–35. trans. J. L. Stocks, in Aristotle, *The Complete Works of Aristotle*, edit. J. Barnes (Princeton, 1984), p. 450.

[8] Aristotle, *On the Heavens* 304^{b} 25–30.

> The mere evidence of the senses is enough to convince us of this, at least with human certainty. For in the whole range of time past, so far as our inherited records reach, no change appears to have taken place either in the whole scheme of the outermost heaven or in any of its proper parts. The name, too, of that body seems to have been handed down right to our own day from our distant ancestors who conceived of it in fashion which we have been expressing.[9]

Obviously, Aristotle knew that sometimes planets perform motions which are neither circular nor uniform. But, he explained those apparently non-perfect motions as the resultant of two or more perfect motions. The celestial region was immune from any disorder, impurity, and chaos. Consequently, those phenomena such as comets, shooting stars and novae that demonstrated changes, could not be a part of the unchangeable celestial region; they belonged to the sub-lunar realm, where change, in all forms, was allowed.[10] Therefore, those phenomena were studied under the subject of meteorology, which dealt with a major part of the sub-lunar events, or the inanimate nature.

The Aristotelian Structure of the Sub-lunar Region

In Aristotelian natural philosophy, meteorology is not merely the science of atmospheric phenomena. Aristotle, at the beginning of his *Meteorology*, defines the subject of the book and gives a general layout of his project of explaining nature:

> We have already discussed the first causes of nature, and all natural motion, also the stars ordered in the motion of the heavens, and the physical elements – enumerating and specifying them and showing how they change into one another – and becoming and perishing in general. There remains for consideration a part of this inquiry which all our predecessors called meteorology. It is concerned with events that are natural, though their order is less perfect than that of the first of the elements of bodies. They take place in the region nearest to the motion of the stars. Such are the Milky Way, and comets, and the movements of meteors. It studies also all the affections we may call common to air and water, and the kinds and parts of the earth and the affections of its parts.[11]

Aristotle, in Book I of *Meteorology*, after giving a detailed description of the sub-lunar substances (the four elements) and their arrangement and motions, elaborates his theory of shooting stars, comets, and the Milky Way. In fact, as we find in *Meteorology*, these three phenomena are three different manifestations of a single atmospheric activity, which occurs in the upper parts of the sub-lunar sphere. Therefore, it is necessary to understand the fundamentals of the atmospheric dynamics as Aristotle laid down in his *Meteorology*.

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[9] Ibid., 270^b 10–20.

[10] Aristotle defines six kinds of change, which are: generation, destruction, increase, diminution, alteration, and change of place. See Aristotle, *Categories*, 15^a 10–15^b 20. In the celestial region only one kind of change, change of place produced by the uniform circular motion, can occur. Aristotle discusses motion in detail in *Physics*, III 1–3, V, VII and VIII.

[11] Aristotle, *Meteorology*, trans. E. W. Webster, in Aristotle, *The Complete Works of Aristotle*, ed. J. Barnes, 2 vols. (Princeton: 1984), vol. 1, 338a 20–338b 25.

The sub-lunar region is composed of four bodies: earth, water, air and fire. Fire[12] is the lightest body and is located immediately below the sphere of the moon. Earth is the heaviest and occupies the center. In between are placed air, which is close to fire, and water, which is above the earth (Fig. 1.1). The sub-lunar region, however, is not completely disconnected from the celestial world; it is in touch with the upper region but there is not a mutual interaction between them. In fact, though the two worlds are contiguous, it is only the celestial part that has a direct influence on the terrestrial part:

> This world necessarily has a certain continuity with the upper motions: consequently all its power and order is derived from them. …So we must treat fire and earth and the elements like them as the material causes of the events in this world (meaning by material what is subject and is affected), but must assign causality in the sense of the originating principle of motion to the influence of the eternally moving bodies.[13]

Therefore, the interaction between the four elements in the sub-lunar region is induced by celestial motions. This influence – at least in the realm of the atmospheric phenomena – occurs at two different levels. At one level, the sun warms the earth and, consequently, exhalations rise from the surface to the upper parts of the atmosphere.[14] In the other level, the motion of the first element, the celestial ether, inflames the materials in the uppermost parts of the sub-lunar region and produces heat.[15] When the earth and water derive heat from the sun, two kinds of exhalation are produced. One kind is a vapor, which comes out from the moisture existing in the earth and on its surface. The other is windy and dry, which rises from the earth itself.[16] Obviously, according to the Aristotelian configuration of the elements, the moist vapor, which is potentially like water, cannot rise to higher elevations. But, the windy exhalation, which is dry and hot in nature and is potentially like fire, can ascend to higher altitudes and stay above the moister vapor. Thus, the region from the surface of the earth to the sphere of the moon, though 'gaseous' in modern terms, is divided into two different parts. The lower part, which is called air, is the place for the formation of clouds, wind, precipitation, rainbows, and so on; and the higher part, the fire, is the space where the shooting stars, comets, and the Milky Way appear (Fig. 1.2).

The fire is not in the form of a flame or blaze; it is a kind of warm and dry element, which is highly inflammable. Aristotle, for lack of an appropriate terminology employs the term 'fire' to name "the most inflammable of all bodies."[17] Therefore,

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[12] Though this element is commonly called fire, it is not really the combustive fire of ordinary experience; it emits neither heat nor light. See: Ibid., 340^b 20–25. We will discuss it later.

[13] Ibid., 339^a 20–35.

[14] Ibid., 341^a, 20–35.

[15] Ibid., 340^b, 10–15.

[16] Ibid., 341^b 5–10. It is important to know that none of the exhalations is pure. Aristotle in book II, 4 of *Meteorology*, at the starting of his theory of winds, declares that "moist cannot exist without the dry nor the dry without the moist: whenever we speak of either we mean that it predominates". See Ibid., 359^b 30–35.

[17] Ibid., 341^b 15–20. Also in 340^b 15–25: "So at the center and round it we get earth and water, the heaviest and coldest elements, by themselves; round them and contiguous with them, air and what we commonly call fire. It is not really fire, for fire is an excess of heat and a sort of ebullition."

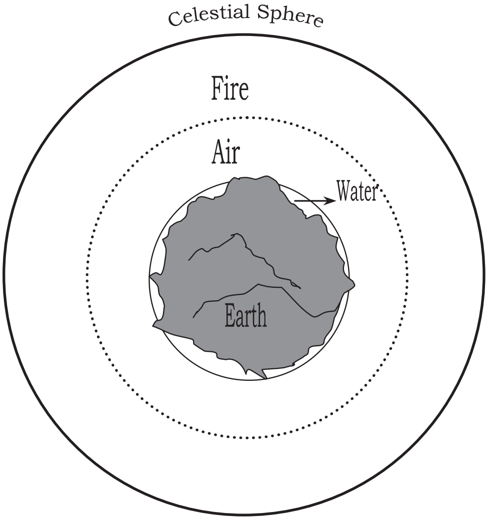

Fig. 1.1 Aristotelian configuration of the sub-lunar region. The heaviest element, earth, is located at the center of the universe and fire, the lightest, is situated immediately below the celestial sphere

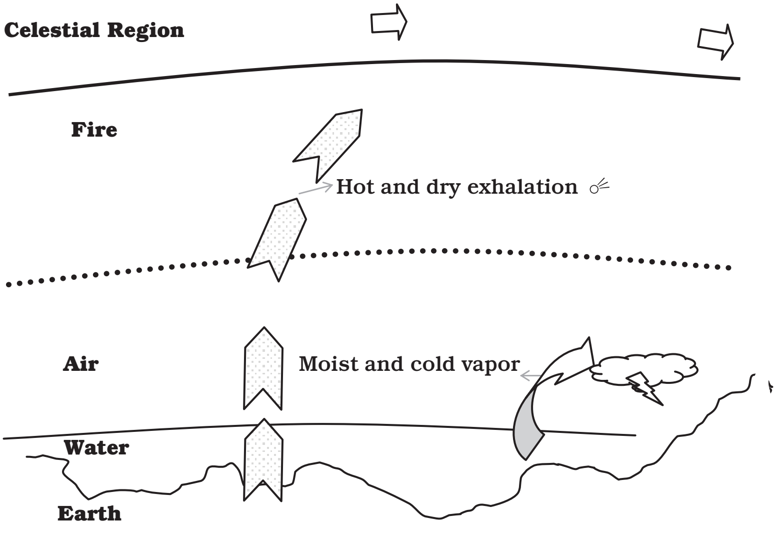

Fig. 1.2 The material cause of all meteorological phenomena is an exhalation: one kind, which comes out from the earth, is dry and hot, and the other is moist and cold, which originates from water. The hot exhalation rises up to the so-called fire layer and participates in rotational motion imposed by the celestial sphere. The moist and cold exhalation returns to the earth in the form of precipitation. None of the exhalations is pure. The moist cannot be found without the dry and vice versa. When an exhalation is called moist or dry it just refers to the predominant part

when the element fire is added to a form of fuel, it bursts into flame. As a result, if the hot and dry exhalation (which is potentially inflammable and functions as fuel) meets fire, the fuel will ignite. Aristotle's explanation implies that the dry exhalations have different degrees of flammability. Therefore, the most inflammable parts of the exhalations will burn most easily.

Aristotle admits that a kind of 'convection' occurs in the air. The sun's heat transforms water into vapor, vapor condenses into cloud, and cloud condenses to water, which finally falls on the earth.[18] In the dry exhalation, however, an ascending motion is dominant.[19] The most inflammable exhalation rises to the highest part of the fire layer. The ascending of the exhalation is due not only to its natural motion (which is directly towards the fire), but also the rotation of the celestial sphere stirs the exhalations up.[20] In fact, the revolution of the celestial sphere induces a motion both to the entire fire layer and a great part of the air below it.[21] Although Aristotle

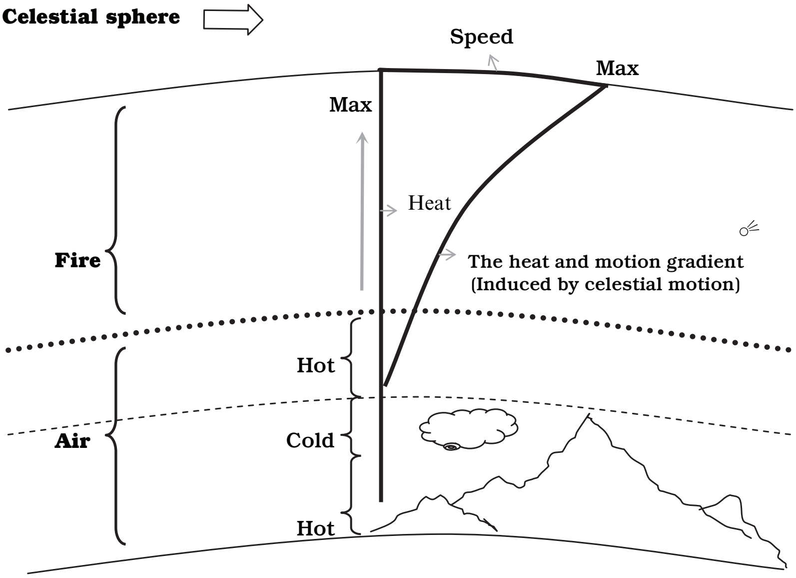

Fig. 1.3 Superimposition of the gradient of heat and motion in the air and fire produced by circular motion of the celestial sphere. Based on its temperature, the air itself can be divided into three levels: close to the earth it is hot due to reflection of the sun's rays. At the level that reflection of the sun's rays ceases (about the height of the highest mountains), it becomes cold and clouds can be formed. Above that, the air becomes hot again due to the influence of the circular motion of the celestial sphere. Since Aristotle does not give any quantitative information about the spheres of the elements, the diagram, obviously, is not to scale

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[18] Ibid., 346^b 33–35.

[19] Aristotle, at the end of his discussion of heat transfer from the sun and the revolution of the celestial sphere to the earth mentions: "fire surrounding the air is often scattered by the motion of the heavens and driven downwards in spite of itself."(Ibid., 341^a 25–35) He does not explain how the motion of the heavens can drive the fire downward. On the other hand, in 341^b 21–22, he says that the circular motion stirs the exhalations up. It seems that he also admits the occurrence of a kind of convection or swirling in the fire layer, but his explanation is not clear.

[20] Ibid., 341^b 20–25.

[21] Ibid., 344^a 5–15.

does not strictly talk about the production of heat in the lower parts of the sub-lunar realm due to the motion initiated by the celestial sphere, it can be deduced from his explanation of the relationship between motion and heat that there is a vertical temperature gradient in the fire layer. In other words, since the uppermost part of the fire moves faster and experiences more friction, it is the hottest part; similarly, the lowest part of fire has the lowest temperature. Therefore, when the dry and hot exhalation ascends from the earth to the fire layer, it not only gains more and more motion in the fire, but also its temperature goes up (Fig. 1.3).

Having established the fundamental factors of the dynamics of the sub-lunar region, Aristotle theorizes the formation of the shooting stars, comets and the Milky Way. We will focus mainly on comets and discuss shooting stars and the Milky Way briefly, only to show their underlying relationship.

Shooting Stars

Shooting stars are formed when the dry and hot exhalations start to burn. After rising to the fire region, the exhalation is dragged due to the motion induced by the revolution of the celestial sphere. Since the exhalation is like fuel, and motion creates heat, the exhalation catches fire. The amount of the fuel, its overall shape and dimensions, and finally the process that triggers the release of heat determine the type of phenomena seen in the sky. Aristotle, after describing 'torches', 'chasms' and 'goats' which are different forms of the burning exhalation,[22] defines shooting stars as follows:

> If the whole length of the exhalation is scattered in small parts and in many directions and in breadth and depth alike, we get what are called shooting-stars.[23]

Aristotle explains a second mechanism for the formation of the shooting stars in which combustion does not occur, rather, the air condensed by cold ejects the hot element and it appears more like a projectile than a dodging fire.[24] Aristotle then arranges these two mechanisms by the altitudes at which they occur: in the upper parts of the so-called fire the appearance of shooting stars is due to combustion of the exhalation, but in the lower parts it is due to "the ejection of the exhalation by

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[22] In modern nomenclature, *bolide* is a detonating fireball or a very bright meteor that explodes, and *fireball* is a bright meteor of magnitude −5 or −4 (brighter than Venus when the planet is at the greatest brilliancy). Aristotle employs the term 'goat' to name a fireball if it disperse sparks, and uses 'torch' for a fast moving fireball when it does not show sparks. See: Mark Littmann. *The Heavens on Fire*, *The Great Leonid Meteor Storms* (Cambridge: Cambridge University Press: 1998), p. 36. Lettinck defines the 'goat' as a kind of meteorite, which should be defined as a kind of meteor, for meteorites are debris that fall on the earth. See Paul Lettinck, *Aristotle's Meteorology and its Reception in the Arab World* (Leiden: 1999), pp. 18, 66.

[23] Aristotle, *Meteorology*, 341^{a} 30–35.

[24] Ibid., 342^{a} 1–5.

condensing and cooling of the moister exhalation".[25] The latter happens like the ejection of a fruit seed when the fruit is squeezed. Consequently, the first kind of shooting star, which is hot and flaming, ascends to the uppermost parts of the sphere of fire. Its motion, however, is not due to the displacement of a single body of burning exhalation: we see the star as "shooting" because successive combustions happen in the successive clusters of dry and hot exhalation. When the first cluster catches fire, it ignites the next one and the process continues until the fuel is consumed completely. But the second kind of shooting star, which happens only when the hot element is ejected from condensed air, moves obliquely due to the downward motion of the condensation and falls into the sea or onto dry land.[26]

Comets: Formation and Kinds

As mentioned above, in Aristotelian cosmology shooting stars, comets, and the Milky Way are assumed to originate from a single phenomenon. Aristotle, after discussing the configuration and motion of the elements in the sub-lunar region, as a first step explains shooting stars, which implicitly are understood as the simplest among the three phenomena. Based on the concepts developed for the explanation of the shooting stars, comets are examined in the next step. However, in order to solve problems concerning the appearance, motion and trajectory of comets, Aristotle considers comets as a specific form of shooting star that can occur under a very delicate combination of physical conditions.

It is not known exactly how many comet appearances Aristotle and his contemporaries witnessed or how much quantitative observational information they had about the trajectory, motion and duration of the comets.[27] Aristotle, in the *Meteorology* mentions only three comet appearances and it seems that he observed two of them.[28] However, it is obvious that Aristotle was aware of *some* critical observational facts, which led him not only to criticize other natural philosophers' ideas, but also to develop a practically consistent theory of comets. Aristotle, before explaining his own theory of comets, introduces two major theories developed by his predecessors. His assessment of these theories provides an important source to compare Aristotle's cometary knowledge with that of the pre-Socratic philosophers.

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[25] Ibid., 342^{a} 15–20.

[26] Ibid., 342^{a}, 1–35.

[27] For a catalogue of cometary appearances in ancient and medieval times see: Donald K. Yeomans, *Comets*, *A Chronological History of Observation, Science, Myth, and Folklore* (New York: Wiley, 1991), pp. 361–424 (covers from eleventh century B.C. to A.D. 1700); A. A. Barrett, "Observations of Comets in Greek and Roman Sources before A.D. 410," *Journal of the Royal Astronomical Society of Canada* 2 (1978), 81–106 (covers from 480 B.C. to A.D. 410), and for a catalog covering from the ancient time to 1980s see Gary W. Kronk, *Comets, A Descriptive Catalog* (Hillside: Enslow Publishers, 1984).

[28] Aristotle, *Meteorology*, 345^{a} 1–5, 343^{b} 1, 343^{b} 1–5.

The core concept in the two theories that Aristotle criticizes is the attribution of the appearance of comets to a celestial cause.[29] Anaxagoras (500–426 B.C.) and Democritus (fl. 410 B.C.) believed that the conjunction of planets is seen as a comet. They state that when planets come near to each other, the combined image of them appears in a stretched shape, similar to a comet. Pythagoreans (sixth–fifth centuries B.C.), on the other hand, supposed that the comet is a planet with a long period of revolution and a path of motion that keeps it closer to the horizon.[30] Hippocrates of Chios (fl. 430 B.C.) and his student, Aeschylus, proposed another version of the latter theory. They assumed that while the comet itself is a planet, the tail is not a part of it; rather it is a meteorological effect like a halo or a rainbow. According to this hybrid theory, the tail is seen when "our sight is reflected to the sun from the moisture attracted by the comet."[31] The planet that is seen as a comet moves very slowly and most of the time it is very close to the sun. Between the tropics, where the sun's heat dries up the exhalations, it cannot attract moisture. Although it can attract moisture when it moves towards the south, its path above the horizon is too short and human sight cannot be reflected to the sun. Therefore, neither in the southern tropic, nor at the summer solstice is the planet seen with a tail. But when it is in the north, its path is long enough above the horizon and our sight can be reflected from the sun. As a result, we can see the planet with a tail.

Aristotle criticizes all three theories for their intrinsic inconsistencies. His arguments against the astronomical origin of comets, in which comets are assumed to be planets, are based on three observational facts:

I. All planets are seen in the zodiac, while many comets are found outside of the zodiac.
II. Sometimes more than one comet has been seen at the same time, which is contrary to the idea that the comet is one of the planets.
III. Only five planets have been observed; but, sometimes, when all of them are observable above the horizon, comets also can be seen.

He refutes the reflection theory of the tails (Hippocrates' and Aeschylus' theory) by referring to a simple optical fact: since the appearance of the tail is due to the reflection of human sight to the sun, and because only under a specific

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[29] For a comprehensive comparison of the cometary theories in Antiquity see: C. D. Hellman. *The Comet of 1577: Its Place in the History of Astronomy* (New York:1944), or James Alan Ruffner. *The Background and Early Development of Newtown's Theory of Comets*, Ph.D. diss., Indiana University, 1966, pp. 12–34. A brief comparison, with an informative table of classification of ancient theories of comets can be found in: Sara Schechner Genuth. *Comets, Popular Culture, and the Birth of Modern Cosmology* (Princeton: Princeton University Press, 1997), pp. 17–19. Aristotle's methodology in his *Meteorology* and the way he criticized his predecessors' ideas on comets, hail, wind, etc. is discussed in: Cynthia A. Freeland. "Scientific Explanation and Empirical Data in Aristotle's *Meteorology*," *Oxford Studies in Ancient Philosophy* 8 (1990), 67–102.

[30] According to Plutarch (ca. 50–120 A.D.) some of the Pythagoreans believed that "a comet is one of those stars which do not always appear, but after they have run through their determined course, they then rise and are visible to us". See Ruffner, "The Background," p. 14.

[31] Aristotle, *Meteorology*, 343^{a} 1–5.

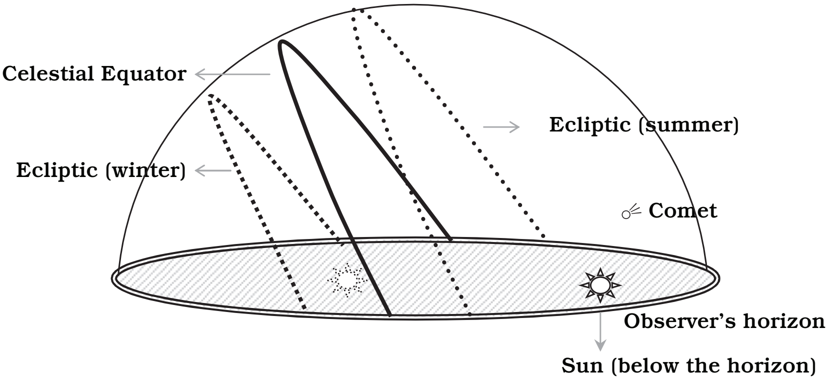

Fig. 1.4 According to Hippocrates of Chios and his student Aeschylus, the comet is one of the planets and its tail is a meteorological effect. When the planet is to the north of the tropics and the sun at the summer solstice (bold sun, right), our sight can be reflected to the sun from the moisture attracted by the planet and seen as a tail. When the sun is at the winter solstice (dotted sun, left) and the planet (=comet) is at the north, they are far apart and our sight cannot be reflected from the moisture to the sun. The tail cannot be seen also when the planet is between the tropics because the sun dries up the exhalation

geometry of sun-comet-observer can such a reflection occur, then the comet should sometimes be seen without a tail. Based on the position of the comets seen in 373 and 427 B.C., Aristotle also rejects Hippocrates' idea that the comet is only visible north of the tropics when the sun is at the summer solstice (Fig. 1.4). Besides several comets seen in the south, in 373 B.C. a great comet was seen in the west and in 427 B.C. a comet appeared in the north while the sun was in the winter solstice.[32]

To reject the conjunction theory of Democritus, Aristotle once more refers to some interesting observational facts. He states that some of the fixed stars have tails, among them the star 'in the thigh of the Dog'. It is not obvious if you fix your sight on it, but if you just glance at it, the tail becomes visible.[33] On the other hand, if the comet appears due to the conjunction of a planet with a planet or a planet with a fixed star, they should resolve after a while and leave behind two individual stars. Aristotle says that there is no report of such an event; he also reports his own observation of a conjunction of Jupiter with a star in constellation Gemini, which did not result in a comet. Finally, Aristotle indicates that since the stars are seen as points

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[32] Ibid., 343^{b}1–5.

[33] Ibid., 343^{b} 10–15. It is not clear if Aristotle refers to M41 (an open cluster in Canis Major) or a chain of faint stars near Delta Canis Majoris. To observe the faint 'tail', Aristotle employs the technique of *averted vision*, which is still popular among astronomers. One averts the vision about 2 degrees to send the light not to the central cells of the retina but to the peripheral cells which are more sensitive. See: A.A. Barrett, "Aristotle and Averted Vision," *Journal of the Royal Astronomical Society of Canada*, 4 (1977), 327.

of light, even in conjunctions they cannot produce a larger magnitude and are still seen as a shining point.[34]

Aristotle, after criticizing his predecessors' theories of comets, elucidates his own theory. In his assessment of those theories, he tries to show that any acceptable theory must be able to explain three essential aspects of comets: (1) their sporadic appearances, (2) their random trajectories (which are not zodiac-bounded), and (3) the process that produces the tail. As Aristotle deduces that the comet is not a planet (and obviously is not a fixed star), it becomes clear for him that it belongs to the realm of generation and corruption and must be treated under the 'laws' of the sub-lunar region.

As mentioned earlier, in Aristotle's cosmology, shooting stars, comets and the Milky Way originate from a single meteorological phenomenon. We will see later that Aristotle interprets comets as a special kind of shooting star, and the Milky Way as a special form of comet.

When the hot and dry exhalation rises to the so-called fire layer, it participates in the circular motion of the fire caused by the revolution of the celestial sphere. As explained above, under special conditions, either due to combustion of the exhalation or to ejection of the hot element from condensed air, shooting stars appear in the sky. Shooting stars, however, consume their fuel quickly and burn out in a matter of seconds. The cause of this rapid burning is either the higher degree of heat introduced by the circular motion or the higher degree of inflammability of the exhalation. Aristotle states the degree of inflammability is inversely proportional to density. A highly inflammable and less condensed fuel burns very fast and the result is always a kind of shooting star. By contrast, it is expected that if a mass of condensed (and therefore less inflammable) exhalation encounters an adequate amount of the element fire (not so strong as to burn the material instantly and not so weak as to extinguish it quickly) it will create a longer lasting fire. In fact, in such a case, the flame cannot spread rapidly through the fuel, but stops in the densest part of it. Then, this semi-steady burning fuel, which is moving with the motion of the so-called fire layer, will create a relatively durable fire, seen as a comet. Aristotle tries to make the process clear by drawing an analogy between the burning of a mass of hay and the burning of dry exhalation:

> We may compare these phenomena to a heap or mass of chaff into which a torch is thrust, or a spark thrown. That is what a shooting-star is like. The fuel is so inflammable that the fire runs through it quickly in a line. Now if this fire were to persist instead of running

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[34] Aristotle, *Meteorology*, 343^{b} 30–40. Aristotle's point about the combined visual magnitude of the stars is interesting. A numerical system to measure the brightness of the stars appeared later (Hipparchus, second century B.C.) in which the stars divide into six classes from first magnitude (the brightest) to the sixth (the dimmest) with a linear decrease in brightness. Calculations by N. R. Pogson (1856) show that a difference of five magnitudes corresponds to a difference in apparent brightness by a ratio of 100, or each class of magnitude differs by a ratio of 2.512. Therefore, the combined magnitude of two stars of, for example, second magnitude will be: $m_{comb} = m_2 - 2.5 \log (2.512 \Delta^{m} + 1) \Rightarrow 2 - 2.5 \log 2 \Rightarrow 1.25$. Thus, even a conjunction of two celestial bodies of magnitude two will result in a brightness of magnitude 1.25 which is only a little brighter than each individual star. See: Michael A. Seeds, *Horizon, Exploring the Universe* (Pacific Grove: Brooks/Cole, 2000), p. 14.

> through the fuel and perishing away, its course through the fuel would stop at the point where the latter was densest, and then the whole might begin to move. Such is a comet -like a shooting-star that contains its beginning and end in itself.[35]

However, the right density and the right amount of heat, although necessary factors, are not sufficient to complete the process. Aristotle adds one more requirement, which is the rising of 'exhalation of the right consistency from below' to feed the process of burning.[36]

Therefore, the physical constituents and the process of formation of shooting stars and *one* type of comet are the same, except that in the case of comets a denser mass of exhalation encounters an adequate amount of fire. Borrowing Ruffner's word, this cometary theory of Aristotle is based on the concept of 'coincidence'.[37] The comet appears if the density of exhalation, the altitude it reaches, the amount of heat it absorbs, and the quality of rising exhalation are 'just right'. We shall discuss the advantages of this 'coincidental' approach in our evaluation of Aristotle's cometary theory.

Aristotle introduces another type of cometary appearance, which is based on optical effects. This type of comet does not come into view due to the burning of exhalations as explained above; rather it is seen because of the reflection of our sight from an exhalation that is caused by a star or planet. In this case, the exhalation follows the star, as a halo moves with the sun or moon. The star is seen with fringes, which do not belong to it but to the fire layer. The difference between Aristotle's optical theory of comets and that of Hippocrates and Aeschylus lies in the reference star and the path of reflection. In Hippocrates' theory the moisture attracted by a special planet with a distinctive course reflects the observer's sight to the sun, but in Aristotle's it can be any star and the reflection happens when the observer's sight hits the pure fuel constituted by the star. This kind of comet, which is dependent on a star or a planet, moves with the motion of the celestial object it accompanies and rises or sets with that object[38](Fig. 1.5). The fringe around the star, however, is not a *halo*; for a halo is moisture which is attracted by a star and formed in a part of the air that is closer to the earth, where the air is calmer.[39] In addition, the color of a halo is produced by reflection or refraction, but the color of a dependent comet is the real color of the ignited exhalation.[40]

By explaining the second type of comet, Aristotle's theory of comets is complete. At the end, in a few paragraphs, he describes the meteorological influence of cometary appearances. The chief concept in comet-based weather forecasting is the influence of the fiery constitution of the comets, which heralds a windy and dry year. Aristotle refers to three sets of observations to correlate the appearance of

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[35] Aristotle, *Meteorology*, 344^a 20–35.

[36] Ibid., 344^a 20.

[37] Ruffner, "The Background," p. 20.

[38] Aristotle, *Meteorology*, 344^a 30–344^b 10.

[39] Ibid., 373a 20–25.

[40] Ibid., 344b 5–10.

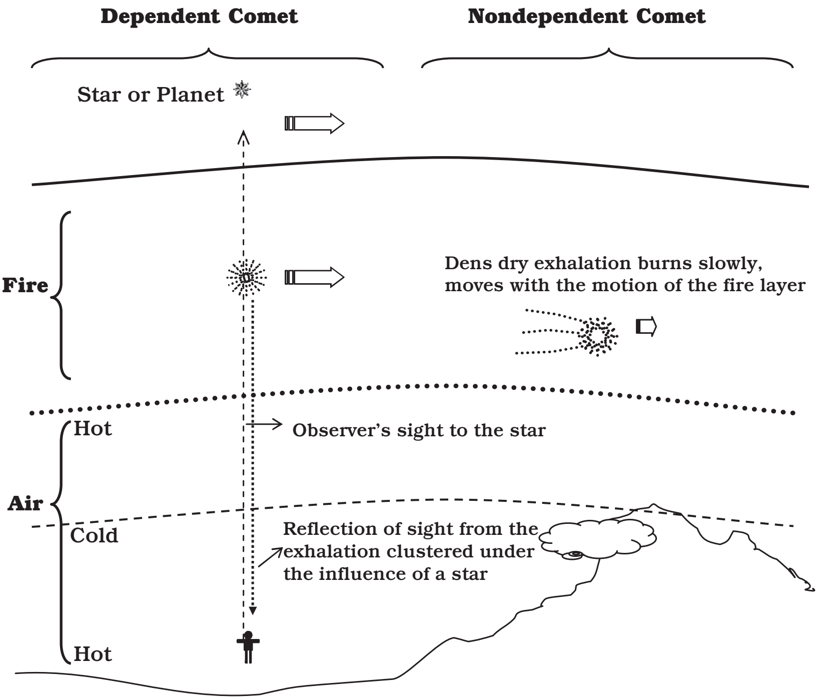

Fig. 1.5 Formation of the two kinds of comets according to Aristotle: a dependant comet appears when a star or planet creates exhalations, which move with the star as a halo moves with the sun or the moon. The reflection of the observer's sight (to the star) from this exhalation is seen as a comet. A nondependent comet appears when a dense mass of hot and dry exhalation burns slowly above the air

comets with forthcoming windy or dry periods. A stone carried by wind which fell in Aegospotami[41] is related to a comet that appeared in the west; the appearance of a great comet[42] is assumed as the cause of a dry winter and the blowing of north winds, and the comet that appeared in the 'archonship of Nicomachus' (341 B.C.) is connected to the occurrence of a storm at Corinth.[43]

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[41] About this meteorite and the story that Anaxagoras had predicted its fall see: Dreyer, *From Thales to Kepler*, pp. 31–33, and G. S. Kirk, *The Presocratic Philosophy* (Cambridge: Cambridge University Press, 1983), pp. 382, 354, 446.

[42] Here, Aristotle does not give a direct clue about the approximate date of appearance of this comet, but in *Meteorology* 343^{b}1, he mentions the 'great comet', which appeared at the time of the earthquake in Achaea. The earthquake occurred in 373 B.C.

[43] Ibid., 344^b 25–345^a 5. The ancient city of Corinth was located to the west of Athens and southwest of the modern city Corinth.

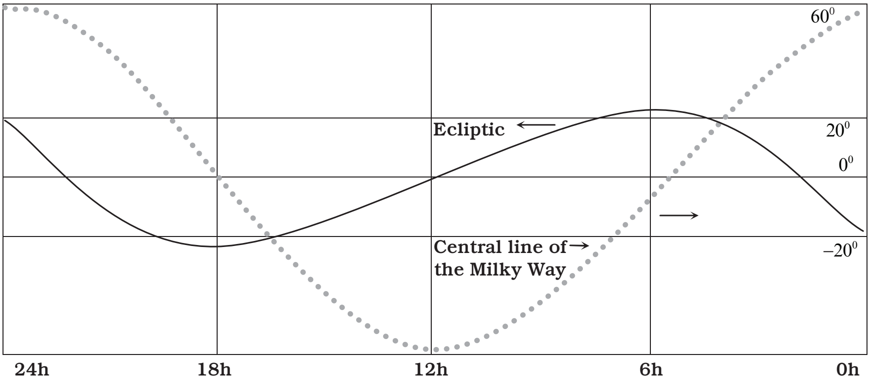

Fig. 1.6 The Milky Way is not located within the tropic circles, and its central line is inclined at 62^0 to the celestial equator. Therefore, it is outside of the region which dries up by the motion of the sun, the moon and the planets. For that reason, numerous bright stars there can collect exhalations in the sub-lunar region and the effect is seen as the hazy Milky Way

Aristotle, before closing his discussion of comets, refers to a point that was already articulated in criticizing Hippocrates' theory. He states once more that comets are rare and appear more outside than inside of the tropics. Here, besides the role of the sun, moon, and planets in dissolving the hot and dry exhalation in the tropics, Aristotle introduces a more important cause for the rarity of the comets. The chief reason, is the gathering of exhalations in the Milky Way region, which is outside of the tropics. This statement, in fact, changes the topic of discussion to the Milky Way (section 8 in *Meteorology*), where Aristotle illustrates his theory of the Milky Way and shows one more time how shooting stars, comets, and the Milky Way are related to each other and originate from a single principle.

The Milky Way

Aristotle's theory of the Milky Way is basically the same as his theory of dependent comets. As the dependent comet is seen due to the combustion of the dry exhalation under the influence of a single fixed star or a planet, 'the whole of the heavens' can cause a similar effect. Since the distribution of the fixed stars is not homogeneous throughout the sky, obviously there are portions that are highly populated compared to other portions. Consequently, those rich star fields can ignite more exhalations in the sub-lunar region. Accidentally, the high-populated parts of the sky are not located within the tropic circles, which means that they are located outside of the strip that dries up by the motion of the sun, the moon, and the planets (Fig. 1.6).

Consequently, there is enough exhalation to be collected under the bright stars of the Milky Way region. Aristotle claims that the Milky Way is brighter in the part where it is double and this part is crowded by numerous luminous stars and constellations.[44] Thus, "it is natural to suppose that they are the most appropriate cause of the affection in question."[45]

Aristotle's Theory of Comets: A General Evaluation

Aristotle's theory of comets was one of the most widely accepted and long-lasting theories in the history of natural philosophy. Although most of Aristotle's doctrines in astronomy, physics, zoology and, even meteorology were modified, changed, or even rejected by medieval scholars, his theory of comets remained almost intact. This was not a consequence of triviality of his cometary theory or its neglect by Aristotle's commentators or critics; it was due to the compatibility of the theory with the available observations and its ability to answer questions concerning the appearance and motion of comets. Whilst we will discuss the ideas of Aristotle's successors in the next section of this chapter, it is pertinent now to consider the observational aspects of Aristotle's theory of comets.

Comets are sporadic. Contrary to the planets, their paths are not confined to a distinct part of the sky, and they can be seen in any elongation from the sun. The brightest part of the comet, the coma or head, is not a shiny and twinkling point like a bright star or planet, rather it is a fuzzy patch of light without any clear edge. Comets are not similar to each other and each one may have a different size, brightness, and path. But, above all of these irregularities associated with comets, it is their tails that make these objects peculiar. The length, width, orientation, brightness, and even color of the tails are different in various comets. While they are visible, comets do not have a constant brilliancy and their tails do not have a fixed length. In the clear night skies of ancient times, where there was no sign of pollution, especially light pollution, keen eyes should have distinguished many details of comets. Evidently, any theory of comets ought to be able to give explanations for these observed features.

Aristotle mentions in the *Meteorology* that he witnessed at least two comet appearances and had information about several others. His careful generalization of the basic information he had about comets resulted in a powerful theory which was able to explain most of the above-mentioned peculiarities of comets. First of all,

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[44] Ibid., 346^{a} 20–30. The part of the Milky Way that Aristotle calls 'double' is located in the vicinity of the constellation Cygnus, which is best seen in the summer. The brightest part of the Milky Way in the northern hemisphere is towards Sagittarius (the direction of the galactic center) which is in the south of Cygnus. See Valerie Illingworth, *Macmillan Dictionary of Astronomy* (London: 1985), pp. 234–235.

[45] Aristotle, *Meteorology*, 346^{a} 30–35.

Aristotle freed these objects from the zodiac by arguing against the celestial nature of the comets. The theory that attributed comets to the conjunction of planets or planets with fixed stars did not have a firm observational basis. Although the planetary theory of Hippocrates and Aeschylus might be a plausible theory for those comets seen within the zodiac, Aristotle's access to more observational evidence enabled him to emphasize the possibility of cometary appearances in the whole sky. Even though Aristotle's own theory predicts more cometary appearances outside of the zodiac, it does not mean an exclusion of comets from the zodiac. It is only a matter of distribution of the comets in the sky and creates a consistency between Aristotle's theory of comets and his theory of the Milky Way.[46]

The other important advantage of Aristotle's theory is its ability to explain the sporadic nature of the comets. The theory is based on a set of completely non-predictable phenomena: the rising of hot and dry exhalations, the part of sky where they move, and the time that all the 'right' elements meet together to shape the final product are not foreseeable. Therefore, Aristotle's theory not only explains the infrequent appearance of the comets, it also justifies the randomly distributed trajectories of the comets. On the other hand, the nature of the process, that is the burning of hot and dry exhalation, can explain the smoky shape of the comet and the formation of the tail. Moreover, it gives reasons for the fading and disappearing of comets.

Aristotle's theory, however, had some crucial problems, which became more and more noticeable under the light of new observations. One of the gravest problems in this theory was related to the orientation of the cometary tails. As explained above, the comet and its tail is driven by the motion of the upper parts of the fire layer, which in turn moves under the influence of the celestial sphere. In Aristotle's configuration of the celestial spheres, which is a modified version of the Eudoxus-Callippus system, there is not an *unrolling* sphere between the innermost sphere of the moon and the terrestrial sphere. To avoid the motion of the outermost sphere of one planet being disturbed by the motion of the innermost sphere of the next planet, Aristotle introduced a number of additional spheres named unrollers. Since there was not a planet under the sphere of the moon, there was no need to add such a neutralizing sphere between the moon and the earth. The uppermost part of the so-called fire layer is in touch with the innermost sphere of the moon.[47] In both

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[46] Comets' speed is at maximum when they are closest to the sun. Therefore, comets are seen for a short while during the time of perihelion passage. In addition, since in the time of perihelion passage the comet is very close to the sun in the horizon (either at evening or before sunrise) the visibility time is short. It is possible that due to these reasons Aristotle's information about the time that comets are seen inside the tropic circle or close to that was insufficient.

[47] For the details of the Eudoxus-Callippus model and Aristotle's modification see: Otto Neugebauer, *A History of Ancient Mathematical Astronomy*, 3 vols. (New York: Springer–Verlag, 1975), vol. 2, pp. 624–627, 677–685, Dreyer, *From Thales to Kepler*, pp. 87–122, and James Evans, *The History and Practice of Ancient Astronomy* (Oxford: Oxford University Press, 1998), pp. 305–312.

arrangements of the lunar spheres, either by Eudoxus with three nested spheres or by Callippus with five spheres, the dominant motion imposed on the upper part of the fire layer is the east-west daily motion of the celestial sphere.[48]

If the fire layer follows the east-west motion of the celestial sphere, then the orientation of *all* cometary tails must lie on an east-west line. Comets may have prograde or retrograde motion, but as we will see later, their tails are always pointed away from the sun. This orientation is not always in the east-west direction. When a comet is far away from its perihelion, its tail may be seen in such an orientation, but as the comet approaches its perihelion, the orientation of the tail deflects drastically, except in rare cases in which its inclination (angle between the orbital plane of the comet and plane of ecliptic) is very small.

Aristotle's account of cometary tails is implicit and very short. He says "the kind of comet varies according to the shape which the exhalation happens to take. If it is diffused equally on every side the star is said to be fringed; if it stretches out in one direction it is called bearded".[49] A few lines later, using the analogy of burning of a 'mass of chaff', he says that fire stops at the densest part of the fuel and the 'whole' may begin to move. Furthermore, in the case of dependent comets, he just says "the tail stands in the relation of a halo to the star, except that the colour of the halo is due to reflection, whereas in the case of comets the colour is something that appears actually on them."[50] Most probably, Aristotle's ambiguous description of the cometary tails is a result of his insufficient data; otherwise, he would have employed observational facts to elucidate his theory as he had done in other aspects of his cometary theory.

Aristotle's explanation of dependent comets is also incomplete. He does not give any examples of the occurrence of such a comet. It is obvious from the Aristotelian fundamentals of cometary formation that the brighter the star (or planet), the higher the probability of attraction of an exhalation by the star. However, in Aristotle's account there is no report of any accumulation of exhalation under bright fixed stars or under planets when they are at their highest luminosity. On the other hand, Aristotle does not explain the process of burning of the attracted exhalations clearly. In the case of the independent comets, it is necessary that the right amount of new exhalation continuously refresh the process; but it is not clear if the same condition is required for continuation of dependent comets.

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[48] In Eudoxus's model, three homocentric spheres produce the motions of the moon: the outermost sphere rotates westward once a day to produce the daily motion; the middle sphere turns every 18.6 years to create the motion of the nodes of the moon, and the innermost sphere turns once a month to produce the monthly motion. Callippus added two more spheres to produce the lunar anomaly. It is not exactly known how the additional spheres produced lunar variable speed. See: Evans, *History and Practice*, p. 311.

[49] Aristotle, *Meteorology*, 344^{a} 20–25.

[50] Ibid., 344^{b} 5–10.

Despite these problems, Aristotle's theory was able to answer major questions about the formation and extinction, material, motion, and even the subsequent effects of the comets on the terrestrial realm.[51] We will see in the next chapter that even though most of Aristotle's commentators and critics, from Alexander of Aphrodisias to Ibn-Rushd (Averroes), expressed different viewpoints on some issues of Aristotle's *Meteorology* or modified some concepts, they followed Aristotle's footsteps in his discussion of comets. Perhaps, these successors of the Aristotelian theory of comets and its explanation of the randomness of cometary nature were the main reasons that for a long time, from Aristotle to the dawn of the modern era, none of the astronomers and natural philosophers we know about bothered themselves with producing accurate observational data about comets.

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[51] In *Meteorology* 344^b 20–345^a 1–5, Aristotle discusses the effects of comets on the terrestrial realm. In the framework of his cometary theory, he makes an acceptable link between the appearance of the comets and occurrence of dry and windy weather. However, in spite of such a plausible correlation between comets and atmospheric conditions – which was completely out of the domain of the astrology – comets became one of the main elements of astrological prediction by Aristotle's followers, Platonists or neo-Platonists in medieval times. We will discuss this subject later.

Chapter 2
After Aristotle

Cometary theories continued in three different traditions after Aristotle. One tradition, which followed Aristotle and was widely accepted, continued in the Islamic world and then transferred into pre-modern Europe. The second tradition, which was highly developed by the second century A.D., followed an astrological trend and lasted much longer than the first tradition. Both believers in the celestial and meteorological origins of comets were involved in this tradition. The third one, developed by Seneca (ca. 63 A.D.), was the continuation of those theories which assumed comets to be celestial objects. We will discuss Seneca first, and then will focus on the continuation of Aristotle's cometary theory in the Islamic world and early modern Europe. The astrological tradition is outside the interests of this study.

Non-Aristotelian Theory of Comets

Seneca

Seneca did not actually develop a physical theory of comets. In a large part of his discussion of comets in the *Naturales Quaestiones*, he refutes the preceding cometary theories and tries to prove the celestial origin of comets. Aristotle, as we have seen, relegated the comet to the terrestrial region, based on dissimilarities he found between comets and celestial bodies. In contrast, Seneca focused on resemblances between comets and heavenly bodies to elevate the comet to the ethereal realm:

> A comet seems to have certain things in common with them [planets and stars]: rising and setting, the same appearance, although a comet is scattered and extends farther. It is also fiery and bright. And so, if all planets are earthy bodies, comets will also have the same condition. But if comets are nothing but a pure fire which remains for six months at a time and they are not broken up by the turning and speed of the universe, then stars, too, can consist of thin matter and are not scattered by this continuous rotation of the sky.
>
> Also, it will be relevant to investigate these matters so that we may know whether the universe travels around while the earth stands still or whether the earth turns while the universe stands still. […] The subject deserves study so that we may know what our status is,

T. Heidarzadeh, *A History of Physical Theories of Comets,*
From Aristotle to Whipple,

> whether we possess the most inactive abode or a very swift one, whether god causes all things to move around us or causes us to move around.[52]

It is remarkable that Seneca relied on old cometary appearance reports to explain the nature of the comets; for based upon such data one could determine the periodicity of comets. Any sign of periodicity, obviously, was further evidence for the celestial origin of the comet. For Seneca, there was a contradiction between theory and observation in Aristotle's theory of comets: while the comets were assumed to be temporary phenomena in the atmosphere, there was observational evidence that some comets had been visible for more than six months. Furthermore, it was difficult to accept that in a part of the atmosphere subjected to daily and seasonal changes, burning clusters of exhalation followed such smooth trajectories and showed such regular increase or decrease in brightness.

Seneca, based on these unsolved observational and theoretical difficulties in Aristotle's theory of comets, concluded that the comet is a permanent supra-lunar phenomenon. It moves like a planet on its own path (though the path is not known) and fades out not because it runs out of fuel but because it moves farther away from the observer. Seneca's main contribution in the history of cometary theories is his negative assessment of all preceding theories and criticism of their weak reasoning:

> I do not think that a comet is just a sudden fire but that it is among the eternal works of nature. First of all, all things the atmosphere creates are short-lived, for they are produced in an unstable and changeable element. How can anything remain the same for long in atmosphere when atmosphere itself never remains the same for very long? […] Second, if fire clings to its fuel it should always descend, for the atmosphere is thicker the closer it is to the earth. A comet never descends all the way to the lowest regions of the atmosphere and does not approach the ground. […] None of the ordinary fires in the sky has a curved path. It is characteristic of a planet to follow a curve. And yet did other comets do this? I do not know. The two in our time did. Next, everything which a temporary cause sets afire quickly dies out. […] Comets, however, do something: they move, preserve their continuity, and are uniform. If their fires were merely collected, the sudden occurrence of some accidental cause, they would become larger or smaller on alternate days. […] A comet has its own position and so is not quickly expelled but measures out its own space.[53]

Seneca, on the other hand, did not confine his cosmological ideas to the rules established by observational astronomers. If the five planets were moving in a specific band in the sky, it did not mean that *all* planets would be discovered on the same band. In other words, to observe a comet outside of the zodiac does not imply that the phenomenon is not celestial:

> "If a comet were a planet," someone said, "it would be in the zodiac." Who places one boundary for planets? Who confines divine things in a narrow space? Yet those very stars which you believe are the only ones that move obviously have circle that are different from one another. Why, then, should there not be other stars which have entered on their own route far removed from them?[54]

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[52] Seneca, *Naturales Quaestiones*, trans. Thomas H. Corcoran, 2 vols. (Cambridge: Harvard University Press, 1971–1972), II: p. 231.

[53] Ibid., II: 273–275.

[54] Ibid., II: p. 275. I have replaced Corocran's anachronistic 'orbit' with the more accurate 'circle'.

Seneca did not elucidate his ideas in a consistent theory of comets. He brought into question the whole of cometary theory and believed that contemporary knowledge of astronomy was not capable of solving those problems. He was very optimistic that in the future men would discover everything unknown about comets.

Since Seneca did not explain the formation of the tail and the material and motion of comets, his ideas about comets remained marginal for centuries. However, his criticisms were very thought provoking and inspiring. In the sixteenth and seventeenth centuries he became the center of focus for critics of Aristotle's theory of comets, and his revolutionary conjectures on the origin and trajectory of comets stimulated astronomers to perform accurate observations.

Continuation of Aristotle's *Meteorology* in the Early Medieval and Islamic Era

Theoretical meteorology, as laid down by Aristotle, continued in the Hellenistic and Roman period and transferred into the Islamic world. Although some commentators on Aristotle's *Meteorology* or authors inspired by this book criticized a number of Aristotle's ideas, their natural philosophy remained completely Aristotelian. Before the eighth century, when Islamic scholars gave a new momentum to scientific activities, commentators on Aristotle played a major role in transferring and developing meteorological theories. Among them were Theophrastus (*fl.* 320 B.C.), Alexander of Aphrodisias (second century A.D.), Olympiodorus (*fl.* 540), and Philoponus (*ca.* 490–570). One can add Ptolemy to this list, though there is no evidence of his writings on a theory of comets. Ptolemy's astronomy, which was the main way of dealing with celestial bodies in almost entire 'populated quarter' for about fifteen centuries, assumed comets to be sub-lunar phenomena. Consequently, for centuries, in any standard astronomy textbook comets were not treated as celestial objects. Ptolemy had a major role in the astrological tradition too and was one of the main sources for cometary prognostication.[55]

The commentators explained Aristotle's theory of shooting stars more clearly and criticized his Milky Way theory but did not add any new concept to Aristotle's theory of comets. Alexander of Aphrodisias rendered the *Meteorology* faithfully and only criticized Aristotle's theory of wind. He asked why, if wind is the motion of exhalations from the earth, it does move horizontally. Olympiodorus asked the same question along with a few others about the formation of rainbows and halos.

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[55] For a survey of Greek and Islamic commentaries on Aristotle's *Meteorology* see Lettinck, *Aristotle's Meteorology*, pp. vii–ix, 1–31; pages 39–96 contain a detailed account of the commentators' interpretations of the structure of the atmosphere and phenomena in the upper atmosphere. Also see Schoonheim's introduction in Pieter L. Schoonheim, *Aristotle's Meteorology in the Arabico-Latin Tradition: A Critical Edition of the Texts, with Introduction and Indices* (Leiden: Brill, 1999).

He introduced a new way to ignite the exhalation that forms a comet and criticized Aristotle's theory of the Milky Way gravely. Following Aristotle in his explanation of comets, he only proposed that if a cluster of hot and dry exhalations with an appropriate density were hit by a shooting star it would transform into a comet.[56]

Olympiodorus' questioning of Aristotle's theory of the Milky Way, which was based on observational facts, had a great influence on his successors, especially in the Islamic world. Olympiodorus argued first, that if the Milky Way were a sub-lunar phenomenon it would change during the year due to the changes that occur in rising of exhalations from the earth, and second, that the shape of the Milky Way would not be the same for observers in different places on the earth. Based on Ptolemy's *Almagest*, he agreed that the moon has parallax, but the Milky Way does not, showing it cannot be located under the moon. If the Milky Way were a meteorological phenomenon, planets should be seen in different colors when passing through it; and the Milky Way should not be seen where it crosses the zodiac, for the sun, the moon, and planets dissolve the exhalations in the zodiac.[57] Philoponus also questioned Aristotle's Milky Way theory in the same manner.

A string of commentators, translators, and philosophers transferred all of these ideas to the pre-modern era. From the eighth century to the twelfth century, Muslim scholars not only translated all available meteorological writings from the Greek and Hellenistic traditions, they also developed different ideas or elaborated the previously stated criticisms.[58] A summary of these ideas is given in Table 2.1, which in large part is an abstract of chapter II of Paul Lettinck's book, *Aristotle's Meteorology and its Reception in the Arab World*. The table covers only theories of shooting stars, the Milky Way, and comets. In fact, from the beginning of the thirteenth century when the translation movement commenced in Europe, scholars had access to the original meteorological theories of Aristotle along with their highly structured criticisms and commentaries.[59]

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[56] Lettinck, *Aristotle's Meteorology*, pp. 72–73.

[57] Ibid., pp. 6–7, 71–74.

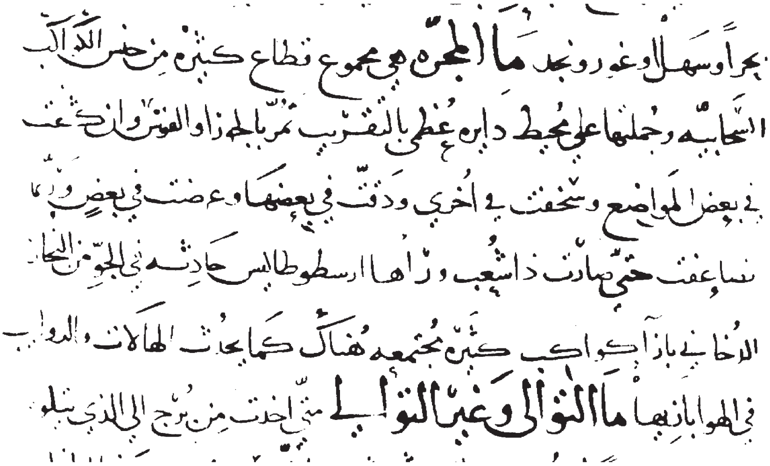
[58] Although a majority of Muslim scholars criticized Aristotle's theory of the Milky Way and accepted the phenomenon as celestial, almost all of them believed that the comets were sub-lunar phenomena. Criticism of Aristotle and Ptolemy, which became a tradition in the Islamic world since Muslims first acquaintance with Greek science, concentrated mainly on those concepts that either intrinsically had problems or were subject to change in the light of new observations and measurements. As the best example for the first group one may refer to Muslim astronomers' attempts to introduce a new configuration of the spheres for the planets, and for the second group, one may point to debates on the origin of the Milky Way. Many Muslim astronomers and philosophers placed the Milky Way in the celestial region based on the fact that it does not show a parallax. So far, I have not seen any Islamic reference mentioning particular observations designed to measure the parallax of Milky Way or a comet. However, emphasis on the celestial origin of the Milky Way due to lack of parallax is an indication of their attempts to measure it.

[59] In the second half of the twelfth century, Gerard of Cremona translated Books I–III of Aristotle's *Meteorology* from Arabic into Latin. Other translations from Greek, as well as translations of the works of the Arab commentators and philosophers, such as Ibn Rushd and Ibn Sīnā, continued criticisms on Aristotle's meteorological ideas in pre-modern Europe. See Lettinck, *Aristotle's Meteorology*, pp. 1–17.

Table 2.1 Continuation of Aristotle's theoretical meteorology in the Islamic world. Only shooting stars, the Milky Way and comets are listed here. This table in a large part is an abstract of chapter II of Paul Lettinck's *Aristotle's Meteorology and Its Reception in the Arab World*

Commentator/philosopher	Shooting Stars *(SS)*	The Milky Way *(MW)*	Comets *(C)*
Alexander of Aphrodisias (2nd A.D.)	• Follows Aristotle • More details on chasm & trench	• Follows Aristotle	• Follows Aristotle
Olympiodorus (fl. 540)	• Questions 2nd kind of *SS*	• Criticizes Aristotle • *MW* is celestial	• *SS*s also can be a *C* if they hit a dense cluster of exhalation
Philoponus (ca. 490–570)	• Follows Aristotle • More details on chasm & trench	• Criticizes Aristotle • *MW* is celestial	• Follows Aristotle
Ibn al-Biṭrīq (d. ±830)	• Follows Aristotle • Some details on chasm & trench	• Criticizes Aristotle • *MW* is celestial	• Incomplete, but Aristotelian, • Differs in criticizing Hippocrates' theory
Hunayn ibn Ishāq (d. 876)	• The same as above	The same as above	The same as above
Pseudo-Olympiodorus (Arabic version of Olympiodorus' commentary on Aristotle's *Meteorology*)	• Divides *SS* into two kinds • Some details on chasm & trench	• Criticizes Aristotle • *MW* is celestial	• Follows Aristotle • *SS*s can also be *C* if they hit a dense cluster of exhalation
Ibn Sīnā (d. 1037)	• Follows Aristotle	• Doesn't explain explicitly	• Follows Aristotle • Defines novae as a kind of long lasting comet
Ibn al-Haytham (d. ca. 1040)		• Criticizes Aristotle • *MW* is celestial	
Bīrūnī (973–1048)	• Follows Aristotle	• *MW* is celestial	• Follows Aristotle
Ibn Rush (d. 1098)	• Basically Aristotelian • Some details on types of shooting stars	• Similar to Ibn Bājja's theory (below)	• Follows Aristotle
Ibn Bājja (d. 1138)		• Light of closely packed stars refract from layers of sub-lunar material	
Tūsi (1201–1274)	• Follows Aristotle	• *MW* is celestial	• Follows Aristotle

As Table 2.1 shows, almost all Islamic commentators on Aristotle's *Meteorology* adopted Olympiodorus's version of the Milky Way theory, but they followed Aristotle in treating comets. Islamic astronomers also found five stars of the same nature as the Milky Way. These had not been catalogued by Ptolemy. Abd al-Rahmān al-Sūfi (903–986 AD), a Persian astronomer, prepared a new star catalogue in 964 AD, in which he recorded a star in the constellation Andromeda as a " patch of cloud."[60] This was, in fact, the Andromeda galaxy (M31) which keen eyes in a dark and clear sky can see as a small piece of cloud. The total number of these hazy stars, which Bīrūnī defined as "stars of the character of the Milky Way, like fragments of cloud," and catalogued as fixed stars, he found to be five.[61] He did not explain the phenomenon further (Fig. 2.1).



بحرا وسهيل او غيره ونحوه ما المجرة هي مجموع قطاع كثيرة من جنس الكواكب

السحابية وجملتها على محيط دائرة عظمى بالتقريب تمر بالجوزاء والقوس وان كانت

في بعض المواضع وتخفت في اخرى ودقت في بعضها وعرضت في بعض وربما

تضاعفت حتى صارت ذا شعب ورآها ارسطوطاليس حادثة في الجو من البخار

الدخاني بازاء كواكب كثيرة مجتمعة هناك كما تحدث الهالات والذوائب

في الهوا بازائها ما التوالي وغير التوالي متى اخذت من برج الى الذي يتلوه

Fig. 2.1 A section of Bīrūnī's *al-Tafhim* (*The Book of Instruction in the Elements of the Art of Astrology*) where he defines the Milky Way: "The Milky Way is a collection of countless fragments of the nature of nebulous stars." Bīrūnī mentions Aristotle's idea that the Milky Way is formed in the atmosphere from fiery exhalation in front of the assembly of numerous stars, as halos are formed in the air.[64] The book was written in1029

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[60] Richard Hinckley Allen, *Star Names, Their Lore and Meaning* (New York: Dover Publications, 1963), p. 39.

[61] Abū Rayhān al-Bīrūnī, *al-Tafhīm li-Awāil Sinā't al-Tanjīm* (*The Book of Instruction in the Elements of the Art of Astrology*), trans. Ramsay Wright (London: 1934), p. 69. Aristotle also states that some stars have a tail (cit. n. 33), however, the Islamic astronomers did not relate them to comets. For example, Bīrūnī in his discussion of the number of the fixed stars, refers to those five cloudy stars after giving the number of 'regular' fixed stars, and says that "with them [cloudy stars] the number of stars registered is one thousand and twenty-two in all." (*al-Tafhīm*, p. 69). Ptolemy's catalogue contains 1,028 fixed stars. There is inconsistency between Ptolemy and Bīrūnī in sorting and counting of the stars. See *al-Tafhīm*, p. 68.

Ibn Sīnā, a contemporary of Sūfi and a leading figure in Islamic natural philosophy, discussed the 'phenomena in the upper atmosphere' extensively. He followed Aristotle in describing the shooting stars and comets and even defined novae as a kind of long lasting comet.[62] However, there is no trace of the Milky Way in Ibn Sī nā's works: neither in *Shifā*, nor in *Dānishnameh*, and *Najāt*. The only exception is a short paragraph in *Qurāze ye Tabiyyāt* (in Persian) in which the author considers the Milky Way as a celestial phenomenon. This book is attributed to Ibn Sīnā and not written by him. It seems that there were two traditions concerning the Milky Way among the Islamic scholars. One, the "physical", tried to explain the phenomenon in the framework of the Aristotelian theory. The other, the "mathematical," believed that it was a celestial phenomenon. To the first tradition belong authors like Ibn Bājja and Ibn Rushd, despite the fact that they tried to give some place to the light of the stars in formation of the Milky Way. What they chose at the end was a sort of intermediate solution. To the second tradition belong the authors like Ibn al-Haytham and Bīrūnī (in his *Al-Qānūn al-Mas'ūdī* and *al-Tafhim*). For this second group, the decisive argument is the absence of parallax and they do not enter into the details of the Aristotelian theory.[63]

In the establishment and continuation of the Aristotelian theory of comets, Ptolemy had a very important role. He also facilitated the development of cometary astrology. Ptolemy, on the one hand, remained completely Aristotelian in the *Almagest*, in such a way that in this work, which was devoted to mathematical astronomy, did not mention comets even a single time.[65] On the other hand, in the *Tetrabiblos* he used comets in a totally astrological context and treated them as omens heralding unfortunate events.[66] Although Aristotle himself concluded that the appearance of comets was a sign of dry and hot weather ahead, there is a fundamental difference between him and Ptolemy in using comets as an aid for prediction. A comparison of their conclusions shows their conceptual differences clearly.

> **Aristotle**: The fact that comets when frequent foreshadow wind and drought must be taken as an indication of their fiery constitution. For their origin is plainly due to the plentiful supply of that secretion. Hence the air is necessarily drier and the moist evaporation is so dissolved and dissipated by the quantity of the hot exhalation as not readily to condense into water. But this phenomenon too shall be explained more clearly later when

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[62] Lettinck, *Aristotle's Meteorology*, pp. 81.

[63] Hossein Ma'soumi Hamadani, "La Voie Lactee: Ibn Al-Hayṯam et Ibn Rušd," in *Proceedings of the Cordoba Colloquium on Ibn Rushd*, forthcoming.

[64] al-Bīrūnī's, *al-Tafhīm*, p. 87. Wright's translation of the part that al-Bīrūnī talks about Aristotle's idea is ambiguous: "it [the Milky Way] is formed by an enormous assemblage of stars screened by smoky vapours in front of them." But, al-Bīrūnī states that the Milky Way is formed in the atmosphere from fiery exhalation (*bukhār dukānī*) in front of or opposite to a populated assemblage of stars.

[65] From the meteorological phenomena, only the Milky Way has mentioned in the *Almagest* without any reference to its origin or any explanation about its nature or location. Ptolemy just defines the boundaries of the Milky Way among the fixed stars. See Ptolemy, *Almagest*, trans. G. J. Toomer (Princeton: Princeton University Press, 1998), pp. 400–404.

[66] Ptolemy, *Tetrabiblos*, trans. F. E. Robins (Cambridge: Harvard University Press, 1998), pp. 193, 217.

> the time comes to speak of the winds. So when there are many comets and they are dense, it is as we say, and the years are clearly dry and windy.[67]
>
> **Ptolemy:** We must observe, further, for the prediction of general conditions, the comets which appear either at the time of the eclipse or at any time whatever; for instance, the so-called "beams," "trumpets," "jars," and the like, for these naturally produce the effects peculiar to Mars and to Mercury – wars, hot weather, disturbed conditions, and the accompaniments of these; and they show, through the parts of the zodiac in which their heads appear and through the directions in which the shapes of their tails point, the regions upon which the misfortunes impend. Through the formations, as it were, of their heads they indicate the kind of the event and the class upon which the misfortune will take effect; through the time which they last, the duration of the events; and through their position relative to the sun like-wise their beginning; for in general their appearance in the orient betokens rapidly approaching events and in the occident those that approach more slowly.[68]

In the framework of his natural philosophy, Aristotle takes a logical approach and seeks a causal relationship between different natural phenomena. His prediction is simply based on 'thermal' changes in the earth: excess of heat increases the amount of hot and dry exhalation, which causes the formation of comets, which in turn, herald dry, hot and windy weather.[69] Ptolemy, however, takes an astrological approach: he tries to interpret the geometrical arrangement of comets with the planets or stars in order to prognosticate not only impending natural phenomena, but also subsequent *civil* disasters.[70]

Comets in the Islamic World

Ptolemy did not add a word to the physical theory of comets, but he canonized cometary prophecy, which continued and developed after him. Beginning with the eighth century, when scholars in the Islamic civilization translated Greek and Hellenistic scientific and philosophical writings, Ptolemaic astronomy became the standard astronomy in the Islamic world.[71] The adoption of Aristotle's meteorology

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[67] Aristotle, *Meteorology*, 344^b 20–30.

[68] Ptolemy, *Tetrabiblos*, pp. 193–194.

[69] It should be mentioned that in Aristotle's meteorology, wind is not moving 'air', it is moving 'dry exhalation'. See Aristotle, *Meteorology*, I, 13 and II,4.

[70] Two major figures in the development of astrology before Ptolemy are Seneca and Pliny the Elder (23–79 A.D.). Pliny did not have a specific theory of comets and mostly followed Aristotle. He described nine different types of comets and used the color, orientation of tail and location of the comet as criteria to predict natural or civil disasters. He explained these ideas in section 22 and 23 of book II of his *Natural History*. See Pliny the Elder, *Natural History*, trans. H. Rackham, W. H. S. Jones, and D. E. Eichholz, 10 vols. Loeb Classical Library (Cambridge: Harvard University Press, 1969–1986). For Pliny's cometary prognostication see: Schechner Genuth, *Comets, Popular Culture*, pp. 20–26, and Donald K. Yeomans, *Comets*, pp. 10–14.

[71] The *Almagest* was translated into Arabic several times in the ninth century. At the same time, Muslim astronomers had access to some Persian and Indian astronomical sources which influenced Islamic astronomy, especially in mathematical aspects. See F. Jamil Ragep, "Arabic/Islamic Astronomy," in J. Lankford, ed., *History of Astronomy: An Encyclopedia* (New York: Garland, 1997), pp. 17–21.

and the reception of Ptolemaic astronomy in Islam led to the acceptance of comets as a subject of meteorology, and at the same time, a significant issue of astrology. While the majority of Islamic astronomers accepted the Milky Way as a celestial phenomenon in most astronomical texts, they rarely mentioned comets. In some Islamic *Zījes*[72] there are tables for the motion of a kind of 'star' called *al-Kaid* (or *al-Kayd* with a different transliteration), which is described as a comet.

Abū 'Abd Allāh Muhammad al-Khawārazmī (tenth century A.D.), in his encyclopedic work named *Mafātīh al-'ulūm* (*The Keys of the Sciences*) defines al-Kaid as "an ill-omened invisible star in the heaven, having a known ephemeris from which its position can be derived."[73] The earliest source that mentions al-Kaid as a comet is *al-Mughnī* written in 829 A.D. by a Christian astronomer and astrologer of Baghdad named Ibn Hibintā. He defines al-Kaid as "one of the stars with a tail; it appears once every hundred years and travels retrogradely, like the lunar nodes, through the zodiac, making one sign in 12 years."[74] The star was assumed to have six companions, all traveling the ecliptic with the same speed and unvarying distance from al-Kaid. Ibn Hibintā also gives a rule to compute al-Kaid's motion. Kennedy published a list of daily and annual motion of these stars using ten sources wherein periods of motion of al-Kaid were given.[75] The sources containing these data were astronomical tables in which the authors did not discuss natural philosophy; only in one astrological source written by Abū Ma'shar, did the author explicitly recognize the comets as celestial objects. This treatise, titled *Albumasar in Sadan* (written in 829 A.D.), while discussing the astrological features of the comets, takes a glance at the physical aspects of the phenomena:

> The philosophers say, and Aristotle himself, that comets are in the sky in the sphere of fire, and that nothing of them is formed in the heavens, and that the heavens undergo no alteration. But they all have erred in this opinion. For I saw with my own eyes a comet beyond Venus. And I knew that the comet was above Venus, because its color was not affected. And many have told me that they have seen a comet beyond Jupiter and sometimes beyond Saturn.[76]

Abū Ma'shar then discontinued the discussion of the origin of comets and returned to his previous subjects. Despite the fact that Abū Ma'shar did not mention the origin of

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[72] For a recent reference on the *Zījes* see: David A. King, J. Samsó and B. R. Goldstein, "Astronomical Handbooks and Tables from the Islamic World (750–1900): an Interim Report," *Suhayl*, 2 (2001), 12–105. For a comprehensive discussion see E.S. Kennedy, "A survey of Islamic Astronomical Tables," *Transactions of the American Philosophical Society*, 42:2 (1956), 123–177.

[73] W. Hartner, "al- Kayd," *The Encyclopedia of Islam*, new ed., 10 vols. to date (Leiden: 1960 to present), vol. IV, pp. 809–811.

[74] Ibid., p. 810.

[75] E. S. Kennedy, "Comets in Islamic Astronomy and Astrology," *Journal of Near Eastern Studies*, 16 (1956), 44–51.

[76] L. Thorndike, "Albumasar in Sadan," *Isis* 45 (1954), p. 23. Albumasar (Abū Ma'shar Ja'far ibn Muhammad ibn 'Umar al-Balkhī), died in 886, was one of the most eminent figures in Islamic astrology. Most of his works were translated into Latin from the twelfth century and some of them printed in incunabula. The treatise discussed here, which was published by Thorndike using two manuscripts from the fourteenth and fifteenth centuries, was not printed in Europe. See Thorndike, *op. cit.*, p. 22.

comets in his main astrological writings, this short passage contains some interesting points. Firstly, to prove that the comet has a celestial origin, he mainly emphasizes observational facts. Secondly, he does not refer even to a single philosophical opponent of Aristotle to support his own findings. Finally, he does not explain whether this discovery has any influence on cometary prognostication. The latter issue is not within our focus of interest, but his observation would have been a strong source of inspiration for astronomers to measure cometary parallaxes.[77] However, such inspiration, at least among the Islamic astronomers, has not been reported.

The data about al-Kaid in the Islamic *Zījes*, as Kennedy concludes, are not driven by observation. The earliest author, Ibn Hibintā, states that he has taken the computation rule from some ancient books; and some other authors also have mentioned their skepticism in the matter. On the other hand, most of the authors have been careless about the accuracy of the data. It is most likely that the subject had a pre-Islamic origin and just continued as a tradition in the Islamic period.[78] Hartner, in his article on "al-Kayd" in the *Encyclopedia of Islam*, defines it as a fictitious star.[79]

In addition to *Zījes*, a number of Islamic scholars have mentioned comets for a completely different purpose in their astronomical discussions. Confirming their sub-lunar origin, these astronomers were using comets as a possible criterion to prove or reject the possibility of the rotation of the earth. Ptolemy, in the *Almagest*, rejects the possibility of rotation based on various problems arising from a rotating earth inside a stationary shell of air. He also argues that a rotating earth with a shell of air (rotating with the same speed) is impossible due to similar problems.[80] However, Naṣīr al-Dīn al-Ṭūsī, a thirteenth century Persian astronomer, suggests that if the air were rotating with the earth then it would be impossible for an earth-bound observer to determine the motion of the earth. A fact adduced by Ṭūsī to prove this idea was the situation of comets. As explained earlier, the uppermost part of the atmosphere moves with the same speed as the celestial sphere, and when comets are formed there, they participate in the daily motion of the celestial sphere. Ṭūsī says that if such an idea were accepted about comets, one could also accept that air rotating with the earth would not be disturbing. Ṭūsī's idea was a subject of debate among his successors, but it is interesting that Copernicus also used the same concept to justify the rotation of the earth.[81]

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[77] For the probable influence of Abū Ma'shar on Tycho Brahe see W. Hartner, "Tycho Brahe et Albumasar," *La science au seizième siècle* (Paris, 1960), pp. 137–150. Westman discussed the influence of Abū Ma'shar on Mästlin and Brahe in: Robert S. Westman, "The Comet and the Cosmos: Kepler, Mästlin and the Copernicus Hypothesis," *Studia Copernicana* 5 (1972), 20.

[78] Kennedy, "Comets in Islamic Astronomy," p. 51. The tradition, amazingly, continued even until the sixteenth century.

[79] Hartner, "al- Kayd," p. 809.

[80] Ptolemy, *Almagest*, trans. and annotated by G. J. Toomer (Princeton: Princeton University Press, 1998), pp. 44–45.

[81] F. J. Ragep, *Naṣīr al-Dīn al-Ṭūsī's Memoir on Astronomy*, 2 vols. (New York: Springer-Verlag, 1993), vol. 2, pp. 383–385; *idem*, "Ṭūsī and Copernicus: The Earth's Motion in Context," in Mohammad Abattouy, Jurgen Renn, Paul Weinig, eds., *Transmission as Transformation*. Special Issue. *Science in Context*, 14 (2001), 145–163.

Comets remained at the focus of interest of astrologers in the Islamic world and were mainly discussed in astrological context. Cometary appearances were mostly reported in general history books, literary writings or chronicles. As a result, though the authors of those books might have been familiar with astronomy, the way they reported comets in their literary or historical writings was not accurate. One encounters several reports like "in the beginning months of the year 860 A. H. (1455/6) a comet with an extreme exaltedness and dreadfulness was resident in the realm of the sign Taurus."[82] Such reports contain an approximate date and position of the comet, but they are not useful to calculate its trajectory or duration in the sky. In my survey of some Persian and Turkish sources, I have not found so far any report showing sequential observations to determine the trajectory or other properties of comets, though general descriptions like the one mentioned above are numerous. An extensive survey of Arabic sources by David Cook, which contains more than one hundred reports of comet appearances and meteor or meteor showers, shows the same low accuracy in the majority of the reports.[83]

Some other indications also imply that there was not a serious interest in cometology among Islamic scholars. If writing distinct treatises on a specific topic is a criterion of interest, comets were among the less-attractive topics. As an example, a survey of a major catalogue of astronomy literature shows that of nearly 2,450 works written from 820 to the first decades of the twentieth century, only two distinct treatises were produced about comets, while there were six treatises on the rainbow, 273 *Zījes* (133 with unknown authors) and 608 treatises on astronomical instruments (229 with unknown authors).[84] It is also interesting that in the main languages of the Islamic world, Arabic, Persian and Turkish, there is a limited vocabulary relating to comets compared to Latin. While in Latin numerous terms, either technical, verbal expressions, or fanciful words, have been used to denote comets,[85] there are less than ten terms related to the phenomenon in the *three* above mentioned Islamic languages altogether.[86]

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[82] Ghiyāth al-Dīn ibn Humām al-Dīn al- Husainī, *Tārikh Habīb al-Siyar*, 4 vols. (Tehran: Khayyām Publications, 1974), vol. 4, p. 55.

[83] David Cook, "A Survey of Muslim Material on Comets and Meteors," *Journal for the History of Astronomy*, 30 (1999), 131–160.

[84] Ekmeleddin İhsanoğlu (ed.), *Osmanli Astronomi Literatürü Tarihi* (*History of Astronomy Literature During the Ottoman Period*), 2 vols. (Istanbul: 1997), vol. 1, p. CIX. The number of the cometary writings is not in the statistics worked out by the editors (pp. XCIX–CXII). With a careful survey of the "Index of the Titles in Arabic Characters" (vol. 2, pp. 1076–1111), I found only two titles on comets among all titles written in Arabic, Persian and Turkish. Obviously, comets were discussed within astrological or history texts, but there have been quite a small number of treatises totally devoted to comets.

[85] Umberto Dall'Olmo, "Latin Terminology Relating to Aurorae, Comets, Meteors and Novae," *Journal for the History of Astronomy*, 11 (1980), 10–27.

[86] A comet is called *Kawkab dū du'āba*, *dū danab* and *mudannab* in Arabic, *setāre-ye gisūdār* and *setāre-ye donbāleh dār* in Persian, and *Kuyruklu yildiz* in Turkish. In Arabic and Persian literature, there are also a few rarely used names as *fāris*, *'usīy*, and *wardī* to denote a comet with a tail like horse mane, a comet with a straight tail, and a comet like rose, respectively. See Ali Akbar Dehkhoda, *Loghatnāmeh* [Dictionary], 30 vols. (Tehran: Tehran University Press, 1964–1981).

To end this section, let us consider the observation of the 1577 comet in the last observatory of the Islamic world in Istanbul. Islamic astronomy witnessed a revival from the mid thirteenth century, when the Marāgha observatory was established in North-West Iran under the supervision of Naṣīr al-Dīn al-Tūsī. In the mid fifteenth century, a greater observatory was built in Samarqand by Ulugh Beg, who was a mathematician and a generous prince. After the fall of Ulugh Beg's dynasty in the 1450s, a number of scholars in the circle of Ulugh Beg emigrated to the newborn Ottoman Empire and had a deep influence on development of science there. In 1575, Taqī al-Din, the court astronomer of Sultan Murad III (reigned 1574–1595), established an observatory in Istanbul, fulfilling a dream that the Turkish Sultans had had from the time they conquered Constantinople in 1453. About fifteen astronomers participated in building and using the instruments, which would be used to produce a new *zīj*. However, after two years, a great comet (the famous comet of 1577) appeared in Sagittarius. Taqī al-Din predicted that the comet was a sign of the victory of the Turkish army against Persia. Although the Persian army was defeated in the war, the Turkish troops also suffered heavy losses. In the same year several dignitaries died within short intervals, and also there was a plague. Referring to these unpredicted horrifying events, Taqī al-Din's rivals (astrologers and clerics) convinced the Sultan to destroy the observatory! They believed that the comet appeared because of the establishment of the observatory and that it would go away if its cause (the observatory) were removed. The observatory was demolished at once, before Taqī al-Din was able to finalize his *zīj*.[87] It is one of the ironies of history that the destruction of the last observatory in the Islamic world coincided with the construction of the first observatory in the modern Europe by Brahe.

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[87] A Persian poet named ʻAlā al-Dīn Mansour Shirāzī illustrated the whole story in a long poem written in 1581. He explains the type of instruments and gives information about the number of Taqī al-Din's assistants and their observations. In one part he describes the comet under the title of 'Appearance of a Fiery Stellar Body.' The following is Sayili's translation of the poem. See Aydin Sayili, *The Observatory in Islam* (Ankara: Turk Tarih Kurumu Basimevi, 1988), pp. 289–292.

A still more remarkable thing is that through the ignition of vapor,
And as an occurrence pertaining to the fiery phenomena of the high regions,
A strong flame, one of those stellar bodies referred to as the seven sinister objects*
Which is quick in vengence and is called "the one with the forelock,"
Like a turban sash over the Ursa Minor stars,
It soared like the sun for many nights.
Through it the night of the Moslems became blessed
And its light was world-pervading like that of the full-moon.
In the apogee of the firmament it remained for forty days,
And sent a gush of light from the east to the west.
As its appearance was in the house of Sagittarius,
Its arrow promptly fell upon the enemies of the Religion
At the end its longitude and latitude were in Aquarius,
And its descent and disappearance coincided with that watery sign.
As its tail extended in the direction of the east.…

*refers to the types of al-kaid

ʻAlā al-Dīn Mansour's description of the comet of 1577 and several other evidence indicate that, despite extensive contact between Turks and Europeans, Turkish scholars were not aware of the antisolarity of comet's tail forty years after its discovery.

Fig. 2.2 A late sixteenth century picture of Taqi al-Dīn's observatory. At the top, three lines of 'Alī al-Dīn's poem, in Persian, say that a small observatory was built (close to the place of the large armillary sphere or the main observatory) and fifteen scientists served Taqi al-Dīn; for each observation five keen and learned individual were assigned.

It seems that the painter wanted to illustrate all activities in the observatory, as well as the people and instruments: there are sixteen persons in the picture, doing observation, instrument building and recording or calculating. Taqi al-Dīn should be the one at the top right wearing the largest turban. Behind him, a servant (?) is standing in front of the bookshelves.

Sadly, the last observatory of the Islamic world was destroyed at the same time that the first European modern observatory was founded by Tycho Brahe. (Picture from *Shahinshāhnāma*, ms. Istanbul University Library, F-1404., copied from Hoskin, *Illustrated History*, p. 57)

At the Threshold of the Quantitative Study of the Comets: From Peter of Limoges to Regiomontanus

The first reports of cometary observations with astronomical instruments appeared in the early fourteenth century.[88] Observation of the position and the direction of a comet successively, even for astrological prognostication, was a new approach in cometology of the pre-modern era. Peter of Limoges (d. ca. 1306), canon of Evreux (Northwestern France) wrote two treatises on the comets of 1299 and 1301 and mentioned his use of a torquetum in his observations.[89] He used the torquetum to measure the latitude and longitude of the comets, and consequently he could obtain a quantitative idea about their motions on the celestial sphere. Peter assumed the comets formed at the uppermost part of the air, and since air lagged behind fire's motion, the comet should move eastward (against the background of fixed stars). However, after giving positional data of the comet and considering the positions of Mercury and Mars, which were near it, he concluded that the attraction of the two planets was responsible for the observed motion of the comet and its tail. Peter explained his observations of the comet of 1301 in a similar way.[90] Another French physician and astrologer named Geoffrey of Meaux observed the comets of 1315 and 1337, and in two treatises gave quantitative information about their positions.[91] A century later, Jacobus Angelus, a German scholar, wrote a treatise containing a theoretical discussion of comets in general and observational data of the position and direction of the tail for the comet of 1402.

These observations were very important in the history of cometary theories, and in fact, they paved the way for a conceptual change in cometology. Although the observations were made in the service of astrology, the procedure differed from traditional practice. The phenomenon was examined with an astronomical instrument and described quantitatively. This was fundamentally different from the preceding reports of comets that gave general information such as the date and position of the first appearance of the comet or the orientation of its tail. Such general information, which could be found by using simple measurement instruments or even by the naked eye, was enough for a traditional astrologer to predict the influence of a comet. What we see in these works is an attempt to observe the comet in a continuous way and, more important, to report it. This had not been done before. By contrast, the comet of 1299 (reported by Peter of Limoges) and the comet of 1402 (reported by Jacobus Angelus) were also reported by Muslim scholars, but in history books and without any details.[92]

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[88] C. Doris Hellman, "The Role of Measurement in the Downfall of a System: Some Examples from Sixteenth Century Comet and Nova Observations," *Vistas in Astronomy*, 11 (1967) 43–52, and Jervis, *Cometary Theory*, pp. 29–31.

[89] Based on its design, a torquetum can make measurements in the three astronomical coordinates, horizontal (alt-azimuthal), equatorial, and ecliptic.

[90] Ibid., pp. 30–31.

[91] Ibid., pp. 31–32.

[92] Cook, "Muslim Material," pp. 148, 149–150.

The intention behind these observations, however, was not to fit a trajectory for the comet, nor were these astronomers inclined to treat the comet as a planet to calculate its anomaly or mean motion. They wanted to use accurate observational results in their astrological prognostications. The remarkable point in their work was that their treatment of the comet was neither Aristotelian nor Ptolemaic. It seems that comets were not some *already known* phenomena for them: they needed to acquire more information about the phenomenon. Later, in the second half of the fifteenth century, when the Hermetic and neo-Platonic literature attracted scholars' minds, astrologers were thinking of a broader goal for astrology. The role of an astrologer-magus was "to use the astrological influence of the stars for human ends" and to control "the powers of the stars in their psychical interaction with things on the earth."[93] In this process, interpretation of some unusual phenomena, such as comets, was much more interesting than describing the regular heavenly events.

From the mid-fifteenth century the art of observation of comets converged gradually with mathematics. This was a turning point in the history of comets. Among the Aristotelian 'phenomena in the upper atmosphere' comets were the first that became mathematized. The first step in this process was 'mapping' comets. Paolo Toscanelli (1379–1482), a humanist, mathematician, physician, astronomer, and astrologer, observed carefully the comets that appeared in 1433, 1499–50, 1456, 1457 (two comets), and 1472. Toscanelli plotted his observations of the comets on a star chart and tried to find an accurate way to determine the position of the comets with respect to the fixed stars. In his forty years of cometary observation, he refined his methods of observing and determining of the position of the comets. The maps produced by Toscanelli were not merely illustrations of the phenomena; he used this method to increase the accuracy of his observations and positioning of the comets. Toscanelli may have been the first who charted the comets as a part of his observational procedure.[94]

Georg Peurbach, a contemporary of Toscanelli, also observed the comet in 1456 and described its motion in detail. While Toscanelli tried to elaborate the technique of comet positioning, Peurbach tried to calculate its distance based on parallax. Peurbach measured the comet's parallax and concluded that it was at an altitude of more than 1,000 German miles, which placed the comet at the highest part of the air, below the fire layer. According to his calculation, the comet's length was 80 miles and its thickness more than 4 miles. Peurbach perhaps was the first who measured the cometary distances based on parallax.[95]

To calculate any position on the celestial sphere it is necessary to adopt a coordinate system and measure the position of the observed point with regard to the reference points or circles in that coordinate system. The simplest coordinate system, which is horizontal, gives the position of a heavenly body with respect to the

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[93] Peter Dear, *Revolutionizing the Sciences* (Princeton: Princeton University Press, 2001), p. 25.

[94] Jervis, *Cometary Theory*, pp. 43–69; Hellman, "The Role of Measurement," p. 44.

[95] Jervis, *Cometary Theory*, pp. 86–92. It was Levi Ben Gerson (1288–1344) who, for the first time, worked out the theoretical basis for determination of the distance of a comet by parallax. See Bernard R. Goldstein, *Astronomy of Levi Ben Gerson* (New York: Springer Verlag, 1985), pp. 179–181.

cardinal points of the local horizon and the zenith; but one needs a great deal of calculation to reduce these figures to astronomically meaningful data. Therefore, the most convenient coordinates in astronomy are ecliptic and equatorial systems.[96] Trigonometric knowledge is needed not only to perform conversion between the coordinates, but also to design and align the observational instruments. By the mid-fifteenth century, the standard astronomical texts contained the required technical procedures for observing the planets, the sun and the moon. Comets were not on the list. A new procedure was needed to locate a comet in the celestial sphere based on astronomical methods. Johannes Regiomontanus produced the first trigonometric and observational handbook of cometary observation with the title of *Sixteen Problems Concerning the Magnitude*, *Longitude and True Position of a Comet*. This book, which had a significant influence on succeeding astronomers, was published posthumously in 1531.

Regiomontanus's observational and mathematical procedures were not new discoveries. The majority of problems and solutions given in his book were already known, but they all were concerning *celestial* bodies. Regiomontanus's innovation had two important aspects: he not only used astronomical methods (both observational and mathematical) in studying comets, he also produced a source book containing the theoretical basis of cometary observations. The problems that Regiomontanus discussed in his book were theoretical, without referring to any example or observed comet. However, it contained all knowledge then required to find the position and distance of comets. The following is the list of the problems: (1) Problem to investigate the distance of a comet from earth, (2) Inquiry into the comet's parallax in the altitude circle, (3) To conclude the same thing in another way, (4) To prove what went before by another argument, (5) To find the comet's true position in the ecliptic, using an instrument, (6) To measure the comet's parallax in longitude, (7) To investigate the comet's apparent latitude, if any, (8) To investigate the comet's parallax in the altitude circle in another way, (9) To determine the comet's apparent position simply, (10) To measure the comet's distance from the center of the world and from the observer, (11) To learn the distance in miles between the comet's center and the earth's center or the observer, (12) To find the comet's apparent diameter by means of an ingenious instrument, (13) To compare the comet's diameter to the earth's radius, (14) To measure the comet's volume, (15) To inquire into the length of the comet's tail, and (16) To find the volume of the tail.[97]

In a treatise named *On the Comet*, which is attributed to Regiomontanus, there appeared detailed information about the motion, direction of the tail, distance, size and length of the comet 1472. The author, after describing the motion of the comet, investigated the changes in the direction of the tail. Since in any cometary prognostication the orientation of the tail was a chief parameter, studying the behavior of

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[96] There are trigonometric formulas to perform conversion between all three sets of coordinates. However, in astronomical tables there were tables that correlated degrees on the ecliptic to the correspondent point on the celestial equator.

[97] Jervis, *Cometary Theory*, pp. 95–114.

the tail was a major task for astronomers (from these observations the correlation between the position of the sun and the orientation of the cometary tail was discovered in the early sixteenth century, see below). The third part of the *On the Comet* deals with the distance of the comet 1472, which is given as nine times the earth's radius or 8,200 German miles from the surface of the earth. This figure again places the comet not in the fire layer, but at the highest region of the air. The size of the comet's head is given as 26 miles and the size of the coma as 81 miles. The measured parallax of the comet was 6 degrees, which based on modern calculations, should be about 3 arc seconds.[98] In other words, the measured value was 7,200 times greater than the true value. While the observational methods and the required mathematics for interpretation of the data were in hand, the crude instruments did not yield appropriate results.

Antisolarity of the Tail: A New Chapter in Cometology

From Regiomontanus's death in 1476 to the 1530's no major development came about in cometology. However, in three successive years starting in 1531, the appearance of three bright comets caused a series of new studies, which finally led to one of the most influential discoveries about comets. Peter Apian (1495–1552) from Bavaria and Girolamo Fracastoro (ca. 1478–1553) from Verona in north Italy, independently discovered that the direction of cometary tails is always away from the sun (Fig. 2.3). This discovery opened a new era in the theory of comets. For more than three hundred years after this, any effort to develop a theory concerning the physical constitution of comets was in fact an attempt to explain this tail-sun alignment. Before the introduction of spectroscopy in astronomical studies, only four chief discoveries (basically yielded from positional astronomy) enabled scientists to guess the physics of comets. The tail-sun alignment was the first one, followed by the discovery of the comets' distance by Brahe, the discovery of cometary orbits by Newton, and finally the estimation of the cometary masses by Laplace.

The antisolarity of cometary tails was a difficult discovery to explain in an Aristotelian framework. Fracastoro did not explain the phenomenon, but introduced a new sphere in which the comets were located. This sphere was concentric with the earth and placed immediately under the sphere of the moon. Apian, however, correctly tried to connect the tail's direction to the sun's rays. His idea inaugurated the development of the optical theory of comets, which lasted until the late seventeenth century.[99]

Gemma Frisius, inspired by Apian's idea, proposed that the tail was formed due to refraction of the sun's rays. Gemma did not develop his theory in detail, but in

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[98] Ibid., pp. 117–120.

[99] For the optical theory of comets see: Peter Barker, "The Optical Theory of Comets from Apian to Kepler," *Physis*, 30 (1993), 1–25.

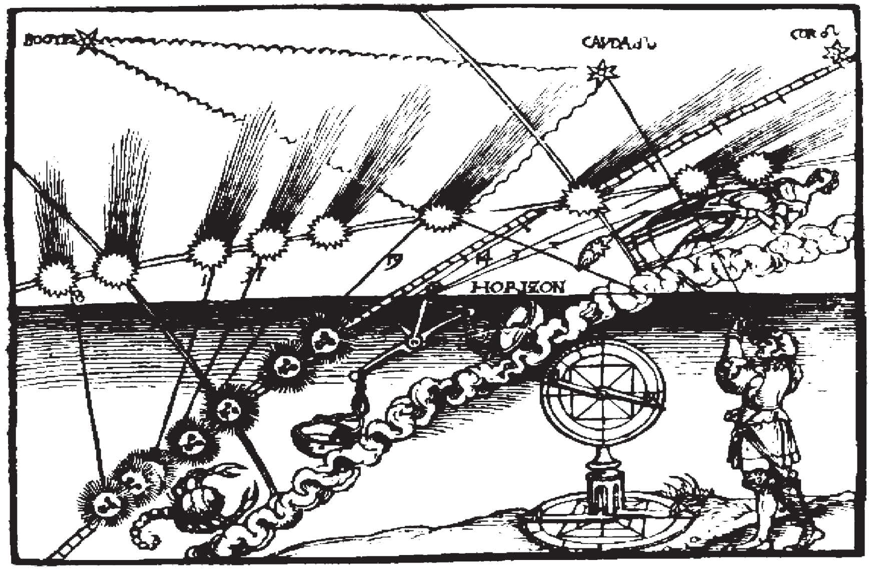

Fig. 2.3 The title page of Peter Apian's treatise on the comet of 1532 (*Ein kurtzer bericht…*, Ingolstadt, 1532) showing the anti-solar direction of the comet's tail. (From Barker, "The Optical Theory of Comets", p. 8)

his book *De Radio Astronomico et Geometrico Liber* (1545), based on his own measurements, argued that the relative positions of stars are identical at the horizon and far above the horizon. In other words, he rejected the concept of atmospheric refraction. Jean Pena, a professor of mathematics at the College Royale, Paris, accepted this erroneous idea and concluded that air filled the space between the earth and the stars. It meant that there were no Aristotelian spheres in the celestial region and no fire layer above the air. Thus, in such a non-Aristotelian universe, Aristotle's explanation of the comet and its tail was useless. Pena, using the science of optics, developed Frisius's notion of refraction and suggested a novel optical theory of comets. Three basic premises in Pena's argument were (1) the medium in the entire universe was air, (2) comet tails were always directed away from the sun, and (3) the parallel rays of the sun became divergent at the tail side of the comet. Pena knew that a cone or pyramid of refracted rays could only form by the refraction of light in a spherical glass. By what we would today call *reduction to the familiar*, he concluded that the comet's body functions as a spherical lens. Since the heavens were filled by air, comets were assumed to be transparent bodies denser than the air. On the other hand, since the focused solar-rays produces heat, comets also could produce heat, which was in agreement with the long standing popular idea in cometary astrology.[100]

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[100] Ibid., pp. 11–13.

Girolamo Cardano (1501–1576), a famous mathematician, physician, and astrologer from Milan, independently developed an optical theory of comets. He assumed the comet was a globe which refracted the sun's rays and produced the tail. For Cardano the nature of comets placed them between the moon and the stars. Cardano came to this conclusion after he was convinced that comets were located above the moon. However, he did not find their distance from parallax measurement. What he measured was the motion of the comet 1532 which was slower than the moon, and based on the Aristotelian rule of cosmic speeds (the slower is the further) the comet was assumed to be above the moon.[101] Cardano also claimed that all comets have three different motions, which were an east-west motion (with the diurnal motion of the celestial sphere), a west-east motion, and a motion in latitude. This classification motivated succeeding observers to measure cometary motions carefully.[102]

Parallax

In the almost three centuries from Peter of Limoges to Tycho Brahe one may distinguish three different periods in cometology: a period of curiosity about comets, followed by a period of skepticism on the Aristotelian theory of comets, and finally a period of new theories worked out to replace the rejected theory of Aristotle. The first period started with cometary observations by early fourteenth century astronomers and lasted about a century and half. This period culminated in the works of Toscanelli and Regiomontanus, who introduced accurate observational and mathematical methods of studying comets. The second period started with the discovery of the antisolarity of cometary tails and led to the introduction of the optical theory of comets, though the real distance of comets was still unknown. In this period comets were observed with the same accuracy that astronomers were observing the planets, the sun and the moon. The third period started with Tycho Brahe. Tycho, by measuring the parallax of the comet of 1577, not only overcame a long lasting measurement barrier, he put an end to an ongoing debate about the location of comets.

Parallax is the angular displacement in the apparent position of a celestial body when observed from two different locations. If a comet is observed from two points A and B (Fig. 2.4), it will be seen in two different positions, A1 and B1, relative to the background stars. The closer the comet is, the greater is the arc A1 B1. To measure the parallax of a transient event, such as a fireball, two simultaneous observations at A and B are required. Arranging such simultaneous observations was very difficult or in some cases almost impossible for pre-modern astronomers. However, for enduring phenomena one can measure the diurnal parallax of the object. Instead of observing the object from two different positions, one observer

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[101] Jervis, *Cometary Theory*, p. 122.

[102] Hellman, "The Role of Measurement," p. 45.

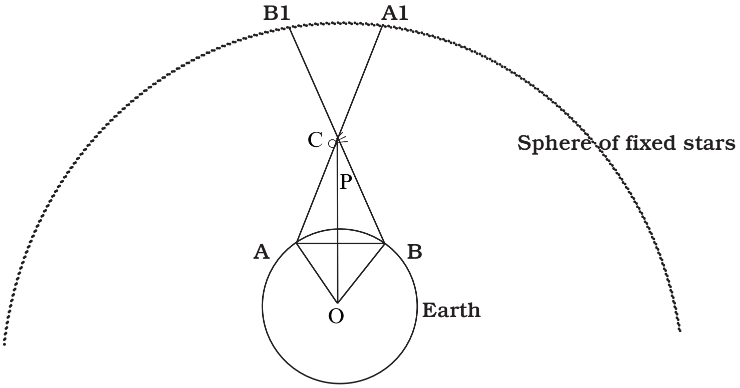

Fig. 2.4 Observers at A and B will see the object C at different positions. Angle P is called the parallax of the object C

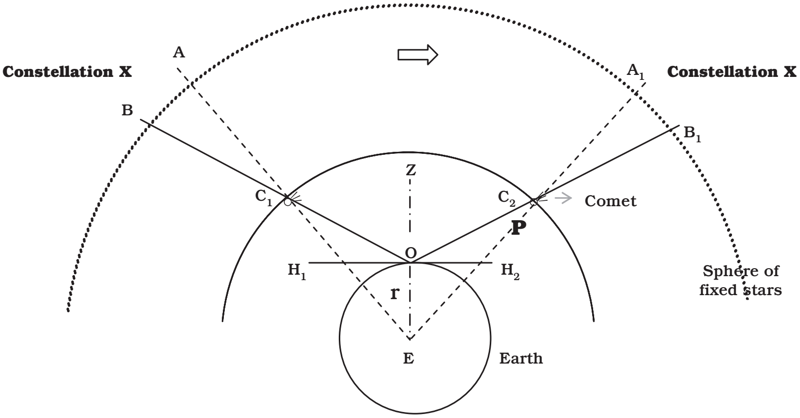

Fig. 2.5 An observer at O observers the object C_1 among the background stars at B. After several hours, due to diurnal motion of the celestial sphere, the same object is seen at B_1. However, an imaginary observer at the center of the earth, E, will see the same object at A and A_1 respectively. The difference between the topocentric zenith distance $\angle ZOB$ or $\angle ZOB_1$) and geocentric zenith distance ($\angle ZEA$ or $\angle ZEA_1$) is called *diurnal parallax*

from a fixed position can make two observations with an interval of several hours. In the intervening time, the rotation of the earth displaces the observer (in four hours, the displacement of an observer on the equator is equal to the Earth's radius), but the observer supposes that the celestial sphere rotates around the center of the earth (Fig. 2.5) and C1 moves to C2 which is seen at B1 among the stars of the constellation X. By measuring the angles $\angle H_1OC_1$ and $\angle H_2OC_{2,}$ or more practically the angles $\angle ZOC_1$ and $\angle ZOC_2$, or measuring the position of C_1 and C_2 relative to the position of the nearby stars (when their positions are accurately known), the amount of the angular displacement of the comet can be found. Since r (the earth's radius) and $\angle AEA_1$ (the angle of rotation of the celestial sphere between the two observations) are known, using the law of sines we have

$$(\sin P) / r = \sin (180 - \angle ZOC_2) / EC_2$$
$$\text{or} \sin P = (r / OC_2) \sin \angle OEC_2$$

The parallax angle is very small. For instance, the diurnal parallax of the moon is about 60 arc minutes (1 degree) and that of the sun is about 8.8 arc seconds.

Stellar parallaxes are even smaller. The annual parallax of the nearest star is 0.76 arc seconds or about 1/4736 of 1 degree. When Copernicus proposed his heliocentric theory, the immediate problem that astronomers sought to solve was the detection of any stellar parallax, which would be a direct observational proof of the revolution of the earth around the sun. However, measurement of such a small angle was far beyond the precision level of astronomical instruments of Copernicus's time. The accuracy of Copernicus's observations is estimated to be not more than 1/8° (7½') or 1/10° (6´), which was almost ten times better than the accuracy of medieval European astrolabes. However, an estimation shows that the average accuracy of Tycho's instruments was 30" to 50", or about ten to twenty times more than Copernicus's accuracy.[103] Judged by standards of accuracy, it might be said that Tycho transformed the *art* of observation and instrument making into a *science*.[104]

Tycho Brahe and the Comet 1577

In November 1577 a bright comet with a long tail appeared in the sky. That was almost five years after Tycho's crucial measurement of the parallax of the 1572 nova and a year after he was granted the island of Hven, where he built a permanent observatory and installed more accurate observational instruments. Tycho measured the position of the comet in both ecliptic and equatorial coordinates and carefully measured its motion and parallax. He repeated the observations on all nights he could observe (about thirty nights that the sky was clear). Then he calculated the parallax and spatial displacement of the comet for each set of observations. Tycho determined the minimum distance of the comet to be at least 230 earth radii, which

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[103] Allan Chapman, "The Accuracy of Angular Measuring Instruments Used in Astronomy Between 1500 and 1850," *Journal for the History of Astronomy*, 14 (1983), 136.

[104] Brahe brought three major innovations to observational astronomy: (1) He used diagonal scales at the reading limbs of the instruments which let him measure fractions of a degree without increasing the size of the instrument, (2) He improved the sighting parts (the parts with slit on the alidade) of the sextant or quadrant and decreased the alignment errors, and (3) He improved the data gathering method by repeating observations and obtaining more data for each observational element. See Victor E. Thoren, "New Light on Tycho's Instruments," *Journal for the History of Astronomy*, 4 (1973), 25–45, Walter G. Wesley, "The Accuracy of Tycho Brahe's Instruments," *Journal of the History of Astronomy*, 9 (1978), 42–53.

placed the comet four times as far away as the moon (later he recalculated it as 300 earth radii or five times farther than the moon).[105] Brahe in *De Nova Stella*, his report on the new star of 1572, had already implied that Aristotle's explanation of comets might be invalid, as the new star showed he was not correct about the inalterability of the celestial region. Now, Tycho's calculation of the distance and motion of the 1577 comet gave more evidence against Aristotelian cosmology. Firstly, the comet was far beyond the terrestrial region and therefore could not be made up of sub-lunar exhalations. Secondly, the comet moved in such a way that it traversed the spheres of Mercury and Venus. The first result just elevated the origin of the comets to the heavens, a notion that was not so odd, especially after new attention to Seneca's cometary theory following the 1530s. But it was the second result that had a destructive effect on Aristotle's cosmology. It was a direct challenge to the onion-like nested spheres.

Brahe, in a German treatise about the comet 1577, gives his general ideas about comets. First, he tries to establish a philosophical foundation for his new discoveries and ideas:

> This miracle [the nova of 1572] has made it necessary for us to abandon the opinion of Aristotle and take up another: that something new can also be born in heaven […] The Paracelsians hold and recognize the heavens to be the fourth element of fire, in which generation and corruption may also occur, and thus it is not impossible, according to their philosophy, for comets to be born in the heavens, just as occasional fabulous excrescences are sometimes found in the earth and in metals, and monsters among animals. For Paracelsus is of the opinion that the Superior Penates, […] at certain times ordained by God, fabricate such new stars and comets out of the plentiful celestial matter and display them clearly before mankind as a sign of future things which do not have their true origin in the planets but are rather caused and augured in opposition to the planets by the Pseudoplanet, as a comet is called.[106]

Thus, the comet can be thought an extraordinary entity, made from celestial matter, which is sent as a messenger by God. The comet, therefore, is not a permanent object but is created for a special occasion from the already existing material. This celestial matter is taken from the Milky Way. Brahe already suggested in *De Nova Stella* (1573) that the nova of 1572 was made from the same celestial matter that formed the Milky Way, and he even located a dark area in the Milky Way, close to the nova, as a cavity which was left due to the formation of the new star.[107] The 1577 comet was, according to Brahe, "at the margin of the Milky Way, from which it is believed that all comets take their origin."[108] In the next section titled 'on the tail of the comet', Brahe explains the celestial matter, as well as the formation of the tail, with more detail:

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[105] Victor Thoren, "Tycho Brahe." in *The General History of Astronomy: Planetary Astronomy from the Renaissance to the Rise of Astrophysics*, vol. 2A: *Tycho Brahe to Newton*. Edited by R. Taton and C. Wilson (Cambridge: Cambridge University Press, 1989), p. 6.

[106] J. R. Christianson, "Tycho Brahe's German treatise on the comet of 1577: A study in science and politics," *Isis*, 70 (1979), 133.

[107] A. Pannekoek, *A History of Astronomy* (New York: Dover Publications, 1961), p. 208.

[108] Christianson, "Tycho Brahe's German Treatise," p. 134. Contrary to his account of the origin of the nova, Brahe does not mention any dark space in the Milky Way as the detachment place of the comet.

> All [comets] have turned their tails away from the sun. From this, it appears that the tail of a comet is nothing but rays of the sun which have passed through the body of the comet, for this body, not being diaphanous like other stars, cannot transmit the rays invisibly, and not being opaque like the moon, cannot reflect the rays, but since the body of the comet is some medium between rare and dense, it holds a part of the radiance from the sun within itself, and from this comes the light of the head by reason of the resistance of celestial matter of which the head is fabricated, but because it is also somewhat rare and porous, it lets those solar rays pass through which are seen by us as a long tail hanging to the head of the comet. This is indeed so and has been demonstrated so by all comets observed at various times by mathematicians, and it is no longer to be doubted.[109]

Accordingly, the celestial matter is in three forms: a pure form which is completely transparent (as in the stars), an opaque form which can reflect the sun's rays (like the moon), and a third form which is in between the first two. The latter is not rare or dense, but is porous. The new star, comets, and the Milky Way are constituted from the third form of the celestial matter. While the Milky Way and the new star are located at the sphere of the fixed stars, comets are created to travel towards the center of the world. And since they are "a new and supernatural creation of God the Almighty placed in the heavens in His good time," they "overwhelm the natural signs of the stars with much greater powers", and they have "much greater deeds to accomplish than all other natural courses of the heavens."[110]

Brahe was a Lutheran. Martin Luther and Philip Melanchthon had already established a greater role for the comets. They diverged from the traditional view and claimed that the comet was not merely a portent natural phenomenon, but that it was created by God to instill horror, and it was a sign of the last days.[111] Brahe repeated the same core idea too, but it seems that he exaggerated the comets' role by considering them superior to all other celestial bodies. One may suggest that he may have had a different picture of the comet in mind and that there were crucial differences between Brahe's understanding of the comet and that of his masters: Brahe, in the light of his parallax measurements, was able to perceive the extraordinary size of these supernatural creations of God.

Brahe's calculations placed the 1577 comet at a minimum distance of 230 times the earth's radius (E_r) or 197,800 German miles (Gm). The moon's closest approach to the earth was believed to be 52 E_r or 44,720 Gm, and the closest and farthest distances of Venus (in the Ptolemaic system) were 164 E_r and 1,104 E_r respectively. In Copernicus's model (and also in Tycho's system) Venus could not come closer to the earth than 296 E_r, and the moon could not move farther than 68 E_r from the earth. Therefore, the space between the farthest point of the moon's sphere and the closest point of the Venus's sphere was 228 $E_{r.}$ Since the average distance of the comet was 230 E_r, therefore, the comet originated in this space.

At the distance of 230 E_r, the apparent diameter of the comet was 8 arc minutes, which was equal to 465 Gm. In other words, the diameter of the comet was almost a quarter of the earth's diameter. The tail, which was seen at an angle of 22 degrees from a distance of 230 E_r, worked out to be 76,000 Gm, or 88.37 E_r. And finally, the

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[109] Ibid., p. 135.

[110] Ibid., p. 137.

[111] Schenchner Genuth. *Comets, Popular Culture*, pp. 47–50.

thickness of the tail was 2½ degrees (in the thickest part), which was equal to 5,000 Gm, or 5.81 E_r. This magnificent creature was wandering in a universe whose size had already been reduced by a third from the Ptolemaic measure. In the Tychonic cosmos, the sphere of the fixed stars was located at a distance of 14,000 E_r rather than the 20,000 E_r of Ptolemy's.[112] Tycho's measurement of cometary sizes and distances was not merely a correction to the previous measurements. It was an observationally and mathematically demonstrable upheaval in understanding comets. The size of the comet that had been calculated as 4 Gm (almost the distance from Copenhagen to the island Hven) by Peurbach, and 26 Gm at the time of Regiomontanus, suddenly increased to an enormous size of 465 Gm or the size of the moon (or the planet Venus). The increase in the size of the tail was even more. The comet 1456 had a tail of 10 degrees that according to Peurbach's calculations was equal to about 80 Gm. Tycho's comet, however, had a tail of 22 degrees, which based on pre-Tychonic measures should be estimated as 175 Gm. But Tycho's figure was 430 times greater! The new tail was almost as extended as the thickness of Mercury's orb. A glance at the Table 2.2 shows how the measurement of the comet's parallax changed the size of the comet radically.[113]

Tycho was not as concerned about the details of the trajectory of comets. For him each comet was a transitory object which would not return again. However, he worked out a circular path outside of the planet Venus for the comet 1577. Michael Mästlin had already published a similar theory of comets in mid 1578 (see below). In Tycho's model the maximum elongation of the comet from the sun was 60 degrees, and the comet had a retrograde motion. Tycho's observations indicated that the motion of the comet was not regular. He sought to solve the problem by introducing an epicyclic mechanism; but since the amount of inequality was only 5 arc minutes, he argued: "It would be very inappropriate to make such quickly vanishing bodies as comets liable to follow artificially compounded and much involved curves of motion."[114] Since comets, according to Tycho, were not as perfect as the fixed stars and the planets which perform uniform circular motion, "they mimic to a certain extent the uniform regularity of the planets but do not follow it altogether."[115] However, they were moving around the sun and one should justify the path assigned to them. A non-perfect celestial body, which had a non-uniform motion and was not eligible to possess an adjusting tool (epicycle) to create uniformity in its motion, might have a non-circular or a non-uniform circular motion:

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[112] Data for sizes and distances of the planets is adopted from: Albert Van Helden, *Measuring the Universe, Cosmic Dimensions from Aristarchus to Halley* (Chicago: The University of Chicago Press, 1985).

[113] In the history of astronomy, there have been a few moments like this that an accurate observation caused a radical change in our understanding of the physical world. As another example, one can refer to Harlow Shapley's measurement of the size of our galaxy in 1917, which increased its size by a factor of 10.

[114] Ruffner. "The Background," p. 62, originally in Tycho Brahe, *De Mundi Aetherii Recentioribus Phaenomenis* (Uraniborg, 1588), pp. 191–194, quoted from Marie Boas and A. Rupert Hall, "Tycho Brahe's System of the World," *Occasional Notes of the Royal Astronomical Society*, 3/21 (1959), 263.

[115] Ibid., p. 62.

Table 2.2 A comparison of three cometary sizes and distances. The radius of the earth is 913 Gm for Regiomontanus and 860 Gm for Brahe

Author	Comet's distance	Comet's size	Size of the tail	Size of the world
Peurbach	≥1,000 Gm	4 Gm	≥80 Gm (10°)	
(1423–1461)	≥1.1 E_r	0.004 E_r	0.088 E_r	20,000 E_r
Regiomontanus[a]	8,200 Gm	26 Gm	81 Gm (Coma)	
(1436–1547)	9 E_r	0.029 E_r	0.089 E_r	20,000 E_r
Brahe	197,800 Gm	465 Gm	76,000 Gm (22°)	
(1546–1601)	230 E_r	0.54 E_r	88 E_r	14,000 E_r

[a] These figures are from the treatise attributed to Regiomontanus. Whoever the author was, the treatise was circulated and the figures in it were familiar to people.

> either the revolution of this our comet about the sun will not be at all points exquisitely circular, but somewhat oblong, in the manner of the figure commonly called ovoid; or else it proceeds in a perfectly circular curve, but with a motion slower at the beginning, and then gradually augmented.[116]

Thus, Brahe, in order to maintain the idea of the inferiority of the comets to the stars (which he took as an axiom), not only proposed that they might move in a path that is not exactly circular, he made non-uniform circular motions acceptable in the celestial region.

Brahe's Optical Theory of Comets

In Brahe's cosmology, the space between the earth and the moon is filled by air; however, the air is gradually thinning from the earth to the moon.[117] In the part close to the earth, air is denser and containing impurities, but in the vicinity of the moon it is thin and clear, almost like the ether. Beyond the moon, the whole universe is filled with the ether. Unlike Gemma Frisius and Pena, Brahe does not extend the air up to the fixed stars. He admits that atmospheric refraction is created by impurities in the denser part of the air.

Comets, obviously, were moving inside the ether. Since the ether was pure and subtle, rays could not be reflected from or refracted in it. Therefore, if comets were composed of pure celestial matter, they would not be seen as a result of refraction or reflection of the sun's rays. However, as explained earlier, Brahe believed that the comet was formed of a third kind of celestial matter, which was neither completely pure and transparent like stars, nor opaque and reflective like the moon. Since the body of the comet was not absolutely transparent, rays could not pass

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[116] Ibid., p. 63.

[117] Brahe believed in three elements. For him fire was not "other than an ignition of the uppermost air by the rapid motion of the heavens." See Christianson, "Tycho Brahe's German treatise," pp. 128, 132. [Did Brahe try to make symmetry between the three sub-lunar elements and three supra-lunar celestial matters?]

freely through it. In fact, they became partially trapped inside the head of the comet, and as a result, the comet's head became visible. However, since the substance of the head was porous, it let the solar rays to move out. These outgoing rays were seen as the comet's tail. Therefore, the tail was formed by the rays, and was not a material extension of the comet's head. If it were, there would be no reason for its invariable antisolar direction. On the other hand, the head and the tail were seen in different colors. One more difference between the head and the tail was their different degree of transparency. The tail was completely transparent and the stars behind it were visible, but the head was completely opaque.[118]

Tycho, following Apian, Gemma Frisius, and Fracastoro, asserted that the direction of the tail is away from the sun. For example, his explanations and drawings of the position of the comet 1577 in the "German Treatise" confirm the antisolarity of the tail. However, in 1585, his calculations showed that the tail, the head and the sun are not located on a great circle, but a great circle passing through the tail and the head of the comet intersects Venus instead. In other words, the tail is directed opposite to Venus. Brahe published this new idea in *De Mundi Aetheri Recentioribus Phaenomenis* in 1588, where he proposed the Tychonic system of the world. However, he later corrected his calculations and again acknowledged the antisolarity of cometary tails.

Tycho's Contemporaries

Tycho published his *De Mundi* almost half a century after the publication of Copernicus's *De revolutionibus*. Although Tycho was not completely Copernican, he had a great influence in the promotion of the Copernican astronomy. In a review of events from Copernicus (mid-sixteenth century) to the mid-seventeenth century (when Kepler's laws were established), one encounters one of the most creative periods of the history of astronomy. This period started with the introduction of a mathematically plausible alternative system of the world by Copernicus, followed by Brahe's anti-Aristotelian discoveries, which were mathematically and observationally demonstrable, and ended with Kepler, who in turn, became the founder of a new era. Brahe's achievements marked a turning point in this period. He not only shed a new light on the physical universe by his accurate measurements, he revolutionized the practice of astronomical observation and measurement. His accurate observations' impact on the refutation of the Aristotelian cosmos can be compared only to the discoveries made after the invention of the telescope. Brahe's discoveries, especially his cometary studies, merged physics and mathematics together in astronomical studies.[119]

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[118] Barker, "The Optical Theory of Comets," p. 17.

[119] For Brahe's role in the establishment of modern astronomy see: Peter Barker, Bernard R. Goldstein, "The Role of Comets in the Copernican Revolution," *Studies in History and Philosophy of Science* 19 (1988) 299–319.

Brahe was not alone in studying comets. There were many other astronomers with different affiliations and world-views who devoted time and effort to cometology. Within less than a decade after the appearance of the 1577 comet, about one hundred treatises and pamphlets were published in Europe discussing comets. Brahe himself mentioned nineteen authors, and reviewed the results of eight of them.[120] Among the observers of the comet 1577, besides Brahe, there were four astronomers who concluded that the comet was located above the sphere of the moon: Helisaeus Roeslin (1544–1616), William IV, Landgrave of Hesse-Kassel (1532–1592), Cornelius Gemma (1535–1579) and Michael Mästlin (1550–1631). Copernicus himself was an Aristotelian in dealing with comets. He mentioned comets in *De revolutionibus* only in his discussion of the rotation of the earth and the air around it, as bodies generated in the upper air.[121] Mästlin, however, attempted to measure the distance of the 1577 comet. Although the instruments he used were very simple, his clever method of positioning the comet relative to the background stars helped him to obtain relatively accurate results. He concluded that the comet was located above the moon and tried to devise a trajectory for it.

Mästlin was the first astronomer to work out a circle of motion like those calculated for planets for the comet. A review of the problems that the first calculators of the comets' motion encountered will reveal the extent of the impact of cometology on observational and mathematical astronomy after 1577:

I. To find the position of a comet, one of the best methods was to measure the comet's position relative to the fixed stars; therefore, a precise catalogue of stars was required.
II. For the first time astronomers were observing and calculating the motion of a body *outside* of the ecliptic. They had to reduce the acquired data (either from observations in alt-azimuth coordinates, or measuring zenith distances, or positioning relative to the neighbor stars) to a unique system, then perform the desired calculations.
III. Comets have a proper motion. The observed change in the position of a comet is the apparent motion of the comet that should be corrected after finding the inclination or obliquity of its plane of motion.
IV. For the first time astronomers encountered a highly inclined plane of motion, which made it very difficult to treat the latitude of the comet.
V. Astronomers had a chance to observe only a small portion of a comet's motion and they had to deduce the entire trajectory from their limited data.

Mästlin, in successive observations, calculated the positions of the comet relative to some reference stars whose coordinates were known. Then, he passed a great circle through those calculated positions to find the plane of motion of the comet. The angle between this circle and the ecliptic would be the obliquity of comet's circle. Mästlin found that the positions he had calculated all lay on a unique circle

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[120] Thoren, "Tycho Brahe," p. 6.

[121] Nicolaus Copernicus, *On the Revolution*, trans. Edward Rosen (Baltimore: The John Hopkins University Press, 1978), p. 16.

with a fixed obliquity, which was strong evidence that he was not dealing with an irregularly moving object. Having established the obliquity of the circle, he could measure either the angular displacement of the comet on its own circle or the angular velocity of the comet. Mästlin soon realized that the comet's motion was not uniform. He could devise an epicycle or a circle of liberation to create the observed non-uniformity, but first he had to find an appropriate place for the comet's circle. Mästlin supposed that the comet was moving inside the orb of one of the planets. After some trial and error, Mästlin finally found that it would be more appropriate to place the comet's circle inside Venus's orb. He assumed a circle outside the circle of Venus and devised a circle of libration to recreate the non-uniform motion of the comet. In contrast, Copernicus had used the circle of libration to represent minor changes in latitude of the planets.[122] The 1577 comet vanished before Mästlin (and Brahe) could test their proposed circle by gathering more data.

Mästlin and Brahe, in a similar way, worked out a circle of motion for a comet, path they calculated, the idea they had about the substance of the comet, and the theory they suggested for the formation of the tail were all erroneous by later standards. However, they established one certain fact: *the comet was celestial*. Of the three major anti-Aristotelian events in the second half of the sixteenth century – the introduction of the Copernican system, the discovery of the supra-lunar origins of the new star of 1572 and the comet 1577 – the latter was the most influential in diverging from Aristotelian notions of cosmology. The Copernican system, despite having the capability of solving several physical and astronomical difficulties associated with the Ptolemaic system, was accepted for a relatively long time only as a mathematical model. Furthermore, the empirical verification of the Copernican system was extremely difficult and, in some cases, was absolutely impossible in the sixteenth century. It is true that the measurement of the parallax of the new star 1572 shook the foundations of the Aristotelian cosmic theories, but the phenomenon was non-repeatable on the one hand, and on the other hand there was no general agreement on Tycho's results.[123] However, the results of the observation of the 1577 comet were persuasive and accepted by several astronomers.[124] After about two millennia, Aristotle's theory of comets was proved to be invalid and contrary to the observational and mathematical facts. Hence, a new era in cometology began.

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[122] For Mästlin's measurements of cometary motions see Robert S. Westman, "The Comet and the Cosmos: Kepler, Mästlin and the Copernicus Hypothesis," *Studia Copernicana* 5 (1972), 7–30; Ruffner. "The Background," 49–57.

[123] Not all astronomers agreed with Tycho's results on the nova. For example, John Dee (1527–1608), Thomas Digges (ca. 1543–1575) and the Landgrave of Hesse-Kassel (1527–1608) assumed that the decrease of the nova's brightness must be completely apparent and argued that it was dimming out due to change in its altitude. Some other astronomers, including Digges, related it to comets and obviously many Aristotelians denied its supra-lunar origin. See Thoren, "Tycho Brahe," p. 5; Marie Boas Hall, *The Sientific Renaissance 1450–1630* (New York: Dover Publications, 1994), pp. 110–111.

[124] From 1577 to Brahe's death in 1601, five more comets (in 1580, 1582, 1590, 1593, and 1596) were observable in Europe and Brahe, as well as many other astronomers, reached the same results he had obtained in 1577.

Tycho caused a real revolution in our understanding of comets, which in turn paved the way for a greater revolution in our understanding of the universe as a whole. Although he developed an optical theory of comets, it was too early for him and his contemporaries to suggest a well-defined and consistent theory of comets. Tycho was living in a transitional period in which divergence from the traditional science (or normal science, according to Thomas Kuhn) was happening, but the new paradigm has not yet been established.[125] The intellectual atmosphere and even a single theory contained a spectrum of old and new ideas simultaneously. Tycho's physical theory of comets was one of those hybrid speculations, yet it contained a new core concept that changed the route of cometary research.

Conclusion

From Aristotle to the mid-sixteenth century, comets were treated as atmospheric phenomena and mainly were a subject of interest to astrologers. Descriptions of comets, as of other phenomena in Aristotelian natural philosophy, were explanatory and qualitative. Although there were scholars who accepted comets as celestial phenomena, there was no attempt to perform specifically designed observations to measure their position, distance, and motion. Even in the periods when large observatories were active in the Islamic world (for example in Marāgha and Samarqand, in the thirteenth and fifteenth centuries), a general belief in the atmospheric origin of comets prevented astronomers from applying astronomical methods to comets.[126] In the late fifteenth and early sixteenth centuries, European scholars began to study comets in a quantitative manner. This change soon brought about decisive results, the discovery of the anti-solar direction of the cometary tail being the most important one. This discovery attracted more attention to comets and also initiated the first non-Aristotelian theory of comets. In the new theory, the body of comets was assumed to be a kind of crystalline matter, like a spherical lens,

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[125] The second half of the sixteenth century also has been called a period of consolidation and transition: "consolidation of the mathematical techniques of Copernicus and transition from the purely mathematical account of planetary motions to a wider discussion of the actual nature of the universe." See Richard A. Jarrel, "The Contemporaries of Tycho Brahe." in *The General History of Astronomy: Planetary astronomy from the Renaissance to the rise of astrophysics*, vol. 2A: *Tycho Brahe to Newton*. Edited by R. Taton and C. Wilson (Cambridge: Cambridge University Press, 1989), p. 22. For a study on the nature of the astronomical theories in the sixteenth century see Peter Barker, Bernard R. Goldstein, "Realism and Instrumentalism in Sixteenth Century Astronomy: A reappraisal," *Perspectives on Science* 6 (1998), 208–227.

[126] Islamic historians reported the appearance of the 1264 and 1265 comets, which might have been seen by astronomers of the Marāgha observatory (established 1259 and active after 1274). Also, there are reports of the 1430, 1433 and 1456 comets, which were appeared when Samarqand observatory was active (from 1420–1449). The observatory was abandoned after the death of its founder Ulugh Beg in 1449, but several astronomers were still active in Samarqand schools. No reports of cometary observation from neither observatory have been found. See Cook, "Muslim Material," pp. 147, 150.

and the tail was believed to be solar rays. However, the location of the comet had not been determined observationally.

A radical development in instrument designs and observational procedures by Tycho Brahe enabled him to observe at least ten times more accurately than the previous generation. He proved the supra-lunar origin of the comets, which terminated the Aristotelian theory of comets. The comet, which was a small sized burning cluster of terrestrial exhalations in the atmosphere of the earth, and a herald of hot weather or other kinds of disasters, now became a planet-size celestial object, created by God to perform a specific mission. In other words, the location, the material, and the philosophy of existence of comets were promoted to a higher rank.

The notion of comets that Tycho introduced initiated new challenges in natural philosophy, mathematical sciences, and practical astronomy. In fact, any attempt to develop a plausible theory of comets was an attempt to answer a set of questions arising from different fields of science. The enigma of comets was not a one-dimensional astronomical problem such as calendar calculation or even devising extra epicycles to adjust the motion of a specific planet. Cometology appeared as a new enterprise that needed simultaneous speculations in both philosophical and mathematical dimensions.

In natural philosophy, it was accepted that not only was the celestial region perfect, there were crystalline orbs. New findings about the motion and distance of comets were not in agreement with traditional dogmas. Consequently, theorizing a new doctrine about the entire universe became a major occupation of scholars. At the same time, a new technical theory had to be developed to explain comets as celestial bodies. Applying astronomical procedures to observe the comets (though for a relatively long time they were thought a transient phenomenon) was an interesting approach and new in the history of natural philosophy.

Besides the general inquiries related to the origin and place of comets, new investigations of the shape, extension of the tail and movement of comets stimulated the idea that they were made of a different kind of celestial matter. This idea, which was developed decades before the telescopic observation of the celestial bodies, initiated a new scientific enterprise. Scholars were challenged to define the nature of the building substance of comets based on the data they acquired from comets' motion, size, and tail properties.

In observational astronomy, measuring the motions of objects like comets moving on highly inclined circles developed observational skills and the process of reducing observational data (Fig. 2.6). To increase accuracy, systematic observations replaced the traditional procedures of observation. To measure the minor displacements of comets, precise observational instruments, accurately graduated scales, and properly mounted sighting devices were needed. Since the positional data of comets mostly were recorded relative to reference stars, the importance of preparing a new accurate star catalogue was underlined.

Finally, finding the general path of a comet from its observed segment of trajectory opened a new trend in mathematical astronomy. In the absence of an established science of celestial mechanics, astronomers had to deduce a comet's trajectory by applying data acquired from successive estimations of its distances to

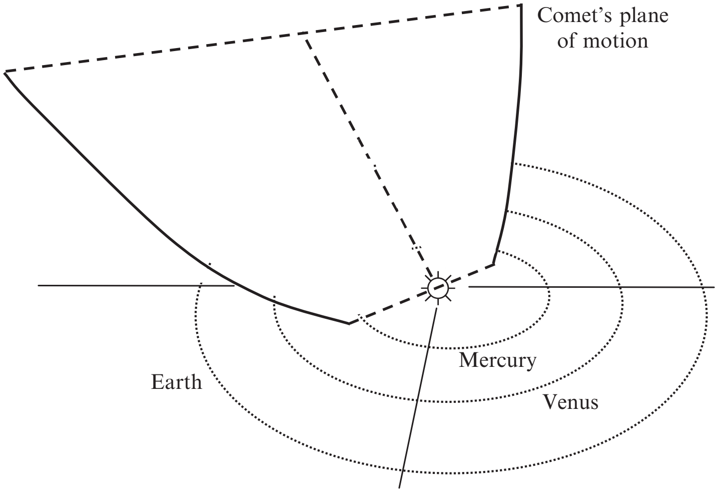

Fig. 2.6 The orbit of the comet 1577 was highly inclined. That was the first time that astronomers were calculating the motion of a body moving on such an oblique 'circle'. (Adopted from Robert S. Westman, "The Comet and the Cosmos," p. 18)

the comet's apparent path and then extrapolating the segment's data to find a general path. Calculations became more sophisticated when the earth was not assumed to be the center of the universe. In any case, the procedure of path fitting developed the techniques of distance estimation and trigonometry.

At the beginning of the seventeenth century (before the introduction of telescopic observations), a typical European astronomer was struggling to solve two major problems: the situation of the earth in the universe, and the trajectory (and consequently the nature) of comets. New theories of comets, although they did not directly support the technical aspects of Copernican system, provided a firm foundation to build non-Ptolemaic systems of the world.[127] In the next chapter we will trace the development of the physical theories of comets in the period that the heliocentric system found its ultimate form in Newtonian physics.

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[127] The role of cometary theories of the late sixteenth century on the Copernican revolution has been a subject of debate, notably after the publication of Thomas Kuhn's *Copernican Revolution*. In Kuhn's account, the role of cometary discoveries, especially Brahe's achievements, was misunderstood and underestimated. See Barker and Goldstein, "The Role of Comets in the Copernican Revolution."

Chapter 3
From Brahe to Newton

Brahe died in the first year of the seventeenth century and left astronomers and natural philosophers with a number of crucial questions regarding comets. These questions, however, arose from a single fundamental philosophical inquiry related to the nature of comets. Cometology, during almost the entire seventeenth century, was a struggle to answer this basic question, which finally was resolved in Newton's *Principia*.

The seventeenth century was, to say the least, a productive period in the history of astronomy: the heliocentric system of Copernicus was recast in the more elaborate Keplerian system, which finally was demonstrated and proved by Newtonian celestial mechanics; telescopic observations, besides many other discoveries, enabled scientists to deal with the surface features of the celestial bodies and consequently to discuss their nature based on observational facts; a concept of central force, acting at a distance and governing all motions in the solar system, was developed; a new mathematics made it possible to calculate motions of the celestial bodies caused by their mutual attractions; and finally, the application of the micrometer in observation increased the angular resolving power up to 15 arc-seconds by 1700, an increase by a factor of four compared to the early decades of the seventeenth century.[128] Benefiting from all these achievements, cometary theories drastically changed at the end of the seventeenth century, a time when the physics and kinematics of comets became two independent subjects of study.

For almost the entire seventeenth century, the nature and motion of comets were assumed to be the two sides of one coin: it was generally accepted that a transient object had to move on a straight or curvilinear line and a permanent body had to travel on a circular path periodically. This presumption was based on a kind of Aristotelian interpretation of the newly discovered phenomena. In the Aristotelian supra-lunar region, motion on a straight line was not allowed. However, when transient objects were discovered in the ethereal region, they were assumed not to move perpetually like permanent objects. In other words, comets could be celestial but would not perform circular motions. Therefore, the most secure criterion to infer the nature of a comet was its trajectory. Consequently, until the introduction of the Newtonian theory of comets in 1687, any theory about the physics of comets was dependent on their kinematics.

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[128] Allan Chapman, "The Accuracy of Angular Measuring," p. 134.

T. Heidarzadeh, *A History of Physical Theories of Comets,*
From Aristotle to Whipple,

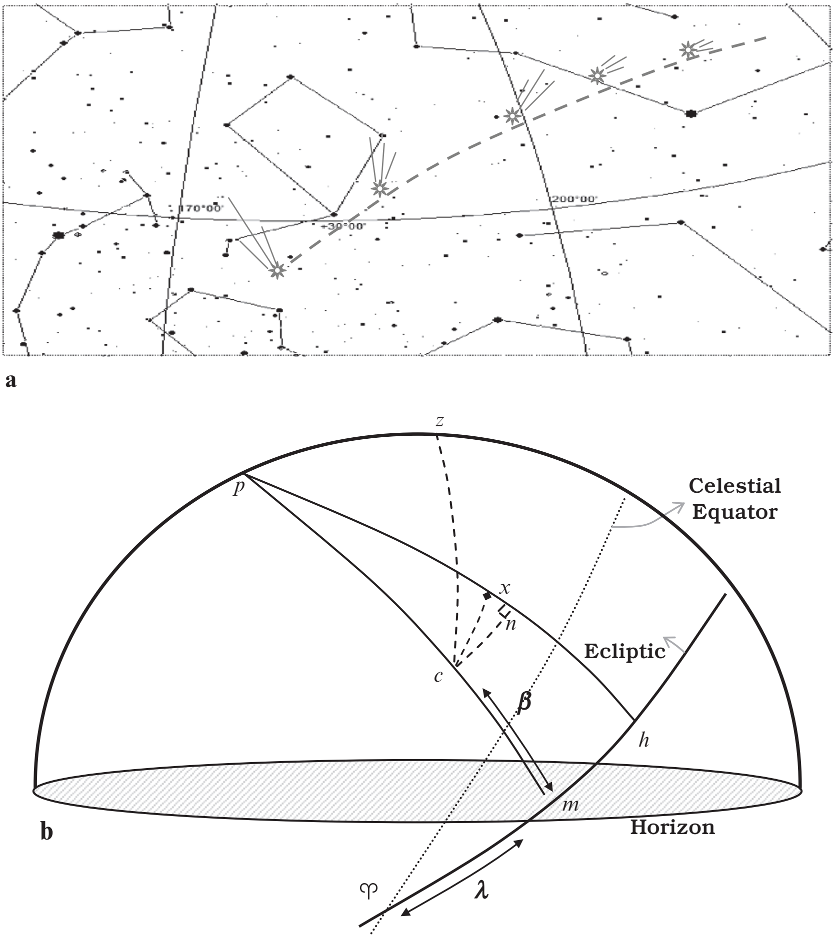

Fig. 3.1
z = Zenith
p = Ecliptic pole
c = Comet
γ = Vernal Equinox/First point of Aries
x = Reference star
λ (comet) = γh - mh
β (comet) = hx - nx

Calculating the actual trajectory of comets, however, was not straightforward. Like the trajectory of planets, a comet's apparent course in the sky is the projection of its true path among the background stars. But, regarding their motions, there are two major differences between the planets and comets: planets' speeds do not vary as greatly and their planes of motion are not as inclined as those of comets. These circumstances sometimes make the apparent path of a comet very different from its real path. Although we will discuss cometary orbit determination in sections related to Newtonian and post-Newtonian theories of comets, a brief review of problems facing the pre-Newtonian calculators of comets' path will reveal why it was almost impossible to find comets' true trajectories without using a celestial dynamics based on gravitational laws.

In Fig. 3.1a, the apparent path of an imaginary comet is shown on a star chart. The main task of astronomers was to perform successive measurements of the position of the comet to establish its path relative to the ecliptic as accurately as possible. The common procedure was to compare the positions of the comet relative to reference stars whose coordinates were precisely known (Fig. 3.1b).

The observed path, however, was no more than a small segment of the projection of the real path on the celestial sphere. As can be seen in Fig. 3.2, any change in the position of the earth, obliquity of the comet's orbit, or comet's proper motion will affect the shape of the apparent trajectory (here we neglect the influences of the atmospheric refraction and the variation in the earth's orbital speed).

Moreover, the calculated path does not give any clue about the variation in the comet's distance from the sun. That determination was beyond the capability of astronomical instruments and techniques of the seventeenth century, which could not calculate the parallax of a comet accurately enough that one could employ the data of changing distance of a comet to approximate its real path. The best result that astronomers could obtain was that comets moved in curved paths. We will see that an improved picture of cometary trajectories became available in 1681 when Flamsteed discovered that the two comets of 1680 were a single comet observed

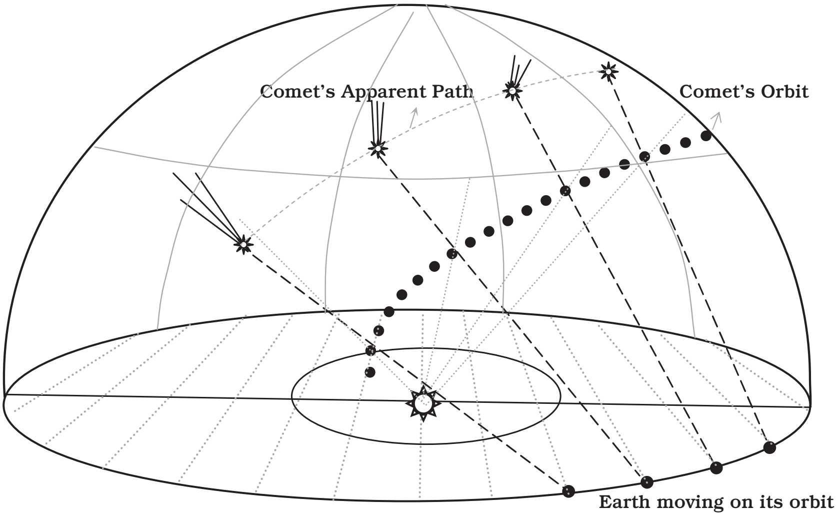

Fig. 3.2 A comet's apparent path among the stars is a projection of the real trajectory of the comet on the celestial sphere. The apparent path is affected by the obliquity of the comet's orbit (here, perpendicular to the plane of the ecliptic), the comet's proper motion, and the position and the revolution of the earth around the sun. Calculations will be even more in error when the earth is assumed to be stationary

before and after its perihelion. This observation, which provided enough data to establish the comet's behavior in the vicinity of the sun was crucial to Newton's analysis of cometary orbits based on the gravitational law.

Although new discoveries about comets seriously undermined Aristotle's cosmology, they did not directly affirm the validity of a heliocentric system. Although cosmological debates in the post-Copernican era were held carefully to avoid any conflict with the Church, discussion about comets was an exception. Neither Ptolemy nor Copernicus had introduced comets as a pivotal part of their system of the world. Therefore, in the early decades of the seventeenth century (especially after the introduction of telescopic observations), when Copernicans were cautious in asserting their non-Ptolemaic ideas about the physics of the cosmos, they found no obstacle to rendering new cometary theories. The comets that appeared in 1607 and 1618 prepared the ground for European scholars to discuss comets in light of new developments in observational and mathematical astronomy.

The comets that appeared in 1607 and 1618 led to the involvement of two leading figures of history of astronomy in cometary theories. Johannes Kepler (1571–1630) and Galileo Galilei (1564–1642) both developed theories about the nature and motion of comets. While Kepler worked out a new version of the optical theory of comets, Galileo introduced a completely different idea, a hybrid of Aristotelian and Pythagorean theories of comets. At the same time, Galileo become involved in a heated debate over the nature of comets with Jesuit mathematicians, who were following Brahe's cometary theory. We shall discuss Galileo first, leaving Kepler and his astronomy for the next section.

Comets of 1618: The Great Debate

In 1618, the appearance of three comets within five months created a new wave of cometary observations and many publications from small astrological pamphlets to technical treatises. One of these treatises, published anonymously in 1619, was written by Horatio Grassi, professor of mathematics at the Collegio Romano, then the leading center of Jesuit scholarship in Europe. Grassi's treatise, entitled *An Astronomical Disputation on the Three Comets of the Year 1618*,[129] contains a great deal of detailed information about the comets of 1618. The way that the author employs mathematical and physical evidence to prove the supra-lunar origin of comets resembles Brahe's *German Treatise on the Comet of 1577*,[130] but is more elaborate and illustrates the physical aspects of comets deliberately.

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[129] The original title is *De tribus cometis anni MDCXVIII disputatio astronomica*. An English translation of this treatise along with Guiducci's answer (*Discourse on Comets*), Grassi's reply to Guiducci (*The Astronomical Balance*), Guiducci's *Letter to Tarquinio Galluzzi*, Galileo's *The Assayer*, and Kepler's *Appendix to the Hyperaspistes*, is in Stillman Drake and C. D. O'Malley, trans., *The Controversy on the Comets of 1618* (Philadelphia: University of Pennsylvania Press, 1960).

[130] See n. 106, Chapter 2.

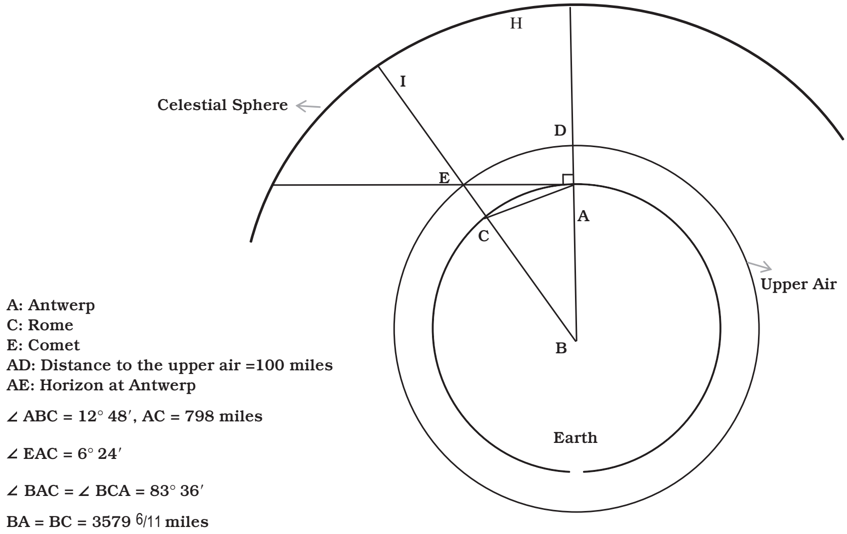

Fig. 3.3 Grassi's initial data for estimating the distance of the third comet of 1618

After a brief introduction, Grassi describes the position and motion of the comets, which appeared in August, mid-November and early December of 1618. He concentrates, however, on the third comet, which was brighter and larger, and led to more observational data all around Europe. A large section of Grassi's treatise is devoted to parallax calculations and the description of the physical features of the third comet of 1618.

Grassi compares two sets of observations, one done by himself at Rome and the other prepared in Antwerp, in northern Belgium. As can be found in Fig. 3.3, the parallax angle E will be at a minimum if the observer at A observes the comet at the horizon. Therefore, knowing the length of the baseline (linear distance between Rome and Antwerp) it can be calculated that if the comet were at a distance of 100 miles, the minimum parallax which occurs at E (the angle AEC) can not be less than 56°56'. Grassi, although he assumes the uppermost part of the air to be at a distance of 100 miles (40 miles more than the commonly accepted value) concludes that "the difference in aspect [the parallax] is found scarcely ever to exceed 1°. Therefore, this phenomenon was not in the highest region of the atmosphere."[131]

Data obtained by a network of Jesuit observers enabled Grassi to increase the accuracy of his parallax measurements. He received records from Innsbruck (in western Austria, about 400 miles north of Rome) that on the thirteenth of December, 1618, the distance of the comet from Arcturus (α Boötes) was 10°53', while his measurement of the same distance at the same date was 10°55′. Grassi stated that even if the comet were located at the border of the sphere of the moon, its parallax should be more than 2 minutes of arc for observers about 400 miles apart.

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[131] Drake, *The Controversy*, p. 13.

To reassure his readers who might be doubtful about the accuracy of the instruments he used, Grassi referred to another observational report which confirmed the celestial origin of comets even without using an observational instrument. On December 13, observers at Rome noticed that the comet covered the tenth star of Boötes. Grassi received a report from Cologne (about 650 miles north-west of Rome) verifying the same occultation at the very same date and time. It was obvious that the occultation could not be seen by those observers simultaneously if the comet was sub-lunar.[132]

In the next step, Grassi concentrates on the physical aspects of comets and creates a picture which is very important in studying the transformation of the Aristotelian concept of comets. Grassi tries to render his mathematically obtained figures into a physically comprehensible object. He assumes the comet (the third comet of 1618) to be located at the same distance as the moon or 121,704 miles from the center of the earth. Therefore, the circumference of the inner circle of the moon's sphere will be 764,966 4/7 miles. Since on December 12 the total length of the comet was 60 degrees, then its linear measure at the distance mentioned would be about 127,499 1/3 miles. On the other hand, the smallest width of comet was measured as 2 minutes of arc, equal to 70 5/7 miles. If the comet is assumed to be a cylinder with a circular base of 70 5/7 miles in diameter and a length of 127,499 1/3 miles, its volume will be 490,871,150 cubic miles! Demonstrating the enormous volume of the comet, Grassi wonders "how great an amount of fuel would be consumed by such an immense fire over so long a time."[133] He concludes that the comet could not be located in the sub-lunar region.

Grassi now tries to explain the nature and motion of comets as celestial bodies. Although observation of comets through a telescope does not reveal more details for him,[134] Grassi infers the structure of comets from the antisolarity of their tails. From the recorded positions of the sun and the comets of 1618, he finds that the

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[132] Ibid., p. 14. Grassi admits that the instruments he used were not as accurate as those used by Brahe.

[133] Ibid., p. 15. Based on the early seventeenth century commonly used figures for the radius of the earth and the moon, Grassi's volume for the comet was about 1/390 and 1/10 of the volumes of the earth and the moon respectively.

[134] Grassi's idea about telescopic magnification was erroneous, which caused a bitter reply of Galileo through his student Guiducci. Grassi claims that the magnification power of a telescope decreases by the distance of the observed object, in such a way that the fixed stars receive no magnification from the telescope. Since the comet's (the third comet of 1618) magnification through a telescope was not considerable, then it was assumed to be located at a great distance. In the first decade of telescopic observations, there was not a clear technical idea about the magnification powers of the telescope. A telescope may increase light gathering power, or angular size, or resolution power. A typical telescope may not *magnify* the angular size of a star perceptible, but it *resolves* the foggy Milky Way into individual stars. On the other hand, the optical quality of the objective and ocular lenses made in the early seventeenth century was too poor to reveal details of comets. It should be noted that even with modern telescopes (of the same size used by Galileo, for instance) the cloudy feature of comets can not be resolved into more details. For the history of the telescope, see pp. 111–116

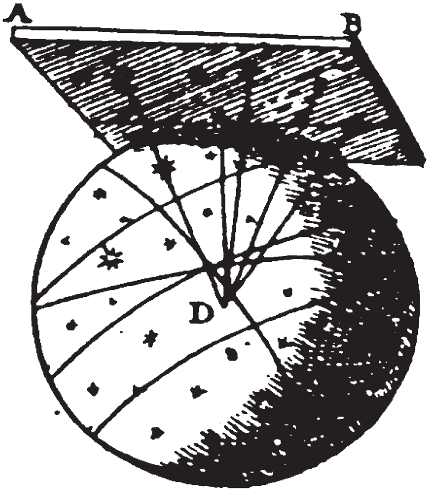

Fig. 3.4 According to Grassi, the apparent straight path of a comet is the stereographic projection of the comet's real trajectory, where the rays of projection are radiating from the earth, located at D, the center of the world. (From Grassi's anonymously published treatise, 1619)

orientation of the tails changes diametrically to follow the motion of the sun on the ecliptic. Then, he concludes that, first, comets are not shine by their own light and second, their tails are created either by refraction or reflection of the sun's rays. Grassi also briefly refers to Kepler's optical theory of comets, in which the head of a comet is assumed to be a crystalline globe, refracting the solar rays in the opposite direction.[135]

Grassi interprets his observational data in such a way that he concludes that comets follow a uniform motion on a great circle. He states that as the great circles of meridian, equator, or colures are projected as straight lines on the plate of a sundial, the path of comets on great circles also are projected as straight lines on the sky. In fact, he considers the apparent path of a comet as the stereographic projection of its real trajectory on the celestial sphere, where projection rays are emerging from the central earth (Fig. 3.4). The true place of the comet, however, is between the moon and the sun. This result does not originate from parallax measurements but from comparing the speed of the comet to the speeds of the sun and the moon. The comet's speed was calculated to be midway between the speeds of the two luminaries.

Placing the comet midway between the sun and the moon, at a distance of 572,728 miles from the center of the earth, Grassi attempted to calculate the actual dimensions of the comet.[136]At such a distance, the size of the comet's head, which was seen at an angle of 2 arc minutes on December 12, would be 333

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[135] Kepler changed his theory of comets in several later publications. We will discuss this in the section devoted to Kepler's cometary theory.

[136] This is not exactly the middle of the distance between the moon and the sun. Grassi's value for the earth's radius is 3,579 miles; therefore, he locates the comet at a distance of 160 E_r from the earth's center. In Tycho's system, the moon and the sun are located at 60 and 1,150 E_r from the earth respectively. Thus, the comet is much closer to the moon than the sun.

miles,[137] and its entire size, seen under an angle of 60°, turns out to be about 600,000 miles.[138] Although Grassi believes that the tail is nothing but an optical effect created by refraction or reflection of the solar rays, he calculates the volume of the entire comet (head and the tail altogether) to be 52,276,200,000 cubic miles, with the volume of the head (excluding the tail) being only 19,361,555 cubic miles.[139]

Grassi's account of the comets of 1618 is an exemplar of a quantitative report on cometary phenomena in the early modern era. His approach in providing this report makes it a good example of technical writing about comets. First of all, employing different sets of observational data provided by the Jesuit network of observers makes the parallax calculations more reliable and defendable. Secondly, Grassi puts his initial results to the test by comparing them to other observations and calculations. Thirdly, he tries to create a realistic view of a comet by giving its dimensions and volume. And finally, he steps away from metaphysical interpretation of comets, by being silent about their cosmological role or destiny. Diverging from Aristotle and at the same time from Copernicus, Grassi acknowledges Brahe's system of the world, then the best available alternative system. His account of the comets of 1618 was a great support for Brahe's model.

Grassi's work triggered a heated and bitter dispute between him and Jesuit scholars on one side and Galileo and his disciples on the opposite side. For Galileo, this was a great opportunity, after the decree of 1616, to exploit comets in order to attack Brahe's geocentric system for the benefit of the Copernican heliocentric world. While Galileo was bedridden at the time, his student Mario Guiducci replied to Grassi immediately and a long dispute began over the nature and motion of the comets.[140]

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[137] Based on Brahe's scheme of sizes and distances for the planets, this value is about on third of the diameter of the moon. See Van Helden, *Measuring the Universe*, p. 50.

[138] Grassi's calculations are confusing. If the comet is at the distance of 572,728 miles from the center of the earth, the circumference of its circle will be 1.029974^{12} miles and 60 degrees of it equals to 1.716624^{11} miles.

[139] Drake, *The Controversy*, p. 18.

[140] The debate on the comets of 1618 has been the subject of many studies. See Drake, *The Controversy*, pp. vii–xxv; William Shea, "The Challenge of the Comets," *Galileo's Intellectual Revolution* (New York: Science History Publications, 1977), pp. 75–108; Pietro Redondi, *Galileo Heretic* (Princeton: Princeton University Press, 1987), pp. 28–67; Mario Biagioli, *Galileo Courtier* (Chicago: The University of Chicago Press, 1993), pp. 267–311; Richard R. Westfall, "Galileo and the Jesuits," in *Essays on the Trial of Galileo* (Vatican City: Vatican Observatory, 1989), pp. 31–57, Ruffner, *The Background*, pp. 72–93, Yeomans; *Comets*, pp. 57–62.

Here, we concentrate mainly on the ideas and theories exchanged between both sides on the physics of comets.

Galileo’s Comet

Guiducci, speaking for Galileo in *Discourse on the Comets*,[141] starts his work by followings Aristotle’s assessment of the opinions of the ancients in *Meteorology*. Then, he explains Galileo’s theory of comets, which is based on three major assumptions: (1) Comets are not planets or planet-like objects performing circular motion, (2) Comets are not real objects as planets are, or even a burning exhalation, and (3) Since comets are mere appearances, parallax does not function in them.

To conclude that comets are not planet-like objects moving on circular paths, Galileo compares the apparent size and brightness of the planets and comets. Planets, when they are at their greatest distance from the earth, appear small and shine less. However, when they approach the earth, they become gradually brighter and larger until they reach their greatest magnitudes.[142] Then, they become steadily smaller and this variation repeats itself periodically. Comets, however, show an opposite change in their brilliancy. They are brighter when they first appear, but diminish slowly until they become invisible. Nevertheless, one can assume that comets are moving on very large circles. Galileo states that if the comet of 1618 was the same as the comet of 1577[143] (because no previous comet had been seen similar to the comet of 1618 in size and duration except that of 1577), then a contradiction arises between the observed speed and the size of the comet’s circle. The comet of 1618 traveled more than a quarter of a great circle in the celestial sphere in about forty days. If it took forty-one years for the comet to complete one round of its trajectory, it would have not moved even 1 degree in forty days.[144]

Galileo rejects Aristotle’s idea that comets are fiery objects. He does not admit that the hot and dry exhalation are carried by the revolution of the heavens (since more subtle materials move straight); he says that even if the celestial orbs sweep the uppermost elements, they should produce cold and extinguish fire rather than create heat. Galileo states that the duration of fire depends on the fuel and not upon the quality of fire by which the fuel ignites to burn. Also, it is not probable that the exhalation burns for a long time in the uppermost part of the atmosphere and burns for a very short time (as shooting stars) when its altitude is not so high. Moreover, no lucid body is transparent, but the light of stars can penetrate through a comet

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[141] Mario Guiducci, *Discorso delle comete* (Florence, 1619); An English translation is in Drake, *The Controversy*, pp. 21–65. The original manuscript of the book is largely in Galileo’s own handwriting, and the sections drafted by Guiducci are edited and signed by Galileo. See Shea, “The Challenge of the Comets,” pp. 75–76.

[142] The inner planets are seen in their greatest brilliancy when they are at quadrature.

[143] This assumption, based on the information that Galileo gives a few pages later, could not be valid. Galileo says that the inclination of the circle of the comet of 1577 was less than 30 degrees, while that of 1618 was 60 degrees. Furthermore, the comet of 1577 moved in the order of signs, but the comet of 1618 moved against the signs. See Drake, *The Controversy*, p. 49.

[144] Drake, *The Controversy*, p. 27.

which is many yards or even miles in thickness.[145] Finally, Galileo discards Aristotle's opinion even by exploiting parallax measurements. He states that "it is quite impossible to support the view that a comet is a fire and yet to locate it under the moon, this being repugnant to its small parallax as observed by so many excellent astronomers with extreme care."[146]

Although Galileo acknowledges the validity of parallax measurement as a criterion of distance of objects, he does not concede it as a distance indicator for *everything* visible:

> There are two sorts of visible objects; some are real, actual, individual, and immovable, while others are mere appearances, reflections of light, images, and wandering simulacra which are so dependent for their existence upon the vision of the observer that not only do they change position when he does, but I believe they would vanish entirely if his vision were taken away. Parallax operates reliably in real and permanent things whose essence is not affected by anyone's vision; these do not change place when the eye is moved. But parallax does not function in mere appearances.[147]

Therefore, it has to be proved first that comets are real objects and then parallax may be used to measure their distances. Galileo's argument that comets are mere appearances, however, does not go beyond drawing a few analogies between comets and some optical phenomena such as halos, mock suns, and sunbeams penetrating through small openings of clouds in the horizon.

For Galileo there is a similarity between the formation of comets and the Aurora borealis. He assumes that sometimes the vapor-laden air around the earth becomes extremely rarefied and rises so high that it passes the shadow cone of the earth (Fig. 3.5). There, it reflects the solar rays which an observer at the northern latitudes can see as the northern lights.[148]

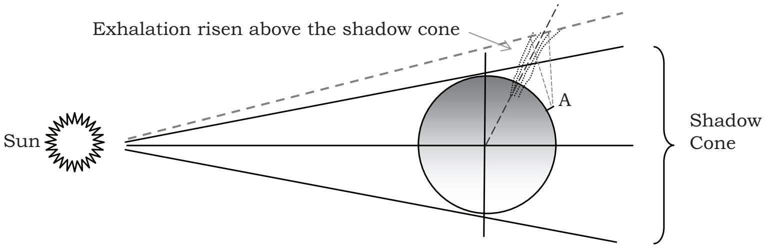

Fig. 3.5 Galileo's theory of the Aurora Borealis: rarified vapor rises above the shadow cone of the earth and reflects the sun's rays to the observer A

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[145] Ibid., pp. 28–35.

[146] Ibid., p. 35.

[147] Ibid., pp. 36–37.

[148] Ibid., pp. 53–54. Galileo imagines that the aurora borealis is seen most frequently in the summer and says that since in the summer the sun is at the north of the celestial equator, the shadow cone tilts towards the south and the vapor needs to rise only a short distance to reflect the sun's rays from the outside of the shadow cone.

Galileo theorizes the phenomena of comets in a similar way. He takes it for granted that exhalations move uniformly along a straight line from the surface of the earth to the sky and even to the celestial region.[149] Using a diagram similar to Fig. 3.6, Galileo shows that when a cluster of exhalation rises from the earth (circle ABC) it moves along the straight line DF and travels the equal segments of SO, ON, NI, and IF in equal times. The observer is located at A, where the sun is below the observer's horizon, AG. When the exhalation is at O, it reflects the sun's rays to A which is seen as a comet. The reflected rays, however, have to pass through the earth's atmosphere which is not pure and simple air. Since the atmosphere to a certain height is mixed with gross vapors and fumes, it is denser at the lower parts and tenuous in higher altitudes. Thus, the reflected rays are refracted in the earth's atmosphere. Now, if the observer is at A, the point of incidence and the refracted rays are located in the same plane that passes through the length of the comet, and the tail of the comet will be seen to be straight. On the contrary, if the eye is outside of that plane, the tail will be seen to be curved.[150]

In this theory, Galileo tries to save all observed features of comets using several *ad hoc* arrangements of analogies and experiments.[151] The random appearance of comets is explained by accidental rarefaction of some exhalations and their sublimation to the celestial region (therefore, comets are not periodical); the antisolarity of cometary tails is justified by the reflection of the sun's rays from the exhalations; the progressively diminishing size and brightness of comets is understood as the result of their recession from the earth; and the cometary trajectory, which is assumed to be rectilinear, is explained by the straight motion of the substance that reflects the sun's rays.

Galileo's comet, however, is a mere appearance. There is no detailed quantitative information about the physical constitution of comets in Galileo's works. There is no description of cometary sizes, the minimum and maximum distance of comets from the earth, and the volume and shape of exhalations responsible for cometary appearances. The theory is a qualitative description of cometary appearances in which a century of observational and computational achievements is neglected.

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[149] Galileo states this idea more clearly in his *Dialogue:* "… Neither do I feel any reluctance to believe that their [comets] matter is elemental, and that they may rise as they please without encountering any obstacle from the impenetrability of the Peripatetic heavens, which I hold to be far more tenuous, yielding and subtle than our air." See Galileo Galilei, *Dialogue Concerning the Two Chief World Systems*, trans. Stillman Drake (Los Angeles: University of California Press, 1967), p. 52.

[150] Drake, *The Controversy*, pp. 56–62.

[151] Galileo's ideas about comets are scattered in his various writings. After Guiducci published the *Discourse*, Grassi, under the pseudonym of Lothario Sarsi, replied to Galileo directly by writing a treatise entitled *Libra astronomica* (*The Astronomical Balance*, see Drake, *The Controversy*, pp. 67–132). The debate was continued by Guiducci's letter to Father Tarquinio Galluzzi (Ibid., pp. 133–150), and finally, in 1623, Galileo published one of his masterpieces named *Il saggiatore* (*The Assayer*, Ibid., pp. 151–336) in which, along with many other topics in physics and astronomy, he expanded and explained parts of his cometary theory that had been rejected or misunderstood by Grassi and the Jesuits. Furthermore, Galileo in the *Dialogue* explains his cometary theory briefly. See Galileo, *Dialogue*, p. 52, 218.

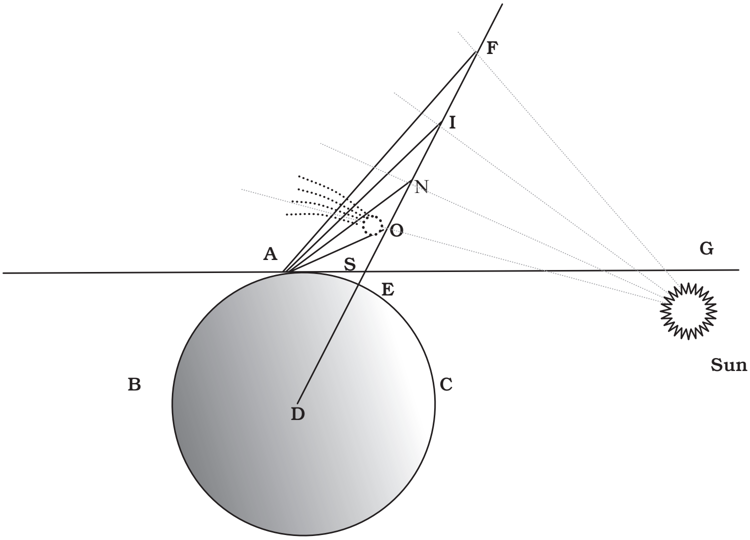

Fig. 3.6 Galileo's theory of comets: A cluster of exhalation moves uniformly along a straight line, into the celestial region, and the observer A sees it under progressively decreasing angles. Therefore, the comet appears steadily smaller and slower, while moving on a rectilinear trajectory

Galileo's theory of comets did not attract supporters except in a small circle of his disciples and faded out even when the master was alive.

The debate between Grassi and Galileo brought Kepler indirectly into the throes of the dispute. Exploiting Kepler's ideas about optics and comets in the writings of the both sides was not important enough for Kepler to respond, but Galileo's bitter argument against the discoveries and measurements of Tycho invited a response. Kepler, however, entered in the debate after receiving a copy of the *Assayer* when he had just completed a treatise in defending Tycho. The treatise, entitled *Tychonis Brahei Dani Hyperaspistes* (The Shieldbearer to Tycho Brahe the Dane), was an answer to Scipio Chiaramonti's attack against Tycho Brahe, and Kepler added an appendix to respond to Galileo's anti-Tycho ideas.[152] In this appendix, besides answering arguments related to Brahe or himself, Kepler gives a brief account of his own theory of comets.

Kepler's Theory of Comets

If Galileo's theory of comets was a divergence from the mainstream of contemporary cometary ideas, Kepler's theory was the continuation of the tradition that related the nature of comets to their kinematics. Kepler, however, diverged from

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[152] An English translation of this appendix is in Drake, *The Controversy*, pp. 337–355.

Tycho Brahe's idea by assigning a rectilinear trajectory to comets. For Kepler, comets were ephemeral but the way he described the life period of comets was completely new. In fact, he introduced a new solar-comet relationship that directly governed the physics of comets.

Kepler's first theory of comets appeared in his 1604 work entitled *Astronomiae pars optica*.[153] There, his idea about comets was reminiscent of the optical theory of Tycho and Mästlin, but his notion of cometary material and motion was opposite. He thought comets to be spherical transparent objects *refracting* the sun's rays. Kepler refers to an experiment in which the sun's rays fall on a glass globe – either solid or filled with water – in front of a wall. He noticed that a part of the rays passes through the globe and strike the wall and a part is intercepted by the glass. This might have been a plausible presentation of the formation of cometary tails, but later a critical question showed Kepler how such an analogy was inept. He wrote:

> This manual experiment was then proposed by me, but it was not applied to true comets themselves seen in the sky. But if anyone wishes to apply this, then he must set up in the open spaces of the universe some real object which has the nature of a glass globe and something else to take the place of the wall. For reflection alone would not form a comet.[154]

Kepler indicates that the refraction of the sun's rays can not be seen in the pure ether behind the comet's head, unless there is some matter dense enough to be illuminated by the refracted rays.[155] In other words, there must be a reflective matter behind the head of a comet to make the refracted rays visible.

Kepler devised a genuine mechanism to solve the problem. He assumed that the head of a comet is a globe of transparent nebula-like matter which is denser than the surrounding ether, but is not solid and indissoluble. When the sun's rays pass through the head they expel a stream or effluvium of the nebulous matter of the head in the opposite direction. This stream, which obviously is denser than the pure ether, reflects the sun's rays and becomes visible as the tail of the comet. Evidently, the matter of the head is gradually consumed and the head finally dies out, or as Kepler stated "the tail represents the death of the head."[156]

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[153] The complete title of Kepler's work is *Ad Vitellionem Paralipomena, quibus Astronomiae pars Optica traditur* (Frankfurt, 1604). For an English translation see: William H. Donahue, trans., *Optics: Paralipomena to Witelo and Optical Part of Astronomy* (Santa Fe: Green Lion Press, 2000). For the development of Kepler's optical theory of comets see Barker, "The Optical Theory," pp. 18–25. A brief account of Kepler's cometary theory and a list of Kepler's works on comets is in C. Doris Hellman, "Kepler and Comets," in Arthur Beer, Peter Beer, ed., *Kepler*, Proceedings of Conferences held in honour of Johannes Kepler, *Vistas in Astronomy*, 18 (1975), 789–796. For Kepler's treatment of cometary motion see Ruffner, *The Background*, pp. 94–118; Ruffner, "The Curved and the Straight," 178–183; Westman, "The Comet and the Cosmos."

[154] Kepler, *Appendix to the Hyperaspistas*, in Drake, *The Controversy*, p. 346. From 1604 to 1625, Kepler published several works devoted partially or totally to his cometary theory. His *De Cometis libelli tres* (Augsburg, 1619) contains his mature version of theory of comets. A brief summary of it can be found in the *Appendix to the Hyperaspistas*, Ibid.

[155] Rothmann also pointed this problem in a letter to Brahe in 1588. See Barker, "The Optical Theory," p. 22.

[156] Kepler, *Appendix to the Hyperaspistas*, in Drake, *The Controversy*, p. 347.

Kepler's theory is almost equivalent to the modern theory of tail formation, which was developed after the theoretical discovery and experimental verification of the pressure of light.[157] Although this modern theory has been mentioned in almost all writings related to Kepler's theory of comets, a very important aspect of his theory has not been discussed adequately. The theory, due to its novel approach in treating celestial phenomena, opened a new chapter in physical astronomy. Kepler's theory of comets, on the one hand, explained the formation and change of the tails based on mechanical interaction of celestial bodies, and on the other hand, it acknowledged a kind of matter circulation (or re-distribution) in the heavens. Later, modified versions of these concepts formed the foundations of Newton's theory of comets.

Although Kepler maintained the idea that comets were ephemeral and ominous, he interpreted their life in a different way. Kepler assumed that comets emerged from the coagulation of thick and unpurified parts of the ether. Therefore, one of the reasons for their creation was to clear the ether and consequently prevent the accumulation of the thick parts of the ether, which might dim the light of the sun and stars. Besides considering comets as portentous celestial creations, Kepler assigned them a cosmological role. He noted that there are as many comets in the heavens as fish in the oceans and only those comets can be seen that come close to the earth. Therefore, it seems that comets were created to counterbalance those processes that condense the ether or make it impure.[158] However, in Kepler's theory, comets played an opposite role as well. Because Kepler's comet had a material tail (it was not mere reflected or refracted rays), it could spread the impure ether again in the heavens when it was moving and leaving behind an effluvium of the head's material. Because the total number of comets was assumed to be much greater than those exposed to the sun, cometary appearances would not greatly increase the impurity of the ether in the world.

What made Kepler's comet different was the unavoidable cosmic-scale *physical* influence that was associated with it. Contrary to all previous theories, Kepler's theory admitted that comets could transfer impurities from the distant parts of the universe:

> But what if we mingle the Aristotelian opinion of the tail with the more recent one, so that some luminous matter really does exhale from the head, and indeed in that direction in which it is sent forth, by the sun's rays, as it were? Then if the tail were to touch the earth, no wonder that the air be infected by a poisonous influence.[159]

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[157] Although the concept of light pressure was proposed before the mid-nineteenth century (for example, Descartes defined light as a pressure transmitted through the subtle matter of vortices, or Newton theorized that light consist of particles possessing momentum) it was James Clerk Maxwell (1831–1879) who showed that transverse electromagnetic waves should exert a force. Maxwell's theory was experimentally verified in 1901 after developments made by Pëtr Lebedev (1866–1912), Ernest Nichols (1869–1924) and Gordon Hull (1870–1956). See Morton L. Schagrin, "Early Observations and Calculations on Light Pressure," *American Journal of Physics* 42 (1974), 927–940.

[158] Johann Kepler, *Aussführlicher Bericht von dem newlich im Monat Septembri und Octobri diss 1607. Jahrs erschienenen Haarsten oder Comten und seinen Bedeutungen* (Halle in Saxony, 1608), Aij^{r} or Christian Frisch, ed. *Johannis Kepleri Astronomi opra omnia*, 8 vols. (Frankfurt: Heyder & Zimmer, 1858–1871), vol. 7, p. 25. In the 1670s, Pierre Petit in a similar way thought of comets as universal garbage collectors. See Yeomans, *Comets*, p. 73.

[159] Johann Kepler, *Optics: Paralipomena to Witelo and Optical Part of Astronomy*, trans. William H. Donahue (Santa Fe: Green Lion Press, 2000), p. 278.

Therefore, comets were not simply inert transparent spheres in the sky. They were able to undergo a reaction with the sun's rays, spread unpurified ether in the heavens, and finally become extinct. For the first time, in Kepler's theory, a changing object in the celestial region was explained on a naturalistic causal basis.

Kepler did not include comets in the solar system, and obviously did not apply his laws of planetary motions to comets. Because comets were not made from planetary material, he did not try to involve comets in his dynamical theories of motion based on magnetic attraction and repulsion. In his theory, comets could move freely along straight lines above or below the moon, but their trajectories might appear as curved lines due to the motion of the earth around the sun.

In Kepler's theory, some other quantitative descriptions of comets also are missing. Since the tail is a stream of matter coming out of the comet's head, and given that some comets have maintained their long tails for sixty or even ninety days, the size of the head should be an interesting question to be answered. Kepler, by drawing an analogy between comets and whales indirectly refers to the enormous size (and violent nature) of comets, but does not use the observational data to make conjectures about the size of the heads of comets. Although Kepler believed that "nothing is more in concord with nature than that the order of the sizes should be the same as the order of the spheres,"[160] (or sizes and distances should be proportional), he applied this rule solely for the permanent members of the planetary system.

While Kepler had constructed a heliocentric system after analyzing a massive amount of observational data, the French philosopher René Descartes (1596–1650) laid down his mechanical philosophy in which heliocentrism was a fundamental concept. Contrary to Kepler, Descartes' system of the universe was built upon a number of principles defining the relation between matter and motion. In Descartes' philosophy, comets are the final products of the cosmos and contain the densest substance in the universe. They have a planet-like head, but their tails are optical. They always are moving beyond the realm of the farthest planets and bear little threat to human beings. Descartes' theory of comets was one of the most influential pre-Newtonian theories in cometology.

Comets in Descartes' Cosmos

Descartes' physical theory of comets is a part of his theory of the cosmos, in which all observed phenomena can be explained based on the mechanics of matter and motion. Since Descartes' speculations over the formation, motion and physical properties of comets occupy the last parts of his theories of the visible universe, many preliminary definitions and principles must be mastered before the main theory of comets is reached. It is first necessary to comprehend the basic concepts of matter and motion within the framework of Descartes' mechanical philosophy, and next to consider the

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[160] Johannes Kepler, *Gesammelte Werke* (Munich: C. H. Beck, 1937-), 7: 281, cited from Van Helden, *Measuring the Universe*, p. 84.

theory he developed to explain the life of stars. For, in Descartes' theory, comets and planets are dead stars that are pushed out from the center of their vortices.

According to Descartes, at the beginning, the cosmos was filled by a primary matter, with particles that were uniform but not spherical.[161] God then endowed a motion to the particles collectively and two kinds of motion appeared: each particle started to rotate around its own center and also several particles together revolved around certain other centers.[162] Because of these motions, the particles of the primary matter rub each other and friction between them makes most of them spherical with the passing of time. Whatever was the shape of the particles of the primary matter, most of them lost their edges and angles through continuous friction with the adjacent particles. In this process, three kinds of elements appeared. Those particles, which become completely spherical, constitute the second element.[163] The particles of the second element (E2), which Descartes calls *boules* or globules, are the building units of the heavens or the vortices. However, since void is not admitted in Descartes' cosmos, the small empty spaces between the spheres of the second element should be filled with a kind of matter. These spaces are filled by the scrapings produced during the rubbing and striking of particles of the primary matter. When particles of the primary matter collided with each other, broken parts and scrapings resulted. The broken smaller parts, in turn, acquired spherical shape through rubbing and friction and left more scrapings. The scrapings, being very small and moving very rapidly, were broken into even smaller pieces and filled all the angles between the spherical particles. For Descartes, the first element (E1) is composed of these very tiny particles that fill the entire cosmos. The third element (E3), in contrast, is composed of those particles of the primary matter which are not broken more and are left in irregular shapes (Fig. 3.7). The sun and stars are made of the first element; the planets and comets consisted of the third element; and the heavens (vortices) are made of the second and the first elements.[164]

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[161] If they were spherical, there would be void spaces between the spheres. Vacuum is not admitted in Descartes' cosmos as that of Aristotle. Descartes developed his theory of elements mainly in *Le monde, ou Traité de la Lumière* (1633) and *Les Principes de la Philosophie* (1647), and mentioned it briefly in *Dioptrique* (1637) and *Météores* (1637). Because of the Church's condemnation of Galileo in 1633, Descartes did not publish *Le monde* (*The World*), in which he had adopted a heliocentric model of the world. But, parts of the *Le monde* published by 1637 and some of it was published posthumously. The theory of elements discussed here is taken from: René Descartes, *Principles of Philosophy*, trans. Valentine Rodger Miller and Reese P. Miller (London: D. Reidel Publishing Company, 1983). To trace the development of Descartes' theory of elements see John W. Lynes, "Descartes' Theory of Elements: From *Le Monde* to the *Principles*," *Journal of History of Ideas* 43 (1982), 55–72.

[162] Descartes, *Principles*, III, 46.

[163] The particles of the second element are not equal in size; their sizes gradually increase from the vicinity of the central star to the outer parts of the vortices. Their agitation, however, decreases from the center of the vortices towards the outer parts. See ibid., III, 82.

[164] Ibid., III, pp. 49–54. The three elements of Descartes, in fact, are three manifestations or forms of a single primary matter, which based on their different shapes, sizes and motions, have different functions in the universe. Similarly, the three different kinds of celestial bodies known for Descartes (stars, planets, and comets) have a single origin.

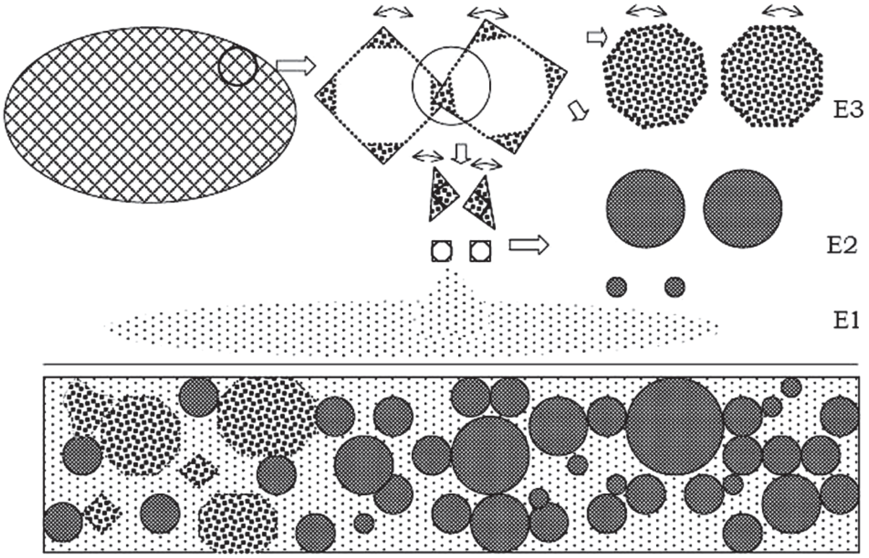

Fig. 3.7 Descartes' cosmos, at the beginning, was filled by non-spherical particles of the primary matter. When the Creator gave motion to the cosmos, most of those non-spherical particles became spherical due to friction and rubbing. In this process, a great amount of scrapings (first element, E1) was produced too. The rapidly moving scrapings, colliding with the larger particles, became more and more small and filled all spaces between the elements E2 and E3. Descartes does not specify the shape of the primary matter

Friction between the constantly moving particles of the second element in the vortices increased the amount of the first element and an excess amount of the latter appeared after it filled all spaces between the particles of the second element. Based on mechanical laws,[165] particles of the second element, which were bigger than the particles of the first element, receded away from the centers of the vortices and the particles of the first element flowed towards the centers of the vortices S, F, *f*, and so on (Fig. 3.8). There, they formed spherical bodies, which are called the sun or the fixed stars.

The first element, however, is not entirely composed of particles with equal shapes, sizes, and speeds. There are particles of the first element that are less broken than the rest and move with a lower speed (or they are not as agitated as the other particles). Since they are less agitated, they can easily attach to each other and make larger particles. These particles, which are called grooved particles, are triangular in cross-section (but with concave sides), and are smaller than the space between three tangential spheres of the second element (Fig. 3.9). To pass the small spaces between the particles of the second element, the grooved particles should be

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[165] Descartes, *Principles*, III, pp. 58–60, 62.

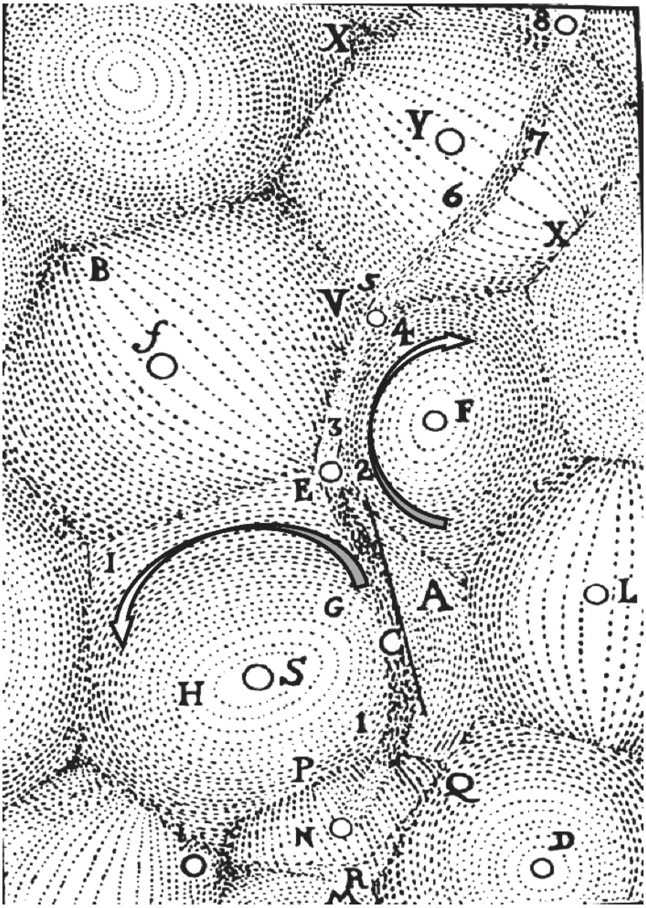

Fig. 3.8 The Cartesian vortices are swirling particles circling around central stars S, F, Y, *f* and so on. The vortices consist of the second element (E2), the stars are made of the first element (E1) and planets and comets are composed of the third element (E3) (From Descartes' *Principles of Philosophy*, 1644) The arrows are superimposed to show the direction of rotation of the vortices S and F

twisted like the shell of a snail.[166] Consequently, they can move like a screw among the intervals of the adjacent spheres.

Particles of the first element (including the grooved particles) flow continuously from the poles of the vortices towards the center (where the sun or a star is located) and then move out through the parts distant from the poles [167](Fig. 3.10). In the same way, when the particles of the first element reach the sun or a star, they flow

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[166] Ibid., III, pp. 87–92.

[167] Ibid., III, p. 69. The vortices are arranged in such a way that two vortices cannot touch at their poles. Therefore, particles that are flowing out from the equatorial parts of a vortex can easily enter the polar region of a vortex above or below, see Fig. 3.10.

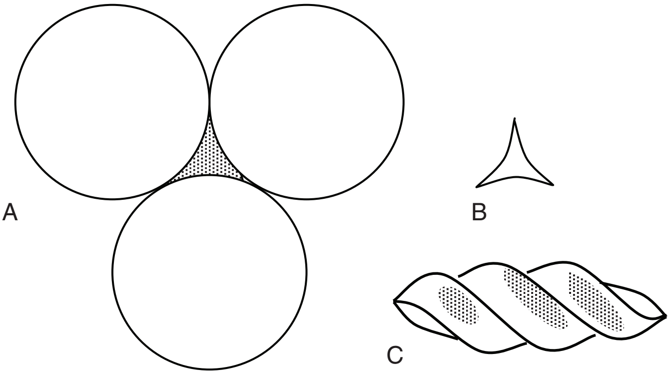

Fig. 3.9 The cross-section (B) of a grooved particle (C) is triangular with concave sides. It is slightly smaller than the space between three adjacent spheres of the second element (A). The grooved particle is twisted like a screw which makes it easier to move among the particles of the second element

from the poles towards its equator. The only difference is that in the vortices the particles of the first element are moving among the particles of the second element; but inside the stars they have to move among the particles of the first element, which are moving with high speed. Consequently, inside the sun or another star, the received particles are being sorted by their agitation. The finest particles can easily move, but the grooved particles (and other particles which are not as fine as the particles of the first element), can not move as rapidly as the first element because of their angular shapes or larger sizes. They stick together and make very large masses. These masses are sunspots and are located on the surface of the star, in such a way that their outer surfaces are in touch with particles of the second element of the encompassing vortex.[168]

Sunspots were among the most important discoveries made by the telescope. After a long debate about the nature of the spots, which started immediately after their discovery, most astronomers and natural philosophers became convinced that the spots on the sun were not external objects such as planets or satellites.[169]

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[168] Ibid., III, pp. 93–94.

[169] Besides the dispute about the priority of discovery, a heated debate was going on over the nature of the sunspots, which lasted even till the end of the seventeenth century. Galileo and his followers believed that the spots were located on the sun, but Christopher Scheiner, Jean Tarde, Athanasius Kircher and others (mostly Jesuits) assumed the spots to be external bodies. For a detailed account of the debate between Galileo and Scheiner see: William R. Shea, "Galileo, Scheiner, and the Interpretation of Sunspots," *Isis* 61 (1970), 498–519. Tarde's argument is discussed in Frederic J. Baumgartner, "Sunspots or Sun's Planets: Jean Tarde and the Sunspots Controversy of the Early Seventeenth Century," *Journal of History of Astronomy* xviii (1987), 44–54. In 1640, William Crabtrie in an interesting letter to William Gascoigne (the inventor of the micrometer) gives all evidence then available to prove that the spots are not external bodies. See William Derham, "Observations upon the Spots that have been upon the Sun, from the Year 1703 to 1711. With a Letter of Mr. Crabtrie, in the Year 1640. upon the same Subject. By the Reverend Mr William Derham, F. R. S.," *Philosophical Transactions of the Royal Society of London*, 27 (1710–1712), 270–290.

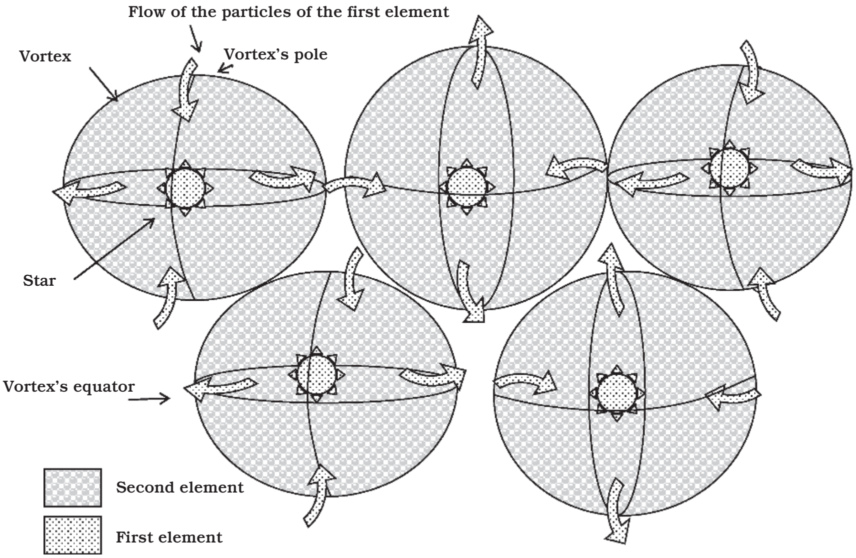

Fig. 3.10 Flow of the particles of the first element among the vortices. Vortices are attached to each other, but the poles of a vortex do not touch the poles of another one

The nature of these irregular speckles and their origin were not known. By the time that Descartes was developing his theory of comets, astronomers had discovered several facts about the sunspots, including that the spots mainly appeared in the equatorial region of the sun, that they disappeared after a week or so, that they moved (due to the rotation of the sun), and that they might be seen in groups consisting of several spots.

Descartes' theory of sunspots was able to explain all of the observed features of the phenomenon plausibly.[170] However, its importance was not merely its explanatory power for the phenomenon of sunspots: it had a much more important role in Cartesian cosmogony by preparing a physical ground to explain the origin of the planets, comets, and even novae. In Descartes' cosmos, planets and comets were degenerate stars and sunspots were the main cause of that degeneracy.

According to Descartes, sunspots, which are made up of the grooved particles, resist the action corresponding to the force of light and are seen as dark spots on the bright surface of the sun (Fig. 3.11). Light, in Descartes' optics, is a force or pressure that arises from a luminous body and transfers through the medium. Since the sun is made up of the particles of the first element and the plenum encom-

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[170] Descartes, *Principles*, III, p. 95. Descartes mentions the equatorial appearance of the sunspots, their irregular shapes, and their motion around the axis of the sun.

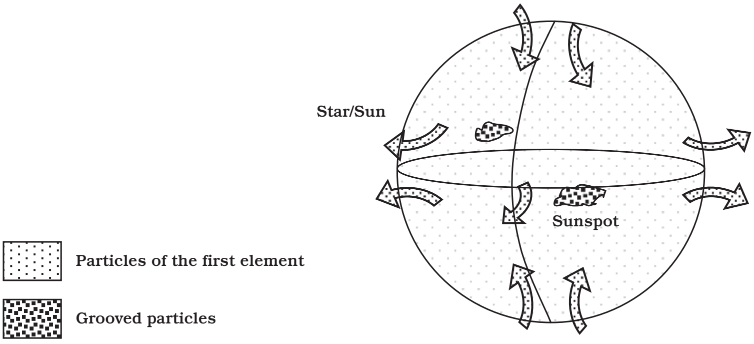

Fig. 3.11 The low-speed grooved particles attach together and appear as sunspots on the surface of the sun or other stars

passing it is composed of the particles of the second and first elements, propagation of light is interpreted as a physical interaction between these particles. Based on Cartesian mechanics,[171] since all particles are striving to recede from their centers of motion, light can transfer from the stars through the vortices.[172] Although all particles are moving away from certain centers, there is a kind of equilibrium between the pressure of the receding particles of the first element of a star and the pressure of the immediately adjacent particles of the second element in the encompassing vortex. Hence, when spots appear on the surface of the sun (or other stars) they make the star-vortex equilibrium vulnerable.

Descartes knew that the spots were temporary phenomena. He compared sunspots to some dense scum which appears on the boiling liquids. As by the continuation of boiling the scum is consumed and reabsorbed in the liquid, the spots also are broken and destroyed. However, when they disintegrate, they do not break into the same particles from which they were formed. The spot may produce very fine particles (which may return to the sun or move into the vortex), particles bigger than the first element but capable of moving among the particles of the second element, and finally large particles composed of several grooved or other angular particles. The latter cannot move inside the vortex, but they take the place of the adjacent particles of the second element in the vortex.[173]

When the spots form for the first time they are very soft, but their inner surfaces are continuously bombarded by the fast-moving particles of the sun. As a result, the inner side of the spot gradually becomes polished, denser, and harder. The outer sides, however, are raised from the surface and can grow from its edges. Therefore, the spot becomes bigger and bigger and finally cover the entire surface of a star (Fig. 3.12).

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[171] Ibid., III, pp. 59–62.

[172] Ibid., III, pp. 55, 64

[173] Ibid., III, p. 99.

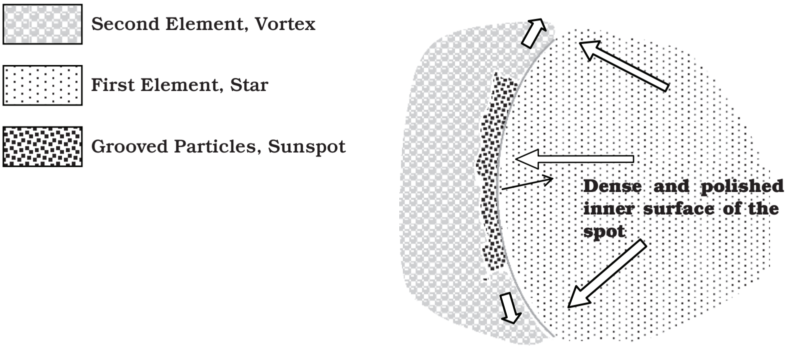

Fig. 3.12 Spots on the surfaces of a star block the flow of the particles of the first element into the vortex. As a result, the star-vortex equilibrium undergoes a disturbance which triggers the collapse of the entire vortex

This theory enabled Descartes to explain a category of stars which is called 'variable stars' in modern astronomy.[174]

Descartes, after giving details of different changes that may occur for a star and its vortex, explains the final stage in the star's life, which is its transformation into a planet or a comet. This transformation occurs when the equilibrium between one vortex and the neighboring vortices disappears, which in turn, happens when the equilibrium between a certain star and its vortex diminishes. In the Fig. 3.13, the vortex of star S is surrounded by six vortices of stars A, B, C, D, E, and F. When the star S is without spots, its vortex remains stable and so all the neighboring vortices maintain their state of equilibrium. However, if spots cover the surface of S, the star-vortex balance undergoes a disturbance. As explained earlier, the particles of the first element flow continuously from the poles of the vortices and leave them from the equatorial parts after passing through the central star. Formation of the spots on the star hinders the free flowing of the particles of the first element and result in a state of instability. Depending on the situation of the vortices, the instability may develop in two different ways. If the vortex of the star S is situated in such a way that it prevents the movement of the particles of the first element to the neighboring vortices, it would be destroyed by them even if there were not a great

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[174] Any star whose brightness is changing, periodically or irregularly, is a variable star, including cataclysmic variable stars (novae and supernovae). Although the latter phenomena had already been observed, by the mid seventeenth century only one star (Mira or omicron Ceti) was discovered to have a changing magnitude. David Fabricius observed Mira in 1596 and 1609 and found a considerable difference between the observed magnitudes. In 1638 Phocylides Holwarda of Holland ascertained its periodicity, but it was Ismael Boulliau who established the period of 333 days for the star in 1667 (the modern value is 331 days and the magnitude of the star changes from 1.7 to 9.5). See Allen, *Star Names*, pp. 164–165, and N. T. Bobrovinkoff, "The Discovery of Variable Stars," *Isis* 33 (1942), 687–689. Descartes, however, claimed that the sun was variable too. See Descartes, *Principles*, III, p. 103.

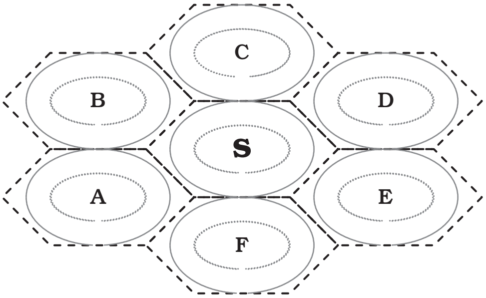

Fig. 3.13 The six vortices encompassing S maintain a state of equilibrium between themselves and S. When the central star of S is covered by spots, its vortex shrinks until nothing remains of it except the central star. The star, finally, will be carried by one of the neighboring vortices which expands. In this diagram, all vortices are assumed to have the same size and lie on the same plane

number of spots on the star. But, if it is not blocking the flow of the first element, it will shrink gradually. Meanwhile, the number of spots will increase on the star and the surrounding vortex will be smaller and smaller. When numerous dense spots cover the star and the vortex has completely disappeared, a dark object will be left, which is a conglomeration of grooved and irregular particles. Finally, when one of the neighboring vortices becomes larger and extended enough to encompass the whole space of the shrunk vortex, the dead star will be carried by it.[175] There, based on the path that it takes, the dead star will appear as a planet or a comet.

A Comet's Trajectory Among the Vortices

According to Descartes, planets and comets are composed of the same matter, except that comets are more 'solid'. Here, solidity means "the quantity of the matter of the third element"[176] in the dead star, which bears a resemblance to the modern concept of mass. When the dead star is carried by a new vortex, its potential trajectory depends on the *relative* agitation it acquires and this agitation, in turn, is determined by the solidity of the dead star. In other words, to determine the trajectory of a body in a vortex, it is necessary to know its agitation relative to the agitation of the neighboring particles of the second element, which are moving around the center of the vortex. This means that the agitation of these particles is not equal in the entire vortex. Descartes states that the particles of the second element are smaller and moving faster in the inner parts of a vortex than its outer parts.

At a specific distance from the center of the vortex, there is a dividing ring that separates the fast moving small particles from the slow moving bigger particles. This dividing ring splits the vortex into planetary and non-planetary (or cometary) regions. Beyond this ring up to the boundary of the vortex, particles of the second

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[175] Ibid., III, pp. 110–119. In other words, the density of comets is higher than the density of planets.

[176] Ibid., III, p. 121.

element are equal in size, but their motion increases progressively.[177] In other words, particles in the dividing ring have the slowest speed in the whole vortex. If the dead star were solid enough and gained agitation equal to agitation of the particles of the second element before descending to the dividing ring, it would move as a comet beyond the dividing ring. On the contrary, if the solidity of the dead star were not enough, it would pass the dividing ring and revolve as a planet around the central star. The dividing ring in the vortex of the sun is marked by Saturn's circle of motion.

Outside the dividing ring, the comet moves tangentially to the circular paths described by the particles of the second element (Fig. 3.14) and travels between the vortices. Therefore, comets always move farther than the farthest planet of a typical vortex, between the largest particles of the second element in the vortex.[178] There, the agitation or momentum it gains is enough to shoot the comet to the next vortex.

When the comet passes the boundary of a vortex and enters into the adjacent vortex, it remains again outside the dividing ring of the new vortex and is agitated by those particles that describe the largest circles in the vortex. After passing about

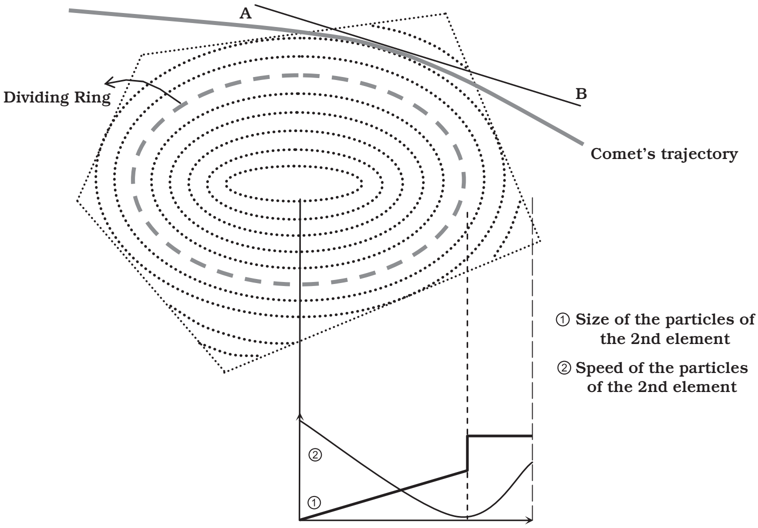

Fig. 3.14 The pattern of variation in size and speed of the particles of the second element in a vortex. Since there is no quantitative explanation in Descartes' account, the slope of the lines are taken arbitrarily

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[177] Ibid., III, p. 119.

[178] Descartes is not explicit about the distance between the boundaries of a typical vortex and the dividing ring. For the distances between the planets and stars see Ibid., III, pp. 7, 20, 41.

half of the vortex, once more, it obtains enough agitation to move to the next vortex, and the process repeats[179] (Fig. 3.8). Consequently, the maximum course of a comet in a vortex cannot exceed half of a complete revolution of the outermost particles of the vortex.[180]

According to Descartes, because comets reflect the light of the central star, they can only be seen when they arrive in the observer's vortex. However, it is a reasonable question to ask why the comets of other vortices cannot be seen, even though their stars are visible. He states that when a comet passes from one vortex to another, it always pushes a portion of the matter of the previous vortex to the new one. This ex-vortex matter stays with the comet for a while until it is removed by the motion of the particles of second element of the new vortex.[181] Therefore, comets can be seen in the new vortex only after losing the material of the previous vortex. Another possible reason for the ephemeral visibility of comets, as Descartes explains, is the rotation of comets by changing their vortices. It is expected that only one side of each comet is suitable to reflect light, as we see in the case of the moon. Accordingly, when a comet passes from one vortex to another, it turns in such a way that its reflective side faces the central star of the new vortex.[182]

Descartes' Theory of Cometary Tails

Descartes explains cometary tails based on the reflection of the sun's rays from the body of comets. However, he introduces a new kind of refraction that can take place only in the heavens.[183] This reflection is due to the fact that the particles of the second element are not equal in size in the vortex. As mentioned earlier, particles of the second element gradually become bigger from the sun towards the outer parts of the vortex. But, beyond the dividing ring – where comets move – those particles are larger and equal in size. Since propagation of light is described as the transfer of pressure between the particles of the second element, inequality in their sizes (outside and inside of the dividing ring) causes different optical effects, which we can not experience in the vicinity of the earth, where the particles are smaller and equal in size (Fig. 3.15).

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[179] Ibid., III, pp. 126–127.

[180] Ibid., III, p. 129.

[181] It is also interesting that in Descartes' theory comets are vehicles to transfer matter from one vortex to another, although he used this concept to explain problems associated with the visibility of comets at their entrance to the new vortex.

[182] Ibid., III, p. 132.

[183] Descartes did not discuss this kind of reflection in his *Dioptrics*, because it was not observed in terrestrial bodies. See Ibid., III, p. 134.

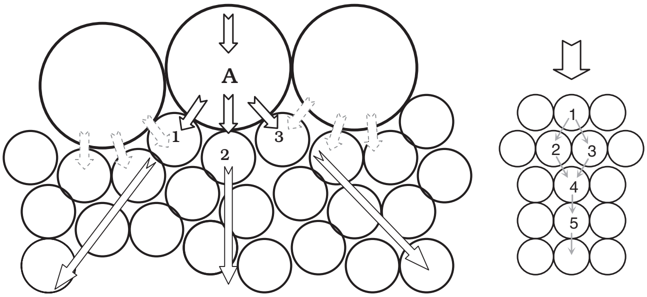

Fig. 3.15 Left: the pressure of sphere A is distributed between three smaller spheres and therefore, propagates in three different directions. If all the spheres were equal in size, the pressure would be exerted in one direction (right)

According to Descartes, when a comet reflects the sun's rays, the reflected rays, or the pressure that is transferred between the particles of the second element, experience the changing circumstances arising from the inequality of particles of the second element. When the large particles of the outside of the dividing ring exert pressure on the smaller particles of the inside, the pressure is divided and propagated in different directions as illustrated in Fig. 3.15. This dispersion of light, in effect, is seen as the tail of the comet.[184] However, the possible directions and shapes of tails which are shown in Fig. 3.16 (taken from Descartes' original work) were not compatible with observation. The mechanism introduced by Descartes does not yield the kind of antisolarity that had been observed in a majority of cometary appearances.

Descartes' theory of comets, to some extent, was an accepted theory for the reminder of the seventeenth century.[185] As a part of Descartes' physical theory of cosmos, it was an attempt to lay down the mechanical foundations of comets' formation and motion. The theory, however, did not provide any quantitative approach in treating comets' motions, locations, and trajectories. Hence, Descartes' theory of comets was not very attractive for technical astronomers. However, in the Cartesian cosmology, natural philosophers could find a plausible philosophical explanation for the newly proposed heliocentric system. Descartes' vortices and Kepler's solar

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[184] Descartes, *Principles*, III, pp. 135–138.

[185] Aspects of Descartes' theory of vortices were modified or developed by Cartesians even after the publication of Newton's *Principia*. In the late seventeenth and early eighteenth centuries, Christian Huygens (1629–1695), Philippe Villemot (1651–1713), Nicolas Malebranche (1638–1715) and Joseph Saurin (1659–1737) were among those who developed theories of planetary motion or explained the earth's gravity based on Cartesian concepts. See: Aiton, *The Vortex Theory*, chapters IV to IX (pp. 65–209), Eric J. Aiton, "The vortex theory in competition with Newtonian celestial dynamics," in *The General History of Astronomy: Planetary Astronomy from the Renaissance to the Rise of Astrophysics*, vol. 2B: *The Eighteenth and Nineteenth Centuries*, Edited by R. Taton and C. Wilson (Cambridge: Cambridge University Press, 1995), pp. 3–21.

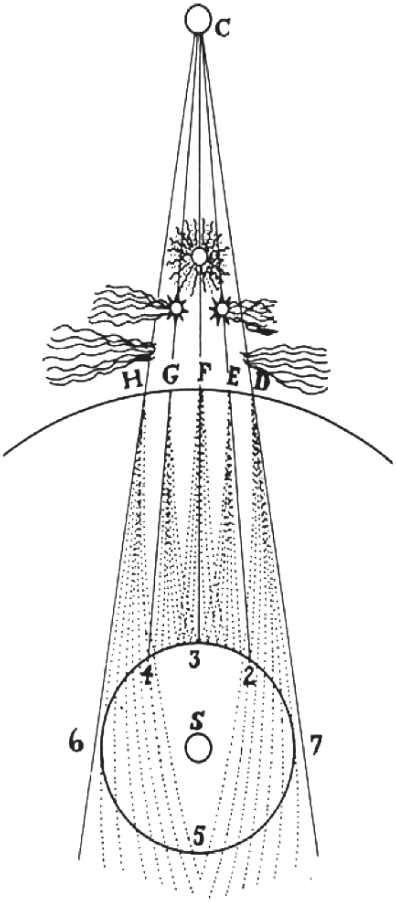

Fig. 3.16 S is the sun, 2 3 4 5 is the orbit of the earth, DEFGH is the dividing ring, and C is a comet. The reflected ray CH when it reaches the smaller particles of the inner part of the vortex, not only continues to 6, but also is deflected towards 4. In the same way, deflection of CG covers 4-3, that of CF covers half of 4-3 and half of 3-2, and so on. If the earth is at 4, the comet's head will be seen at the direction of 4GC, but the dispersed rays between 4 and 6 will make the tail. At 3, comet's tail will be seen symmetrical to the line 3FC (Descartes calls this type of comet 'Rose'). Since the dividing ring DEFGH is a spheroid, the tail of comets may be seen curved and sometimes not directly away from the sun (From Descartes' *Principles of Philosophy*, 1644)

rays[186] were the first mechanical tools used to explain the motions of planets around the sun.

The theory that Descartes developed about comets, at first glance, may not seem a drastic deviation from the post-Tychonic theories: the celestial origin of comets and their straight paths (hitherto two major concepts in cometology) were both

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[186] Kepler, influenced by William Gilbert (1544–1603), proposed a magnetic philosophy to explain the planetary motions. In his theory, a magnet like force or virtue inhabited in the sun and planets cause the orbital motions of planets. See: Johannes Kepler, *New Astronomy*, trans. William H. Donahue (Cambridge: Cambridge University Press, 1992), pp. 376–406; Stephen Pumfrey, "Magnetical Philosophy and Astronomy, 1600–1650" in *The General History of Astronomy: Planetary Astronomy from the Renaissance to the Rise of Astrophysics*, vol. 2A: *Tycho Brahe to Newton*. Edited by R. Taton and C. Wilson (Cambridge: Cambridge University Press, 1989), pp. 45–53; J. A. Bennet, "Cosmology and the magnetical Philosophy, 1640–1680," *Journal of History of Astronomy* 12 (1981), 165–177.

acknowledged by Descartes. However, by a detailed analysis one can demonstrate that the Cartesian theory of comets marked a major divergence from all previously stated theories.

First of all, Descartes' cosmos is an infinitely extended space in which stars are distributed in a three dimensional configuration. Contrary to Copernicus, Brahe, or Kepler, who confined the fixed stars in an incredibly thin shell,[187] Descartes' universe is infinite and the sun with its vortex is only one among countless other stars, like one pomegranate seed among many others. Comets are the only celestial objects that can travel in between all the vortices. In their travel, comets are transporting particles of the second element from one vortex to another.

In Descartes' theory, comets are not temporary phenomena. They are assumed to be a major part, or in fact, the epilogue of the cosmic drama. As modern astronomy predicts that stars, based on their masses, will die as white dwarfs, neutron stars or black holes, in Descartes cosmos, a star's last stage of life is in the form of dense comets wandering among the vortices. During their motion, they collide with each other and only the largest comets can survive.[188]

For the first time, Descartes supposed that comets were as big as stars, and placed them far beyond the farthest planets. He ranked comets, physically and spatially, in between stars and planets. Though Descartes attributed a rotational motion to comets, he allowed them to perform only half a revolution in each vortex. Therefore, comets were not periodical, and because they were moving at a great distance from us, they contributed no hazard to the people on the earth. Descartes removed comets from all cosmic and astrological roles.[189]

Descartes' theory of the cosmos, because of its simplicity and plausibility in explaining heavenly phenomena, was a great philosophical achievement for heliocentric astronomy. Nonetheless, it was not a helpful tool for predictive astronomy. In the mid seventeenth century, Descartes' philosophy was finding its place among natural philosophers when Kepler's rules (especially the first two ones) had already shown their exactness; and motion on an ellipse was being accepted as the actual motion of the planets.[190] On the other hand, from the 1660s, the micrometer-equipped

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[187] For example, in Tycho's system, all stars were located at a distance of 14,000 Er (earth radii), while the thickness of the sphere of the fixed stars in Kepler's universe was only 2 German miles or 9 English miles at a distance of 60,000,000 Er. See Van Helden, *Measuring the Universe*, pp. 50, 87–88.

[188] Descartes, *The World*, p. 40.

[189] As we shall see in the next chapter, in Newtonian celestial mechanics, periodicity, and close approach of comets to the earth (both absent in Cartesian theory of comets) were acknowledged, which led to development of a new brand of cometary prognostication and earth theory.

[190] According to Kepler scholar John L. Russell, after the publication of the *Rudolphine Tables* in 1627, there was a steady increase of interest in Kepler's laws and by the 1660s many astronomers adopted ellipses as the true planetary orbits. See Wilbur Applebaum, "Keplerian Astronomy after Kepler: Research and Problems," *History of Science*, 34 (1996), 456. It has to be mentioned that although the Cartesian vortices were assumed to be elliptical, planets were not moving in them according to Kepler's laws. The sun was located at the center of its vortex and not in one of the foci of the ellipses described by the planets.

observational instruments revolutionized precision astronomy, which yielded more accurate positional data. In addition, the application of logarithms to astronomical calculation and developments in mathematical astronomy (by Boulliau, Ward, Streete and others – see Chapter 4) improved data processing and increased the accuracy of solar and planetary parameters. As a result, in the three decades before the appearance of the Newton's *Principia*, Descartes' philosophy remained important and Cartesians, maintaining some basic notions of Descartes, created modified versions of planetary and cometary theories compatible with the new achievements. Non-Cartesians also developed new theories, sometimes borrowing concepts from Cartesians.

Between the publications of Descartes' *Principles* and Newton's *Principia*, more than a dozen astronomers and mathematicians developed theories specifically about either only the motion or the motion and physics of comets. In most of them, the influence of Descartes, as well as Kepler, are apparent. Here, we shall mainly focus on these physical theories that contain new concepts or genuine combinations of previously stated ideas. We shall briefly discuss Jean-Dominique Cassini (1625–1712), Adrien Auzout (1622–1691), Pierre Petit (1597–1677), and Johannes Hevelius (1611–1687). The cometary ideas of Robert Hooke (1635–1702) and John Flamsteed (1646–1719) will be discussed in the next chapter, which is devoted to Newton and his contemporaries.[191]

Cassini's theory of comets was a combination of ideas drawn from Seneca, Galileo, Kepler, and Descartes, with some interesting additions of his own. He thought comets were made up of terrestrial and planetary exhalations moving far from the earth. He located the comets of 1652 and 1653 beyond Saturn, but imagined they were moving around the stationary earth on a very eccentric circle. After observing the comet of 1664, Cassini proposed that the comet was circling on an epicycle about the bright star Sirius (α Canis Majoris) and that the whole system was revolving about the central earth. This highly eccentric path was seen as a straight trajectory in the sky. Cassini also assigned a specific pathway, or a cometary zodiac, for comets in the celestial sphere.[192]

Adrien Auzout's theory was almost the same as Cassini's, but he had a tendency to accept comets as permanent celestial objects that moved periodically on their circles. He mostly worked on the computation of a comet's path, speed, perigee, and other elements to deduce a periodicity for the cometary motions. He even published an ephemeris to predict cometary position.[193]

Following Cassini and Auzout, Pierre Petit located comets' apogee beyond Saturn. He believed that comets were periodic, with very long periods of 100 or

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[191] For the works of Giovanni Borelli (1608–1679), Georg Samuel Dörffel (1643–1688), Christian Huygens (1629–1695), Christopher Wren (1632–1723) and John Wallis (616–1703), who mostly worked on cometary trajectories, see Ruffner, *The Background*, pp. 184–204, and Yeomans, *Comets*, pp. 70–99.

[192] Ruffner, *The Background*, pp. 134–139.

[193] Ibid., pp. 140–146.

1,000 years. However, he admitted short period comets too. Petit supposed that the comet of 1664 was the same as the comet of 1618 and predicted its return in 1710. On the physical constitution of comets, Petit assumed them to be globes of exhalations from the earth and other planets. In fact (rather like Kepler) he thought comets were cosmic garbage collectors, which in their travel collect the waste exhalations emanating from the planets.[194]

Hevelius believed that all planets possessed atmospheres like the earth. Beyond the planetary atmosphere, there was the ethereal region, but the difference between the air and ether was only in purity. Exhalations coming out from the sun, the earth, and other planets could enter the ethereal realm and coagulate there steadily. The amount of these exhalations could be huge, for "the Sun alone may cast out so much Matter at any time in one Year, as that thence shall be produced not one or two Comets, equaling the Moon in Diameter, but very many."[195] However, according to Hevelius, the size of comets is changing. A comet grows little by little to a large size, then condenses to a smaller body, and then resolves again in the ether. He estimated that the comet of 1664 was moving at a distance of 4,300,000 German miles and its diameter was 2,560 German miles or three times bigger than the earth.[196]

Hevelius' comet, however, was not spherical. Since it was made from imperfect planetary effluvia it was shaped as a disk rather than a sphere. An exhalation's radial ascending motion in the atmosphere of the parent planet, in combination with the planet's rotation about its axis, moves the exhalation along a spiral path. This motion, giving enough impetus to the exhalation, ejects it along the tangent line to the circle of motion at the ejection point. Then, in the ethereal region, the disk-shaped object moves in such a way that one of its sides always remains perpendicular to the sun's rays. A mechanism, similar to one that adjusts the orientation of a magnetic needle on the earth, always keeps the face of the comets towards the sun. Due to the friction between comets and the ether, the 'aerodynamics' of a comet affects its speed. When a comet is ejected face-on, the friction is at maximum and the speed is at minimum. As, the comet gradually turns its face towards the sun, and finally at perigee, when it moves edge-on, it acquires the highest speed[197] (Fig. 3.17). This mechanism can also create the observed speed variations in cometary motions. Hevelius, based on the similarity of comets' and planets' colors, assumed Saturn and Jupiter as the most probable birth places of comets.

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[194] Ibid., pp. 146–152.

[195] Anonymous, "An Account of Hevelius His *Prodromus Cometicus*, Together with Some Animadversions Made upon it by a French Philosopher," *Philosophical Transactions*, 1 (1665–1666), 106; Anonymous, "An Account of Some Books: Joh. Hevelii *Cometographia*. Printed at Dantzick A. 1668, in large Folio," *Philosophical Transactions*, 3 (1668), 805–809.

[196] Ibid.

[197] Ruffner, *The Background*, pp. 163–166.

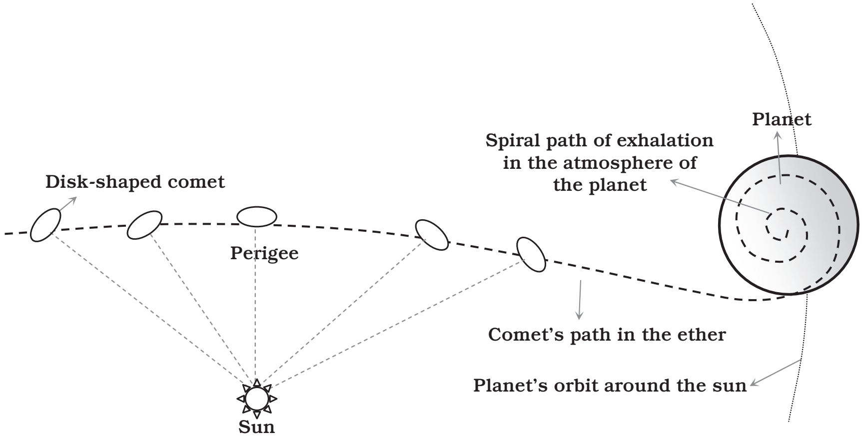

Fig. 3.17 In Hevelius' theory, comets are disk-shaped objects, composed of the solar and planetary exhalations. A magnetic mechanism always keeps one side of the comet perpendicular to the sun's rays

Hevelius' theory, which was a combination of ad-hoc arrangements and hypotheses to explain various aspects of comets, can be regarded as the last one of its kind in the pre-Newtonian era. In Yeomans' words, the few decades prior to the publication of Newton's theory of comets was a period when "confusion" reigned in cometology.[198] Many astronomers, although they had common basic ideas about comets, proposed diverse theories of cometary nature and motion. While Hevelius, the owner of the world's leading observatory,[199] was thinking of comets as disk-shaped ephemeral planetary exhalations moving along deflected linear paths, Auzout, a key member of the Paris Academy of Science and one of the developers of the wire micrometer, assumed comets to be permanent celestial bodies moving about Sirius. At the same time, while Cartesians believed that comets were the most solid objects in the universe, Hooke thought they were magnetic but dissolvable in the surrounding ether. In late seventeenth century astronomy, while the majority of astronomers proposed linear or semi-linear paths for comets, no other subject in the whole of astronomy was as controversial as the nature of comets. Newton's specification of the orbits of comets did not put an end to the ongoing controversy about the physics of comets, but at least gave it a reasonable framework.

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[198] Yeomans, *Comets*, p. 93

[199] When Hevelius built an observatory at his home and constructed a telescope of a very large focal length, his observatory for a while received many visits from leading European astronomers. See Steven Shapin, *A Social History of Truth* (Chicago: The University of Chicago Press, 1994), p. 272.

Conclusions

Although the period from Brahe to Newton witnessed major discoveries and developments in astronomy, it did not bring about a widely held theory of the motion and nature of comets. From 1600 to 1665, at least seven bright comets were observed by a troop of eminent astronomers using accurate observational tools. For instance, the motion of the comet of 1665 was under scrutiny by at least a dozen professional astronomers, some of them using instruments twice as accurate as Brahe's equipment. Parallel to those observations, an inevitable demand to establish the philosophical basis of comets in a non-Aristotelian framework encouraged most astronomers and natural philosophers to develop cometary theories in accordance with the observational data. This period, then, can be regarded as an era of accumulation of cometary data and introduction of diverse philosophical theories of comets.

In the first half of the seventeenth century, three major developments occurred in astronomical studies. First of all, astronomers began using logarithms extensively in their calculations. As Pierre-Simon de Laplace stated, the invention of logarithms, "by shortening the labors, doubled the life of the astronomer."[200] Application of logarithms not only shortened the calculation time, it also increased accuracy remarkably. While multiplication and division of long numbers were always accompanied by errors, reducing them to addition and subtraction by the rules of logarithms left little place for errors.[201] Since finding the location of a comet with regard to reference stars involved solving spherical triangles (such as triangle *cnx* in Fig. 3.1b) and this had to be done numerous times during the appearance of a comet, the significant impact of logarithms on cometary positioning can be understood clearly.

The second revolutionary development was the invention of telescopes which enabled astronomers to see more celestial objects with minute details. Successive discoveries from the rocky surface of the moon to spots on the sun and from Saturn's 'ansea' to Jupiter's companions all led to major developments in planetary science and stellar astronomy. In cometology, however, the impact of telescopes was almost nothing. John Bainbridge, the future Savilian professor of astronomy at Oxford, was among the first astronomers who observed a comet (the comet of 1618) with a telescope and drew its daily changes. In the subsequent cometary appearances, astronomers zealously pointed their improved telescopes to reveal the surface features of comets.

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[200] Victor J. Katz, *A History of Mathematics, An Introduction*, 2nd ed. (New York: Addison-Wesley, 1998), p. 420.

[201] Scot John Napier (1550–1617), realizing that the major calculations in astronomy were trigonometric (and especially that they involved sine equations), attempted to built a conversion table in which multiplication of sines could be performed by addition. He published his first logarithmic tables in 1614 and his full account of logarithm was published posthumously in 1619. Kepler was one of the astronomers who employed logarithms in his calculations immediately after Napier's publication. See: Ibid., pp. 418–419; Carl B. Boyer, *A History of Mathematics*, 2nd ed. (New York: Wiley, 1989), pp. 311–318.

Hevelius, for example, included about sixty drawings in his *Cometographia* to illustrate the variations in the heads of the comets seen in 1664 and 1665. These drawings, however, revealed little. Based on modern astronomy, we know that a comet's nucleus – the solid body of the comet – is always covered by a coma which is a gaseous sphere engulfing the nucleus. In a typical comet, while the diameter of the nucleus is about 10 km, the coma can grow up to 100,000 km in diameter (as large as Saturn or Jupiter) when it is close to the sun. Therefore, even the powerful modern telescopes cannot reveal the surface features of the cometary core.[202] The coma itself can be seen only as a patch of shiny cloud.

The drawings of Bainbridge, Hevelius and others do display some dark spots or lines on cometary heads. These are created by a combination of several causes. The optical insufficiency of the early telescopes, light contrast between the central and peripheral parts of the coma, and in some cases, distinguishable traces of dust or ion jets from the nucleus may create a non-smooth picture of the coma. On the other hand, human eyes under physiological stress tend to link those dim features which are separated but are close to each other.[203] Hevelius, based on his telescopic observations (as are seen in Fig. 3.18), assumed that the heads of comets are made

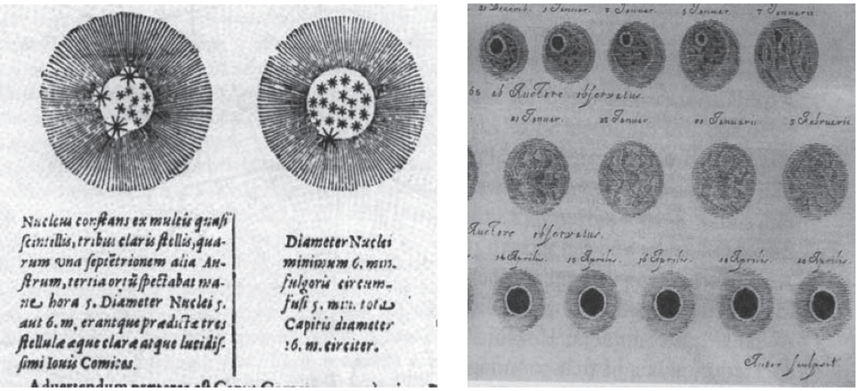

Fig. 3.18 Right: John Bainbridge's sketch of the comet of 1618 (From Johann Baptista Cysat, *Mathemata astronomica de loco, motu, magnitude, et causis cometae* (Ingolstadt, 1619), copied from Schechner Genuth, *Comets, Popular Culture*, p. 110). Left: A part of Hevelius' drawings of the comets of 1664 and 1665 (From Hevelius, *Cometographia* (1668) copied from Shapin, *A Social History of Truth*, p. 279)

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[202] Chaisson, *Astronomy Today*, pp. 362–366.

[203] Observation of canals on Mars is an excellent example of this vision illusion. In 1877 after the observation of a network of linear marking on Mars by Giovanni Schiaparelli, telescopes pointed to the red planet to see the details of those marks. Percival Lowell (1855–1916), the most famous of those Mars observers, used one of the best telescopes of his time and created numerous drawings of Martian connected canals. Observations made by larger telescopes and photographs taken by Viking 1 and 2 (1976) revealed that those connected canals were separate surface features illusively connected through telescopic observation and sketching. See Ibid., p. 259

up of separated particles. Such confusions continued until the invention of achromatic lenses (mid eighteenth century) and the development of large reflective telescopes.

In the second half of the seventeenth century a new era started in precision astronomy. Although telescopes did not help to see the 'surface' of comets as they had shown the features on the moon or the sun, the addition of the micrometer to telescopes equipped astronomers with a very precise tool to locate celestial bodies, including comets. The micrometer, which had been invented by William Gascoigne (*c*. 1612–1644) around 1640, found a systematic application in the late 1660s. Micrometers, attached either to telescopes or to the sighting ends of quadrants, improved the accuracy of observations in such a way that in 1680 Flamsteed was able to locate a point with a resolution power of less than 10 arc-seconds compared to 1 minute-of-arc limit of 1660.[204] Within half a century, while the telescope was being used as a tool of discovery, development in techniques of graduation of sighting instruments, gave it a precision role as well.

Accurate data acquired by precise observational instruments, when treated by improved computational procedures, yielded brilliant results.[205] However, on the threshold of the Newtonian era, though instrumentation and observational techniques for cometary observations had reached new levels of precision, opportunities to use them were lacking. In 1676, when Flamsteed was installed at the Greenwich Observatory he started a project to determine the relative distances of the celestial bodies in order to calculate the elements of his solar theory. His observational procedure consisted of two steps: to find the distance between Venus and the sun in the daytime and the distance between Venus and reference stars at night. In a similar way, Flamsteed developed an inclusive procedure to find the cometary positions. This method included the determination of the latitude and longitude of a comet and the position of the comet relative to reference stars, reduction of the comet's apparent place to its true place, calculation of the node and path of the comet, and calculation of the length and direction of the cometary tails with respect to the sun.[206] The comet that appeared in 1680/1, was just what astronomers needed to employ their innovative observational methods and instruments.

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[204] Chapman, "The Accuracy of Angular Measuring," pp. 134–135. For a review of the history of micrometers see Rondall C. Brooks, "The Development of Micrometers in the Seventeenth, Eighteenth and Nineteenth Centuries," *Journal of History of Astronomy* 12 (1991), 127–173.

[205] As an example, Newton, based on accurate data prepared by Flamsteed, was able to solve the ancient problem of the motion of the moon's orbital apse. The lunar apse (or major axis in its orbit) moves about 3 degrees per month, a problem that had not been explained since antiquity. In 1689, the Royal Society established a mural arc equipped with a micrometer, and Flamsteed, using a new observational technique, produced precise data of lunar position and motion, which were used by Newton. See: Ibid., p. 133; Curtis Wilson, "Newton on the Moon's Variation and Apsidal Motion: The Need for a Newer 'New Analysis,' " in Jed Z. Buchwald and I. Bernard Cohen (eds.), *Isaac Newton's Natural Philosophy* (Cambridge: The MIT Press, 2001), pp. 139–140.

[206] Eric G. Forbes (eds.), *The Gresham Lectures of John Flamsteed* (London: Mansell Publications, 1975), pp. 21–27.

In natural philosophy, however, there remained many divergent ideas in competition. Although Descartes' theory was widely accepted, there was no common idea about the shape, size, physical and chemical constitution, life time, and even the place of a comet. Perhaps, if Newton had been able to find a parabolic path for the comet without introducing a celestial dynamics based on mutual gravitation, diverse cometary theories would have continued. But instead the last two decades of the seventeenth century was a period in history of cometology that saw the ancient problem of comets' trajectory solved. Further, comets – as members of the solar system – found a new identity and became the subject of a brand new project: to study bodies that move from the most remote parts of the solar system to the vicinity of the sun, bodies that can impact the earth or other planets, and bodies that influence the whole solar system with their mysterious tails.

Chapter 4
Comets in Newtonian Physics

Newton's Introduction to Cometary Astronomy

Two comets that appeared in November and December of 1680 (the latter was visible till early March 1681) marked a turning point in the history of comets. As the observation of the comet of 1577 established a new era in cometology by placing comets in the supralunar region, observation of the comets of 1680/1 opened the modern epoch of cometology by introducing comets as members of our solar system. The comets of 1680/1 were in fact a single comet observed *before* and *after* perihelion, a situation that hindsight reveals as critical in the determination of the cometary trajectory. The data collected finally established that comets move around the sun, though in different types of orbits.

The comet of 1680 and the role of Flamsteed and Newton in calculating its orbit have been the topic of several studies.[207] In this chapter, however, we shall focus mainly on the physical and chemical constitution of comets in Newton's theory of comets as it appeared in Newton's main publications, *Principia* and *Opticks*. Thus, it seems appropriate to give first a brief account of the introduction of Newton to cometary studies and contemporary cometary ideas.

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[207] For example see: Ruffner, *The Background*, 239–301; Yeomans, *Comets*, 95–109; Richard S. Westfall, *Never at Rest, A Biography of Isaac Newton* (Cambridge: Cambridge University Press, 1980), pp. 391–397; Eric G. Forbes, "The Comet of 1680–1681," in Norman J. W. Thrower, ed., *Standing on the Shoulders of Giants*: *A Longer View of Newton and Halley* (Berkeley: University of California Press, 1990), pp. 312–323; Forbes, *The Gresham Lectures*, pp. 28–34; D. W. Hughes, "The *Principia* and Comets," *Notes and Records of the Royal Society of London*, 42 (1988), 53–74; Curtis Wilson, "The Newtonian achievement in astronomy," in *The General History of Astronomy: Planetary astronomy from the Renaissance to the rise of astrophysics*, vol. 2A: *Tycho Brahe to Newton*, R. Taton and C. Wilson (eds.) (Cambridge: Cambridge University Press, 1995), pp. 231–274, Simon Schaffer, "Newton and the Transformation of Astrology," in Patrick Curry, ed., *Astrology, Science and Society, Historical Essays* (Woodbridge, Suffolk: Boydell Press, 1987), pp. 219–243.

T. Heidarzadeh, *A History of Physical Theories of Comets, From Aristotle to Whipple,*

Newton's interest in cometary theories goes back to his late student days.[208] There are various documents of his cometary observations, his assessment of cometary theories, and his questions regarding cometary motions and tails. Some documents show that Newton attempted to fit rectilinear paths to comets before 1681.[209] In other words, Newton, more or less, was following the mainstream cometary theories, and his assignment of linear paths to comets implied that he was categorizing them as ephemeral bodies.

Observations made on the comets of 1680/1, however, changed Newton's ideas. John Flamsteed (1646–1719), the Astronomer Royal and one of the leading figures in precise observations during the seventeenth century, proposed that the comets seen in November and December of 1680 were not two different bodies, rather they were a single comet which was seen first as it was approaching and then when it was departing from the sun. In Flamsteed's theory, the comet did not move *around* the sun but it made a U turn just before reaching the center of the solar vortex.

Although Flamsteed embraced the notion of Cartesian vortices, he revised Descartes' cometary theory greatly to make it compatible with the observations. First, he assumed comets to be planets (and not dead stars[210]); secondly, he thought that the motion of comets was due to function of a combination of magnetic forces and the force of vortex particles (which cause the planetary motion); and finally he proposed that the cometary tail was material (and not merely refracted or reflected rays of light). Flamsteed, giving comets a planetary origin, explained their nature thus:

> As for the body of the Comet nothing better occures to my thoughts at present then that it may have beene some planet belonging formerly to another Vortex now ruined […] that its naturall motion being destroyed its body is broke & the humid parts swim over ye rest yet so as some small peeces of ye solid part of ye Masse here & there lie out above them, this its ill defined figure & dusky light persuades me: which in my opinion was not much different from yt of ye obscure large spots in the Moone which are accounted the aqueous part of it […] The humid part of ye body of ye comet being outmost might cause it to have a large atmosphere: & from both when it was near ye Sun the violent action of his raies upon it might carry forth plentifull Steames of matter to a vast distance which caused ye tayle to appeare double the lenghth when neare the Sun it did to the lenght on its perigee where it lay most convenient to be seene & should on yt account have appeared longest. Conceave how yet smoke would appeare from a chimny in a moveing ship or ye steames from a drop of water let fall on a moved hot iron [and] you will apprehend the reason of ye deflection of ye tayle I thinke very naturally.[211]

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[208] For Newton's involvement with cometary theories before 1680 see: Ruffner, *The Background*, pp. 205–238; D. T. Whiteside, "Before the Principia: the Maturing of Newton's Thoughts on Dynamical Astronomy, 1664–1684," *Journal of History of Astronomy*, I (1970), pp. 5–19.

[209] Ibid., pp. 215–224.

[210] In Descartes' theory, comets are considered as dead stars – bodies denser and more agitated than the planets – that can not pass the dividing ring. This ring is assumed to be a strip in a vortex which has the slowest revolutionary motion and separates the planetary region from the outer parts of the vortex. In the solar system the trajectory of Saturn marks the dividing ring and all comets are moving beyond that. See "Comets in Descartes' Cosmos," in chapter three (above).

[211] *The Correspondence* of Isaac Newton, 7 vols., H. W. Turnbull (ed.) (Cambridge: Cambridge University Press, 1960), vol. 2, pp. 338–339. For Flamsteed's idea about the cometary tails also see: Forbes, *The Gresham Lectures*, p. 116.

And, about the motion of comets, Flamsteed states:

> Tis a well knowne quality of the Magnet that as it attracts one end of the Needle touched with it so it repells the Contrary, the like wee imagine to have hapned with ye Comet when it came round the Sun [...] had the opposite side to that whereby it had beene attracted turned towards his northerne pole whereby it was repelled most directly then it had beene attracted for as it approached the Sun near it imbibed more of his magnetick particles so had its owne faculty strengthened tho I conceave that it receded not the swifter from him on this account for it acquired that degree of velocity before, yt nature could not admit a greater.[212]

Therefore, a comet, being initially a planet, acquires speed from the particles of the vortex of the sun, and is attracted by the magnetism of the sun. The comet, which now is deflected from its path in the vortex, moves towards the sun, but "Ye Sun hee repells it as ye North Pole of ye loadstone attracts ye one end of ye Magnetick needle but repells ye other."[213] Consequently, the comet turns before reaching to the sun, and moves in the opposite direction (Fig. 4.1).

The theories of Flamsteed and Hooke were two pre-Newtonian cometary theories that diverged from all previous theories by attributing a combination of three properties to comets: they were assumed to be planetary bodies, their tails were thought to be material and originating from the body of comet, and finally, their motions were attributed to the influence of a kind of central force in the solar system.

Robert Hooke's theory was an attempt to explain all observational and physical aspects of comets. Hooke thought the nucleus of a comet "may be of the same nature and constitution with that of the internal parts of the earth."[214] The outer parts of this nucleus may be dissolved by the action of the encompassing ether and lose their gravitating principle. These particles which are changed in their state or virtue recede from the sun and produce the tail. However, the tail "is much of the nature of the parts of Flame."[215] Therefore, the cometary tails are not seen due to reflection or refraction of the solar rays from the cometary particles, but they shine because their particles are agitated by the ether. Hooke came to this conclusion because he found that cometary nuclei did not cast any shadow.

Newton was aware of Hooke's theory, but his serious involvement with cometary theories began with Flamsteed's theory of comets.[216] When Newton became

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[212] Forbes, *The Gresham Lectures*, p. 115.

[213] Newton, *Correspondence*, 2: 337–338.

[214] Robert Hooke, *Lectures and Collections Made by Robert Hooke, Secretary of the Royal Society. Cometa. ... Microscopium* (London, 1678), reprinted in R. T. Gunther, *Early Science in Oxford*, 15 vols. (Oxford: Printed for the author, 1931) vol. VIII, pp. 227–228.

[215] Newton, *Correspondence*, 2: p. 231.

[216] Newton received extracts of three letters that Flamsteed sent to James Crompton, a fellow of Jesus College, about his theory of comets on 15 December 1680, 3 January and 12 February 1681. He also received a copy of Flamsteed's theory sometimes in February 1681. See: Westfall, *Never at Rest*, pp. 391–398. The letters are printed in Newton, *Correspondence*, 2, 315, 319–320, 336.

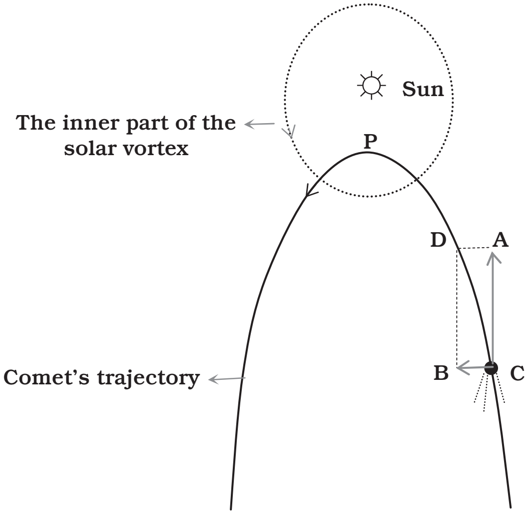

Fig. 4.1 In Flamsteed's theory, the comet C is moving tangentially to the motion of the particles of the vortex (vector A) but, at the same time, the Sun's magnetic attraction (vector B) deflects the comet's path towards D. At P, the sun repels the comet as a magnet attracts one end of a magnetic needle and repels the other end. After passing the point P, the comet moves opposite to the direction of the revolution of the vortex

acquainted with Flamsteed's theory, he rejected both the physical and dynamical basis of the theory. He objected to solar magnetism due to the fact that materials lost their magnetic property when they were heated, and since the sun was assumed correctly to be very hot, assigning a magnetic property to it was absurd. Newton argued that it was also contrary to the well-established magnetic rules that a large magnet could change the orientation of a freely moving small magnet in such a way that the small one turns its opposite end to the large magnet and is thus repelled by it. On the contrary, "the great magnet would make it nimbly turn about into an agreeable position & then attract it."[217] Newton also rejected Flamsteed's theory because there was a serious difficulty regarding the motion of comets after being repelled from the sun. It was difficult to imagine that the comet would move contrary to the direction of the revolution of the vortex.

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[217] Newton, *Correspondence*, 2, 342. In response, Flamsteed proposed that the magnetic property of the sun might be different from that of a loadstone, or the sun might not be a mass of red hot iron but "a Solid globe of grosse matter encompassed with a spirituous liquid which by its violent motion stirring the particles of our aire causes the heat wee feele from him" (Ibid., p. 351). Newton rejected the first idea emphasizing that the only known attraction and repulsion of this type is the magnetic property of loadstones which vanishes by heat. To refute Flamsteed's theory of the sun's structure, Newton calculated the relative surface temperature of the sun and concluded that a body with a hot surface can not sustain a cold interior. Thus, the sun's interior also should be hot which would destroy the magnetic property. Ibid., p. 359.

Although Newton rejected Flamsteed's theory of comets, the idea of a central force acting on comets' motion attracted his attention.[218] Newton continued working on cometary motions and finally, by mid 1684, he acknowledged that the comets of 1680/1 were two apparitions of a single comet before and after its perihelion. However, the orbit he found for the comet was completely different from Flamsteed's. Newton calculated that the comet turned *around* the sun on a parabolic orbit.[219] In other words, the comet was moving due to an attracting force (whatever its nature was) emanating from the sun, and was circling the sun like the other members of the solar system. This major discovery, which defined a new framework for cometary studies, had a deep influence on the formation of Newton's cosmology and cosmogony. By solving the problem of cometary orbits, the two major philosophical and physical issues in cometology – the status of comets' existence in the cosmos, and their physical constitution – were tightly linked to the solar system.

Comets in the *Principia*

Newton discussed comets extensively in his *Philosophiae Naturalis Principia Mathematica* or *Mathematical Principles of Natural Philosophy*. The book was first published in 1687 and a revised edition appeared in 1713. A third edition, which had fewer changes than the second edition, was published in 1726, a year before Newton's death in 1727. In the second edition of the *Principia*, Newton added a few pages – a conclusion under the title of General Scholium – to the end of book three which also contained points about comets.[220] He also discussed comets in his *Opticks*, and several other papers and letters which appeared posthumously.

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[218] Hooke blamed Newton for his neglect of Hooke's priority in discovery of the inverse square law and the influence of a central gravitating body. For a brief review of debates on this issue see: Yeomans, *Comets*, pp. 78–82; Westfall, *Never at Rest*, pp. 382–388, 402–403; A. Rupert Hall, *Isaac Newton, Adventurer in Thought* (Cambridge: Cambridge University Press, 1992), pp. 162–165, 202–207; Alfred Bork, "Newton and Comets," *American Journal of Physics* 55(1987), pp. 1089–1095.

[219] Georg Samuel Dörffel (1643–1688), a German astronomer and mathematician had already calculated the trajectory of the comet of 1680/1 as a parabola with the sun at the focus. Dörffel assumed that the earth was revolving on a circle around the sun (he originally believed in a geocentric system and used the Copernican idea of a moving earth only as a tool to solve the problem of cometary motion) and tried to find the angles between the comet and the sun while observing from a moving earth. Although he fitted a parabolic path to the comet, his measurements of angles between the comet and the sun were not accurate. Dörffel published his results in a tract entitled *Astronomische Betrachtung des Grossen Kometen, welcher in ausgehenden 1680, und angehenden 1681 Jahr hochst verwunderlich und entsetzlich erschienen* (Plauen, 1681). See Forbes, "The Comet of 1680–1681," pp. 312–313; Yeomans, *Comets*, pp. 96–99.

[220] For a complete guide to Newton's *Principia*, its history, structure and fundamental concepts, see I. B. Cohen's " A Guide to Newton's *Principia*" in Isaac Newton, *The Principia, Mathematical Principles of Natural Philosophy*, trans. I. Bernard Cohen, Anne Whitman, assisted by Julia Budenz (Berkeley: The University of California Press, 1999), pp. 3–370; Newton's revisions on the *Principia* is discussed in pp. 11–25, however, the details of changes in the three editions are given as footnotes in related pages.

About one third of book 3 of the *Principia* (the third edition) is devoted to comets. In book 3, Newton applies the mathematical rules he developed in books 1 and 2 to the planets and comets, and tries to illustrate the system of the world based on physical principles. Book 3, composed of six parts, starts with a set of 'rules' (rules for the study of natural philosophy) followed by 'phenomena' (consisting of orbital information of planets and satellites). Then, under 'propositions' Newton applies mathematical principles and gravitational law to explain the orbital motions of planets and their satellites. In the forth and fifth sections, he explains his theory of tides and the motion of the moon. The sixth and last part of book 3 is about comets, their motion, physical properties and tail formation.

Newton's discussion of comets begins with lemma 4 of proposition 39, which states that "the comets are higher than the moon and move in the planetary region."[221] Here, Newton explains the retrograde and prograde motions of comets, their parallax, and the influence of earth's orbital motion on their apparent motions and speeds. He also gives quantitative information about the size of the cometary nucleus and coma, and by comparing comets' sizes and brightness with that of planets, tries to estimate cometary distances. Based on data prepared by Flamsteed, Hevelius, Johann Baptist Cysat and others, Newton comes to a general conclusion that the diameter of a typical coma rarely exceeds 8′ to 12′, and the diameter of the nucleus is about a tenth or perhaps a fifteenth of the diameter of the coma. Because the nuclei of comets are smaller than Saturn or sometimes equal to it and their brightness is comparable to Saturn's brightness, all comets at perihelion should be below Saturn or not very far from that distance.[222] For the same reason, Newton concludes that the idea of those writers who placed comets almost in the region of the fixed stars (Cassini, Petit or even Descartes) is completely wrong.

Lemma 4 ends with three corollaries. The first states that comets shine by the light of the sun, and the second, as a natural conclusion of the first, explains why comets appear so frequently in the region of the sun. The third corollary, however, avows a fact with fundamental cosmological importance. Because comets follow oblique orbits, sometimes move opposite to the direction of motion of the planets, and because they move freely in all directions for a very long time, Newton concludes that "the heavens are lacking in resistance."[223] Newton also deduces that

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[221] Ibid., p. 888. All references to the *Principia* are from I. B. Cohen's translation (above), which is based on the third and final edition of Newton's *Principia*.

[222] Ibid., pp. 891–894.

[223] Ibid., p. 895. This important statement had already been stated in proposition 10 of book 3. There, Newton says that "the motions of the planets can continue in the heavens for a very long time," and referring to the scholium to proposition 22 of book 2, calculates that at a height of two hundred miles above the earth the density of air is 75,000,000,000,000 less than the density on the surface of the earth. Assuming that the medium in which Jupiter (or any other planet) is revolving has the same density as the uppermost part of the air, Newton concludes that the planet would not lose a millionth of its motion in a million years. Thus, " the planets and comets, encountering no sensible resistance, will move through those spaces for a very long time." See Ibid., pp. 815–816.

comets are planet-like objects and are encompassed in a thick atmosphere, which is denser in its lower parts. He infers that any change observed in the appearance and form of comets is change that occurs in the cometary atmosphere and not in the solid nucleus.[224] Referring to an interesting analogy, Newton says that the same situation would be seen if the earth were viewed from another planet: such an observer would see only the clouds and their changes, and not the solid earth.

Proposition 40 and almost half of the proposition 41 deal with cometary orbits. Proposition 40 states that "comets move in conics having their foci in the center of the sun, and by radii drawn to the sun, they describe areas proportional to the times," (Kepler's second law), and in the second corollary of the same proposition Newton concludes that "these orbits will be so close to parabolas that parabolas can be substituted from them without sensible errors."[225] In the succeeding passage, from lemma 5 to lemma 11, Newton derives from the observational data the basic steps of his method of determination of the cometary orbits.

Proposition 41, which Newton calls an "exceedingly difficult problem," is to deduce from three observations the orbit of a comet moving on a parabola. The problem is difficult because the earth and the comet are moving with different speeds on different planes. In brief, Newton's method consists of obtaining three positions of a comet that is observed in nearly equal time intervals. By finding the projection on the ecliptic of the three directions (in which the comet was observed), the vertex of the comet's parabolic segment can be obtained. Then, given the latitudes of the comet and considering the distance-velocity relationship of a body moving on a parabola around the sun, the length of the projection of the parabola's segment on the ecliptic can be calculated. In the next step, the length of the chord is calculated in the plane of the comet's orbit, which gives the positions of the two ends of the chord in the orbital plane of the comet.

Proposition 41 continues by application of the observational data obtained from the comet of 1680 to determine its parabolic orbit. Having established the perihelion distance of the comet, Newton delineates his physical theory of comets. On December 8 1680, when the comet was in its perihelion, the ratio of its distance from the center of the sun to the distance of the earth from the sun was approximately 6 to 1000. Since the heat of the sun is the same as the density of its rays and is inversely proportional to the square of the distance from the sun, the ratio of the heat that the comet obtained to the heat that the earth absorbs in mid-summer from the sun was 1,000,000 to 36 or 28,000 to 1. To render this ratio into a familiar quantity, Newton compared the comet's heat to the heat of boiling water and incandescent iron. Based on his measurements, the heat of boiling water is three times greater than the heat that the dry earth absorbs from the summer sun[226] and the heat

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[224] For example, Hevelius's illustrations of the heads of the comets of 1664 and 1665 shows changes in their appearances.

[225] Ibid., p. 895.

[226] In proposition 8, corollary 4 of book 3, Newton gives a different ratio: "I have found with a thermometer that water boils at seven times the heat of the summer sun," (Ibid., pp. 814–815). This ratio, which lowers the temperature of the summer sun to around 14–15°C, is far from the actual figure.

of incandescent iron is three or four times greater than the heat of boiling water.[227] Therefore, at its perihelion, the heat that "dry earth" on the comet obtained from the sun's rays was two thousand times greater than the heat of incandescent iron.[228]

Newton concludes that if the comet were made up of exhalations or vapors emanated from the earth, planets or the sun, it could not sustain such a tremendous heat and it would disappear at once in the perihelion. Thus, the body of a comet, or its nucleus, must be durable, solid, and very dense. When a solid body absorbs heat, it gives off the heat at a rate that, according to Newton, is proportional to the surface area of the body. For instance, a one-inch wide globe of incandescent iron loses its heat in the air in about an hour. He calculates that a globe of incandescent iron equal in size to the earth (with a radius of about 40,000,000 feet or 480,000,000 inches) will cool off in about 50,000 years. In other words, if we assume a typical comet to be the size of the earth and as dense as iron, when it reaches o a temperature 2,000 times hotter than that of red hot iron, it will lose its heat at least 100,000,000 years after passing the perihelion.[229]

Newton then explains the process of formation of cometary tails. From the fact that the tail of the comet of 1680 (and those of other comets) became longer after passing through the region of the sun, he concludes that there is a direct relationship between the length of the tail and the heat that comets receive from the sun. He indicates that "the tail is nothing other than extremely thin vapor that the head or nucleus of the comet emits by its heat."[230] Although Newton's theory of cometary tails, at the first glance, looks similar to that of Kepler, it is basically different. To make his theory readily understandable, Newton evaluates earlier theories of cometary tails, which he divides into three categories: optical theories that assume the head of comets to be translucent globes and the tails as refractions of the sun's rays through them (theory of Apian, Gemma Frisius, Brahe and others), the theory that says light during its way from comets to the earth undergoes a kind of refraction and is seen as tail (Descartes' theory), and finally the idea that admits tails as clouds of vapor constantly rising from cometary nuclei and moving diametrically away from the sun (Kepler's theory).

Newton rejects the first theory for the same reason that Kepler had already stated. The refracted light from the transparent head of the comet can be seen only

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[227] Newton's figure for red hot iron is at least 100°C off. As judged visually, iron is seen red between 500°C and1000 °C (incipient red: 500–550°C, dark red: 650–750°C, bright red: yellowish red: 1050–1150°C). For Newton's thermometry see: Hall, *Isaac Newton*, pp. 297–298.

[228] Ibid., p. 918.

[229] This last calculation is not done by Newton. However, since he assumes that an earth-size globe of iron with a temperature of red hot iron cools down after 50,000 years, the same globe when is 2,000 times hotter than red hot iron need 2,000 times more time to lose its heat. It has to be noted that for Newton the cooling time was a linear function of the surface area of the heated object. It is important to mention that Newton did not explicitly claim that a typical comet was as large as the earth, however, his analogy implies his inclination to compare comets with earth-like planets.

[230] Ibid., p. 919.

if it hits some matter and reflects toward us. Since the ethereal medium of the heavens does not contain such reflecting material, the refracted rays of the sun can not be seen at all. Therefore, there must be some matter in the region of the comet's tail to reflect the beams of sunlight.

Newton reveals serious difficulties in Descartes' theory of tail formation which is based on a special kind of refraction that occurs only in the heavenly region. He indicates that formation of colors is associated with all refractions, but the tails never consist of different colors. On the other hand, the light of the fixed stars and the planets that travel through the same celestial medium is distinct and show no tail. The stars and planets, even when their light is magnified one hundred times through a telescope, are not seen with tails. Further, if one admits that the tail is created by the refraction of light in the ethereal medium, one has to accept that light must have the same refraction pattern in the same region of space. But, the comets of 1577 and 1680 were seen at the same point of the sky and while the position of the earth in both cases was the same, the tails of the two comets were seen in different orientations. Therefore, the tail cannot be formed by the refraction of light.[231]

Newton states that the only possibility is to concede that comets' tails are formed by some matter that rises from comets' heads and reflects the sun's rays. Before explaining his theory of tail formation, he indicates some important features of cometary tails: the tails are curved; the curvature is more whenever the tail is longer; and in the longer and brighter tails, the convex side (the leading front) is a little more luminous than the concave side. All of these, consequently, indicate that the formation of tails is related to cometary heads (which supplies the matter of tails) and their motion and not to optical effects.[232]

Newton, then, investigates the process of tail formation based on four fundamental assumptions: (1) comets have thick atmospheres, (2) the tail rises from the comet's atmosphere, (3) the tail is due to the sun's heat and not due to the pressure that the sun's rays may exert, and (4) because comets, like other bodies in the solar system, are moving in an ethereal medium, the extension and shape of tails result from interaction between the solar heat, the comet's atmospheric particles, and the ether.

On the earth, the smoke of a burning body ascends directly upward (when the body is at rest) or moves obliquely (when it is in motion). In the solar system, where all bodies are gravitating towards the sun, smoke and vapor from bodies like comets, ascend with respect to the sun, and because comets are moving, their smokes move obliquely. The obliquity of the smoke is influenced by both the speed of its ejection from the comet and the orbital speed of the comet itself. Therefore, the greater the ascending speed of the smoke, the lesser the obliquity of the tail. When the comet is close to the sun and the comet is more heated, the vapor and smoke ascend swiftly, and the tail is less curved. Also, close to the body of comet, where the rising

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[231] Ibid., pp. 920–921.

[232] Ibid., pp. 921–922.

vapor and smoke maintain their initial speed, the tail is not curved. Moreover, since the comet moves and leaves behind the tail it produces, the leading front of the tail always contains the newly produced dense vapor which reflects more light. As a result, the tail is more luminous on the side that the comet precedes.[233]

The tail, however, has a very low density, in such a way that only a small amount of vapor or smoke can expand to create a long tail. Newton calculates that a globe of our air of an inch diameter, with a density that it would have at a distance of one terrestrial semidiameter from the surface of the earth, can expand to fill the whole space below the orbit of Saturn.[234] While such an insignificant quantity of air can be distributed in a huge volume, a small amount of vapor or smoke (which is continuously emanating from the cometary nucleus in the vicinity of the sun) also can expand to produce very large but greatly rarified cometary tails. The immense rarefaction of the tail material is obvious from the fact that even very small stars can be seen through it without any loss of brightness.

From the fact that the comet is moving and leaving behind the vapor it produced, one can calculate the time it took the vapor to ascend from the nucleus to the end of the observed tail. Newton's procedure is to find a point on the comet's trajectory where the comet was located when it produced the vapor that now is seen at the end of the comet's tail. In the Fig. 4.2, SCD is the line that connects the sun to the comet and CF is the orientation of the tail, which is not parallel to SCD. If the tail were

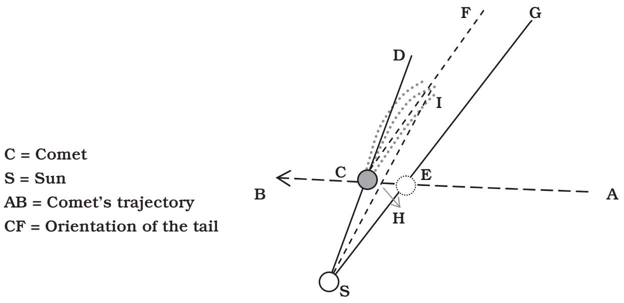

Fig. 4.2 The Comet C is moving along the line AB. Its tail is not exactly antisolar but is curved in such a way that its convex side is towards the direction of motion of the comet. The extremity of the tail, I, was produced when the comet was at E, the intersection of the comet's trajectory with the line parallel to the orientation of the tail passing through the sun

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[233] Ibid., p. 922.

[234] Ibid., pp. 922–923. Newton, in proposition 22 (and its scholium), explains how the density of air in our atmosphere decreases by the altitude (Ibid., pp. 694–696). Also, in query 27 of the *Opticks* he gives a comparative scale of density of air versus altitude. According to this scale, at the height of 7½ English mile from the surface of the earth the density of air decreases to one fourth of its original quantity, and at the heights of 22½, 30, 38, 76, 152 and 228 miles, the density is respectively 64, 256, 1,024, 10^6, 10^{12} and 10^{18} times rarer. See Isaac Newton, *Opticks*, 4th ed. (New York: Dover, 1979), pp. 367, 353. For an aid to comprehend Newton's calculations see: David Gregory, *The Elements of Physical and Geometrical Astronomy*, 2 vols. (London: 1726), vol. 2, pp. 702–707.

ascending along a straight line directly away from the sun, the end part of the tail, I, would be produced when the comet C was located at H. However, the motion of the particles of the tail is a combination of the ascending motion due to heat and the orbital motion of the comet. Therefore, the intersection of the line parallel to the orientation of the tail and the trajectory of the comet (intersection of SG and AB at E) will mark the point where the comet produced the vapor that now is seen at the extremity of the tail, I. The process is illustrated with more details in Fig. 4.3.

Based on this procedure, Newton calculated that in the case of the comet of 1680, within only two days the extremity of the tail reached to a distance of about 70 degrees from the head on December 10, while it reached to a length of around 10 degrees within forty-five days on January 25. Since the comet was at the perihelion of its orbit on December 8, the significant increase of the length of the tail is in agreement with Newton's theory that the tail is rising from the comet's head due to the sun's heat and it ascends most swiftly in the vicinity of the sun where the heat reaches to the maximum. On the other hand, the free motion of the rarified vapor for a very long time indicates that the medium of celestial space does not have any force of resistance.[235]

Although Newton admits that Kepler's idea "is not altogether unreasonable" that the sun's rays can propel particles in very free or empty spaces to produce cometary tails, he interprets the ascending of the tail based on the interaction between the

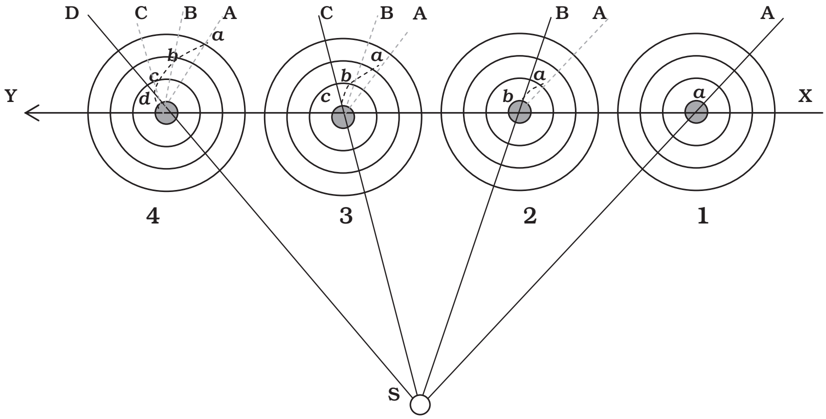

Fig. 4.3 When the comet is at position 1, its tail rises along the direction SA. At position 2, while the extremity of the tail has risen to point *a* (in the middle circle), new vapor rises in the direction SB. At positions 3 and 4, when the comet ejects new vapors in the directions SC and SD respectively, the vapors produced in the previous positions have already risen along their initial directions. As a result, the tail (represented by dashed lines) seems to bend during the motion of the comet. In this diagram the rising speed of the vapor in all positions is assumed to be equal

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[235] Newton, *Principia*, p. 924. In all tables in the *Principia* the first appearance of the comet after its perihelion is December 12.

heated particles of the comet's atmosphere and particles of the encompassing ether. In fact, Newton applies the same rules that govern the ascending of particles of smoke in air to the motion of the particles of the comet's atmosphere in the ether.

In a chimney, heat rarifies the air and reduces its specific gravity. As a result, the rarified air ascends and transfers with it the entangled particles of smoke. In the case of comets, the heat source is the sun's rays. However, light beams do not act on the medium in which they are traveling except in refraction or reflection. The atmosphere of a comet contains particles of vapor and smoke, which rarifies by altitude until the ethereal space begins. In the upper parts of the atmosphere, reflection of the sun's rays from the particles of vapor and smoke warms them. The warmed atmospheric particles, in turn, warm the adjacent ethereal particles, and consequently, the ethereal medium rarifies. The rarified ether, which now has lower specific gravity, moves away from the sun and carries along the particles of the comet's atmosphere. This stream of the atmospheric particles of comets is seen as the tail.[236]

In addition to the thermal process of formation of cometary tails, Newton introduces another mechanism – a direct consequence of the orbital motion of comets – which causes the tails to ascend more in the vicinity of the sun. Since comets are revolving around the sun and their velocities are at the maximum in the perihelion area, the outer parts of the tail can recede from the sun and make the tail longer and wider.[237] This mechanism can only be presented in a theory that admits comets as members of the solar system, obeying the laws of planetary motion.

When comets approach the sun, their atmospheres stream out as tails, and the size of their atmospheres reduce. After passing the perihelion, the nuclei are encompassed by the lowest parts of their atmospheres, which are coarser, smoky, and blacker. Therefore, comets, at equal distances from the sun and the earth, appear darker after their perihelion than before. However, as indicated by Hevelius' observations, when comets are receding from the sun and giving off less atmospheric material, they become larger.[238]

Newton, at the end of proposition 41 and also in proposition 42 (the last proposition in the *Principia*), discusses the cosmological importance of comets. Comets in the vicinity of the sun produce large tails that accompany the cometary heads in their journey across the heavens. The tails, in the free spaces away from the solar atmosphere,[239] become continually rarified and scatter in the entire cosmos:

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[236] Ibid., p. 925. It has to be noted that Newton accepted that heat was not a substance but was an increase in the vibration of the particles of the matter. Therefore, reflection of the sun's rays from the atmospheric particles of the comet can increase their vibration and consequently the vibration of the adjacent ethereal particles. Newton in queries 5, 8 and 18 of the *Opticks* mentions the mutual action of bodies and the light.

[237] Ibid.

[238] Ibid., pp. 926–927.

[239] Newton admits that the sun is also encompassed by an atmosphere which sometimes comets, in their closest approach, can pass through it. See below: "A General Assessment of Newton's Theory of Comets."

> and then [the vapor] is by degrees attracted toward the planets by its gravity and mixed with their atmospheres. For just as the seas are absolutely necessary for the constitution of this earth, so that vapors may be abundantly enough aroused from them by the heat of the sun, which vapors either–being gathered into clouds–fall in rains and irrigate and nourish the whole earth for the propagation of vegetables, or–being condensed in the cold peaks of mountains (as some philosophize with good reason)–run down into springs and rivers; so for the conservation of the seas and fluids on the planets, comets seem to be required, so that from the condensation of their exhalations and vapors, there can be a continual supply and renewal of whatever liquid is consumed by vegetation and putrefaction and converted into dry earth. For all vegetables grow entirely from fluids and afterward, in great part, change into dry earth by putrefaction, and slime is continually deposited from putrefied liquids. Hence the bulk of dry earth is increased from day to day, and fluids–if they did not have an outside source of increase–would have to decrease continually and finally to fail. Further, I suspect that that spirit which is the smallest but most subtle and most excellent part of our air, and which is required for the life of all things, comes chiefly from comets.[240]

And further:

> And the vapors that arise from the sun and the fixed stars and the tails of comets can fall by their gravity into the atmospheres of the planets and there be condensed and converted into water and humid spirits, and then–by a slow heat–be transformed gradually into salts, sulphurs, tinctures, slime, mud, clay, sand, stones, corals, and other earthly substances.[241]

Thus, comets in their periodical returns toward the sun produce a mass of vapors and exhalations and spread them into interplanetary space. The vapors and exhalations, being attracted by planets, are mixed in their atmospheres and through precipitation participate in chemical and physical reactions occurring on the planets. Therefore, the first cosmic role that Newton assigns to comets is a universal chemical role: comets by periodically furnishing the planets with vital liquids renew the supplies they need for the continuation of vegetation and life.

As the planets may gradually run out of liquids and other indispensable material, the fixed stars also may lose material because of their continual emission of light and exhalations. Obviously, any loss in the mass of stars changes their gravitational attraction, which finally causes instability in stellar and planetary systems. Comets can provide stars with new material (or increase their masses) by falling on them. Newton introduced this second role of comets – replenishment of the fixed stars – in the second edition of the *Principia*.

According to Newton, when the perihelion of a comet is very close to a star (as the comet of 1680 passed the sun by a distance less than a sixth of the sun's diameter) the comet passes through the atmosphere of the star. Since the density of the stellar or solar atmosphere is greater than the ethereal space, the comet encounters resistance and its speed decreases in the vicinity of the star. Consequently, the comet approaches closer to the star and in every return its distance from the star decreases more and more and finally it falls on the star. The comet may also be attracted by other comets in its aphelion and be slowed down. In any case, the

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[240] Ibid., p. 926.

[241] Ibid., p. 938.

comet that falls on the star supplies it with new material. The process is seen as the appearance of a new star (nova) such as the new star of 1572 or that of 1604.[242]

In the General Scholium, the final part of the *Principia*, there are only a few sentences about comets. Newton states that comets move according to the same laws that govern the planetary motions; comets move along eccentric orbits in all directions and this can not happen in the presence of Cartesian vortices; comets are at greatest distance from each other in their aphelia and therefore their mutual attraction is at minimum there; and finally, the ingenious system of the sun, planets, moons and comets could not have come to being without the supervision of a wise and omnipotent supreme being.[243]

Comets in the *Opticks* and Later Works

Although the *Principia* contains the most comprehensive account of Newton's theory of comets, it is not the only source in which its author has stated his cometary ideas. Newton discusses comets in his second major work, the *Opticks*, and in his scientific papers and correspondence. However, the majority of these writings (except in the *Opticks*) are related to the orbital motion of comets and only on a few occasions consider the physical characteristics of comets. Nevertheless, to acquire a complete picture of comets in Newton's physical astronomy it is necessary to review all of these available writings, including memoranda of Newton's friends and colleagues.

Newton, in the queries of book 3 of the *Opticks*, discusses comets: in query 22, referring to the low density of the ether, he mentions that the motion of the planets and comets would not encounter a sensible resistance; in query 28, he points out that the celestial space necessarily is empty except for the very thin vapor and effluvia like that arising from the atmospheres of the earth, planets, and comets and mixing with the ethereal medium. Stating that nature does nothing in vain, he wonders why comets move in all directions in very eccentric orbits, while the planets all are moving in the same manner. In query 31 (the last query and the last part in the *Opticks*), Newton repeats the same notion maintained in query 28 about the motion of comets and the planets seeking the role of an intelligent agent in establishing the principles of the cometary and planetary motions.

Query 31, however, contains a very radical idea which admits that the solar system can be subjected to instability due to the mutual interaction between the planets

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[242] Ibid., pp. 937–938. Newton introduces a different cause for the phenomena of variable stars: "But fixed stars that alternately appear and disappear, and increase little by little, and are hardly ever brighter than fixed stars of the third magnitude, seem to be another kind and, in revolving, seem to show alternatively a bright side and a dark side." See Ibid., p. 938. Newton does not elaborate on the notion of 'bright side and dark side' of a star.

[243] Ibid., pp. 939–940.

and comets. Irregularities that arise from these gravitational actions can increase over time until a reformation (by the Creator) becomes inevitable:

> For while Comets move in very excentrick Orbs in all manner of Positions, blinde Fate could never make all the Planets move one and the same way in Orbs concentrick, some inconsiderable Irregularities excepted, which may have risen from the mutual Actions of Comets and Planets upon one another, and which will be apt to increase, till this System wants a Reformation.[244]

This idea, which initiated an enduring debate – both in dynamics of the solar system, and cosmogony – involved comets in another cosmological action besides their role in redistributing the vapor and heat in the cosmos. Newton's assumption about the role of comets in making the solar system unstable originated from his erroneous overestimation of the masses of comets.

Besides the *Opticks*, there are other sources and documents that shed light on Newton's thoughts about comets. Newton exchanged his cometary ideas in several correspondence with Halley, Flamsteed, Richard Bentley, and others; but, in most of them either the mechanics of cometary motion was the central issue or observational data exchanged.[245] However, this does not imply that discussions about the physics of comets faded out due to the importance of the cometary mechanics. Newton was engaged in speculation about the constitution and cosmic role of comets till the last years of his life, but he was cautious in publishing his ideas.

John Conduitt's memoranda[246] contain some important information about Newton's cometary ideas which Newton never published. In a memorandum written about six years after the second edition of the *Principia*, Conduitt reports:

> [Newton repeated] what he had often hinted to me before, viz. that it was his *conjecture* (he would affirm nothing) that there was a sort of revolution in the heavenly bodies that the vapours and light emitted by the sun which had their sediment in water and other matter, had gathered themselves by degrees in to a body and attracted more matter from the planets and at last made a secondary planett (viz. one of those that go round another planet) and then by gathering to them and attracting more matter became a primary planet, and then, by increasing still became a comet w^{ch} after certain revolutions by coming nearer and

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[244] Newton, *Opticks*, p. 402. This query was numbered 23 in the first edition of the *Opticks* (1706).

[245] One of the occasions that Newton states his ideas about the physical constitution of comets is in his first letter to Bentley where he rejects Descartes' hypothesis of transformation of stars to comets, and classifies stars and comets in different categories. See Isaac Newton, *The Correspondence of Isaac Newton*, ed. H. W. Turnbull, 7 vols. (Cambridge: Cambridge University Press, 1961), vol. III, p. 234. Also available in I. Bernard Cohen, Robert E. Schofield, ed. *Isaac Newton's Papers and Letters on Natural Philosophy and Related Documents*, 2 ed. (Cambridge, MA: Harvard University Press, 1978), pp. 283–284. Since our aim does not include tracing out the development of Newton's physical theory of comets before the publication of the *Principia*, here we consider only correspondence and papers which Newton drafted after the *Principia* and influenced the subsequent cometary theories.

[246] John Conduitt, the husband of Newton's niece, composed his memoirs of Newton which are one of the main sources for the biography of Newton.

> nearer the sun had all its volatile parts condensed and became a matter set to recruit and replenish the sun … and that would probably be the effect of the comet in 1680 sooner or later.[247]

This idea, only the last part of which (falling of comets on stars) was made public by Newton, not only reveals a continuous evolution in the planetary material, but also makes the stability of the cosmos the ultimate cause of this evolution. Comets, which are the main physical agents in maintaining stability in the universe, are the final stage of planetary evolution, when the planets obtain more matter and become denser. This scheme agrees with Newton's standard theory of comets in which comets are assumed to be denser and more durable than the planets. The cosmological importance of this idea will be discussed in the next section.

Another scholar, whose memoranda are a source of technical information on planetary and cometary astronomy, is David Gregory (1659–1708), Savilian Professor of Astronomy at Oxford from 1691 to 1708. In one of these memoranda Gregory reveals an interesting point about the mechanism of ascension of the cometary tails, which was one of the obscure parts of Newton's theory of comets. He describes the interaction between the cometary tail particles and the particles of the ether as follows:

> Although the smoke issuing from a comet owing to heat does not become lighter than celestial matter, yet celestial matter warmed by it, along with the smoke which it absorbs and carries away, can be lighter than the remaining celestial matter that is not heated by the hot smoke, Hence the comparison with smoke rising in a chimney.[248]

As we will discuss later, this problem – that the particles of the ether lift particles heavier than themselves – was one of the issues that Newton had explained clearly neither in the *Principia* nor in the *Opticks*.

Gregory also quoted passages from Newton's conversation about the cosmological role of comets:

> [Newton says] that the great eccentricity in Comets in directions both different from and contrary to the planets indicates a divine hand: and implies that Comets are destined for a use other than the planets. The Satellites of Jupiter and Saturn can take the places of the Earth, Venus, Mars if they are destroyed, and be held in reserve for a new Creation.[249]

And

> A comet passing near the Earth to the east has altered its course in perihelium just as the Moon by attracting the waters caused a deluge.[250]

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[247] Memorandum by Conduitt, Kings College, Cambridge MS, Keynes 130, no. 11, as quoted in David Kubrin, "Newton and the Cyclical Cosmos: Providence and the Mechanical Philosophy," *Journal of the History of Ideas*, 28 (1967), 340. In the same document Newton states that the fixed stars also could be replenished by comets falling on them. When Conduitt asked Newton why he did not publish these ideas, Newton replied that "I do not deal in conjectures." See above. p. 343.

[248] Newton, *Correspondence*, III, p. 316.

[249] Ibid., III, p. 336.

[250] Ibid., IV, p. 277.

The later idea, as we will discuss in the next chapter, was elaborated by William Whiston, Gregory, Halley, and others as the basis of a new theory that linked the history of the earth to comets.

Newton's unpublished scientific papers also contain some of his meditations about the physics of comets. These writings contain no new ideas that had not been stated in the *Principia* or the *Opticks*, nor are they in contradiction with Newton's standard theory of comets. They do include some clarifying points to help us to understand Newton's theory correctly.

In a paper written after the *Principia*, Newton outlines some fundamental characteristics of the celestial bodies under the subtitle of "The Mechanical Frame of the World."[251] Here, Newton states that due to the force of gravity, the sun, the planets, and comets are round. Then he categorizes comets as "a sort of Planets round & opake with very great Atmospheres," which in the vicinity of the sun "send up tails like a very thin smoke from ye exterior part of their Atmospheres boyed up by ye greater weight of ye Suns Atmosphere into wch they dip." Next, Newton explains the orbital motion of the planets and comets, but he assigns rotation only to the planets. Although he declares that comets are a sort of planet, he prefers to be silent about the axial motion of the comets.[252]

Having collected almost all published ideas of Newton about the physics of comets, it is appropriate now to assess his theory of comets in the context of Newtonian physics and cosmology. In the next section, I will analyze Newton's physical theory of comets based on the principles of his physics and astronomy, and in the following one I will illustrate the cosmological consequences of Newton's theory.

Physical Properties of Comets According to Newton: A General Assessment

It seems that Newton treats planets and comets in two different ways, although he does not explicitly declare it. As mentioned above, Newton only strictly divides the celestial bodies into three categories of the fixed stars, planets, and comets in an unpublished paper drafted after the *Principia*. Neither in the *Principia* nor in the *Opticks* does he affirm the same statement. In contrast, in several occasions he

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[251] MS. Add. 4005, fols. 23-5, published in: A. Rupert Hall, Marie Boas Hall (eds.), *Unpublished Scientific Papers of Isaac Newton, A Selection from the Portsmouth Collection in the University Library, Cambridge* (Cambridge: The University Press, 1962), pp. 165–169.

[252] In a paper written after 1684, Newton states that "the Universe consists of three sorts of great bodies, Fixed Stars, Planets, & Comets." However, in all of his published works, he is not explicit about the physical differences between the planets and comets. It is also interesting that in this paper, Newton explains the fixed stars and the planets, but leaves comets unexplained. See Ibid., pp. 374–377.

states that comets are a kind of planet.[253] If the planets and comets were physically and intrinsically similar, then the reason for Newton to treat them in two different parts of the *Principia* could be simply the difference in orbital characteristics and cosmological role of comets and the planets. However, a close look at Newton's treatment of comets as physical objects shows that Newton has not been precise in illustrating the similarities of or differences between planets and comet.

In his calculation of the amount of the heat that the comet of 1680 absorbed at perihelion Newton implies that the comet was a body of the same size of the earth but with the density of iron. However, at the end of proposition 41 of book 3, he states that because the smaller planets revolve in orbits closer to the sun, "it seems reasonable also that the comets which approach closer to the sun in their perihelia are for the most part smaller, since otherwise they would act on the sun too much by their attraction."[254] Therefore, the comet of 1680, which passed the sun in its perihelion at a distance of less than a sixth of the sun's diameter,[255] should be much smaller than Mercury.

As Newton states in the corollary 4 to proposition 8 of book 3, the planets that are smaller are denser. In other words, the closer the planet is to the sun the denser is the planet.[256] Obviously, this correlation between the distance and density is clearly a correlation between a planet's density and the amount of heat it absorbs from the sun. Newton emphasizes that "the planets, of course, had to be set at different distances from the sun so that each one might, according to the degree of its density, enjoy a greater or smaller amount of heat from the sun."[257] Therefore, a comet that approaches the sun closer than Mercury should have a higher density than Mercury.

Newton does not calculate the size or density of Mercury. However, he establishes a method to calculate the mass and density of the sun, the earth, Jupiter, and Saturn. The procedure starts from the calculation of the weight of equal bodies at equal distances to Jupiter, Saturn, earth, and the sun, and then continues to find their weights at the surface of those planets. The weight of equal bodies on the surfaces of the sun and planets can be used to measure the relative masses of those celestial bodies. Finally, by calculating the size of the planets from their apparent diameter and distance, density can be found. This procedure, however, is only applicable to those bodies that have other bodies revolving around them. Therefore, Newton's calculation includes the sun, and three planets (the earth, Jupiter and Saturn) that

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[253] For example in proposition 41 he says: "…the bodies of comets are solid, compact, fixed, and durable, like the bodies of planets," or at the end of the same proposition: " We said that comets are a kind of planet revolving about the sun in very eccentric orbits." See Newton, *Principia*, pp. 918, 928.

[254] Newton, *Principia*, p. 928.

[255] Ibid., p. 937.

[256] Ibid., p. 814.

[257] Ibid.

have moons circling about them.[258] The figures Newton calculated for the weight of equal bodies at the surfaces of the sun, Jupiter, Saturn, and the earth are 10,000, 943, 529, and 435 respectively. Based on proposition 72 of book 1, the weight of equal bodies on the surface of homogenous spheres are as the ratio of the diameters of the spheres. Therefore, the density of the sun and the three planets can be found by dividing the calculated weights by diameters of the sun and the planets. Since the ratio of the diameters of the sun, Jupiter, Saturn, and the earth are as 10,000, 997, 791, and 109, their densities are yielded as 100, 94½, 67, and 400 (the density of the earth is computed based on the period of motion of the moon and its parallax).[259] In proposition 37, corollary 3 of book 3, the density of the moon to the density of the earth is given as 4,891 to 4,000 or 11 to 9, which gives the moon's density around 489, whereas that of the earth is 400.[260]

Although the density of Mercury is not estimated, the increase of density towards the sun is correlated with the size of the orbit and consequently with the amount of heat that the planet receives. Newton says that the distance of the comet of 1680 at its perihelion from the center of the sun to the distance of the earth from the center of the sun was 6 to 1,000.[261] This distance, according to Newton, was less

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[258] For example, the centripetal force acting on the moon is $F = m_m (4\pi^2 R_m / T_m^2)$, where m_m is the mass of the moon, R_m is its mean distance from the earth, and T_m is its period of revolution. If this force is equivalent to the gravitational force which is given by $F = G\, m_m\, m_e / R_m^2$ (G is the constant of gravitation and m_e is the earth's mass) then we will have $G\, m_m\, m_e / R_m^2 = m_m (4\pi^2 R_m / T_m^2)$ or $T_m^2 = (4\pi^2 / G\, m_e)\, R_m^3$ which is the derivation of Kepler's third law from Newton's gravitational law. To have a quantitative example, lets denote the orbital periods of the earth by T_e, the mean distance of the earth from the sun by R_e and the sun's mass by M. Then: $T_e^2 = (4\pi^2 / G\, M)\, R_e^3$ and $T_m^2 = (4\pi^2 / G\, m_e)\, R_m^3$ or $T_e^2 / T_m^2 = (R_e^3 / R_m^3)\, (m_e / M)$ or $m_e / M = (T_e^2 / T_m^2)\, (R_m^3 / R_e^3)$. Since $T_e = 365\,\mathrm{d}$, $T_m = 27\,\mathrm{d}$, $R_m = 384{,}000\,\mathrm{km}$ and $R_e = 150{,}000{,}000\,\mathrm{km}$, then $m_e / M \approx 1/330{,}000$. The ratio of densities also can be calculated by knowing the apparent diameter of the bodies and their distances (which makes their true diameters computable). Newton's figures were erroneous because of his incorrect number for the solar parallax. For the details of Newton's calculations and his different results in different editions of the *Principia* see I. B. Cohen's guide to the *Principia*, Ibid., pp. 218–231, and Dana Densmore, *Newton's Principia: The Central Argument* (Santa Fe: Green Lion Press, 1995), pp. 382–394.

[259] Ibid., pp. 813–814. For Newton's figure for the solar parallax and its influence on the Newtonian planetary data see Van Helden, *Measuring the Universe*, pp. 144–149. Newton's errors in his planetary calculations are analyzed in Robert Garisto, "An Error in Isaac Newton's Determination of Planetary Properties," *American Journal of Physics* 59 (1990), 42–48.

[260] Ibid., p. 878. In the first edition of the *Principia*, where Newton's figure for the solar parallax was about 20″, densities of the earth and moon were calculated as 387 and 700 respectively. Obviously, the distance of the moon from the sun is not so different from the distance of the earth from the sun, and both receive almost the same amount of heat from the sun. Therefore, it is difficult to relate the higher density of the moon to the amount of heat it absorbs. If it is related to the smallness of the moon, then one can assume that while the earth's diameter is about 3.5 times of the moon's diameter, it is 1.2 less dense than the moon.

[261] Ibid., p. 918. The accurate value is 612.5 to 10,000, as Halley reports in his table of cometary data. See Edmund Halley, *A Synopsis of the Astronomy of Comets* (London: 1705), p. 7.

than a sixth of the sun's diameter, causing the comet to be immersed in the atmosphere of the sun.[262] By 1693, before the second edition of the *Principia*, Newton adopted a value of 10″ for the solar parallax (Fig. 4.4) which was equivalent to a solar distance of 20,500 earth radii (e.r.) or about 79,000,000 English miles (Em).[263] Therefore, the comet passed within a distance of 470,000 Em from the center of the sun, or

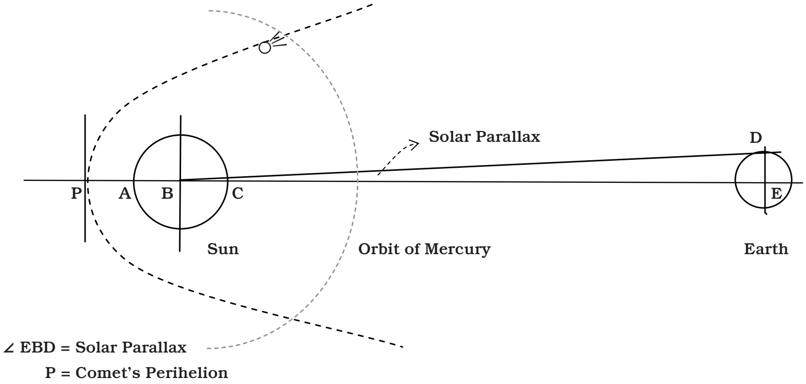

Fig. 4.4 According to Newton, the ratio of distances of the comet of 1680 at its perihelion from the sun to the distance of the earth from the sun was PB/BE = 6/1000, and PA was less than 1/6 of AC. Obviously, adopting different values for the solar parallax affects the ratios. With a solar parallax of 10′, AP would be about 114,000 English mile and the comet would fall inside the solar atmosphere. Newton believed that the sun's atmosphere was extended as far as Mercury's orbit

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[262] Ibid., p. 937. Newton believed that the sun is encompassed by a huge atmosphere. In an unfinished paper written after 1710 he wrote: "That the Sun is indeed surrounded by a huge Atmosphere appears from eclipses of the sun, in which the Moon where it covers the whole Sun appears as a black circle, surrounded by a shining corona like a halo. […] Imagine that the atmosphere of the Sun does not end where it ceases to be visible but that it extends as far as the orb of Mercury and far beyond as a more tenuous medium. It is also conductive to the ascent of vapours…. [sic]." See Hall, *Unpublished Scientific Papers of Newton*, p. 319. Also in query 11 of the *Opticks* he refers to the great weight of the atmosphere of the sun. See: Newton, *Opticks*, p. 344. The solar atmosphere is so dense that it retards comets' motion when they approach the sun. See: Newton, *Principia*, p. 937.

[263] Van Helden, *Measuring the Universe*, pp. 151–152. Newton in the second edition of the *Opticks* adopts 70,000,000 English miles for the earth-sun distance, which is equal to a solar parallax of 12″. See Isaac Newton, *Opticks: or a Treatise of the Reflections, Refractions, Inflections and Colours of Light*, 2 ed. (London: 1718), p. 325 (or p. 351 in the fourth edition of the *Opticks*, published by Dover in 1979). Newton's adoption of different values for the solar parallax and planetary data in different editions of the *Principia* is given in Garisto, "An Error in Newton's Determination of Planetary Properties," p. 44. In 1715, William Whiston (1667–1752), Newton's successor in the Lucasian chair at Cambridge, published his results for the size and distances of

114,000 Em from the surface of the sun.[264] Then, the ratio of the comet's distance from the center of the sun to Mercury's distance from the sun would be about 1 to 66. While the sun's heat is 7 times denser in the orbit of Mercury than on the earth,[265] its heat would be slightly above 4,000 times denser on the comet than Mercury.

The ratio of proportionality between the amount of heat the substance of a planet or comet can absorb and its density is not clear in Newton's writings. Although Newton in the first edition of the *Principia* had introduced a few rules which correlated approximate density of planets to their apparent diameters (as seen from the sun) and their true diameters and distances, he omitted those rules in the second and the third editions and preferred to be silent about the masses and densities of the two inner planets and Mars. However, just for comparison, one can point out that according to Newton, the densities of Saturn, Jupiter and the earth (at distances of about 8,500, 5,000 and 1,000 from the sun, while 1AU=1,000) are 67, 94.25 and 400 respectively. In other words, the earth which receives approximately 25 times more heat than Jupiter, is about four times as dense as Jupiter. On the other hand, the moon at a distance of about 60 e.r. from the earth and with a diameter of about one-third of the earth's diameter has a density of 489 or 1.2 times more than the density of the earth.

Whatever the density of a typical comet is, Newton declares that comets are the densest objects in the solar system. The dense cometary nucleus is engulfed in an atmosphere about ten times larger than its radius. Obviously, because of the higher density of the nucleus (which means a higher gravitation at its surface) the atmosphere must be much thicker in the inner parts. The rarified outer part of a comet,

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the sun and planets, based on a solar parallax of 10". His figures (which I have used in my calculations when the needed value was not in the *Principia*) are as follows:

Body	Diameter in	Heliocentric Distance
Moon	2,175 Em	– Em
Sun	763,460	–
Mercury	4,240	32,000,000
Venus	7,906	59,000,000
Earth	7,935	81,000,000
Mars	4,444	123,000,000
Jupiter	81,155	424,000,000
Saturn	67,870	777,000,000

See: Van Helden, *Measuring the Universe*, pp. 155–156.

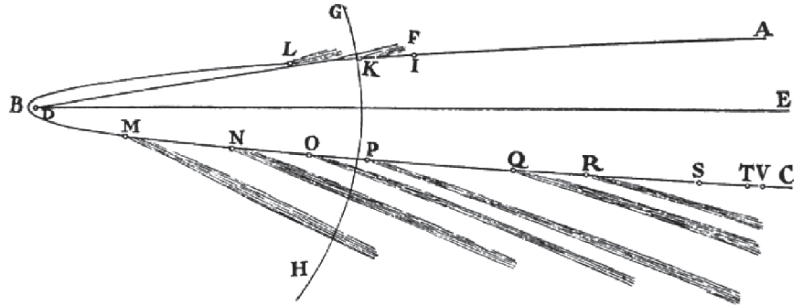
[264] In the *Principia*, Newton simply says that the distance of the comet from the sun was less than one sixth of the sun's diameter. Since usually all distances between the celestial objects are given as distances between their centers, Newton's account should be read as 'comet's distance from the *surface* of the sun. If the comet's distance was less than a sixth of the sun's diameter from the sun's center, then the sun's diameter would be around 2,800,000 Em and the comet would pass directly *through* the body of the sun in a distance of one third of solar radius from the sun's center.

[265] Newton, *Principia*, p. 814. The ratio of 1 to 66 which is yielded from William Whiston's table (above) is approximately in agreement with Newton's figures. Newton calculated that the sun's heat on the comet was 28,000 denser than its heat on the earth, and Mercury was 7 times as hot as the earth. The square of 66 multiplied by 7 is about 30,000.

which is so thin that even the dim stars can be seen through it, heats up due to the reflection of the sun's rays from its particles and as a result, the adjacent ethereal particles become agitated. This process rarifies the ether and its particles move up (away from the sun) and carry along the atmospheric particles of the comet, which is seen as the cometary tail.

Although Newton's theory was developed in a completely different framework than all previous theories and was based on all developments of physics and astronomy in the late seventeenth and early eighteenth centuries, and was much more quantitative than others, a close look at it reveals inconsistencies that either developed due to Newton's belief in intrinsic differences between the planets and comets or had their roots in other reasons that Newton did not made public.

The description of the comet of 1680's motion and the orientation of its tail in proposition 41 of book 3 of the *Principia* indicates that the comet was observable before its intersection with the orbit of the earth (Fig. 4.5). In other words, at such a distance, the heat created by the solar rays in the outer parts of the atmosphere of the comet was intense enough to produce a tail. If the process of tail formation could occur at a distance of more than one astronomical unit, then the earth and the inner planets should have tails also. Although Newton does not specifically say that there are atmospheres around Venus and Mercury, he believes in general that planets have atmospheres[266] and he acknowledges that some kind of effluvia (or planetary exhalations) are associated with the planets. In such a case, considering that the



D = Sun, **GH** = the earth's orbit, **ABC** = the trajectory of the comet, **DF** = the line of nodes
I= the place of comet on 4 Nov. 1680, **K**= on 11 Nov., **L** = on 19 Nov., **M** = on 12 Dec.,
N = on 21 Dec., **O** = on 29 Dec., **P** = on 5 Jan. 1681, **Q** = on 25 Jan., **R** = on 5 Feb.,
S = on 25 Feb., **T** = on 5 March, **V** = on 9 March,

Fig. 4.5 Orbit of the comet of 1680, from the third edition of the *Principia* (Copied from *The Principia*, translated by I. B. Cohen et al., p. 916)

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[266] For example, he maintains that the tail of comets is finally scattered and "attracted towards the planets by its gravity and mixed with *their atmospheres*." (my emphasis). See: Ibid., p. 926; or "it's necessary to empty the Heavens of all Matter, except perhaps some very thin Vapours, Steams, or Effluvia, arising from the *Atmospheres of the Earth, Planets, and Comets*, " (my emphasis). See: Newton, *Opticks*, p. 368.

amount of release of exhalations is directly related to the intensity of heat the planet receives from the sun, one can conclude that Venus and Mercury are planets suitable to create tails.

Newton denies the formation of tails behind the planets. In his rejection of Descartes' theory of tail formation, he clearly says that although the planets shine with more light, they have no tails.[267] Now, we encounter some crucial questions: are the atmospheres of Mercury, Venus, and the earth (which are revolving around the sun at an appropriate distance to create tails) made up of a different kind of exhalation that does not produce tails? Are Mercury and Venus so heated that they have already lost their atmospheres and consequently can not form tails? And finally, are their atmospheres so rare that we can not detect any tails even if they can be formed?

The first question does not seem to be apt in the framework of Newtonian cosmology. It is contrary to the universal chemical unity that Newton observes in the cosmos. Newton, in his several explanations of the cycle of vapor and exhalations in the universe, has not differentiated the planets regarding their exhalations. If each planet had an exclusive brand of exhalation, then different kinds of comets would be needed to replenish them.

The possible answers to the second question lead us to a few new unanswered questions. The atmosphere of the sun, as Newton asserted in an unpublished paper (see above), stretches up to the orbit of Mercury. Therefore, it would be acceptable to say that Mercury has lost its atmosphere with the passing of time. Does this mean that Mercury is so heated that it has no exhalation? Or if it continuously produces exhalation, is the exhalation swept by the sun's atmosphere? In the first case, Mercury should be the densest body in the solar system,[268] and in the second case Mercury has to have an extremely huge resource of volatile matter. The same queries can also be put forth about Venus.[269]

If it is difficult to analyze the physical conditions of the inner planets, we will have fewer problems in seeing if Newton's theory of tail formation is pertinent to the earth. We know that the earth is engulfed in an atmosphere with a density that decreases with the increase of the altitude until it merges in the celestial ether. As Newton calculated, at a height of two hundred miles above the earth (about 1/20 of

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[267] Ibid., p. 920. Also, at the end of proposition 41 of book 3 of the *Principia* he declares that the planets have no tails. See: Ibid, p. 928.

[268] Recalling Conduitt's memorandum that Newton suggested a sort of revolution in the celestial bodies (wherein bodies by attracting more and more vapor and light emitted from the sun grow sufficiently and become a moon then a comet), and Gregory's report of Newton's idea that "Satellites of Jupiter and Saturn can take the place of the Earth, Venus, Mars if they destroyed," it seems that the denser bodies (or the more close ones to the sun) are the most potential planets to evolve to a comet. Was Newton thinking that the planets, one by one, gain more light and vapor from the sun and turn into a comet?

[269] Newton in a letter to Flamsteed, which is written before the *Principia*, admits that Jupiter, Mars and Venus are encompassed in fine and thin atmospheres which allow their limbs to appear distinct. See: Newton, *Correspondence*, II, p. 345.

the earth's radius) the atmosphere is 7.5^{13} times rarer than on the earth, or its density is equal to the density of the medium in which the planets are moving.[270] Therefore, as the comet of 1680 produced a tail at the same distance of the earth from the sun, one can expect that a terrestrial tail can be formed above an altitude of 200 miles.

Newton, however, did not suggest that such a tail exists.[271] One of the reasons could be related to the rotational motion of the earth. This is only a suggestion, but it reveals a major physical difference between comets and planets in Newton's theory. Although Newton does not explicitly discuss the rotation of comets, it seems that there is a major dynamical difference between the planets and comets in Newton's theory: comets do not rotate about their axes.

There are two items of evidence which help us to prove this claim. First, Newton does not involve the rotation of the body of a comet in his theory of formation and orientation of tails. Since a comet's rotation would affect the orientation of its tail, especially after the perihelion when the size of the coma is reduced, Newton should have mentioned it if he had assigned rotational motion to comets.[272] Secondly, Newton in his description of the atmospheres of comets in the vicinity of their perihelion says that "their atmospheres are diminished by running out into tails and *(certainly in that part which faces toward the sun*) are made narrower,"[273] which implies that comets always have the same hemisphere towards the sun.

If all planets and even the sun, as a typical star, are rotating around their axes,[274] Newton's exclusion of rotation from comets (or at least his silence about the issue) should be based on reasons. It remains obscure whether it was due to a major difference he assumed to exist between planets and comets or whether he was aware

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[270] Ibid., p. 816. Since the coma of a comet – with a diameter approximately ten times larger than the comet's diameter – is observable, it means that its density in this entire large volume is higher than the density of the ether. Newton's calculations, however, show that the density of the terrestrial atmosphere at an altitude of 200 miles is the same as the density of the ether, which implies that an alien observer would see our atmosphere with a maximum thickness of 200 miles. In other words, the thickness of the atmosphere of the earth is 200 times less than of a typical comet at an equal distance from the sun.

[271] Based on Newton's theory of orientation of cometary tails, if the earth had a tail, its extremities might have been observed from the earth. In other words, the end parts of the tail – raised a few days earlier – would have enough distance from the earth to reflect the sun's rays and be distinguished as patches of light.

[272] David Gregory also refers to a similar fact in his discussion of the possibility of rotation of comets: "It is not known whether a Comet revolves about itself, but it is probable that, like all the other great bodies of the World, it turns all its Faces towards the Sun […] If the Nucleus be turn'd about […] that Vapour, which, going out of the Comet, makes the Tail, is not so much to be look'd upon, as the Atmosphere of the Comet join'd with it (as the denser Atmosphere of the Earth is join'd with it) and making Part of it;" See Gregory, *The Elements*, vol. 2, pp. 851–852.

[273] Newton, *Principia*, p. 926, emphasis is mine.

[274] Newton in an unpublished paper (MS. Add. 4005, fols. 45-9) discusses the motion of the planets and stars about "their several axes." See: Hall, *Unpublished Scientific Papers of Newton*, p. 380. In his fourth letter to Bentley, Newton affirms that "the diurnal Rotations of the Planets could not be derived from Gravity, but required a divine Arm to impress them." See: Newton, *Correspondence*, III, p. 244.

that by admitting rotation he would be obliged to alter his theory of tail formation and orientation.

The substance from which comets are made is another issue which Newton discusses very little. Again, scrutinizing Newton's ideas about the planets and comets reveals that he has not treated them the same way. It seems that Newton either had a different understanding about the substance and internal structure of comets that he never made public or he just did not apply the physical laws he introduced in other subjects to comets as physical bodies.

Comets absorb a great amount of heat in the vicinity of their perihelion. As Newton calculated, the comet of 1680, at its perihelion, was about 2,000 times hotter than incandescent iron. When a comet circles the sun and becomes visible again (as the comet of 1680 became visible on December 12, four days after perihelion), its coma is seen to be smaller and dimmer while its tail becomes more extended. All of these changes are due to the heating of the nucleus and the atmosphere of comet:

> In the descent of comets to the sun, their atmospheres are diminished by running out into tails and (certainly in the part which faces towards the sun) are made narrower; and, in turn, when comets are receding from the sun, and when they are now running out less into tails, they become enlarged, if Hevelius has correctly noted their phenomena. Moreover, these atmospheres appear smallest when the heads, after having been heated by the sun, have gone off into largest and brightest tails, and the nuclei are surrounded in the lowest parts of their atmospheres by smoke possibly coarser and blacker. For all smoke produced by great heat is generally coarser and blacker. Thus, at equal distances from the sun and the earth, the head of the comet which we have been discussing appeared darker after its perihelion than before.[275]

However, based on Newton's explanation about the physical condition of the heated material, a different behavior is expected from a comet after its perihelion.

Newton in queries 6, 8, 9, 10 and 11 of the *Opticks* investigates the phenomena related to heat and the influences of heat on gross material. In query 8 he says:

> Do not all fix'd Bodies, when heated beyond a certain degree, emit Light and shine.[276]

And in query 11:

> Do not great Bodies conserve their heat the longest, their parts heating one another, and may not great dense and fix'd Bodies, when heated beyond a certain degree, emit Light so copiously, as by the Reflexions and Refractions of its Rays within its Pores to grow still hotter, till it comes to a certain period of heat, such as is that of the Sun? And are not the Sun and fix'd Stars great Earths vehemently hot […].[277]

Thus, if any solid matter radiates light when heated to a certain degree, why do not the nuclei of comets shine after being 2,000 times hotter than incandescent iron? According to Newton, a piece of iron becomes 'red hot' when it is about three or

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[275] Newton, *Principia*, pp. 926–927.

[276] Newton, *Opticks*, p. 340.

[277] Ibid., pp. 343–344.

four times as hot as boiling water. In other words, this degree of heat marks the threshold of emission of light in a substance like iron. Therefore, a globe as large as a planet and composed of dense matter should shine with a high luminosity when its heat surpasses the threshold of radiation by a factor of 2000.

If we were to apply these rules to Newton's theory, the whole theory would collapse. A typical cometary nucleus with a temperature about 2,000 times as intense as red hot iron would heat the whole coma drastically. In fact, the coma would obtain heat from both internal and external sources – the hot nucleus and the sun – which could make the coma extremely hot. This situation, obviously, makes the coma rarer and larger, and finally turns a considerable part of it into the tail. The exceedingly hot nucleus would shine inside the coma, which now is rarer and cannot block the glow of the nucleus. Therefore, after the perihelion, a comet should be seen with a shining nucleus engulfed in a rare coma ending to a highly extended tail.

Newton's description of the physical properties of cometary nuclei after passing their perihelia contains a point which, at the first glance, might solve the problem of nucleus radiation just mentioned. Newton states that the nuclei "are surrounded in the lowest parts of their atmospheres by smoke possibly coarser and blacker." One may assume that this coarser and blacker smoke can block the light that is emitting from the comet's nucleus. But why does Newton presume the physical conditions of the heated nuclei to be this static? Why does he not apply his 'chimney' analogue here? If the nucleus is 2,000 times hotter than red hot iron, why should the atmosphere around it stay steady and not lift the particles up?[278] Furthermore, if the particles of smoke are exposed to such tremendous heat, why do not the smoke and exhalation glow, based on the fact stated in query 8 of the *Opticks*?

Radiation of a heated exhalation seems to be a modern physics concept. But, in queries 9 and 10 of the *Opticks* Newton defines a flame as:

> Is not Fire a Body heated so hot as to emit Light copiously? For what is a red hot Iron than Fire? And what else is a burning Coal than red hot Wood?

And,

> Is not Flame a Vapour, Fume or exhalation heated red hot, that is, so hot as to shine? For Bodies do not flame without emitting a copious Fume, and this Fume burns in the Flame. [...] red hot Smoke can have no other appearance than that of Flame. [279]

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[278] According to Newton, the corpuscles that make the black color are smaller than any other particles which exhibit colors, and "Fire, and the more subtile dissolver Putrefaction, by dividing the Particles of Substances, turn them to black" (Ibid., p. 260). On the other hand, Newton, in query 6 of the *Opticks* says that "black Bodies conceive heat more easily from Light than those of other Colours do" (Ibid., p. 339). Therefore, the black particles of the smoke on the surface of the nucleus must have the strongest vibrations.

[279] Ibid., pp. 341–342.

Based on this definition, it would be permissible to think that the coma of a comet, surrounded a body 2,000 times hotter than red hot iron, should turn into flame. In such cases, after their perihelia comets should be seen to be much more luminous than any star or planet.[280]

Similar ambiguity is seen in Newton's description of the development of cometary atmospheres and tails. A typical comet, which is surrounded by an atmosphere, develops a tail when it reaches an appropriate distance from the sun. The tail is in fact a very small fraction of the exhalations of the upper atmosphere, which spreads into interplanetary space. Newton compares the tail to the smoke coming out of a chimney. However, there is an essential difference between the process of smoke rising in the air and the extension of cometary tails in the ether. [281]

On the earth, when air is rarefied, it rises vertically. Thus, the smoke of an imaginary conflagration on the day side of the earth will rise directly towards the sun. But, the heated ethereal particles around the comet are not moving vertically away from the nucleus towards the sun. Newton's notion of 'ascent' for the ethereal particles is equivalent to their motion away from the sun. He states that when the ether becomes rarified due to the heat it receives, "because its specific gravity, with which it was formerly tending towards the sun, is diminished by this rarefaction, it will ascend and will carry with it the reflecting particles of which the tail is composed."[282] Newton stresses that "in the heavens, where bodies gravitate toward the sun, smoke and vapors must ascend with respect to the sun."[283]

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[280] Newton in a letter to Flamsteed in February 1681 says "that ye atmosphere about ye head [of the comet] shines also by the suns light, though perhaps not *altogether by it*." (Newton, *Correspondence*, II, p. 346, my emphasis). Why he emphasized on *not altogether by it* is not known, but is interesting.

[281] Newton developed several theories of the ether, most of them unfinished. However, he proposed two major concepts of the ether in two different periods of his life. In the 1670s he thought the ether to be a subtle air capable of penetrating the pores of glass, crystal and other terrestrial matters. This mechanical ether, acting by impact, was responsible for gravity and action at a distance. However, after 1710, Newton adopted a new definition in which the ether consisted of very small particles that repelled one another and were repelled by particles of the gross matter. The particles of this ether are rarer in the stars, planets and comets than the space between them. Therefore, gravity is the force that pushes bodies from the denser parts of the medium to the rarer parts. For Newton's theory of ether see: Drake Gjertsen, *The Newtonian Handbook* (New York: Routledge Press, 1986), pp. 190–192; G. N. Cantor, M. J. S. Hodge, "Introduction: major themes in the development of ether theories from the ancients to 1900," in G. N. Cantor, M. J. S. Hodge (eds.), *Conceptions of Ether, Studies in the History of Ether Theories*, 1740–1900 (Cambridge: Cambridge University Press, 1981), pp. 1–60; B. J. T. Dobbs, "Newton's Rejection of the Mechanical Aether: Empirical Difficulties and Guiding Assumptions," in Arthur Donovan, *et al*, eds. *Scrutinizing Science: Empirical Studies of Scientific Change* (Dordrecht: Kluwer Academics, 1988), pp. 69–83.

[282] Newton, *Principia*, p. 925.

[283] Ibid., p. 922.

Although the rarified exhalation and vapor rise perpendicular to the surface of the comet and heat the particles of the ether, these rarified ethereal particles do not move in the direction of the atmospheric particles. They move away from the sun and carry with them the most rarified particles of the atmosphere. Thus, the tail is formed in a direction opposite to the sun (Fig. 4.6).

Two interrelated issues that are left unexplained in Newton's account of tail formation are the process of lifting the heavy particles of the atmosphere by the light particles of the ether, and the length of the tail. In queries 18 to 21 of the *Opticks*, Newton proposes that heat is transferred by the vibration of the particles of ether. On the other hand, he declares that the density of ether is lower in the dense bodies of the sun, stars, planets, and comets, but that it increases in the empty spaces between them (which causes the gravity of those bodies towards one another).[284] When the ether is rarified by the vibration of the heated atmospheric particles and moves away from the sun, it encounters the denser parts of the eather. At the same time, it carries some denser particles of the cometary exhalations (Fig. 4.7). Newton does not clarify how the ethereal particles can maintain their vibrations in such conditions to create a tail as long as 70 degrees and how they move inside the atmosphere of the sun, which is so

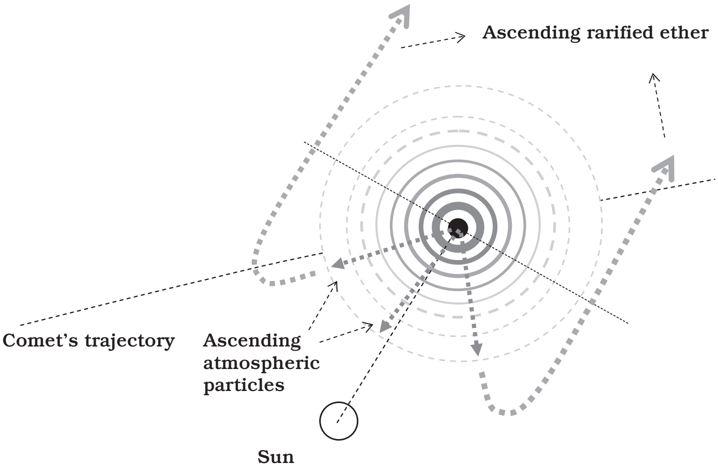

Fig. 4.6 Newton's comet is engulfed in a thick atmosphere (or coma) with a radius about ten times the radius of the nucleus. Although the rarified exhalation and vapor of the atmosphere of the comet rise vertically with respect to the surface of the nucleus, the ether rarified by the heat of the atmospheric particles of the comet moves away from the sun

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[284] Newton, *Opticks*, p. 350.

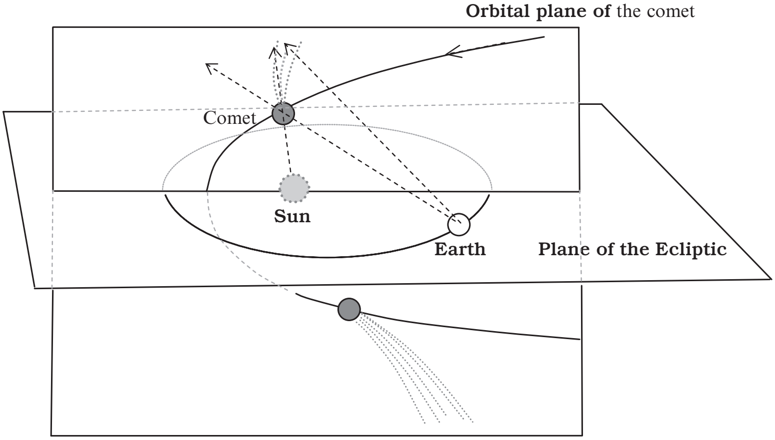

Fig. 4.7 Rarified particles of the ether, while moving away from the sun in the plane of orbit of the comet, carry along the particles of the outer atmosphere of the comet and produce a tail. The tail of the comet of 1680, just after its perihelion (12 December 1680) was about 70 degrees. This would mean that the rarified particles of the ether moved hundreds of thousands of miles into the denser parts of the ether, while they were carrying the particles of the comet's atmosphere

dense that it can retard the motion of the comet.[285] Furthermore, if the increase in density of ether outside of the celestial bodies is responsible for their mutual gravity, why does not the rarifaction of ether for hunderds of thousends of miles behind a comet affect its gravitational influence?

Besides this equivocation in the description of the tail formation, there is another subject that is left unclear in Newton's theory of comets. This problem is simply related to the amount of vapor and exhalations that a typical comet spreads in the cosmos. Based on Newton's description, the rate at which atmosphere runs into the tail is directly related to the amount of heat it receives. Thus, "in the descent of comets to the sun, their atmospheres are diminished by running out into tails."[286] In other words, by increase of the heat – in the vicinity of perihelion – the entire atmosphere (or a large part of it) turns into a tail. But when the comet is receding from the sun it develops an atmosphere again. In this account, the comet continuously produces exhalation and vapor and loses them either entirely in the perihelion or partially in other positions when the heat is reduced. This ability of comets to continually produce atmosphere introduces two major questions about the physical properties of the substance of the comet, and the cosmological role of comets.

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[285] One of the reasons that comets may fall on the sun is their retardation in the solar atmosphere: "…and also because the atmosphere of the sun has some density, the comet must have encountered some resistence and must have been somewhat slowed down and must have approached closer to the sun." See: Newton, *Principia*, p. 937.

[286] Newton, *Principia*, p. 926.

The Cosmological Roles of Newton's Comet Versus Its Physical Constitution

Although the key role of comets in construction of the Newtonian grand picture of the universe has been discussed in several studies,[287] the relationship between the cosmological role of comets and their physical properties has not been adequately considered. Since, according to Newton, a universe without comets will be dynamically and chemically unstable, it is crucial to see if this vital role of comets is consistent with the physical properties of comets, as Newton describes them. Newton's theory of comets was hitherto the most quantitative approach to the motion and nature of comets, and exactly for this reason it is critical to find out if Newton was successful in quantification of the cosmological aspects of comets based on their physical effects.

Newton's system of the world, at its first appearance, seemed to be as mechanical as Descartes' cosmology. In the mechanical philosophy of Descartes, although God created matter and motion, He did not intervene to preserve them. Motion was conserved, so there was no decline in motion and regularity in the universe. In other words, Providence was absent in Descartes' universe. This aspect of Cartesianism was held by many philosophers, especially in England, as the most threatening part of the mechanical philosophy which relegated the omnipotent and omnipresent God to a mere Creator. When the first edition of the *Principia* appeared with Newton's silence about the role of God in the functions of the universe, philosophical debates attempted to consolidate the mathematical principles of the cosmos with the role of its Creator.

Between the first and the second editions of the *Principia* (1687–1713) Newton published his *Opticks* in 1706, in which he declared that, due to irregularities developed over the long term by the mutual attraction of the planets and comets, the system of the world was not perennial. When those irregularities built up, the system needed a reformation by the Creator. Before the appearance of the *Opticks*, Newton in his correspondence with Richard Bentley had conceded that he "had an eye upon such Principles as might work wth considering men for the Belief of a Deity,"[288] but

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[287] See: David Kubrin, "Newton and the Cyclic Cosmos: Providence and the Mechanical Philosophy," *Journal of History of Ideas*, 28 (1967), 325–346; Sara Schechner Genuth, "Comets, Theology, and the Relationship of Chemistry to Cosmology in Newton's Thought," *Annali dell'Instituto e Mouseo di Storia della Scientza di Firenze*, 10, pt. 2 (1985), 31–65; Idem, "Newton and the Ongoing Teleological Role of Comets," in Norman J. W. Thrower, ed., *Standing on the Shoulder of Giants* (Berkeley: University of California Press, 1990), pp. 299–311. Pierre Kerszberg, "The Cosmological Question in Newton's Science," *Osiris*, 2 (1986), 69–106.

[288] Newton, *Correspondence*, III, p. 233. Richard Bentley (1662–1742), delivered a series of lectures in 1692, entitled "A Confutation of Atheism from the Origin and Frame of the World," and before publishing his work consulted Newton to correct his teachings of Newton's ideas. They exchanged four letters, discussing mainly philosophical aspects of universal gravity, mechanical philosophy and deity. The four letters and also Bentley's work can be found in *Isaac Newton's Papers and Letters on Natural Philosophy and Related Documents*, I Bernard Cohen (ed.), with Robert E. Schofield (Cambridge: Harvard University Press, 1978), pp. 279–312, 313–394.

it was the discovery of the periodicity of comets that provided him with a plausible agent of restoration.

Newton envisages two sorts of restoration in comets. Comets, on the one hand, can replenish the earth and the planets, and on the other hand, can refuel the sun (and the stars). Thus, comets are created to accomplish both chemical and dynamical reformations simultaneously. Vapors that spread from the cometary tails into space fall on the atmosphere of the earth and the planets and in the form of precipitations renew the liquids and vapors that are consumed by vegetation and putrefaction. However, after a number of revolutions, perturbations arise from the mutual attraction of the planets and comets to change the orbit of comets in such a way that they fall on the sun. As a result, the gradually decaying sun finds a new resource of replenishment and continues to govern the solar system. The latter phenomenon (which in the case of the fixed stars is seen as novae) is a real catastrophe:

> He could not say when this comet would drop into the sun; it might perhaps have five or six revolutions more first; but whenever it did, it would so much increase the heat of the sun, that this earth would be burnt, and no animals in it could live.[289]

Then, the burnt earth (and obviously the scorched Mercury and Venus) would need a source to renew their vital vapor and exhalations, and new comets would furnish them to continue the cycle. Accordingly, comets not only refresh the planets and stars, but also continue the cycle by their cataclysmic impact on the sun.

Assigning such essential roles to comets in the stability of the cosmos, Newton's theory of comets, however, is founded on an incoherent physical basis. The cosmological aspect of Newton's theory is unclear on two sides: firstly, it is the only part of the theory that is free from quantification and, secondly, Newton fails in a complete explanation of the underlying physical process. Although Newton did not publicize some of his ideas concerning the cosmological functions of comets in order to 'not deal in conjectures,'[290] the published sections should contain the most elaborated parts of his theory. However, a close look at those sections reveals major inconsistencies.

Newton's theory of the cometary role in replenishment of the earth and planets lacks any quantitative approach. Admittedly, Newton did not have any estimation of the rate by which the earth wasted its vapors and exhalations, nor had he any idea

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[289] Conduitt memorandum on March 7, 1724/5, concerning Newton's idea about the fate of the comet of 1680, from Turnor, *Collections*, p. 172.

[290] Once when Newton was explaining his ideas about the reconstitution of the earth by comets, Conduitt asked him why he did not publish his ideas and Newton replied "I do not deal in conjectures." Kings College, Cambridge MS, Keynes 130, no. 11; cited from Kubrin, "Newton and Cyclic cosmos," p. 343.

about the number of comets.[291] However, he had a rough estimation of the dimensions of a typical comet, the sizes of the planets, the sun, and the solar system. Furthermore, he had developed theories in solid and fluid mechanics, heat, and optics. Such an important theory as the cosmological role of comets should be compatible with all of the basic data and rules he had already established.

Based on general information Newton gives in the *Principia*, and using the same mathematical rules available to Newton, the size and mass of the atmosphere of a typical comet can be estimated. Newton was able to. To obtain an upper estimation, we suppose that a typical comet is the same size as the earth (although Newton assumes them to be even smaller than Mercury), engulfed in an atmosphere with a radius 10 times the earth's radius. Using Newton's data in proposition 22 of book 2 of the *Principia* and query 29 of the *Opticks* we find that for every 7½ miles the density of air decreases by a factor of 4. As the density decreases exponentially, after a height of about 100 miles it practically approaches zero.[292] Given the density of air as 1/850 the density of water and the radius of the earth as about 4,000 miles, the ratio of the mass of the atmosphere to the mass of the earth will be approximately one to 1,000,000.[293]

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[291] Edmund Halley was very interested to calculate the amount of vaporization of the waters of the earth and the heat of the sun which the earth receives in various latitudes. He also tried to calculate the rate by which the bulk of the earth was growing through attraction of particles from the space. From 1692 to 1714, Halley published at least five studies as follows: "An Account of the Circulation of Watery Vapours of the Sea, and the Cause of Springs," *Philosophical Transactions*, 16 (1686–1692), pp. 468–473; "An Estimate of the Quantity of Vapour Raised out of the Sea by the Warmth of the Sun…," *passim*, 16 (1686–1692), 366–370; "A Discourse concerning the Proportional Heat of the Sun in all Latitudes…," *passim*, 17 (1693), 878–885; "An Account of the Evaporation of Water, as it was Experimented in Gresham College in the Year 1693. With Some Observations Thereon," *passim*, 18 (1694), 183–190; "A Short Account of the Cause of the Saltness of the Ocean…With a Proposal …to Discover the Age of the World," *passim*, 29 (1714–1716), 183–190.

[292] David Gregory in his memorandum of 20 February 1697 wrote: "In drawing up the table of refraction of the stars he [Newton] does not consider that the height of the atmosphere extends further than 40 or 50 miles." See: Newton, *Correspondence*, IV, p. 267.

[293] Newton's data are: at the height of 7½ English mile from the surface of the earth the density of air decreases to one fourth of its original quantity, and at the heights of 22½, 30, 38, 76, 152 and 228 miles, the density is respectively 64, 256, 1,024, 10^6, 10^{12} and 10^{18} times rarer (Newton, *Opticks*, p. 367); the air is 860 times lighter than water (Newton, *Principia*, p. 816; the same ratio is given 850 in proposition 41 of book 3, see: Ibid., p. 922); the density of the earth is five or six times greater than the density of water (proposition 10 of book 3, Ibid., p. 815). Based on these information one can calculate the mass of the atmosphere as: $\rho_r = \rho_0{}^{[-\alpha(r-r')]}$ where ρ_0 is the air density at the surface of the earth, ρ_r is the air density at any point from the center of the earth, α is the ratio by which – as Newton stated – the density of air decreases by the increase of the altitude, and r' is the radius of the earth. Therefore, M (mass of the atmosphere) will be the integral of $\rho_r.4\pi.r^2\,dr$ from r' to $10\,r'$ (it does not make a difference if we extend the limit of integration to infinity). Solving this integral equation based on $r' \approx 4{,}000$ English mile ($\approx 6{,}400\,\text{km}$) and $\rho_{water} = 850\,\rho_{air}$ (or $\rho_{air} = 1.2\,\text{kg/m}^3$), the mass of the atmosphere will be about 5×10^{18} kg. This value (based on Newton's data) is very close to modern value for the mass of the atmosphere.

The dynamical consequences of a mass reduction of the original mass of a comet in the order of magnitude of one millionth may be negligible. However, due to exponential variation of the atmospheric mass, by admitting a higher density for the atmosphere (as Newton was thinking for cometary atmospheres) or a different size for the nucleus, the result may change drastically. Newton's neglect of the dynamical effect of the mass loss in comets indicates that he assumed its effects to be negligible. Be that as it may, we come across a question concerning the role of that insignificant amount of vapor and exhalation.

If the entire atmosphere of a typical comet is transformed into a tail, it will be distributed in the enormous volume of the solar system and will gradually be attracted by the planets in a ratio proportional to their masses. Obviously, the large planets of Jupiter and Saturn (which are far from the sun and lose fewer exhalations), and the sun itself will receive the largest part of the cometary emissions. Even wandering comets, which Newton believes exist in great quantity, will absorb parts of the released exhalations. Thus, if the earth is to regains its lost vapor and exhalations from cometary tails, the only three possibilities are either to believe in an incredible number of comets, to assume that comets release much more exhalation at each return, or to admit a much older universe.[294]

Newton affirms that there are a great number of comets in the cosmos[295]; however, he does not give any statistical, physical or cosmological reason for this assumption. He is reticent about the physical and cosmological consequences of a high population of comets. A profusion of comets means a great amount of vapor and exhalations spread in space and contaminating the ether which in turn will slow down the planetary motions. Considered from an ontological viewpoint, the abundance of comets raises important teleological questions. Is the world unwinding so frequently that God needed to create this many comets? Or, instead of periodic reformations, is there a continuous renewal in the world?

Newton is very equivocal in theorizing the process by which comets rebuild their atmospheres after their perihelia. Comets, as Newton describes them, are planet-like bodies having thick atmospheres. Before passing its perihelion, a comet loses a fraction of its atmosphere as a tail. But in the vicinity of the perihelion, due to the tremendous heat of the sun, its atmosphere diminishes and runs away in the form of a

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[294] Newton, in the first edition of the *Principia*, suggested that the bulk of the solid earth is continually increased. In 1694 he told Halley that "there was reason to Conclude That the bulk of the Earth did grow and increase … by the perpetuall Accession of New particles attracted out of the Ether by its Gravitating power, and he [Halley] Supposed … That this Encrease of the Moles of the Earth would occasion an Acceleration of the Moons Motion, she being at this time Attracted by a Stronger Vis Centripeta than in remote Ages." From *Journal Book of the Royal Society*, Oct. 31, 1694. cited from Kubrin, "Newton and Cyclic Cosmos," p. 337. Newton omitted the idea of increase of the mass of the earth in the second edition of the *Principia*.

[295] " But because of the great number of comets, and the great distance of their aphelia from the sun […] they should be disturbed somewhat by their gravities toward one another." See: Newton, *Principia*, p. 936.

tail. Newton does not explain why the vapors and exhalations in the cometary atmosphere are not transformed into salts, sulphurs, and other substances, as happens even by a slight heat on the earth.[296] Furthermore, it is not explained how the nucleus produces a new atmosphere after losing the original one. If comets develop new atmospheres after getting 2,000 times as hot as red hot iron, a new process has to be introduced to convert the extremely hot planetary material into vapor and moisture. Again, one may ask, if comets continuously produce and lose thick atmospheres, why was Newton indifferent to the dynamical effects of this mass reduction.

Conclusion

Newton, by introducing comets as members of the solar system, opened the modern era of cometology. In this era, it was accepted that comets were planet-like objects orbiting around the sun (although in highly elongated orbits) and obeying the same laws governing the motion and trajectory of other planets. After centuries of debate on the origin and location of comets, an agreement – at least on one fundamental subject – was concluded: by showing that returning comets were part of the solar system, the problem of the origin of comets was solved. This great achievement, although it put an end to all debates concerning the trajectory of comets, initiated different sets of physical and philosophical queries and founded new areas of research.

Newton's achievement in predicting the path of comets was a consequence of developments made in observational and mathematical astronomy. Three elements that contributed to this advancement were the development of methods to render the positional data of a comet as a true spatial path; the discovery of gravitational laws which brought comets into the realm of lawfulness[297]; and the application of accurate observational instruments, which reduced data gathering errors.[298]

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[296] As already noted, Newton at the end of the last proposition of the *Principia*, summarizes the cycle of transformation of the cometary exhalations and vapors as follows: "And the vapors that arise from the sun and the fixed stars and the tails of comets can fall by their gravity into the atmospheres of the planets and there be condensed and converted into water and humid spirits, and then – by a slow heat – be transformed gradually into salts, sulphurs, tinctures, slime, mud, clay, sand, stones, corals, and other earthly substances." See: Newton, *Principia*, p. 938.

[297] The history of the development of Newtonian celestial mechanics has a close relationship with Newton's study of comets. In Ruffner's words, Newton's theory of comets "was not an afterthought in the *Principia*, nor was it a casual deduction after the principles had been established. The theory of comets was an essential part of the *Principia*, which would have been incomplete without it." See Ruffner, *The Background*, pp. 352–353.

[298] Application of the micrometer in sighting tools, either in the focal plane of a telescope (as used by Picard, Newton and Kirch) or in the eyepiece of a telescopic quadrant (as used by Flamsteed, Cassini, Picard and others) produced highly precise and reliable data which reduced the errors of the calculated path. At the same time, use of Huygens's pendulum clock in observatories helped astronomers to correct their solar and planetary data, and also calculate the position of reference stars accurately.

During the second half of the seventeenth century, when Descartes' vortex cosmology was almost the most accepted system of the world, comets were thought to be dead objects, sporadic, far away from our planetary system, not bearing any influence on earth and its habitants, and lacking any cosmological importance. Newton, illustrated an exactly opposite picture of comets. Newton's comets were periodic, moving along computable trajectories, and approaching the sun even closer than Mercury. They might have destructive influences on the earth, but their cosmological role was to renew the resources of the planets and stars. Comets, which were dead stars in the Cartesian cosmology, turned out to be agents of revival for decaying stars in the Newtonian system of the world.

Newton's theory of comets changed the three interrelated fields of cometology – trajectory calculation, physical constitution, and cosmological role of comets – in a revolutionary manner: the predictive astronomy of Newton made it possible to calculate and predict the path of comets precisely; Newton's introduction of comets as planetary bodies brought about a new cometology based on planetary physics; and in cosmology, Newton's theory originated a long-lasting study concerning the problem of stability of the solar system. In addition, Newton's cosmology, in which comets had a pivotal role, caused the development of a new kind of cometary prophecy, new theories of the earth, and finally a new approach to discovering divine presence and divine providence.

Although Newton's theory of physical constitution of comets and cometary tails explained the main observational features of comets, it was not coherent. The major difficulties of Newton's theory were the lack of a clear description of similarities and differences between planets and comets and ambiguity in describing the process of formation and orientation of tails (especially the interaction of the ethereal particles and the atmospheric particles of comets). At the same time, the cosmological role of comets, which had a direct relationship with their physical constitution, did not attract attention widely. The question of the stability of the solar system, which was closely related to the cosmological role of comets, initiated a sequence of projects concerning the observation and calculation of perturbations in the solar system and remained open until the nineteenth century.

The relationship of Newton's cometary theory and his ideas about the chemistry of the universe and the transmutation of bodies has been a subject of interest for many historians of science. It has been extensively discussed that Newton believed in only one catholic matter which, through its transmutation, formed the diverse substances. Cometary exhalations and vapors, regardless of their final destination, could be involved in this universal chemical process and keep the cycle of the cosmic transmutation running. In other words, whether the particles of a comet are absorbed by a secondary planet (moon or other satellites), by a low-density and cold planet like Jupiter, by a hot and dense planet like Mercury, or even by sun, the result would be the same.

Newton, did not employ comets to merely illustrate the intrinsic unity of chemicals in the universe in a qualitative manner. His attempt was to establish his theory on quantitative and mathematical foundations. When he concluded, based on his celestial mechanics, that the solar system was not stable, he tried to find (again based on his celestial mechanics) a mechanism to stabilize the world. Comets, whose periodicity had been discovered, could serve as agents to replenish the decaying planets and the sun. Thus, Newton tried to quantify the function of this revivatory agent. He calculated the density of cometary tails, the amount of the heat a typical comet can absorb in its perihelion, the period of time that it takes the heated comet to cool down, the speed of the motion of the tail particles, and finally the periods of revolutions of comets. He even estimated the magnitude of the fire created during the impact of a comet on the sun. However, it seems that at some point this project of quantification came to a halt. Newton did not publish even his estimates about the key items in the renewal process: a typical comet's mass, its atmospheric mass, and the amount of exhalation that it could spread into space.

Even though, Newton did not have precise data about the dimensions of a comet comparable to available knowledge about the planets. However, it seems that the main difficulty that prevented Newton from establishing the cosmic role of comets in detail was his uncertainty about the nature of comets. Although Newton categorized comets as planets, he attributed some properties to them that, as explained above, were not compatible with the known physics of ordinary matter in the planets. Newton's comet in the *Principia* fails to obey the rules proposed in the *Opticks*.

This aspect of Newton's theory of comets has been neglected in most studies related to the cosmic roles of comets. Newton, to find an answer for the problem of instability of the world that had been established mathematically, proposed a theory incoherent in its physical bases but plausible in its theological and teleological aspects. Newton did not change the published version of his theory of comets in the third edition of the *Principia* (1726), but he was mentally engaged the issue till the end of his life. His reluctance to publish his conjectures about the cosmic role of comets can be interpreted as an indication that he had realized the incompleteness or inconsistency of his theory.

Inconsistencies in Newton's theory of comets immediately led to the development of new cometary theories. As we shall see in the next chapter, post-Newtonian cometary theories were influenced chiefly by major studies concerning electricity, ether and imponderable fluids, and the dynamics of the solar system. While attribution of cometary tails to the newly discovered phenomena of electrical effluvia remained in the realm of physics, theories related to ether and the stability of the world were the subjects of philosophical and theological debates. Meanwhile, the study of perturbations in the solar system, which was a very young subject in Newton's time, was developed as a highly mathematized branch of celestial dynamics and prepared a quantitative ground for philosophical debates concerning the stability of the solar system.

The problem of stability was handled in different patterns in England and the Continent and consequently two varieties of cometary theory developed in the remainder of the eighteenth century in Europe. While British scholars followed Newton's principles of natural philosophy, the Continental philosophers (especially in France) continued with a purely mechanistic philosophy and argued against the so-called occult qualities reintroduced by Newton. Consequently, the new physical theories of comets were highly influenced by these philosophical reflections.

Chapter 5
After Newton

Newton's scientific and philosophical legacy laid the foundation of a tradition in natural philosophy that became the most accepted way of exploring the universe in the eighteenth and nineteenth centuries. This wide acceptance of Newtonianism, however, did not mean that all parts of Newton's philosophy were clearly comprehended, rather there were enough ambiguities and inconsistencies in his works to cause the emergence of different schools or traditions of Newtonian philosophy.

During Newton's lifetime and after his death, many publications in physics, astronomy, and philosophy appeared with subtitles such as "demonstrated upon the mathematical principles of Sir Isaac Newton," or "deduced from Sir Isaac Newton's philosophy," in which the authors attempted to interpret natural phenomena according to their understandings of Newton's works. Based on various approaches to interpret the "Newtonian Philosophy," as I. B. Cohen classified them, five different meanings of Newtonianism appeared among the followers of Newton.[299]

The first of these, emphasizing Newton's corpuscular philosophy, considered Newtonian philosophy in contrast with the corpuscular thought of Descartes, the Peripatetics, and the ancient philosophers. The second focused on Newton's method of reasoning and the way he attained conclusions directly from phenomena. The third restricted Newton's philosophy to the mechanical and mathematical philosophy. The fourth restricted Newtonian philosophy only to that part of physics handled by Newton; and finally, the fifth found the core of Newtonian philosophy in book three of the *Principia*, where Newton founded the principles of the new system of the world. Consequently, in the post-Newtonian cometary literature, Newton's theory of comets was explained from different perspectives, in which some aspects of the original theory were highlighted, ignored or criticized. There also appeared several non-Newtonian theories of comets which were developed either by Cartesians or by Newtonians who found serious difficulties in Newton's theory of comets.

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[299] I. Bernard Cohen, *Franklin and Newton, An Inquiry into Speculative Newtonian Experimental Science and Franklin's Work in Electricity as an Example Thereof* (Philadelphia: The American Philosophical Society, 1956), pp. 179–181.

T. Heidarzadeh, *A History of Physical Theories of Comets,*
From Aristotle to Whipple,

However, what made the post-Newtonian theories of comets distinctive, at least for about a century,[300] was the introduction of the *physics* of comets as an independent subject of study. By the mid-eighteenth century, there were scientists who developed theories about comets' constitution, atmospheres and tail formation without including their orbital properties; and on the contrary, there were cometary orbit calculators for whom consideration of the physical aspects of comets was not a priority. The emergence of the notion of the universality of physical laws, on the one hand, and treatment of comets as planets, on the other hand, created an encouraging climate to develop cometary theories based on terrestrial knowledge and experiences. The climax of this new science of comets was the electrical theory of cometary tails, which was developed by theorizing about the phenomenon of the Aurora Borealis as an electric luminescence and the generalization of this account to cometary atmospheres.

The post-Newtonian theories of comets were mostly affected by studies in three major fields: the ethereal medium, electricity and celestial mechanics. These three fields, in spite of their apparent divergence, were related to each other in one essential aspect. Any theory of the ether should explain action-at-distance phenomena, such as electricity and gravity. At the same time, any definition of the ethereal medium should answer questions arising from the enduring motion of celestial bodies in such a medium.

Although Newton's theory of comets did not employ any electrical concept in describing cometary phenomena and therefore was not affected directly by studies in electricity, it was susceptible to new theories of ether. The behavior of a comet's atmosphere and tail in Newton's theory was explained by the interaction between the ethereal and cometary particles. Thus, in any new definition of the ether and imponderables, the Newtonian interpretation of tail formation should be recast.

Newton's definition of the ether was ambiguous. Newton developed several theories of ether (a few of them incomplete), but left all of them without adequate details.[301] Based on his definition in the second edition of the *Opticks* (1717) ether consisted of subtle particles that repelled each other and also were repelled by the particles of gross matter: the first kind of repulsion explained the elasticity of the ether, and the second elucidated the phenomenon of gravitational attraction. Newton also introduced the ether as an active principle. However, the ether, which was assumed to be composed of particles of matter, should fall under the category of passive principles.[302]

Newton's theory of ether, in spite of holding these confusing aspects, was not challenged seriously by the 1740s. However, developments in electrical experiments (which caused an intensive interest in explaining the attractive and impulsive forces, and the balance between them in nature), studies in the nature of fire (by

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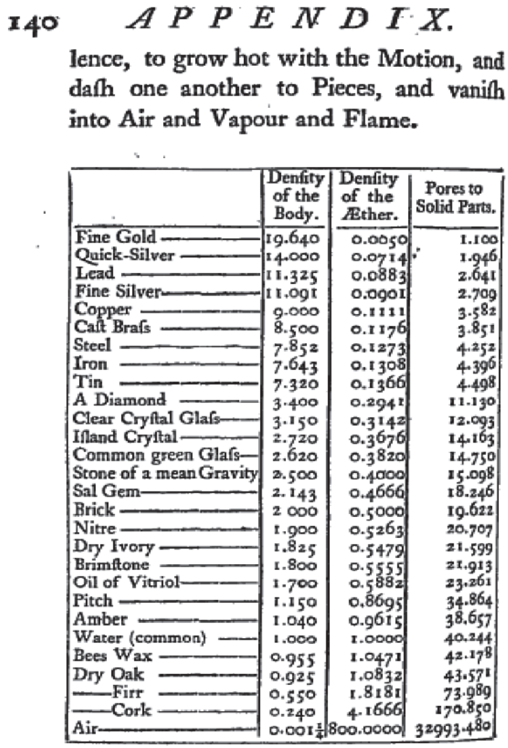
[300] In the late eighteenth century, calculation of the gravitational effects of comets on planets revealed the minimal role of comets in developing planetary perturbations, which meant a typical comet's mass was very much smaller than had been previously assumed. Therefore, studying the orbital properties of comets opened a new window to see their physical characteristics. See Chapter 6.

[301] Cantor and Hodge, "Introduction," p. 19; Betty Jo Teeter Dobbs, *The Janus Faces of Genius, The Role of Alchemy in Newton's Thought* (Cambridge: Cambridge University Press, 1991), pp. 185–187.

[302] P. M. Heimann, "Ether and imponderables," in *Conceptions of ether, Studies in the history of ether theories*, 1740–1900 (Cambridge: Cambridge University Press, 1981), p. 66.



140 *APPENDIX.*

lence, to grow hot with the Motion, and daſh one another to Pieces, and vaniſh into Air and Vapour and Flame.

	Denſity of the Body.	Denſity of the Æther.	Pores to Solid Parts.
Fine Gold	19.640	0.0050	1.100
Quick-Silver	14.000	0.0714	1.946
Lead	11.325	0.0883	2.641
Fine Silver	11.091	0.0901	2.709
Copper	9.000	0.1111	3.582
Caſt Braſs	8.500	0.1176	3.851
Steel	7.852	0.1273	4.252
Iron	7.643	0.1308	4.396
Tin	7.320	0.1366	4.498
A Diamond	3.400	0.2941	11.130
Clear Cryſtal Glaſs	3.150	0.3142	12.093
Iſland Cryſtal	2.720	0.3676	14.163
Common green Glaſs	2.620	0.3820	14.750
Stone of a mean Gravity	2.500	0.4000	15.098
Sal Gem	2.143	0.4666	18.246
Brick	2 000	0.5000	19.622
Nitre	1.900	0.5263	20.707
Dry Ivory	1.825	0.5479	21.599
Brimſtone	1.800	0.5555	21.913
Oil of Vitriol	1.700	0.5882	23.261
Pitch	1.150	0.8695	34.864
Amber	1.040	0.9615	38.657
Water (common)	1.000	1.0000	40.244
Bees Wax	0.955	1.0471	42.178
Dry Oak	0.925	1.0832	43.571
——Firr	0.550	1.8181	73.989
——Cork	0.240	4.1666	170.850
Air	0.001¼	800.0000	32993.480

Fig. 5.1 A page from Robinson's *Dissertation on the Æther of Sir Isaac Newton* (Dublin:1743). Robinson tries to mathematize his theory of ether by calculating the density of substances, the various densities of ether and the size of pores of material. Based on these calculations, he concludes that "the great Porosity of Bodies […] will allow sufficient room within the electrick Vapour to pass freely through them." (p. 139)

Boerhaave[303]), publication of Bryan Robinson's *Dissertation on the aether of Sir Isaac Newton* (1732),[304] and publication of Newton's unpublished letters about the ether to Boyle and Oldenberg in 1744 caused a renewed interest in ethereal studies in the 1740s (Fig. 5.1). Consequently, diverse theories of ether and imponderables

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[303] Herman Boerhaave (1668–1738), a Dutch physician and chemist, developed a theory of fire in which the particles of fire were assumed to be active elements, the cause of chemical changes, space-pervading, penetrating all solid and fluid bodies and not subject to the laws of gravity. This theory was compatible with Stahl's phlogiston theory and had major influence on succeeding theories of heat and electricity. Boerhaave's *Elementa chemiae* (1732) was translated into English by Dallowe in 1735 and Peter Shaw (with explanatory footnotes) in 1741. See Ibid., p. 69.

[304] Bryan Robinson of Dublin published his studies on ether in a systematic way from 1732 and investigating Newton's writings about the ether, showed the inconsistencies of his theory of ether. See: Cohen, *Franklin and Newton*, pp. 418–423; Rupert Hall shows Robinson's erroneous understanding of some aspects of Newton's ether. See: A. Rupert Hall, Marie Boas Hall, "Newton's Theory of Matter," *Isis* 51(1960), 135.

developed that attempted to explain gravity, electrical attraction and repulsion, electric atmospheres, heat transfer, light propagation, and magnetism.

By the end of the eighteenth century, however, a tendency to unify all kinds of ether under a single concept had come to prevail. In this regard, studies in electricity played a leading role. On the one hand, great discoveries about the production, preservation, measurement, and transfer of electricity made electrical studies the most probable vehicle to discover the nature of imponderables. On the other hand, the discovery of a connection between luminescence and electricity, and unity of electricity and lightning, led to a recognition of electricity as one of the most powerful agents in nature, an agent which could be responsible for several atmospheric and planetary phenomena. At the threshold of the nineteenth century, one of the most accepted theories of cometary tails was based on the function of the so called "electric matter."

In parallel to studies about the physics of cometary phenomena, an enduring investigation of planetary motions was continuing to look for any trace of perturbation due to gravitational interactions between the primary planets, and between planets and comets. This field of study not only needed precise observational devices to detect very small changes in position of the planets and comets, it also required elaborated mathematical tools to predict the theoretical positions and analyze the observational data. While improvements in designing and manufacturing the micrometer increased the accuracy of positional observations to ½″ by the late eighteenth century,[305] the innovative mathematical procedures of Euler, Lagrange, and Laplace opened a new era in the field of orbit determination.

As stated above, the post-Newtonian physical theories of comets can be divided into the two main categories of Newtonian and non-Newtonian theories. In the first category, one can find theories that are mainly based on Newton's description of comets but with different interpretations of the basic elements of Newton's theory. Among them are also theories that do not have considerable differences with Newton's theory, but contain conclusions that Newton's published theory of comets did not cover. The theories of William Whiston and Edmund Halley about the Deluge and the history of the earth are among the latter group.

The second category can be divided into two subcategories of non-electrical and electrical theories. In the first group there are theories that mainly use Newtonian or Cartesian concepts to develop non-Newtonian theories of the formation and orientation of cometary tails (for instance, the theories of Rowning or Euler). In the second group, the whole phenomena of cometary tails, their formation, radiation and changes are explained based on the newly developed theories of electricity.

In the next part, we shall first discuss the post-Newtonian theories of comets in chronological order. This part will consider modified versions of Newton's theory,

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[305] Chapman, "The accuracy of angular measuring instruments," p. 135. John Smeaton (1724–1792) and Jesse Ramsden (1731–1800) were two leading designers of micrometers in the second half of the eighteenth century. In Smeaton's micrometer, the screws could move the pointing wires by an accuracy of about 1/2,300 inch. See: Randall C. Brooks, "The Development of Micrometers in the Seventeenth, Eighteenth and Nineteenth Centuries," *Journal of History of Astronomy* 22(1991), 149.

as well as expository works which have information not found in Newton's published works. The works of those Newtonians who just presented a summary of Newton's theory without expressing any different idea (such as the works of J. T. Desaguliers or Willem 'sGravesande)[306] will not be included.

The Post-Newtonian Newtonian Theories of Comets

William Whiston and Edmund Halley

William Whiston (1667–1752), Newton's successor as Lucasian Professor at Cambridge University, developed a theory of earth in which comets had the major role. Whiston in his *A New Theory of the Earth* (1696), which saw several editions published by the mid eighteenth century, proposed a theory in which comets and planets were interchangeable. Although Whiston's theory was basically about the formation and history of the earth, the role of comets was central: The earth was originally a comet; all dynamical and structural changes of the earth were caused by the impulses of comets; and the earth could change its orbit to an elongated ellipse and become a comet by the close approach of another comet. These ideas were generally compatible with Newton's unpublished doctrine of transformation of satellites to planets and planets to comets, and was also very close to Halley's theory about the cause of the Deluge and succession of worlds.

According to Whiston, the close approach of a comet on November 28, 2349 B.C. (in the Hebrew calendar) was responsible for the Biblical Deluge.[307] Based on his descriptions, a typical comet has a nucleus of about 7,000 to 8,000 miles in

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[306] Willem Jacob van 'sGravesande (1688–1742), professor of mathematics and astronomy at Leiden, was one of the first Newtonians who developed a new educational trend in teaching Newton's physics based on experimental courses and illustrating the applications of physical laws in technology and everyday life. His text book in physics entitled *Mathematical Elements of Natural Philosophy Confirmed by Experiments, or An Introduction to Sir Isaac Newton's Philosophy* was translated from its original Latin into English by Jean Theophile Desaguliers (1683–1744) and published in six editions by mid-century. Desaguliers also was one the leading figures in publicizing Newton's physics by performing public lectures and demonstrating experiments. Desaguliers' *A Course of Experimental Philosophy* (1734) and *A Course of Mechanical and Experimental Philosophy, whereby anyone, although unskill'd in Mathematical Sciences, may be able to understand all those Phænomena of Nature, which have been discovered by Geometrical principles* (1725) were popular works on Newton's physics which were published in several editions. Neither Gravesande nor Desaguliers proposed a new theory of comets, nor did they popularize a modified version of Newton's theory of comets. Their account of comets is a brief summary of Newton's theory of comets. See: T. J. Desaguliers, *A Course of Experimental Philosophy* (London, 1734), pp. 409–417; William Jacob van 'sGravesande, *An Explanation of the Newtonian Philosophy* (London, 1735), p. 391; *idem, Mathematical Elements of Natural Philosophy*, 2 vols. (London, 1474), vol. 2, pp. 284, 346.

[307] For Whiston's theory of the earth and his ideas on the universal deluge see: William Whiston, *A New Theory of Earth, from its Original, to the Consummation of all Things. Wherein the*

diameter surrounded by an atmosphere with a diameter of about 100,000 miles. The nucleus of a comet is compact, dense and almost as large as the earth. However, a planet like the earth, according to Whiston, has a smaller core surrounded by a shell of water and covered by a solid crust (Fig. 5.2). Thus, the mean density of a comet is higher than that of the earth and consequently may exert stronger gravitational effects on a planet like the earth. Therefore, when a comet approaches the earth, the latter undergoes severe orbital and structural changes.[308]

As Whiston describes, the atmosphere of a comet not only consists of vapor, it also has great quantities of "opake or earthy Particles, most of them in probability towards

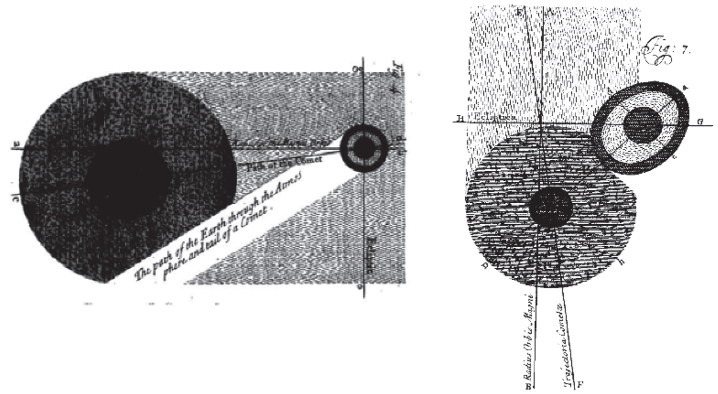

Fig. 5.2 The earth passing through the watery atmosphere and tail of a comet (left). In a closer approach (right), the strong gravitational attraction of the comet distorts the spherical shape of the earth into an ellipsoid. As a result, the outer crust of the earth cracks and releases the subterranean water or "Fountains of the great Deep." From Whiston's *A New Theory of the Earth*, 1755

Creation of the World in Six Days, The Universal deluge, And the General Conflagration, As laid down in the Holy Scriptures, Are Shewn to be perfectly agreeable to Reason and Philosophy. with a large Introductory Discourse concerning the Genuine Nature, Stile, and Extent of the Mosaick History of the Creation (London, 1669), pp. 231–370; Whiston prepared a summary of his theory and published it as an appendix to the sixth edition of *A New Theory of Earth* (London, 1755), pp. 459–478; Kerry V. Magruder, "Theories of the Earth from Descartes to Cuvier: Natural Order and Historical Contingency in a Contested Textual Tradition" (Ph.D. diss., University of Oklahoma, Norman, 2000), pp. 578–590; Schechner, *Comets, Popular Culture*, pp. 189–195; James E. Force, *William Whiston: Honest Newtonian* (Cambridge: Cambridge University Press), pp. 32–61.

[308] Based on Whiston's writings, Magruder summarized the effects of past cometary impacts in four categories. The following is a rewriting of a where he presented those effects: (1) Creation: Earth's watery chaos, from which proceeded the events of the creation week, derived from a comet (no impact; it moved into a regular annual motion; 1 day = 1 year; Edenic conditions of perpetual equinox); (2)Fall: Shock of impact produced daily motion; days shortened to twenty-four hours; Rotational axis inclined to the Sun; Eden replaced by tropical zones as seasons belong; Earth became an oblate spheroid from stress of rotation; created fissures in outer crust; (3) Deluge: The watery head of an approaching comet provided the "windows of heaven," sources of deluge waters; Gravitational tidal forces shattered already cracked crust of Earth, releasing the "fountains of the deep;" Orbit of Earth altered from circular form to an ellipse, increasing the length of a year by ten days; and (4) Conflagration: A fiery comet receding from the Sun will engulf the Earth. See Magruder, "Theories of the Earth," p. 587.

the central Solid [the nucleus], while the lightest and rarest, as Vapours, are most of them towards the Circumference or Parts remotest from the central Solid."[309] Thus, the outer part of the coma, from which a tail is emerging, is vapor in its rarest density. When a comet approaches the sun, the sun's heat makes this vapor highly rarified. Whiston is not explicit about whether it is the reflection of light or some other process that makes the vapor hot and rarified. However, contrary to Newton's theory, it is not the receding ethereal particles that carry along the cometary particles:

> […] the lightest and rarest Parts of its [comet's] Atmosphere rarified by the Sun's Heat; which becoming thereby, if not specifically lighter than the *Æther*, or Atmosphere encompassing the Sun, yet at least so rare and light, as to yield to the Sun's Rays, and to be carry'd away by them, and so rise in a Mist or Steam of Vapours towards the Parts opposite to the Sun; and this is call'd the *Tail* of it.[310]

Whiston, like Kepler, attributed the expansion of the tail to the pressure that the sun's rays could exert on the rarified particles. Although Whiston did not develop a new theory of the ether, his adoption of Keplerian theory of tail formation indicates that he found Newton's interpretation of tail formation inadequate.

For Whiston the constitution of cometary atmospheres is completely different from what we find on the earth. Whiston comes to this conclusion assuming that despite the great amount of heat a typical comet can absorb[311] (as Newton calculated for the comet of 1680), only a small part of its atmosphere turns into a tail. Although Newton, based on Hevelius' observations, claimed that a comet's coma diminishes in the vicinity of its perihelion,[312] Whiston, without referring to any observational data, states that the coma of a comet undergoes a small diminution as its tail grows to its largest extension:

> Whereas the Atmosphere of a Comet is chiefly a Fluid, and yet but a small Part thereof by the utmost Heat capable of Rarefaction (which appears from the but small Diminution of the Atmosphere when the Tail is largest, and the Heat most intense) 'tis evident that its Fluid is a very different one from those we are here acquainted withal. For since the main Bulk thereof retains its Constitution and Situation quite through the Action of the most violent Heat imaginable; which would dissipate and rarefy all the Watery, and perhaps Earthy Parts visible with us; it must by its mighty Density, Gravity, Compactness, or some other property not belonging to Fluids here on Earth, be uncapable of greater Expansion than it has of it self, and be a compact, dense, or heavy Fluid […] for which we have no proper Epithet or Name among us.[313]

However, these unknown conditions and compounds are the consequences of a comet's encounter with the sun. Whiston's point is that the 'chemistry' of a comet

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[309] Whiston, *A New Theory of the Earth*, 6 ed., pp. 50–51.

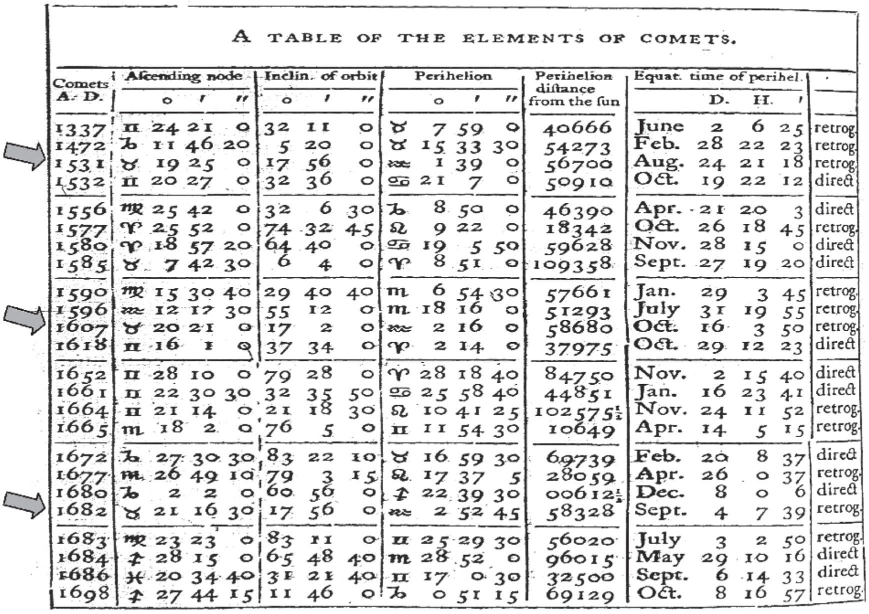
[310] Ibid., p. 52.

[311] Whiston makes a minor mistake in calculating the cooling time of a comet as big as the earth and composed of iron. According to Newton, if such a globe were heated as hot as red hot iron, it would take 50,000 years for it to cool off. However, since the comet absorbed 2,000 times more heat than red hot iron, the cooling time would be about 100,000,000 years. Whiston takes the cooling time of the comet to be only 50,000 years. See Ibid., 53.

[312] Newton, *Principia*, pp. 926–927.

[313] Whiston, *A New Theory of the Earth*, 6th ed., pp. 54.

Table 5.1 The similarity of orbital elements of the comets of 1531, 1607, and 1682 indicated that all of them were a single comet with a period of revolution of about seventy-five years. (From Edmund Halley's *A Synopsis of the Astronomy of Comets* (London: 1705))



A TABLE OF THE ELEMENTS OF COMETS.

Comets A.D.	Aſcending node				Inclin. of orbit			Perihelion				Perihelion diſtance from the ſun	Equat. time of perihel.				
		°	′	″	°	′	″		°	′	″			D.	H.	′	
1337	♊	24	21	0	32	11	0	♉	7	59	0	40666	June	2	6	25	retrog.
1472	♑	11	46	20	5	20	0	♉	15	33	30	54273	Feb.	28	22	23	retrog.
1531	♉	19	25	0	17	56	0	♒	1	39	0	56700	Aug.	24	21	18	retrog.
1532	♊	20	27	0	32	36	0	♋	21	7	0	50910	Oct.	19	22	12	direct
1556	♍	25	42	0	32	6	30	♑	8	50	0	46390	Apr.	21	20	3	direct
1577	♈	25	52	0	74	32	45	♌	9	22	0	18342	Oct.	26	18	45	retrog.
1580	♈	18	57	20	64	40	0	♋	19	5	50	59628	Nov.	28	15	0	direct
1585	♉	7	42	30	6	4	0	♈	8	51	0	109358	Sept.	27	19	20	direct
1590	♍	15	30	40	29	40	40	♏	6	54	30	57661	Jan.	29	3	45	retrog.
1596	♒	12	12	30	55	12	0	♏	18	16	0	51293	July	31	19	55	retrog.
1607	♉	20	21	0	17	2	0	♒	2	16	0	58680	Oct.	16	3	50	retrog.
1618	♊	16	1	0	37	34	0	♈	2	14	0	37975	Oct.	29	12	23	direct
1652	♊	28	10	0	79	28	0	♈	28	18	40	84750	Nov.	2	15	40	direct
1661	♊	22	30	30	32	35	50	♋	25	58	40	44851	Jan.	16	23	41	direct
1664	♊	21	14	0	21	18	30	♌	10	41	25	102575½	Nov.	24	11	52	retrog.
1665	♏	18	2	0	76	5	0	♊	11	54	30	10649	Apr.	14	5	15	retrog.
1672	♑	27	30	30	83	22	10	♉	16	59	30	69739	Feb.	20	8	37	direct
1677	♏	26	49	10	79	3	15	♌	17	37	5	28059	Apr.	26	0	37	retrog.
1680	♑	2	2	0	60	56	0	♐	22	39	30	00612½	Dec.	8	0	6	direct
1682	♉	21	16	30	17	56	0	♒	2	52	45	58328	Sept.	4	7	39	retrog.
1683	♍	23	23	0	83	11	0	♊	25	29	30	56020	July	3	2	50	retrog.
1684	♐	28	15	0	65	48	40	♏	28	52	0	96015	May	29	10	16	direct
1686	♓	20	34	40	31	21	40	♊	17	0	30	32500	Sept.	6	14	33	direct
1698	♐	27	44	15	11	46	0	♑	0	51	15	69129	Oct.	8	16	57	retrog.

changes after the perihelion. While before the perihelion, the tail of a comet is composed of pure vapor, it will be contaminated after the perihelion by gross materials and exhalations produced by the intense heat of the sun. According to Whiston, the heat in the perihelion is sufficient to dissolve and rarify "not Vapours alone, but Sulphur, Nitre, Coal, or other gross and earthy Steams and Exhalations."[314]

Whiston then examines the possibility of diurnal rotation in comets, a question which was left open by Newton. Finding any evidence to verify such motion was a step forward in making comets more similar to the planets. However, Whiston does not acknowledge that even the planets have had axial rotation from the beginning. Our earth, for instance, started spinning due to the impulse of a comet which at the same time tilted its rotational axis. Similarly, comets do not perform axial motion. Whiston deduces this result from the symmetrical shape of cometary heads: since the coma of a comet is composed of fluids, any rotation would give the coma the shape of an oblate spheroid.[315]

Perhaps the core innovative idea in Whiston's theory, regarding the physics of comets, is the *cyclic* transformation of planetary bodies. In Descartes' theory, a

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[314] Ibid. Obviously, if the earth would pass through the tail of a comet before its perihelion, the pure vapor of the tail would cause heavy watery rains.

[315] Ibid., pp. 55–56. Although Whiston's reasoning is interesting, it has to be noted that the shape of a rotating coma would be determined by its angular speed. Therefore, it is possible that a comet might rotate with a low speed (like the moon which its axial rotation and orbital revolution take place in the same interval of time) and sustain a symmetrical shape.

dead star, depending on the agitation it might acquire from the particles of a vortex (which, in turn, was determined by its solidness), could be a planet or a comet. Newton's comet, which is formed from condensed solar material, after performing a number of revolutions around the sun would fall on the sun and replenish the central star. However, in Whiston's thesis a comet can be restrained in an orbit with small eccentricity and revolve around the sun as a planet or the disturbance created by a comet in the orbit of a stable planet can eject the planet in an elongated orbit and turn it to a comet. Under the physical conditions of the adopted orbit, the constitution and structure of the body are modified accordingly.

These drastic changes in physical and chemical conditions of comets make them unsuitable places to sustain vegetation or animal life. Meditation about the possibility of existence of life in other planets, which had its roots in medieval times, became one of the most attractive issues in the astronomy and philosophy of the seventeenth century,[316]and Whiston was one of the first scholars who wrote about the possibility of life on comets. While a comet is moving on an eccentric orbit, it is uninhabitable, unless for a "State of Punishment for their Inhabitants," but when its orbit is changed into that of a planet the circumstances will change.[317]

The foundations of Whiston's theory of cometary impacts had already been stated by Edmund Halley (1656–1743). Although Halley did not develop a theory about the physics of comets, his discovery of periodicity of comets opened a new era in the history of cosmetology.[318] Halley found that the orbital elements of comets can be

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[316] A number of late medieval scholars, among them William of Ockham, Walter Burley, John of Bassols, St. Bonaventure and Francis Mayron, rejecting Aristotle's doctrine, stated that God could create more than one world. This idea later – specially after the introduction of the heliocentric systems – was developed as a theory which admitted the possibility of inhabited planets existing in the solar system as well as other systems. One of the first treatises about this topic was written by Pierre Borel (1620?–1671) entitled *A New Treatise Proving a Multiplicity of Worlds …* (London: 1658). Bernard Le Bovier Fontenelle (1657–1757) also wrote a similar book with the title of *Entretiens sur la pluralité des mondes* (Paris, 1688; its English translation published in London in 1700), and Christian Huygens tried to prove that there were 'animate creatures' in the planets. The issue, from the late seventeenth century, became one of the most interesting chapters of several astronomical books, encyclopedias, as well as some philosophical texts. See: Pierre Duhem, *Medieval Cosmology: Theories of Infinity, Place, Time, Void, and the Plurality of worlds*, Roger Ariew (eds. & trans.) (Chicago: Chicago University Press, 1985); Grant McColley, H. W. Miller, "Saint Bonaventure, Francis Mayron, William Vorilong and the Doctrine of a Plurality of Worlds," *Speculum* 12 (1937), 386–389, Frank J. Tipler, "A Brief History of the Extraterrestrial Intelligence Concept," *Quarterly Journal of Royal Astronomical Society* 22 (1982), 133–145; Steven J. Dick, *Plurality of Worlds: The Origin of the extra terrestrial life from Democritus to Kant* (Cambridge: Cambridge University Press: 1982); Michael J. Crowe, *The Extraterrestrial Life Debate, 1750–1900: The Idea of a Plurality of Worlds from Kant to Lowell* (Cambridge: Cambridge University Press, 1986), pp. 3–41, 41–81.

[317] Whiston, *A New Theory of the Earth*, 6th ed., pp. 51.

[318] For Halley's works on cometary orbits see: David W. Hughes, "Edmund Halley: His Interest in Comets," in Norman J. W. Thrower (ed.), *Standing on the Shoulders of Giants*, pp. 324–372; *Idem*, "Edmund Halley: Why was he interested in comets?" *Journal of the British Interplanetary Society* 37 (1984), 32–44; D. W. Hughes and A. Drummond, "Edmund Halley's Observations of Halley's Comet," *Journal for the History of Astronomy* 15 (1984), 189–107; Donald K. Yeomans et al., "The History of Comet Halley," *Journal of the Royal Astronomical Society of Canada* 80 (1986), 62–86.

used as reliable criteria to identify them, and comets with identical (or very similar) elements of orbits[319] actually are a single comet which has been observed in its different apparitions. Consequently, by comparison of the orbital elements of 24 well-observed comets he discovered that the comet of 1682 was periodical.

Halley, at the same time, was interested in the history of the earth. Referring to discovery of the remnants of marine animals at the top of hills or in the deserts or deep underground, he believed that the earth had encountered some drastic changes. However, whether those changes resulted from a catastrophic event (like the Deluge) or happened gradually, and whether they were performed directly by God's will or through a natural process, were fundamental questions. Halley believed that the Creator accomplished the changes without any previous warning through the function of natural means.[320]

For Halley, the Biblical Deluge, which caused devastating changes on the earth, was triggered by a transient body such as a comet.[321] To explain the magnetic

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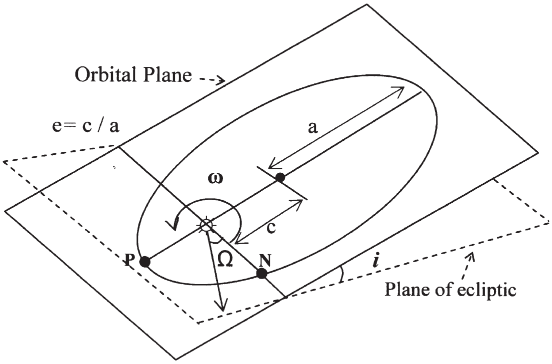
[319] Orbital elements are parameters that specify the position and motion of a celestial body in its orbit: the eccentricity, e, specifies the shape and size of an elliptical orbit; the orientation of the orbit in the space is determined by the inclination of the orbital plane, i (usually regarding to the plane of the ecliptic) and the longitude of the ascending node, Ω (the angular distance from the vernal equinox, γ, to the ascending node, N. The orientation of the orbit in its orbital plane is identified by the angular distance, ω, between the periapsis, P, and the ascending node, Ω. See: Valerie Illingworth, *Macmillan Dictionary of Astronomy* (London: 1985), p. 263 (diagram is adopted from the same).



[320] For Halley's cosmological ideas see: Simon Schaffer, "Halley's Atheism and the End of the World," *Notes and Records of the Royal Society of London* 32 (1977), 17–40; Schechner Genuth, *Comets, Popular Culture*, pp. 156–177; *idem*, "Newton and the Ongoing Teleological Role of the Comets," in Norman J. W. Thrower (ed.), *Standing on the Shoulders of Giants*, pp. 299–311; David Kubrin, "Such an Impertinently Litigious Lady": Hooke's "Great Pretending" vs. Newton's *Principia* and Newton's and Halley's Theory of Comets," *Ibid*, pp. 55–90.

[321] Edmund Halley, "An Account of Some Observations Lately Made at Nurenburg by Mr. P. Wurtzelbaur, Shewing That the Latitude of That Place Has Continued without Sensible Alteration for 200 Years Last Past; as Likewise the Obliquity of the Ecliptick; By Comparing Them with what Was Observed by Bernard Walther in the Year 1487, being a Discourse Read before the Royal Society in One of Our Late Meetings," *Philosophical Transactions*, 16 (1686–1692), 403–406, esp. p. 406.

properties of the earth, he theorized that the earth was not a completely solid globe but that its internal structure consisted of four shells (one core and three concentric shells) with hollow spaces in between.[322] A cometary impact can collapse the upper layers of the earth and bury them in the deep parts of the earth, while the upper parts would be re-formed from the lighter soil.

Halley published his ideas earlier than Whiston,.[323] however, Whiston's approach to the possible consequences of a cometary impact was different. Setting aside the religious premises in their writings, one can find that Whiston, using a methodology like Newton in the *Principia*, was more successful in developing a comprehensive theory of comets and the earth. Whiston's theory illustrates many details of comets including their physical and chemical constitution, their diurnal motion, and the influence of solar heat on their chemistry before and after their perihelia.

David Gregory

David Gregory devoted the fifth book of his *Elements of Physical and Geometrical Astronomy* (1726) to comets. Although Gregory essentially interprets Newton's theory of comets and never suggests a theory of his own, his detailed description of some physical aspects of comets makes his work more useful than Newton's. Gregory starts his account of comets by revealing an interesting point about the differences between comets. Declaring that he is dealing with astronomy and not astrology in his book, Gregory states that there is only one kind of comet "which have those different appearances, according to the Difference of the Vapours which make their Tails, and different Situation of the Comet itself in respect to the Sun."[324] Neither in the *Principia* nor in the *Opticks* had Newton mentioned that comets were different due the type of their vapors. Gregory does not tell us whether he obtained these cometary ideas through his communication with Newton or if he just states his own meditations.

Gregory, after giving a brief account of theories of cometary tails from Aristotle to his time, deliberates about Newton's theory of tail formation. He states that a comet is encompassed in a great quantity of vapors that is condensed when the comet is far from its perihelion and therefore is in the coldest parts of the solar system. Gregory, like Newton, ascribes the extension of the tail to the function of

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[322] One of the reasons that Halley deduced a hollow earth was Newton's calculation of a higher density for the moon. See: N. Kollerstrom, "The Hollow World of Edmund Halley," *Journal for the History of Astronomy* 23 (1992), 185–192; Conway Zirkle, "The Theory of Concentric Spheres: Edmund Halley, Cotton Mather, & John Cleves Symmes," *Isis* 37 (1947), 155–159; For Halley's magnetic theory of the earth see: Edmund Halley, "An Account of the cause of the Change of the Variation of the Magnetical Needle; with an Hypothesis of the Structure of the Internal parts of the Earth: as it was proposed to the Royal Society in one of their late meetings," *Philosophical Transactions of the Royal Society of London* 16 (1691), 563–578; Magruder, "Theories of the Earth," pp. 626–635.

[323] For Halley's priority see: Kubrin, "Such an Impertinently Litigious Lady," pp. 71–73.

[324] Gregory, *Elements*, vol. 2, pp. 693–694.

heated ethereal particles, but, diverging from Newton's theory, he also assigns a pushing role to the solar rays:

> But because beyond the Atmosphere of the Comet the æthereal Aura is very rare and next to nothing, or a Vacuum, therefore I shall attribute something to the Action of the Rays of the Sun, carrying along with it the Particles of the Atmosphere of a Comet, tho' *Kepler* is not of this Opinion;"[325]

No doubt the idea of the 'pressure' of the sun's rays was Kepler's. It seems that Gregory believes that the highly rarified ether beyond the comet makes the weak impetus of the solar rays demonstrate their full effects.

Gregory, like Newton, believes that the tail is very rare and a small amount of exhalation can produce a very extensive tail.[326] However, when he investigates the possible effects of a cometary tail touching our atmosphere, he expects drastic changes for life on the earth:

> […] if the Tail of a Comet shou'd touch the Atmosphere of our Earth, […] the exhalation of it mix'd with our Atmosphere […] may cause very sensible Changes in our Air, especially in Animals and Vegetables: For Vapours, as they call 'em, brought from strange and distant Regions, and excited by a very intense. Heat, may be prejudicial to the Inhabitants or Products of the Earth[327];

This statement, however, is based on some contradictory presumptions. How can a very small amount of a very rare exhalation produce such harmful effects? If comets are spreading exhalations that can refresh all planets, why would the vapors from distant parts of the world be destructive for us? Are comets agents to replenish planets physically yet make vegetables and animals on them extinct?

The first question, as was described in the previous chapter, is related to the problem of the quantity of vapor that a typical comet can distribute in the solar system. A memorandum by Gregory reveals that this problem was known to both Newton and Gregory; but they did not publish their ideas:

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[325] Ibid., p. 714. Benjamin Martin (1704?–1782), a well-known popularizer of science and scientific instrument maker, supports the idea of light pressure in his treatise on comets. He refers to several experiments to measure the impulsive force of the sun's rays. In these experiments light bodies were suspended by a fine thread in a place close to the focal point of very large burning glasses, four or five feet in diameter. He observed that those light bodies move back and forth like a pendulum. Although this was not a real measurement of the light pressure (the movement of the light bodies was due to the convection of heated air), scientists believed that the sun's rays could exert stronger pressure on particles in the highly rarified medium of the celestial region, "where the Matter of a Comet's Tail is very fine and liable to be put in Motion with the least Degree of Force, much more by the prodigious Impetus of a Particle of Light moving with a Velocity not to be expres'd or conceiv'd." See: Benjamin Martin, *The Theory of Comets* (London: Printed for the Author, 1757), pp. 10–11.

[326] Gregory, following Newton's calculations in proposition 41 of book 3 of the *Principia*, demonstrates that how a small amount of air can expand in a vast space. He compares the comets tail to "a prodigious Heap of Smoke a small Piece of Wood or Pit-coal is converted;" Ibid., pp. 705–707, 715.

[327] Ibid., p. 716.

> When Mr. Newton says, in his Princip. Philos., that the Tails of the Comets may likely restore the Fluid to the Earth, […] This is not to be understood of the real fluid water so restored, […] but of that subtile Spirit that does turn Solids into Fluids. A very small Aura or particle of this may be able to doe the business.[328]

Therefore, only a small amount of ‘spirit’ is needed to replenish a planet. But, this is completely opposite to the published version of Newton’s cometary theory: Newton emphasizes that cometary vapor falls to “the atmospheres of the planets and there be condensed and converted into water and humid spirits.”[329] In other words, a great amount of rarified vapor has to be condensed to produce a small quantity of water.

Another difficulty in Gregory’s account is related to the function of the cometary exhalations. While Newton’s theory demonstrates an ultimate unity in diversity of chemical compounds in the entire cosmos and attributes any chemically harmful property to cometary vapors, Gregory assumes the vapors of the remote parts of the solar system to be destructive and incompatible with terrestrial substances.

Gregory explains the motion of the tail particles in more detail. The motion of each particle of the tail is a resultant of two motions, one straight away from the sun (the ascending motion of the ether) and the second, a lateral motion, which is the orbital motion of the cometary nucleus. Therefore, the tail never extends directly away from the sun. The tail bends slightly in such a way that, before and after the perihelion, the convexity of the tail is towards the fore part or the direction of progress (Fig. 5.3). Because after the perihelion the ascending speed of the ether is higher (due to the heat that comets absorb) the curvature of the tail is the least. On the other hand, in the vicinity of the perihelion, the extremity of the tail (which is far away from the nucleus) has to describe a greater circumference than the nucleus itself; which causes the motion of the remote parts of the tail to lag behind the faster motion of the nucleus and the tail bends more. Gregory also explains that if the observer were located at the orbital plane of a comet, the tail would not appear curved.[330]

Gregory defines a visibility zone for comets: Comets become visible after passing the orbit of Jupiter. Based on this estimation, Gregory in proposition V of book five of the *Elements*, establishes that “more comets are seen in the hemisphere

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[328] Walter G. Hiscock, ed. *David Gregory, Isaac Newton and Their Circle: Extracts from David Gregory’s Memoranda 1677–1708* (Oxford: by editor, 1937), p. 26.

[329] Newton, *Principia*, p. 938. The same concept is repeated as follows: “and then [the vapor] is by degrees attracted toward the planets by its gravity and mixed with their atmospheres. For just as the seas are absolutely necessary for the constitution of this earth, so that vapors may be abundantly enough aroused from them by the heat of the sun, which vapors either–being gathered into clouds–fall in rains and irrigate and nourish the whole earth for the propagation of veges, or–being condensed in the cold peaks of mountains (as some philosophize with good reason)–run down into springs and rivers; so for the conservation of the seas and fluids on the planets, comets seem to be required, so that from the condensation of their exhalations and vapors, there can be a continual supply and renewal of whatever liquid is consumed by vegetation and putrefaction and converted into dry earth.” Ibid., p. 926.

[330] Gregory, *Elements*, pp. 715–719.

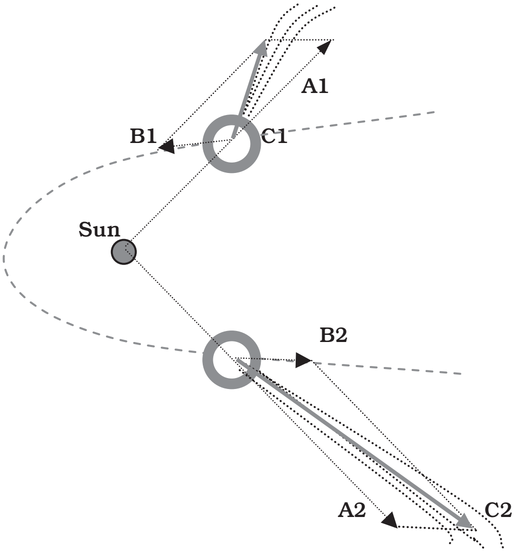

Fig. 5.3 The motion of the particles of a tail can be resolved into two motions. Before the perihelion, the ethereal particles are ascending towards A1 (directly away from the sun) and the nucleus, along its orbit, is moving towards B1. Therefore, the resultant motion, C1, is not directly away from the sun. After the perihelion, C2 is greater than B2, and as a result, the tail bends less. The extremity of the tail is always moving more slowly than the nucleus

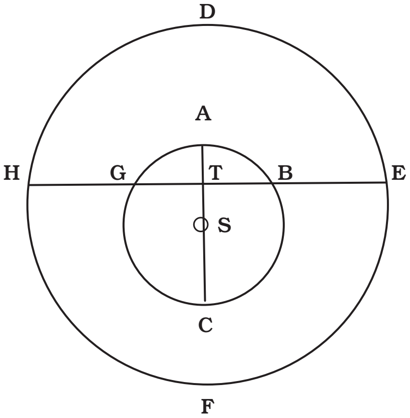

Fig. 5.4 Circle DEFH, centered at T, the earth, is the sphere of the fixed stars. Circle ABCG, centered at S, the sun, is a little less than the orbit of Jupiter. Segment GCB is greater than GAB (Redrawn after Gregory's diagram in: *Elements*, Plate1, Book five, fig. 3, related to page 719)

towards the sun, than in that which is opposite to it." As seen in Fig. 5.4, an observer at T (the earth) will see a comet when it passes the circle ABCG. The observer, who is located at the center of the sphere of the fixed stars, DEFH, is not at the center of the comet's visibility sphere, ABCG. Since the segment GAB is smaller than the segment BCG, more comets can be observed in the latter portion.

Gregory, then, concentrates on techniques of orbit determination and in more than one hundred pages, elucidates the contents of propositions 41 and 42 of book 3 of the *Principia*. An important issue that he points out in his discussion of tables of cometary positions is about the population of comets, which is contrary to

Newton's idea. Gregory believes that "the Number of the Comets is not vastly great: But it is likely that the Periods of some of them are so great, from the immense interval between Saturn, and the nearest Fix'd Stars, that they are not yet descended into the Regions of Planets."[331] This idea is compatible with Gregory's account of Newton's thought about the nature of cometary vapors: if comets only distribute 'spirit' to replenish the planets, then a small number of comets can accomplish the task.

In book VI of the *Elements*, Gregory returns to comets again and describes the 'phenomena' if the observer is supposed to be located on each member of the solar system, including a comet. According to him, comets are chiefly similar to the primary planets, except their orbits are highly elongated. A very thick and dense atmosphere covers a comet, which increases when the comet descends from its aphelion and reaches to the inner parts of the solar system. It is not known whether comets rotate, but since other bodies in the solar system perform rotational motion, it is probable that comets also turn around their axes. However, if the nucleus turns around itself, the outer part of the atmosphere, where the tail is emerging, does not accompany this rotational motion.[332]

In the next part, Gregory articulates his ideas about the cosmological roles of comets. For Gregory (as for Newton) the starting point to attribute a special cosmic role to comets is the peculiarity of cometary orbits:

> As the Way of every Comet about the Sun is a very excenterical Ellipse, it is not likely that they are made to serve the same Purposes in the Universe as Planets, which are carried in Orbits nearly concentric to the Sun, and which seem design'd for production of Things which are almost always to remain in the same State; which Comets are by no Means fit for, by reason of the very different Degrees of that which they sustain.[333]

However, the ambiguity in Gregory's conclusion makes his idea seem incompatible with his ontology of comets. If the things produced in the planets are to remain in a steady state, the need for a revivatory agent is absurd.

Gregory ascribes four roles for comets: their tails serve to renew the fluids of the planets; they fall on the sun to replenish the sun; they may pass near a planet and create such perturbation that the satellite of the planet changes its orbit and becomes a primary planet around the sun; and finally a comet during its close approach to a planet can attract its fluids (which causes great changes such as a deluge) or create other changes in the planet by transferring its immense heat.[334] Gregory, in treating the cosmological role of comets adopts Halley's and Whiston's theories and tries to combine them with Newton's ideas.

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[331] Ibid., p. 804.

[332] Ibid., 851–852.

[333] Ibid., 852.

[334] Ibid., pp. 852–854.

Henry Pemberton

Permberton (1694–1771) was among the three figures that made a popularized version of Newton's ideas available to general readers in the age of Enlightenment.[335] Since he worked closely with Newton to prepare the third edition of the *Principia*, he was in an exceptional position to interpret Newtonian physics.[336] Pemberton began composing his exposition of Newton's philosophy in 1721 or 1722 and published his book in 1728, a year after Newton's death. Pemberton's work covers the main ideas and discoveries stated in the *Opticks* and the *Principia*.

Pemberton calls comets "the third species of the heavenly bodies",[337] which move in very eccentric orbits. Comets are durable, compact, and opaque bodies, shining by the reflection of the sun's rays. Although they are periodic, it is not to be expected that they perform their revolutions regularly. Since their orbits are very elongated, they are liable to be disturbed by the attraction of the planets and other comets.

One of the main differences between comets and planets is the size of their atmospheres. According to Pemberton it is most probable that other planets are engulfed in atmospheres like that of the earth; however, although the atmospheres of the planets are composed of a fine and subtle substance, the atmospheres around the comets are very thick and gross. In addition, the proportion of a comet's atmosphere to its nucleus is much greater than the same proportion in a planet.[338]

Pemberton's idea about the nature of the vapor that exists in cometary tails is very close to the notion that Gregory had reported from Newton, admitting it as a kind of spirit. But, Pemberton, contrary to Gregory, did not find a threatening sign in the tails of comets:

> It is farther our great author's [Newton's] opinion, that the most subtile and active parts of our air, upon which the life of things chiefly depends, is derived to us, and supplied by comets. So far are they from portending any hurt or mischief to us, which the natural fears of men are so apt to suggest from the appearance of any thing uncommon and astonishing.[339]

To answer the question 'why do planets have not tails?' Pemberton admits that the distance of a comet from the sun is not the only cause of the production of the tail. The texture of the cometary vapor is a major factor in the formation of a comet's tail:

> That the tails of comets have some such important use seems reasonable, if we consider, that those bodies do not send out those fumes merely by their near approach to the sun; but are framed of a texture, which disposes them in a particular manner to fume in that fort: for

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[335] The two others were Colin Maclaurin and François Marie Arouet Voltaire, both considered below. See: I. Bernard Cohen's introduction to the reprint edition of: Henry Pemberton, *A view of Sir Isaac Newton's Philosophy* (London, 1728), reprinted by Johnson Reprint Corporation (New York, 1972), p. *v*.

[336] See: A. Rupert Hall, "Newton and His Editors," *Proceedings of Royal Society* 338 (1974), 397–417; Westfall, *Never at Rest*, pp. 798–801.

[337] Pemberton, *A view of Newton's Philosophy*, p. 230.

[338] Ibid., pp. 237–238.

[339] Ibid., 245.

> the earth, without emitting any such steam, is more than half the year at a less distance from the sun, than the comet of 1664 and 1665 approached it, when nearest; likewise the comet of 1682 and 1683 never approached the sun much above a seventh part nearer than Venus, and were more than half as far again from the sun as Mercury; yet all these emitted tails.[340]

Thus, planets are different from comets not only regarding the size and density of their atmospheres, but also in the texture of the vapors they carry. Since the atmospheric vapors and exhalations originate from the body of planets, then Pemberton's statement implies that planets and comets produce two different kinds of exhalations. While Pemberton acknowledges Newton's speculations about the cosmic role of comets, he is reluctant to admit Newton's idea that the sun decays: "Whether the sun does really diminish, as has been here suggested, is difficult to prove."[341]

Although Pemberton was a mathematician, he provided a simplified and non-mathematical account of Newton's theory of comets for general readers. He did not involve himself in technical aspects of the theory, such as analysis of the observational data or orbit determination. Most conspicuously, Pemberton did not incorporate the destructive effects of comets, as Gregory had stressed. The comet that he introduced was a harmless object with the constructive mission of refreshing the planets and the sun.

François Marie Arouet (Voltaire)

François Marie Arouet (1694–1778), best known by his pseudonym Voltaire, was an influential pioneer of Newtonian philosophy in France when Newton's influence was largely restricted to England.[342] In 1726, Voltaire due to his conflicts with authorities, was driven into exile in England, where his philosophical interests became deeper. After spending about two years in London he returned to Paris and during the next four years devoted most of his time to literary compositions, among them the *Lettres philosophiques* (1734), which contained attacks upon the political and religious institutions of France. The consequent conflicts caused Voltaire once more to leave Paris and he found refuge at the Château de Cirey in the independent duchy of Lorraine. There, Voltaire wrote the *Élemens de la philosophie de Neuton* (Elements of the Philosophy of Newton) in which he described his account of the Newtonian theory of comets. [343]

Although Voltaire's goal is to explain the main topics of Newton's theory of comets for general readers, his account in some aspects deviates from what Newton had published about comets. After describing the motion of comets based on Newtonian celestial mechanics, Voltaire explains the structure and constitution of

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[340] Ibid., 245.

[341] Ibid., 246

[342] Newton's philosophy was not popular in France in the first half of the eighteenth century. See: Alexander Koyré, *Newtonian Studies* (Cambridge: Harvard University Press, 1965), p. 54.

[343] John Stephenson Spike, *French Free thought from Gassendi to Voltaire* (London: University of London Press, 1960), pp. 312–324.

cometary atmospheres. He finds two differences between planetary and cometary atmospheres: the atmosphere of comets is larger (sometimes 15 times as large as the comet's diameter) and the size of their atmospheres is changing. However, Voltaire assumes cometary atmospheres to contain an air like the earth's atmosphere and proposes that contrary to Hevelius's observation (which was cited by Newton in the *Principia*) a comet's atmosphere must occupy more space when it absorbs more heat in the vicinity of the sun.[344]

Voltaire strictly rejects the possibility of axial rotation of a comet. He comes to this conclusion by considering the irregular shape of some comets and the orientation of the tails. He says that comets can not have rotation "without having at the same Time a spherical, or a spheroidical Figure, and one Body only enclosed in their Atmosphere."[345] Cometary tails, which are unequal and change continuously, "must either sensibly retard, or totally stop the Rotation in Question; which has not yet been observed."[346]

Voltaire has a major difference with Newton's theory on the constitution of the cometary tails. He is quite explicit that a tail is composed of smoke that is produced by burning of the comet's atmospheric materials:

> The Smoke which issues from the Comets, and which disperses itself in the Regions of Heaven that they traverse, composes their Tails. They began to form themselves a little before the Comets arrive at their Perihelia, and from the Time that the Sun's Heat is intense enough to enflame the combustible Matters on their Surfaces, when the Smoke makes a Breach through their Atmospheres. It is true, however, that this Conflagration begins a little before we perceive the Smoke; but we consider here only the Instant when we first discover their Tails.[347]

He emphasizes again that tails are longer when comets are in the vicinity of their perihelia and since they diminish gradually after that, the "learned Newton found that the Tails of Comets were only Smoke." [348] Voltaire, while explaining the curvature of cometary tails by drawing an analogy between a comet and a moving torch, once more concludes that the "Tails of Comets are real Smoke, caused by their Conflagration on approaching the Sun."[349]

It is not known how Voltaire deduced such a conclusion from Newton's writings on comets. Newton, in all of his publications, speaks about tails as highly rarified

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[344] Voltaire, *The Elements of Sir Isaac Newton's Philosophy*, revised and corrected by John Hanna (London, 1738), pp. 331–332.

[345] Ibid., p. 335. As we saw above, using exactly the same reason, Whiston, proved that comets were not rotating.

[346] Ibid.

[347] Ibid., p. 336. Voltaire uses the French term *fumée* to denote the material of a tail: "La fumée qui sort des Cometes, & qui se disperse dans les Regions du Ciel qu'elles traversent, composent leurs queues […]." For the French version see: Voltaire, *Élemens de la philosophie de Neuton* (Paris: 1738), p. 295.

[348] Voltaire, *Elements of Newton's Philosophy*, p. 337.

[349] Ibid., p. 338. By admitting cometary tails as smoke an observational problem emerges which Voltaire leaves unanswered. Observations confirmed that even very dim stars were observable through the tails. Obviously, the rising smoke from conflagrations on comets should reduce stellar brightness, which had not been reported.

vapors and he never mentions that the combustible material in the atmosphere of comets catches fire by the sun's heat.[350] Voltaire pays no attention to Newton's assumptions about the role of cometary tails in replenishment of the planets. It seems that his interpretation of cometary tails as smoke was not a misunderstanding; rather, he probably modified Newton's theory to negate the cosmological consequences of Newton's comets. Obviously, the smoke coming out of a conflagration could not bear any life supporting substance for the planets.

Voltaire discusses one more topic – the possibility of habitability of comets – in which Newton had shown no interest. The idea of the plurality of the worlds which received new attention by the mid-seventeenth century, became a motivating topic in astronomy in the succeeding era. Voltaire, responding to the newly emerged interest in "extraterrestrial life," examines the different aspects of life on a typical comet. The inhabitants of comets, according to Voltaire, should retire into the interior of caves when the comet approaches its perihelion. On the other hand, since comets do not rotate, one hemisphere is always illuminated, and consequently only that illuminated part can be habitable. A comet, when it is in aphelion, receives 1/10,000 of the solar heat that the poles of the earth attain, but the heat that a comet gains in the perihelion continues to keep it warm even in the aphelion.[351]

Voltaire was not a physicist or an astronomer or even a systematic philosopher. Nonetheless, as a prominent figure of the Enlightenment, he popularized a modified version of Newton's theory in which the strong tendency to observe the role of an omnipresent supervisor was reduced. By ignoring the cosmological role of comets, which was a key element in maintaining the concept of providence in Newton's cosmology, Voltaire prepared a deist account of Newton's theory of comets.

Roger Long

Roger Long (1680–1770), the master of Pembroke Hall in the University of Cambridge, was an astronomer and astronomical instrument maker, who built a 20 foot planetarium.[352] Long's book of astronomy, which first appeared in 1742 and

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[350] Newton only on one occasion addresses the formation of smoke in the atmosphere of comets: "Moreover, these atmospheres appear smallest when the heads, after having been heated by the sun, have gone off into the largest and brightest tails, and the nuclei are surrounded in the lowest parts of their atmospheres by smoke possibly coarser and blacker." See: Newton, *Principia*, pp. 926–927. Newton's idea is clear and does not imply that the tail is a train of smoke formed by burning material of a comet's atmosphere.

[351] Voltaire, *Elements of Newton's Philosophy*, pp. 334–336. Voltaire correctly points out that the comet of 1680 (assumed to be as large as the earth and composed of a substance as dense as iron) needed 108 million years to cool off after passing the perihelion. Newton's result of 50,000 years is only valid for a globe of iron as large as the earth with a temperature of red hot iron. Since, according to Newton, the body of the comet was heated 2,000 times more than red hot iron, the time of its cooling would be prolonged by a factor of 2000. Depending on the adopted value for the temperature of red hot iron and the radius of the earth the final result may vary slightly.

[352] Roger Long, *Astronomy in Five Books* (Cambridge: Printed for the Author, 1742), p. *x*.

was reprinted several times, is an encyclopedia of astronomical theories and a history of astronomy. Although Long mainly explains theories of other scientists and does not suggest a new theory of comets, his delineation of some physical aspects of comets is noteworthy. One of the points he finds problematic in Newton's theory is the amount of the heat that the comet of 1680 absorbed.

Newton based his calculation of the comet's heat in its perihelion on the principle that the sun's heat falling on bodies at different distances is inversely proportional to the square of the distances. Long, however, despite accepting this rule, introduces other factors that practically affect the rate of absorbance of the solar heat by a planet or a comet:

> […] but it may be observed, that the effect of the heat of the sun upon all bodies near our earth depends very much upon the constitution of those bodies, and the air that surrounds them: such bodies as abound with sulphureous particles are heated sooner than others: there is in our air sometimes more fire than at other times: and there is more fire in the atmosphere near the earth than in the upper regions of it; how otherwise comes it to pass the snow will lye unmelted upon the top of an high mountain when it is hot weather in the valley near the foot of it.[353]

Then, in a remarkable step, Long tries to compare a laboratory experiment to a celestial phenomenon:

> The comet in question [the comet of 1680] certainly acquired a prodigious heat, but I cannot think it came up to what the calculation make it: the effect of the strongest burning glass that has ever been made use of was the vitrification of most bodies placed in the focus; what would be the effect of a still greater heat we can only conjecture; it would perhaps so disunite the parts as to make them fly off every way in atoms.[354]

Long perhaps was the first scholar who criticized Newton in this specific issue. While Newton was silent about the specifications of a planetary matter that sustained a heat of 2000 times more than the heat of red-hot iron, Long, applying the terrestrial meteorology and the results of his heat studies to comets, extended the results of his earth-bound experiments to the celestial realm. In other words, he thought comets to be bodies like the earth and subjected to the same physical rules. Based on these premises, he rejected Newton's calculation which attributed some extraordinary qualities to the cometary substance.[355] Long, however, did not develop a new theory to describe the constitution of the body, atmosphere, and tail of comets.

Colin Maclaurin

If we consider Colin Maclaurin (1689–1746), Henry Pemberton, and Voltaire as the three influential advocators of Newton's *philosophy* in the eighteenth century,

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[353] Ibid., book 3, p. 557.

[354] Ibid.

[355] It seems that Newton assumed temperature to be a quantity whose magnitude is additive or extensive (like mass or volume), while the magnitude of temperature is independent of the extent of the system, and is an intensive quantity.

Maclaurin would be credited as the most successful in fulfilling the task. While Pemberton and Voltaire concentrated mainly on presenting the technical aspects of Newton's achievements in physics, mechanics and optics, Maclaurin in addition to delineating a major part of the *Principia*, discussed the philosophical ramifications of Newtonian mechanics thoroughly. Furthermore, Maclaurin's approach in explaining Newton's physics is more technical and mathematical than the two others; however his work does not include Newton's optics.[356]

The philosophical weight of Maclaurin's work is more obvious in his exposition of Newton's theory of comets in which the cosmological role of comets is interwoven with philosophical and theological concepts. Although his discussion of the history, mechanics, and physics of comets occupies only ten pages of his *Account*, his focus on deducing the existence of an Omnipresent All-wise Being from the functions of comets is noticeable.

For Maclaurin that part of astronomy dealing with comets is very imperfect. He states that the periods, magnitudes, and dimensions of orbits of comets are uncertain. Also, "the number of the comets is far from being known."[357] Because some comets are discovered accidentally by telescope that otherwise would not have been visible by the naked eye, Maclaurin concludes that the number of comets must be very great. In a tone reminiscent of Seneca's in the *Naturales Quaestiones*, he describes cometology as a science "the perfection of which may be reserved for some distant age, when these numerous bodies, and their vast orbits, by long and accurate observation, may be added to the known parts of the solar system."[358]

Maclaurin's description of the physics of comets is not different from that of Newton. Although he is silent in categorizing comets as planets or other celestial species, he describes them as solid, fixed and durable bodies. He also has the same idea about the atmosphere and the tail that Newton presented in the *Principia*. However, when Maclaurin explains the cosmological aspects of comets the difference in his tone is more than a nuance.

Maclaurin does not see comets as major restoration agents in the world and they are not potential threats to destroy the earth. Although they may approach near enough to have considerable effects on the earth, the Creator has designed the motions in such manner that nothing catastrophic may happen:

> […] while so many comets pass among the orbits of the planets, and carry such immense tails along with them, we should have been called, by very extraordinary consequences, to

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[356] For a comprehensive account of Maclaurin's exposition of Newton's *Principia* see the introduction of L. L. Laudan to a facsimile print of the first edition (1748) of Colin Maclaurin, *An Account of Sir Isaac Newton's Philosophical Discoveries* (New York: Johnson Print Corporation, 1968), pp. *ix–xxv*.

[357] Colin Maclaurin, *An Account of Sir Isaac Newton's Philosophical Discoveries* (London: Printed for the Author's Children, 1748), p. 369.

[358] Ibid.

> attend to these bodies long ago, if the motions in the universe had not been at first designed, and produced, by a Being of sufficient skill to foresee their most distant consequences.[359]

Here, Maclaurin's account of the planetary motion does not imply that the solar system is unwinding and the Creator by sending comets prevents disorders from appearing. On the contrary, it says that all motions were designed at the Beginning and all subsequent effects of each motion were predicted accurately. Maclaurin, after describing the role of cometary tails in refreshing the planets and the function of cometary nuclei in refueling the sun (and stars) says:

> The argument against the eternity of the universe, drawn from the decay of the sun, still subsists; and even acquires a new force from this theory of comets: since the supply which they afford must have been long ago exhausted, if the world had existed from eternity. The matter in the comets themselves, that supplies the vapour which rises from them in every revolution to the perihelium, and from their tails, must also have been exhausted long ere now. In general all quantities that must be supposed to decrease or increase continually, are repugnant to the eternity of the world[360];

In this temporal world, where the stars are decaying and great number of comets may produce the greatest disorders, what at first glance seems to be irregularity and disorder in nature is "the best contrivance and the most wise conduct" of the Creator, if considered carefully.[361]

Finding the bones of the sea and land animals hundreds of yards beneath the surface of the earth, and finding the 'impression" of plants on the hardest rocks in places where those plants are not growing, indicates that great changes or revolutions have occurred in the history of the earth. However:

> Some philosophers explain these changes by the revolution of comets, or other natural means: but as the Deity has formed the universe dependent upon himself, so as to require to be altered by him, tho' at very distant periods of time; it does not appear to be a very important question to enquire whether these great changes are produced by the intervention of instruments, or by the same immediate influences which first gave things their form.[362]

Although comets may have influences on the earth, their cosmological roles are not as pivotal and as exclusive as what Newton attributed to them. In other words, despite the fact that the Creator assembled the clockwork of the universe by his omniscience, He was not confined by these requirements and He was not obliged to function in a limited fashion.

Conclusion

The reception of various hypotheses in Newton's physics (or experimental philosophy) by British and by the Continental scholars occurred in different ways. While the great achievements of Newton in mechanics and optics were acknowledged by

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[359] Ibid., 372.

[360] Ibid., p. 375–376.

[361] Ibid., p. 377.

[362] Ibid., p. 390.

a majority of natural philosophers both in England and on the Continent[363] (although with a delay in the latter), agreements with Newton were not all-encompassing in two major perspectives: the first was related to some issues in the philosophical foundations of Newton's physics and cosmology, and the second was in the realm of precision in prediction of the behavior of the planets and their satellites calculated by the new laws of celestial mechanics.

Reluctance in admitting the philosophical premises of Newton's physics appeared much earlier. Newton's description of the ether, the nature of action at a distance, the nature of the attractive and repulsive forces, the nature of light, and the way that the Creator was connected to the clockwork of the universe were challenging philosophical issues. These were among the issues that brought about several debates between Newton (and his disciples) and adversary natural philosophers, right after the publication of the *Principia* and the *Opticks*. The debates between Bentley and Newton and Clarke and Leibniz are the most distinguished ones.[364]

At the same time, in predictive astronomy, finding the exact motions and positions of the planets and their satellites based on the law of universal gravity still lacked adequate precision. Demanding new mathematical procedures, the predictive astronomy of Newton, at least in the first half of the eighteenth century, was not able to account for the perturbation of the moon accurately enough to be used for the determination of the longitude at sea; slight changes in the predicted positions of Jupiter and Saturn were not solved yet; and the precession and nutation of the earth's axis were not treated mathematically.[365]

Newton's theory of comets suffered from both kinds of problems. On the philosophical side, there were ambiguities in the function of the Newtonian ether, the cosmological role of comets, and the nature of the comets' bodies and atmospheres. On the side of mathematical astronomy, the exact trajectory of a comet had to be worked out considering the perturbative influence of the planets and retarding effects of the so-called solar atmosphere. Furthermore, this theory had some intrinsic inconsistencies which made the situation even more complicated.

As we saw above, despite a few followers of Newton (among them J. T. Desaguliers, Willem'sGravesande and Edmund Halley) who restated Newton's theory of comets without any criticism or modification, the rest found points in it that had to be clarified, corrected, or even rejected. By the mid eighteenth century, mainly in England, the first group of those Newtonians who wrote about the physics of comets tried to clarify four fundamental concepts: the nature of comets, the exact mechanism of

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[363] For the reception of Newton in the Continent see: Henry Guerlac, *Newton on the Continent* (Ithaca: Cornell University Press, 1981), esp. chapter 3, pp. 41–77; Patricia Fara, Newton*, the Making of Genius* (New York: Columbia University Press, 2002), esp. chapter 5, pp. 126–154; A. Rupert Hall, "Newton in France: A New View," *History of Science* 13 (1975), 233–250; Paolo Casini, "Newton in Prussia," *Rivista di filosofia* 91 (2000), 251–282; Judith P. Zinsser, "Translating Newton's *Principia*: The Marquise du Châtelet's revisions and additions for a French audience," *Notes and Records of the Royal Society of London* 55 (2001), 227–245.

[364] For a review of these debates see: Kubrin, "Newton and the Cyclic Cosmos."

[365] Curtis Wilson, "The Newtonian achievement in astronomy," in R. Taton and C. Wilson, eds. *The General History of Astronomy*, vol. 2A, pp. 233–274.

tail formation, the rotation of comets, and the cosmic roles of comets and their tails (Table 5.2).

The ambiguity of some concepts in Newton's theory of comets (for instance, the kind of 'spirit' in the tail of comets, or the way that ethereal particles interact with the particles of the tail, both mentioned by David Gregory) became apparent even when Newton was alive. However, the intrinsic inconsistencies of the theory were more clearly realized much later. It is amazing that even Newton himself, by the time of the third edition of the *Principia* (which appeared forty years after its first edition) did not try to clarify some problematic issues in his theory. Questions such as why the planets do not have tails, why an extremely hot comet does not shine by itself after the perihelion (when according to the *Opticks* any high-temperature object must glow), and how a very small amount of cometary atmosphere can replenish the planets, are all left unanswered in all editions of the *Principia* and the *Opticks*.

In 1696, nine years after the first edition of the *Principia*, Whiston concluded that the atmosphere of a comet should be completely different from that of the earth. In 1726, David Gregory discussed the role of the pressure of light in formation of cometary tails (to not attribute the whole phenomenon to the motion of the rarified ethereal particles). And finally, in 1728, Pemberton suggested that if the texture of the atmospheres of comets and the planets were the same, some of the planets would also have tails, because the sun's rays could heat their atmospheres adequately. It is noteworthy that all these authors visited Newton many times, and the latter (who started to write his book long before Newton's death) was involved in the third edition of the *Principia*. It seems implausible to believe that they never informed Newton of those difficulties in his theory of comets. Yet Newton did not bother himself even to mention those ideas as a footnote in the third edition of the *Principia* or respond to them through a letter to the *Philosophical Transactions*.

It is important to note that the discovery of the internal inconsistencies in Newton's theory of comets did not depend on further developments in observational or mathematical astronomy; rather it could be achieved by nothing more than a careful and thorough study of the *Principia* and the *Opticks*. Apparently, this was not done for a long period. In the cometary works of the seven Newtonian physicists and natural philosophers discussed in this chapter, there is not any reference to those issues in the *Opticks* that either are directly connected to comets or can be used in explaining their physical properties.

By the mid-eighteenth century when a new generation of theories of cometary tails appeared both in England and in the Continent (considered in next chapter), natural philosophers still were uncertain about the nature of comets. Introducing a third species into the solar system was as problematic as to consider comets regular planets. However, while the majority of astronomers and natural philosophers preferred to introduce comets as *planet-like* objects, the advocates of uniformity of the constitution of the solar system suggested that the only difference between the planets and comets was the form of their orbits, which imposed different physical conditions.

Table 5.2 A comparison of cometary ideas of Newton’s followers by the mid eighteenth century. The dates in the first column refer to the first publication of the idea. The sign of comet (☄) indicates that the idea is not appeared in Newton’s publications on comets

Name	Nature of the comet	Tail formation	Rotation	Cosmic role	Note
Halley (1694)	Followed Newton (A plant-like solid, fixed & durable object)	Followed Newton (A tail ascends by receding ethereal particles)	No comments	☄ Comets’ impacts can create the flood, deluge & conflagration	Linked the history of the earth to comets
Whiston (1696)	☄ Comets can be transformed into planets, and vice versa	Extends due to the pressure of the sun’s rays	Not rotating	Same as Halley	☄ The nature of tail changes after the perihelion
Gregory (1726)	Comets are a kind of planets/ there is only one kind of comet	A tail extends by the ascending rarified ethereal particles + ☄ pressure of the sun’s rays	Most probably not rotating	Same as Halley and Whiston	☄ Cometary vapor is fatal
Pemberton (1728)	☄ Comets are the third species of the heavenly bodies	Followed Newton	No comments	Comet’s vapor is not threatening	☄ The texture of cometary tail is different form planetary atmosphere
Voltaire (1738)	Followed Newton	☄ Tail is composed of smoke	Not rotating (His argument is similar to that of Whiston)	No comments	☄ Comets burn
Long (1742)	Followed Newton	Followed Newton	No comments	No comments	Criticize Newton: Comets can not absorb as much heat as Newton calculated
Maclaurin (1748)	Comets are solid, fixed, & durable (no clue that if they are planets or other kind of celestial body)	Followed Newton	No comments	Assigns not an important cosmological role to comets	Comets are not potential threats to destroy the earth

However, for almost a century after the appearance of the *Principia*, the main controversial issue in cometology remained the process of formation of cometary tails. While in this period mathematical astronomy developed to a level such that cometary orbits and the effects of gravitational perturbations could be calculated with a higher degree of accuracy, a general agreement on the nature of tails and the process responsible for their formation was not achieved. In the next chapter we shall see how the application of electrical studies in the realm of astronomy led to the development of the electrical theory of cometary tails, which on the threshold of the nineteenth century, was the most accepted theory of tail formation.

Chapter 6
Non-Newtonian Theories of Comets

By ‘Non-Newtonian theories of comets’ we refer to those theories that admit comets as members of the solar system but are divergent from Newton’s theory in theorizing other characteristics and properties of comets. The history of the non-Newtonian theories of comets, in large part, is the history of theories of cometary atmospheres and tails.

Newton’s theory of tail formation can be regarded as the Achilles’ heel of his theory of comets. The process that Newton introduced for tail formation was based on the function of the rarified and receding particles of the ether, which carried along the particles of cometary atmosphere. This assumption, as illustrated in chapter four and five of the present work, was unable to answer some challenging questions proposed even by Newton’s disciples. These questions can be classified into three groups based on (1) the role of different agents in the formation of a tail; (2) the interaction of the ethereal particles and the particles of the comet’s atmosphere; and (3) the interaction of the cometary atmosphere and the atmosphere of the sun.

In the first category, the questions were related to the basic factors responsible for triggering tail formation. Since some comets with perihelia around the orbit of Venus produced tails long before and after their closest approaches to the sun, it was a dilemma why the inner planets – including the earth – did not produce tails. In other words, it was a key question whether the amount of heat a comet received or the quality of its atmosphere was the main agent in the formation of a tail.

The second group of questions considered some sophisticated problems regarding the nature and function of the ethereal particles. Defined as the most subtle corpuscles in the cosmos, the ethereal particles had to carry along the atmospheric particles of a comet that undoubtedly were heavier and bigger. The insufficiency of the theory became more evident when it was found that the process had to be performed in a situation where the comet’s head was moving at a speed of a few thousands of miles per minute. Thus, the heating and rarifying of the ethereal particles were taking place in such a manner that they could move away the cometary particles with a speed more than the orbital speed of the comet and continue to recede for millions of miles. Furthermore, it was not known why Newton did not assign a role for the sun’s rays to act on the highly rarified particles of cometary tails.

T. Heidarzadeh, *A History of Physical Theories of Comets,*
From Aristotle to Whipple,

There also were questions about the atmosphere of the sun and its influence on cometary tails. The solar atmosphere was thought to be the white patch of light that glowed around the sun's disk during the total solar eclipses (it is called the solar corona in modern astronomy). Although it was not known how far this atmosphere extended (for some astronomers it extended to the orbit of Mercury, for others even further), its density was assumed to be higher than the surrounding ether. Thus, those comets that were computed to pass the sun so closely that they became immersed in its atmosphere, like the comet of 1680, were to produce their tails inside the dense medium of the solar atmosphere for a while. Besides the uncertainty about the process of tail formation in such a dense medium, there were thought-provoking questions regarding the interaction between the comet itself and the solar atmosphere.

The nature and the volume of the solar atmosphere became increasingly important subjects in astronomy from the late seventeenth century. This was mainly due to the discovery of the zodiacal light, which because of its form and position in the sky was considered to be connected to the solar atmosphere. The zodiacal light is seen along the zodiac as a faint glow rising up to about 20° from the side of the invisible sun in the east before dawn and in the west after dusk. The Italian-born French astronomer Giovanni Cassini discovered it in 1683, and because of its permanence he described it as a non-meteorological phenomenon.[366] While astronomers were still seeking a plausible theory of the zodiacal light, a spectacular display of an aurora in March 1716 (seen in almost all Europe) rekindled interest to investigate the origin of sky lights (Fig. 6.1).

After the display of the Aurora of 1716, Edmund Halley in England and Jacques Philippe Maraldi (1665–1729) in France were two leading figures who tried to explain the phenomenon.[367] Although both Halley and Maraldi interpreted the aurora as a meteorological phenomenon, the processes they introduced to explain it were intrinsically different. Maraldi based his theory on the action of an Aristotelian kind of exhalation emanating from the earth and shining in the upper atmosphere:

> Il paroit donc par les Observations que nous venons de rapporter, que l'apparition de ces Lumieres a été accompagnée d'un air doux & temperé, meme en Hiver & en de climates froids, ce qui donne lieu de croire que ces Lumieres ont été causés par des exhalaisons subtiles & sulphureuses, qui s'étant élevées de la Terre & allumées dans l'air, ont contribué à le rendre doux[368].

Halley, however, realized that the traditional exhalation-based theories of aurora could not answer two important questions appropriately: first, why the aurora

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[366] Ephraim Chambers, "Zodiacal Light," *Cyclopædia, or an Universal Dictionary of Arts and Sciences*, 5 vols. (London: 1778–1788), vol. 4, p. 1394.

[367] For a summary of major theories about the aurora in the eighteenth century see: J. Morton Briggs, Jr., "Aurora and Enlightenment, Eighteenth-Century Explanations of the Aurora Borealis," *Isis* 58 (1967), 491–503.

[368] Maraldi, "Observations d'une Lumiere Horisontale," *Memoires de l'Académie royale des Sciences*, 1717, p. 30. Maraldi published two articles about his observations of the aurora of 11 April 1716 and 15 December 1716 (he did not describe the aurora of March 1716). His theory is stated in his second article. See: Briggs, "Aurora," p. 493.

appeared only in the northern latitudes, and second, how that extraordinary amount of exhalation was released from the earth and was seen as an enormous aurora for several nights from all over Europe. Halley's revolutionary theory, however, was capable of answering both questions. Halley introduced a kind of magnetic effluvium (or as he called it "Magnetical Atoms"), which emanated from the magnetic poles of the earth and had either the capability of glowing itself or making other material glow.[369] Halley's employment of a new effluvium in explaining the Northern Lights (which had a resemblance to cometary tails[370]) can be considered as a source of inspiration for those who developed the electrical theory of cometary tails in the mid-eighteenth century.

The Northern Lights, the zodiacal light and the tails of comets were very similar to each other. All of them seemed to be composed of a rarified matter, all were in the form of a hazy glow, and finally, each one was associated with a main object in the solar system (the zodiacal light with the sun, the Aurora Borealis with the earth, and tails with comets). These features were encouraging enough for astronomers to

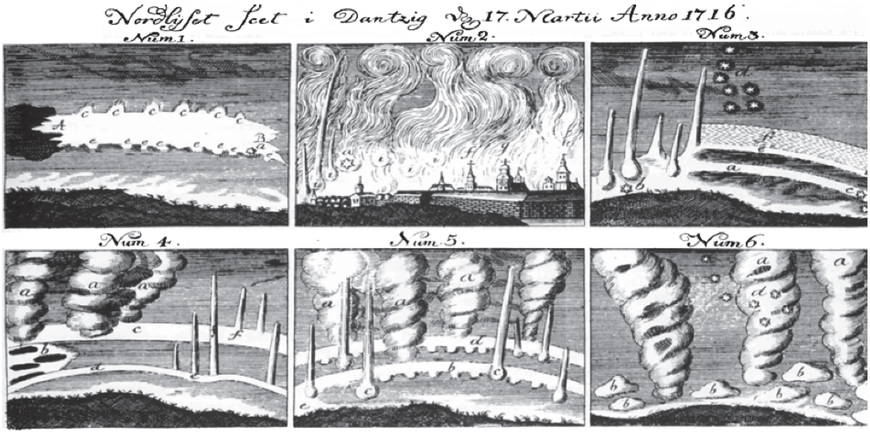

Fig. 6.1 Drawings of the spectacular aurora seen on March 6, 1716. From Joachim Frederik Ramus' *Historisk og physisk Beskrivelse over Nordlysets forunderlige Skikkelse, Natur og Oprindelse* (*Historical and physical description of the peculiar form, nature and origin of the northern light*), Copenhagen, 1745. The title is translated by Dr. Niels Praegel, the senior scientist with the Copenhagen University Library

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[369] Edmund Halley, "An Account of the Late Surprising Appearance of the Lights Seen in the Air, on the Sixth of March Last; With an Attempt to Explain the Principal Phaenomena thereof; As It Was Laid before the Royal Society by Edmund Halley, J. V. D. Savilian Professor of Geom. Oxon, and Reg. Soc. Secr.," *Philosophical Transactions of Royal Society of London* 29 (1714–1716), 406–428, esp. pp. 423–428.

[370] Halley points out this resemblance: "Nor do we find any thing like it [aurora] in what wee see of the Celestial Bodies, unless it be the *Effluvia* projected out of the Bodies of Comets to a vast Hight." See Ibid., p. 427.

seek for an affinity between them. Any unified theory not only would solve a number of enduring problems regarding the nature of those lights, it would also introduce a universal principle governing their formation.

Mairan's Theory of Cometary Tails

Although Cassini mentioned the great resemblance of the zodiacal light to the tails of comets, he did not develop a theory regarding their possible affinity.[371] The first step toward a unified theory of aurora, the zodiacal light and cometary tails was taken by Jean-Jacques d'Ortous de Mairan (1678–1771), a French Cartesian physicist and a member of the Academy of Sciences. In his book about the physics and history of the Northern Lights, which appeared in 1733, he describes the phenomenon in detail, develops his theory of aurora, and considers the relationship between the solar atmosphere and cometary tails (Fig. 6.2).

Mairan suggests that the solar atmosphere (which is denser in its equatorial parts) is extended as far as the orbit of the earth, but its size is variable. When the particles of the solar atmosphere pass the zone of equal gravity – points where the gravitational forces of the sun and the earth on a given particle are equal – they flow into the atmosphere of the earth and glow as an aurora. The difference in the densities of the incoming solar material causes the different colors and distributions of the aurora displays, and the slower angular motion of the earth in the poles causes the cascade of the solar material not to scatter and to be seen conspicuously in the polar regions.[372]

As Newton did at the end of his *Opticks*, Mairan expresses his thoughts on various subjects in 28 questions in the last section of his book. A number of these questions are related to the atmospheres of comets and the process by which the cometary tails are formed. Being inexplicit about the physical properties of the cometary nuclei, Mairan mainly concentrates on the relationship between the atmospheres of comets and the solar atmosphere.

Mairan criticizes Newton's theory of tail formation from different aspects: He asks why, if the sun's heat causes the cometary exhalations to ascend, that part of comets which is towards the sun does not expand considerably. He argues that a tail cannot form due to the ascension of the heated ethereal particles, and attributes a stronger role to the sun's rays in driving the particles of the cometary tails. Mairan, then, seeks for the similarities between the tails of comets, aurora and the zodiacal light:

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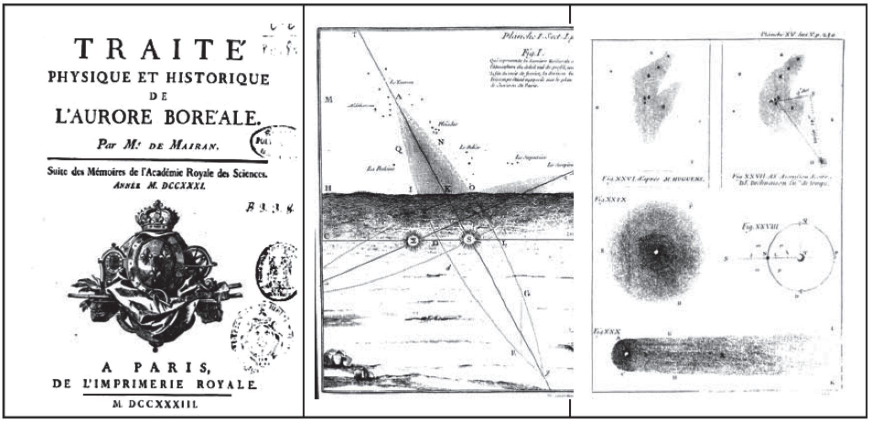
[371] Chambers, *Cyclopedia…*, 4th ed., vol. 4, p. 1394.

[372] Jean-Jacques d'Ortous de Mairan, *Traité Physique et Historique de l'Aurore Boréale* (Paris: 1733), pp. 10–30, 86–94, 142–145, 219–228. For a brief description see: Briggs, "Aurora," pp. 494–498.



TRAITE
PHYSIQUE ET HISTORIQUE
DE
L'AURORE BORÉALE.
Par M.r DE MAIRAN.
Suite des Mémoires de l'Académie Royale des Sciences.
ANNÉE M. DCCXXXI.

A PARIS,
DE L'IMPRIMERIE ROYALE.
M. DCCXXXIII.

Fig. 6.2 The cover page and two diagrams showing the zodiacal light and cometary tails from Mairan's *Traité Physique et Historique de l'Aurore Boréale* (Paris: 1733)

> Malgré cette densité, si notre conjecture est vraïe, la matiére de l'Atmosphere Solaire conserve encore ordinairement sa transparence autour de la Comete, de même qu'elle a coûtume de faire dans la Lumiére Zodiacale, & dans l'Aurore Boréale. Car la Chevelure ou l'Atmosphere qui environne les Cometes, & qui paroît comme une espece de nuage lumineux dont la claret diminuë de plus en plus vers les bords, est presque toûjours transparente, & quelquefois même dans sa partie la plus dense, & tout proche de la Tête, puisqu'on y apperçoit les Étoiles fixes à travers.[373]

And

> L'Atmosphere des Cometes telle que nous venons de la décrire & de l'expliquer, n'est-elle point pour elles, pendant une partie de leur cours, une espece d'Aurore Boréale continue, & permanente, semblable, toutes proportions gardées, à quelques uns des Phénomenes de même nature que nous observons sur la Terre?[374]

When the body of a comet approaches the sun it attracts the particles of the solar atmosphere and forms a coma around itself. Then, due to the pressure exerted by the sun's rays the particles of the coma are driven opposite to the sun and a tail is formed. When the comet moves out of the solar atmosphere it still has enough coma around itself to produce a tail.

According to Mairan's theory, although it is possible that the earth might pass through the coma or the tail of a comet, the consequences would not be cataclysmic. Since the material around the nucleus of a comet is the same as the solar material whose cascade over the earth has created only displays of the Northern Lights, a possible encounter of the earth and the tail of comet will cause not a deluge but a great aurora:

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[373] Ibid., p. 272.

[374] Ibid., p. 273–274.

> Le passage du Globe Terrestre à travers la partie supérieure de l'Atmosphere d'une Comete, & à travers sa Queuë, produiroit-il autre chose sur la Terre que quelques Aurores Boréales à peu-près femblables à celles que nous voyons tous les jours? Et les principes employés dans la Théorie précédente ne mettent-ils pas du moins la Terre à couvert de ces inundations, ou plûtôt de ces Déluges, ausquels un célébre Anglois veut qu'elle soit exposée par la rencontre des Cometes?[375]

In spite of the fact that Mairan's theory was basically a new approach to bringing similar terrestrial, planetary and stellar phenomena under a single umbrella, its technical inconsistencies were too evident to make it a popular theory. One of the main problems in Mairan's theory (which was discussed by Euler thoroughly) was disregarding the retarding influence of the solar atmosphere on the motions of the interior planets and the earth. Mairan's limitation of the solar atmosphere to the orbit of the earth implied that no comet could be seen with a noticeable tail before reaching a distance of one astronomical unit from the sun.

The second edition of Mairan's book appeared in 1754, after Euler demonstrated mathematically that the solar atmosphere cannot extend as far as the orbit of the earth and proposed his own alternative theory in 1746. Mairan responded to Euler's criticism immediately (and repeated his responses in the second edition of his book), but he left his theory intact in the new edition of his book. However, by the time of emergence of the electrical theory of cometary tails in the mid eighteenth century, Marian's theory remained one of the main non-Newtonian mechanical theories of cometary tails, along with the theories of Euler and Rowning.

John Rowning

John Rowning (1701?–1771), a mathematician and an instrument maker of London, was among the first scholars who rejected the Newtonian notion of ether[376] and criticized Newton's theory of cometary tails. In his work entitled *A Compendious System of Natural Philosophy*, Rowning examines Newton's theory in detail and proposes a new theory that had a remarkable influence on subsequent non-Newtonian cometary theories.

Rowning admits that comets are solid bodies like planets, moving on very eccentric orbits, and not confined to the zodiac. On the other hand, comets produce tails that have not been seen in the planets. Rowning accepts that comets undergo tremendous heating when they approach the sun.[377]He also discusses the shape of a typical tail and, like Newton and others, confirms that a tail is always curved in such

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[375] Ibid., p. 279.

[376] E. Schofield, "Rowning, John," in Charles C. Gillispie (ed.), *Dictionary of Scientific Biography*, 15 vols. (New York: Charles Scribner's Sons, 1972), vol. 11, pp. 579–580.

[377] John Rowning, *A Compendious System of Natural Philosophy: With Notes Containing the Mathematical Demonstration, and Some Occasional Remarks. In Four Parts* (London: Printed for Sam Harding, 1744), pp. 98–99.

a way that the convex part of it is towards the direction of motion. However, he rejects Newton's idea that a tail is produced through the interaction of the heated atmospheric particles of a comet and the encompassing ethereal particles.

Rowning investigates the process of tail formation by focusing on the consequences of a comet's motion with its tremendous speed in the Newtonian ether. He says that while a comet's speed is more than a thousand mile per minute, it is improbable that the rising particles, encountering the resistance of the diffused ether, can extend millions of miles in a direction not directly opposite to the sun. In fact, he claims that Newton's theory is unable to explain the orientation and curvature of the tails:

> How is it then likely, I say, that the Æther should by its Gravity alone raise the Vapour of the Comet with such Force, as to cause it to overcome its Resistance, when the Resistance arise from so great Rapidity of the Comet? Would it not rather carry it with it the other Way?[378]

Rowning then proposes his theory of tail formation, which resembles the pre-Newtonian optical theories of comets. His theory is based on the fact that the sun's rays are refracted in the atmospheres of a comet, as they refract in the atmosphere of the earth. In this process the atmosphere of the comet (and not its body) acts as a lens. Consequently, the rays are converged at the opposite side of the comet (its night hemisphere) and illuminate a part of its vapor and exhalation, as a lens concentrates the rays in its focal point. The shining vapors at the back side of the comet illuminate parts of the cometary atmosphere that are extended into space (Fig. 6.3). It is like the falling of the sun's rays from a hole into a dark room that is occupied by smoke: the rays will illuminate portions of the smoke in their path but the rest of the smoke will not be lit up.

Rowning explains the curvature of cometary tails based on a kind of aberration of light. In 1728, James Bradley (1693–1762), who succeeded Edmund Halley as Astronomer Royal in 1742, discovered that the positions of stars are apparently displaced due to the finite speed of light and the orbital motion of the earth. In Bradley's word "if Light was propagated in Time, the apparent Place of a fixt Object would not be the same when the Eye is at Rest, as when it is moving in any other Direction, than that of the Line passing through the Eye and Object; and that when the Eye is moving in different Directions, the apparent Place of the Object would be different."[379] Bradley's discovery, in addition to confirming the orbital motion of the earth, and having a profound impact on precise positional astronomy, introduced a new concept that the true position of a celestial body can be altered due to a combined effect of its motion and the limited speed of light. The higher the speed of the moving body the more deviation occurs between the true and apparent positions of the body.

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[378] Ibid., p. 105.

[379] James Bradley, "A Letter from the Reverend Mr. James Bradley, Savilian Professor of Astronomy at Oxford, and F.R.S. to Dr. Edmund Halley Astronom. Reg. &c. Giving an Account of a New Discovered Motion of the Fix'd Stars," *Philosophical Transactions* 35 (1727–1728), 646.

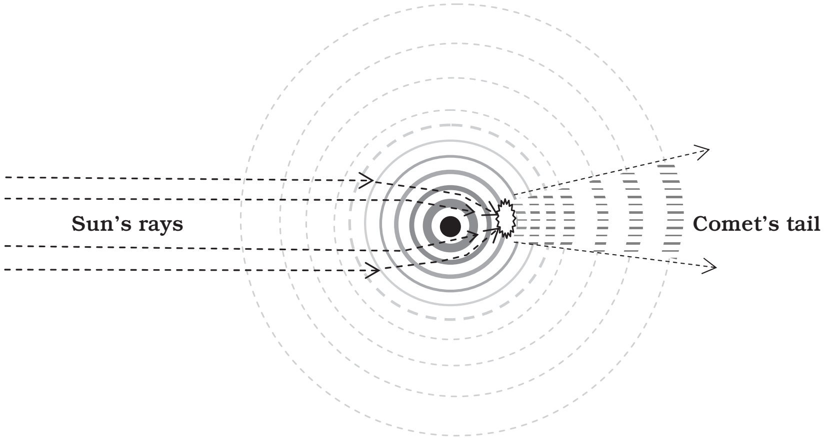

Fig. 6.3 Rowning's theory of tail formation: The atmosphere of a comet refracts the sun's rays and converge them in a focal point at the back of the comet's body. There, the illuminated vapor and exhalation function as a beacon in the fog and enlighten parts of the comet's atmosphere which is seen as a tail

Employing a similar concept, Rowning explains that, since a comet moves with a very high speed, by the time that light propagates to the end of the tail and reflects to our eyes, the nucleus moves and shed light to those vapors that are located right above it. Thus, we see the light of the extremity of the tail a little later than the light of the portions close to the nucleus. The combined effect, then, is observed as a curved tail whose convex side is towards the direction of motion of the comet.[380]

Evidently, Rowning's theory necessitated a comet's atmosphere extending as far as the length of its tail. However, he did not consider the consequent effects of such enormous atmospheres around comets. It is strange that Rowning did not explain how a planet-like nucleus could hold an atmosphere that sometimes grew as large as the orbit of the earth around the sun. Furthermore, he did not discuss the possible effects of the cometary vapors on the planetary atmospheres when the planets became immersed in the immense atmosphere of comets.[381]

Although Rowning's theory had difficulties in both its physical and dynamical aspects, and was not welcomed as an alternative theory, it was important for demonstrating the problems associated with Newton's ideas of the ether. Rowning's *Compendious System* was one of the most popular texts in the eighteenth century and was used at several colleges in England.[382] His criticism of the Newtonian

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[380] Rowning, *A Compendious System*, pp. 108–112.

[381] Roger Long, after mentioning theories of tail formation, including Rowning's, criticizes him regarding the size of comet's atmosphere he adopted in his theory: "the greatest objection to it [Rowning's theory] is the immense largeness of the atmospheres that must now be supposed, to account for the length of the tails of some comets, which have been said to measure above 200 semidiameters of our earth." See: Long, *Astronomy*, p. 555.

[382] Schofield, "Rowning, John," pp. 579–580.

theory of comets was read by a great number of students and instructors, and also appeared in encyclopedic works such as Roger Long's *Astronomy*.[383] Long's presentation of the theory may also have inspired Euler to propose a similar theory of tail formation, which appeared in 1746.

Euler's Theory of Tail Formation

In an article published in 1746, Leonhard Euler (1707–1783) refuted the core concept of Mairan's theory of tail formation by demonstrating that the solar atmosphere could not extend very far from the sun. Euler, using similar concepts employed by Rowning and Mairan, proposed an alternative theory in which the Aurora Borealis and cometary tails were explained as two manifestations of a single phenomenon.

Euler starts his article by calling attention to the affinities between the tails of comets and the Northern Lights. He states that on a comet an observer located at the hemisphere opposite to the sun will see the comet's tail almost similar to the phenomenon of Aurora Borealis.[384] The remarkable differences between the aurora and a comet's tail, Euler says, are that the tail is long-lasting, brighter, and surrounds all parts of the body of the comet; instead, the Aurora Borealis only appears at certain times and is seen from certain places. An imaginary spectator on the moon would see the Aurora Borealis as a little tail extending from the north of the earth.

Euler found three major difficulties in Mairan's theory. First, the vast extension of the solar atmosphere was contrary to several observational and theoretical facts. The sun's enormous gravitation should not let the atmosphere grow so immensely. On the other hand, the existence of such an atmosphere should have a retarding effect on the motion of the nearby planets. Second, several comets (obviously with tails) had been observed before they approached very close to the so-called solar atmosphere. Third, it was not clear why the solar atmosphere was mainly concentrated in the equatorial plane of the sun.[385]

In Euler's theory a comet contains an atmosphere almost with the same properties described by Newton. When the sun's rays hit the comet's atmosphere, its particles

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[383] Long, *Astronomy*, p. 555.

[384] Leonhard Euler, "Recherches Physiques Sur la Cause de la Queüe des Cometes, de la Lumiere Boreale, et de la Lumiere Zodiacale," *Histoire de l'Académie Royale des Sciences et des Belles Lettres de Berlin*, 1746, p. 117. A similar idea was stated by Mairan. According to him, since the sun's rays barely penetrate the denser parts of a coma, only the particles at the outmost parts of it can be pushed by the solar rays. As a result, the tail "former un Cone, ou Cylindre creux." Thus, an observer at the night side of a comet will see the tail as a surrounding illuminated wall. See Mairan, *Traité*, pp. 276–277.

[385] Euler, "Recherches Physiques," p. 119.

receive a pressure which moves them in a direction opposite to the sun.[386] However, the motion of these particles depends on the motion of the light that is subjected to refraction in the atmosphere of the comet. In Fig. 6.4, *ADBD* represents the nucleus of a comet and *EHIF* is the surrounding coma. The solar rays falling from the right hand side may propagate by three different routes depending on their incident points: the rays marked *EEE* and *FFF* which graze the outermost parts of the atmosphere will continue to move without experiencing any refraction or deflection. On the contrary, the ray *GD*, which directly falls on the nucleus, will be absorbed by the dense parts of the atmosphere and obviously will not have any chance to continue its journey. However, rays which enter the coma in the distance between the surface of the nucleus and the extremity of the coma undergo refraction. Their paths will be determined by the density of various parts of the coma which bend the rays in different angles.

Thus, if the ray *EE* or *FF* hits the most subtle particles of the outer atmosphere of the comet *ADBD*, it will be bent slightly and move along the line *EEe* or *FFf*. At the same time, the ray will push the confronted particles to move ahead. However, the motion of each particle is composed of two motions: one is in the direction of the propagation of the ray, and the other, which arises from the particle's weight, is in the direction of the center of the comet's nucleus. As a result, the ray *HHA* or *IIB*, which passes through the densest part of the coma, experiences more refraction and drives grosser particles where the attraction of the nucleus is the strongest. Consequently, the ray bends drastically in the direction of *HHah* or *IIbi*.[387]

In Euler's theory the cometary tails become luminous not only because of reflection of the sun's rays but also they may emit light when their particles attain a state

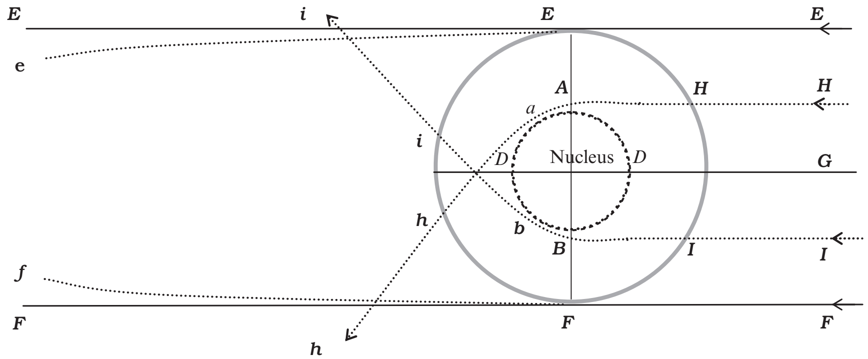

Fig. 6.4 Euler's diagram to illustrate the formation of the cometary tails. Redrawn after diagram 1 in Euler's "Recherches Physiques Sur la Cause de la Queüe des Cometes" (1744)

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[386] Euler does not acknowledge the Newtonian corpuscular theory of light but adopts a wave theory. However, he admits that light rays exert pressure on small particles, such as dust. He also refers to experiments done by burning mirrors to show the effect. See Ibid., p. 121.

[387] Ibid., pp. 122–125.

of radiation. Since Euler embraced a wave theory of light, he explained the radiation of light as the vibration of particles in a certain mode:

> […] il semble suffisant pour expliquer les Phénoménes des Queües des Cometes, de la Lumiere Zodiacale, & de l’Aurore Boreale, de supposer qui’il y a dans ces endroits là des particules opaques, qui reçoivent la lumiere du Soleil. Ce n’est pas que je voulusse depouïller entierement ces particules de toute lumiere propre, puisqu’il peut arriver, malgré leur opacité naturelle, qu’en passant d’une Atmosphére plus épaisse dans un air plus libre, leur etat d’equilibre change de maniere à leur faire aquerir les vibrations requises pour former des rayons lumineux. [388]

Euler discussed various physical properties of comets in his theory, including the rotation of the cometary nuclei, their shapes, and the different forms of the cometary tails. He suggested that the rotation of cometary nuclei influences the tail formation because the difference in angular speed of the equatorial and polar regions of the comet affects the interaction of the sun’ rays and the atmospheric particles: in the polar regions where the angular speed is the lowest, particles stay longer under the action of the rays and are driven for a longer distance. On the contrary, in equatorial parts, due to the higher angular speed, the sun’s rays detach fewer particles from the atmosphere and the tail is not stronger.[389]

Planets also experience the same effect. In Euler’s theory, planets have tails too, but since their atmospheres are much smaller than cometary atmospheres and because they rotate faster, their tails – which are seen as aurora – are shorter, fainter, and observable only in the polar regions.

Euler investigates the possible effects of a non-spherical cometary nucleus on the process of tail formation. He studies a case in which the nucleus is oblong and, using a diagram similar to one in Fig. 6.4, he demonstrates that those “queües fourchuës”, which have been seen in a number of comets, result from the non-spherical cometary nuclei. Other types of tails also may develop due to the combination of different causes. Euler specially considered the comet of 1744, which appeared with a peculiar tail. The six tails of this comet, which were growing like the petals of a daisy from its pistil, were difficult to explain. However, Euler found his theory capable of explaining it.

According to Euler, since near perihelion a comet passes the most curved part of its path with the highest speed, the direction of the line connecting the sun and the comet changes drastically in a short period of time. At the same time, the sun’s rays are stronger and can detach more particles from the atmosphere of the comet (Fig. 6.5). Thus, if the speed of a comet is high enough, a new tail will develop behind it when the comet changes its position rapidly.[390]

Euler’s theory was one of the last attempts to explain tail formation in a mechanical way: an approach to reduce all observed aspects of cometary phenomena to the interaction of matter and in-touch forces. In fact, Euler’s theory was developed in a

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[388] Ibid., p. 120.

[389] Ibid., pp. 126–127.

[390] Ibid., pp. 128–129.

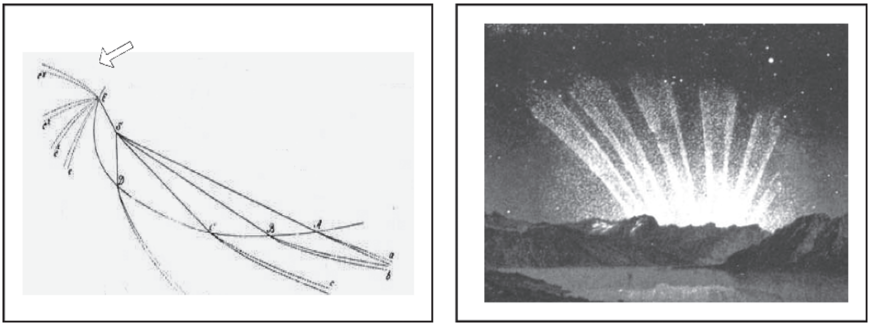

Fig. 6.5 Left: Euler's illustration of the formation of multiple tails in the comet of 1744 (Cheseaux's comet), from Euler's "Recherches Physiques Sur la Cause de la Queüe des Cometes." Right: The six-tailed comet of 1744, from Amédée Guillemin's *The Heavens*, Paris 1868

transitional period when the concepts of ether, action-at-a-distance, and the stability of the solar system were being redefined. Those problems that had not been solved by Newton were finding solutions due to profound developments in mathematics, observational astronomy and experimental physics in the second half of the eighteenth century. Euler himself was one of the chief actors of this transition process.

Euler proposed his theory of comets after revising his theory of ether. As discussed earlier, in analytical celestial mechanics, theories of ether and theories of celestial dynamics were linked together in such a way that considering any one of them without solving the others' problems was fruitless. By the second half of the eighteenth century, the accuracy of observational instruments reached such a level that the discrepancies between the theoretical and observational positions of the members of the solar system, which might have resulted from the secular effects of the interplanetary ether, or gravitational perturbations, or other effects, could be detected within a precision of about 1 arc second.

Euler in the early 1740s was still thinking of gravitational attraction as the centrifugal force build up in Cartesian vortices. However, by 1746, after communications with Daniel Bernoulli (1700–1782), who already had developed an ethereal theory of gravitation, Euler adopted Bernoulli's theory. In the latter theory, the gravitational force was assumed to be a variation in ethereal pressure, arising from differences in velocity of the ethereal particles.[391]Although Euler maintained that the interplanetary medium is composed of very subtle particles of the ether, he did

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[391] Curtis Wilson, "The problems of perturbation analytically treated: Euler, Clairaut, d'Alembert" in Taton and Wilson, eds., *The General History of Astronomy*, vol. 2B, p. 91. For a detailed account of development of Euler's ideas about action-at-a-distance see: Curtis Wilson, "Euler on action-at-a-distance and fundamental equations in continuum mechanics," in P.M. Harman, Alan E. Shapiro (eds.), *Investigation of Difficult Things: Essays on Newton and the History of the exact Sciences in Honour of D.T. Whiteside* (Cambridge: Cambridge University Press, 1992), pp. 399–420.

not involve it in his theory of cometary tails. Euler's theory, thus, was only based on the action of the driving force of the sun's rays on the particles of the coma which could even make those particles glow by changing their mode of vibration. From this view point, Euler's theory can be considered the prototype of the modern theory of tail formation, which appeared in the early twentieth century.

Euler's contribution to cometology was not restricted to his theory of comets. His innovations in mathematics and mathematical astronomy founded an analytical approach to celestial mechanics which facilitated handling the perturbation problem. Perturbation theory, which was studying the gravitational interactions of the members of the solar system (including the interaction between the planets and comets), developed profoundly after Euler's introduction of the integration of trigonometric functions. In the late eighteenth century, the great achievements in mathematical astronomy made by d'Alembert, Lagrange, and especially Laplace which led to attain a clear idea about the mass of comets by solving perturbational problems, were rooted in the Eulerian calculus of trigonometric functions.[392]

Euler's theory of comets was not a part of a well-defined cosmological theory. In fact, after Newton, the majority of astronomers and natural philosophers were occupied with the technical aspects of Newtonian physics and celestial mechanics rather than founding a new cosmology. Although some natural philosophers, especially on the Continent, attempted to reconcile Descartes' cosmology with that of Newton, it was generally accepted by the mid-eighteenth century that Descartes should fade away.[393] The triumphant Newtonian cosmology, however, besides struggling with several technical problems, had an important unanswered philosophical question: to what extent were Newton's laws applicable?

The question, obviously, had two dimensions. The spatial dimension, more or less, should be treated in the realm of astronomy and physics. Any discovery of applicability of Newton's laws in remote parts of the universe depended on developments in observational astronomy. But the temporal dimension of the question could be handled in pure philosophy: was the Creation based on the universal laws of Newton?

Newton's cosmology covers the status of the universe after its creation. In fact, Newton did not have a cosmogony. For Newton there was a clear demarcation between the laws of Creation and the laws of the post-Creation cosmos.[394]

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[392] Euler by proving the formula $e^{ix} = \cos x + i \sin x$ (where i is the complex number, $i^2 = -1$) connected the trigonometric and exponential functions. This innovation laid down a calculus-based approach to trigonometry which was essential in the development of the analysis of orbital elements in perturbed orbits. See: Ibid., pp. 89–107, Wilson, "Euler on action-at-a-distance," pp. 399; Katz, *A History of Mathematics*, pp. 554–558; Curtis Wilson, "Astronomy and Cosmology," in Roy Porter (ed.), *The Cambridge History of Science, Volume 4: Eighteenth-Century Science* (Cambridge: Cambridge University Press, 2003), pp. 328–353, especially pp. 334–337.

[393] For the history of the Cartesian System after the emergence of Newtonian physics see: Aiton, *The Vortex Theory*, 152–193, 209–256, especially pp. 244–256.

[394] Simon Schaffer, "The Phoenix of Nature: Fire and Evolutionary Cosmology in Wright and Kant," *Journal for the History of Astronomy* 9 (1978), pp. 180–200, especially pp. 189–192.

This differentiation, which had not been challenged by any philosopher, was neglected by Immanuel Kant. Kant extended the applicability of Newton's mechanics to the process of creation and developed an evolutionary cosmology in which his God, contrary to Newton's God, was engaged in supervising the evolution of the cosmos rather than merely preventing it from collapse.[395] Here, to avoid unnecessary rehearsal of Kantian cosmogony, which has been the subject of a multitude of studies, we only consider his theory of comets.

Immanuel Kant: Cosmogony of Comets

Immanuel Kant (1724–1804) created the first Newtonian account of creation in which comets were assumed to be as old as any other object in the solar system. Comets, after Brahe, were generally understood by astronomers and philosophers as a kind of secondary object in both the physical and temporal senses: not only were they different from the stars and planets regarding their physical constitution, they also were created long after the creation of the main bodies in the universe. Even in Descartes' cosmology comets were formed from some 'processed' material that had taken a long time to be transformed from the original subtle particles of the stars into cometary substances.

Despite Newton's refutation of Descartes' cometology, his theory of comets admits a similar hierarchy. Although in his published works, Newton was silent about the creation of comets, his unpublished works and citations reported by his colleagues indicate that he acknowledged a hierarchical formation of bodies in the solar system in which comets were assumed to be the last production of the cosmic factory. For Kant, however, the sun, planets and comets were formed through a single process and the only factor that differentiated comets from planets was their orbital elements.

Kant in his major work entitled *Allgemeine Naturgeschichte und Theorie Des Himmels*[396] laid down the foundations of a consistent cosmogony based on Newton's mechanics. Inspired from the observations made on the Milky Way, especially the work of Thomas Wright (1711–1786), Kant developed a theory of the cosmos in

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[395] Ibid., p. 190.

[396] *Allgemeine Naturgeschichte und Theorie Des Himmels oder Versuch von der Verfassung und dem mechanischen Ursprungedes ganzen Weltgebäudes, nach Newtonischen Grundsätzen abgehandelt* (Leipzig: 1755). For English translation see: Immanuel Kant, *Universal Natural History and Theory of Heavens; or an Essay on the Constitution and Mechanical Origin of the Whole Universe Treated According to Newton's Principles*, trans. W. Hastie (Glasgow: 1900). Also: *Kant's Cosmogony, as in His Essay on the Retardation of the Rotation of the Earth and His Natural History and Theory of the Heavens*, trans. W. Hastie, revised and edited with an introduction and appendix by Willy Ley (New York: Greenwood, 1968). All quotations from Kant's *Cosmogony* in this section are from the latter work.

which all stars in a configuration similar to a flat disc were moving around a single center.[397] In fact, for Kant the entire universe was a large-scale model of the solar system functioning under the influence of the same forces which gave the solar system its shape and motion.

In Kant's cosmos the motion of the celestial bodies is performed under the influence of two forces. One force causes a body to fall towards an attracting central object (for example the sun), and the second gives the body an impetus sideways. If the impulsion is weaker than the attracting force, the body will fall on the central object and unite with it. However, if an exact equilibrium is formed between those two forces, the body will move around the central object in a constant circular orbit. But, for the reason that nothing in the entire universe is completely balanced, none of the planets move on an entirely circular orbit:

> The difference between the orbits of the comets and the planets, thus consists in the balancing of the lateral movement with the pressure which impels them to fall […] the comets diverge most therefrom; because the impulsion which has been impressed upon them laterally, has been least proportionated to the central force of their initial distances.[398]

Comets, therefore, not only can be found in very elongated orbits, they may also move in orbits not confined to the zodiac. The same effect may occur in the stellar realm. Although the majority of stars are seen in the plane of the Milky Way, there are also stars located outside of the Milky Way disc. Kant describes the similarity between the configuration of the solar system and that of the Milky Way as follows:

> Those suns which are least closely related to this plane, will be seen at the side of it; but on that account they are less accumulated, and are much scattered and fewer in number. They are, so to speak, the comets among the suns.[399]

According to Kant, the eccentricity of an orbit, which is defined by the proportionality between the attractive and impulsive forces, increases with the distance from the central object. In the case of the solar system, the eccentricities of Venus, the earth, Jupiter, and Saturn are 1/126, 1/58, 1/28 and 1/17 of the semi-axis of their elliptical orbits respectively. Moving in highly eccentric orbits, comets are situated beyond the last object which, regarding the shape of its orbit, can be called a regular planet. Thus, the race of comets (*Geschlechte der Kometen*) and that of planets are deviated just because of a deviation in their orbital eccentricity:

> For it is certain that it is just this eccentricity that makes the essential difference between the comets and planets; and tail and vapour heads of the comets are merely the effect of it.[400]

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[397] For Wright's theory of the Milky Way and its influence on Kant see: Schaffer, "The Phoenix of Nature," pp. 180–200.

[398] Kant, *Cosmogony*, pp. 38–39.

[399] Ibid., p. 47.

[400] Ibid., p. 55.

Since the orbit of the last planet of the solar system is still less eccentric than the orbit of comets, Kant predicts that new planets may be discovered beyond Saturn. These new planets will have orbits more eccentric than Saturn's orbit and therefore their character will be closer to comets than to planets. Because the planets beyond Saturn are moving in very eccentric orbits and would be visible in a short period during their perihelion, their discovery will not be a simple task.[401]

In Kant's account of formation of the planets, the primitive elementary matter that was moving around the sun was distributed in such a way that the particles with higher specific gravity (and therefore with higher velocity and more stable orbits) were closer to the sun. Consequently, when the planets were formed from the primitive matter, the planets closer to the sun were denser than the distant ones.[402] Therefore, comets which were formed far away from the outermost planets of the solar system should be composed of the most subtle particles of the primitive matter of the solar system.

Although in the outer parts of the primitive solar system a great amount of light material existed, the process of accumulation of these particles to form larger objects was too slow. This situation was a consequence of the feeble attraction between the particles (due to their low specific gravity), and their vast diffusion. Unlike the material in the inner parts of the solar system, which had been confined to a certain plane, the outer parts were scattered. As a result, instead of forming a few large planets, numerous small bodies were formed in different distances from the plane of solar system. For that reason, comets are abundant and moved at different orbits not limited to a particular plane.[403]

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[401] Ibid., p. 55. Kant's prediction came true in his lifetime: Uranus was discovered in 1781 by William Herschel.

[402] Ibid., pp. 71–75. Kant criticizes Newton's idea that the Creator situated denser planets closer to the sun because they can endure more of its heat. He argues that in this case the surface material of the earth should be much denser for the reason that the sun has no effect on the interior parts of the planet. Kant also states that "Newton was afraid that if the earth were plunged in the rays of the sun, as near as Mercury, it would burn like a comet, and that its matter would not have sufficient fire-resisting power not to be dissipated by such heat." (Ibid., p. 74; the original text is: "Newton befürchtete, wenn die Erde bis zu der Nähe des Mercurs in den Strahlen der Sonne versenkt würde, so dürfte sie wie ein Komet brennen und ihre Materie nicht genugsame Feuerbeständigkeit haben, um durch diese Hitze nicht zerstreuet zu werden." See Kant, *Allgemeine Naturgeschichte und Theorie Des Himmels oder Versuch von der Verfassung und dem mechanischen Ursprungedes ganzen Weltgebäudes, nach Newtonischen Grundsätzen abgehandelt* (Leipzig: 1755, p. 41, emphasis is mine). However, in the *Principia*, where Newton compares the heat that Mercury and the earth obtain from the sun, he does not state that comets burn: "If the earth were located […] in the orbit of Mercury, it would immediately go off in a vapor," (Newton, *Principia*, p. 814). In the major post-Newtonian cometary works the idea of the burning of comets was held by Voltaire (see chapter five, above), however, Kant does not mention the source of this idea.

[403] Ibid., pp. 86–89. One of the conclusions of this reasoning is that the direction of revolution of the planets and comets must be the same. Kant points out this issue and states that the retrograde comets may have seen due to an optical illusion. Ibid., p. 88.

The material from which comets were formed contained the lightest particles of the primitive matter. The coma and tail of a comet are composed of subtle particles that can be detached from the body of a comet by the action of the sun. However, contrary to Newton, Kant attributes the major role to the sun's rays rather than its heat. His reasoning is based on the observation of cometary tails in comets with perihelia as far as the distances of Venus or the earth from the sun. Kant also refutes the idea that comets can preserve heat from their previous approaches to the sun.[404]

Finally, Kant expresses his theory of tail formation. Having disproved the role of solar heat in the process of the formation of tails, he adopts the idea that cometary tails are formed in the same way that the Northern Lights are produced. Just as the finest particles are driven from the surface of the earth by the action of the sun's rays to form the Northern Lights, particles of a comet are propelled by the solar rays and produce its coma and tail. Kant, however, is not explicit whether comets originally were encompassed in atmospheres.[405]

Kant's cosmos is not static. The present status of the universe is just one phase of the perpetual evolution of cosmic matter. The universe, which was composed of chaotic primitive matter at the beginning, has configured itself in the form of planets, clusters of planets, stars, galaxies and clusters of galaxies. In a cluster of planets, for example in our solar system, planets, satellites, and comets did not have their present orbits from the beginning. Saturn, for instance, once had an elongated orbit (similar to comets) and by approaching the sun its volatile material evaporated and produced a tail. However, when the planet's orbit was changed in a way that it remained a certain distance from the sun, the evaporated material became diffused and finally surrounded Saturn as its rings.[406] Even the earth might have had a ring consisting of watery vapors which once precipitated and caused the Deluge.[407]

Kant was neither a professional astronomer nor a mathematician; however, his theory of comets embraced several important ideas that had not been expressed before. He developed a theory in which comets were as old as the entire solar system and their formation was a natural consequence of interaction of matter and force in the cosmos. Although Descartes' theory also had the same tone, it did not embrace some important contemporary achievements in observational and mathematical astronomy. Kant, however, built his theory upon the major recent discoveries in the physics and astronomy of comets.

On the other hand, Kant excluded comets from bearing any cosmological role. From this viewpoint, his theory was contrary to almost all cometary theories of the modern era. By placing the trajectory of comets in the extremities of the solar system,

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[404] Ibid., pp. 89–90.

[405] Ibid., p. 90.

[406] Ibid., pp. 101–102. For Kant's evolutionary cosmology see: Schaffer, "The Phoenix of Nature," especially pp. 189–193; Schechner, *Comets, Popular Culture*, pp. 203–205.

[407] Ibid., pp. 117–119. Kant explains that a close approach of a comet or cooling down of the region where the ring was located caused the condensation of the vapor and its precipitation.

Descartes had disconnected all relationships between mankind and comets. By admitting comets' approach to the inner parts of our planetary system, Kant sought their possible influences in the realm of physical sciences, without attributing a providential role to them. Kant, in doing so, freed comets from all teleological connotations.

Kant's cosmology, despite its content, had little influence on contemporary natural philosophers. At the same time that Kant's *Allgemeine Naturgeschichte und Theorie Des Himmels* was ready to be distributed, the publisher went bankrupt and all copies of the book were impounded waiting a court decision. The book was released after about ten years when Kant had already become a well-known philosopher. Nevertheless, it did not attract as much attention as Kant's philosophical writings.[408]

In the same years that Kant's theory of the formation and evolution of comets became known to scholars (after the release of his book from the publishing house in Leipzig in 1765), physical cometology in England was starting a new era in the light of extensive studies in electricity. This era, which is distinguished by attribution of tail formation to electrical phenomena, lasted more than a century. In fact, from the 1760s to the late nineteenth century the electrical theory of comets (based on the idea of the existence of electric matter in comets, electrification of cometary atmospheres and production of electric luminescence) was one of the few admissible explanations of cometary phenomena in astronomical texts. The electrical theory of comets found more credibility after the estimation of the actual mass and size of comets in the late eighteenth century, at a time when the standard Newtonian theory of comets had become no longer applicable to such small bodies.

The Age of Electricity

The eighteenth century witnessed some of the most important advancements in the study of electricity. In this period not only were great discoveries made in production, storage, and transmission of electricity; but also departing from qualitative approaches, the study of electricity became more and more quantitative. On the other hand, electricity found a special position as an intersection point of studies about fire, imponderables, attractive and repulsive forces, and light. What made this situation unique was the possibility of performing experiments in electricity without a need of expensive scientific instruments or costly institutions like observatories. Consequently, from the first years of the eighteenth century, when an improved electric machine was made, to the first years of the nineteenth century, when Voltaic

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[408] For the history of Kant's book on cosmogony see the introduction of Willy Ley in Ibid., pp. *vii–xx*.

piles provided a chemical way to produce and transfer electricity, a great leap was taken in the science of electricity.[409]

In the mid-eighteenth century, studies in electricity provided adequate evidence for physicists to generalize their findings about electrical phenomena to the realm of celestial objects. The Aurora Borealis and cometary tails were two enigmatic phenomena which had close similarities to luminescence produced in electrical experiments. The attribution of celestial luminescence to electric phenomena not only attempted to theorize the formation and properties of those lights, but also attempted to introduce a universal ether responsible for similar phenomena in the earth and the heavens.

In the first years of the eighteenth century, Francis Hauksbee (d. 1713) discovered that when an evacuated globe of glass was rubbed with his bare hand, the globe began to glow. This experiment was done with an electric machine (a great wheel spinning a small wheel attached to the evacuated globe) that was improved by Hauksbee (Fig. 6.6). After performing several experiments with metal globes or glass globes containing mercury, sulphur and other material Hauksbee finally decided to repeat the experiment without placing any substance inside the glass globe. He evacuated the air of the globe with an air-pump and spun it in the dark. When he rubbed the globe with his fingers the glass produced enough light to read in the dark.[410]

Hauksbee's electric machine became more and more developed by improvements made in the design and building of effective air-pumps. By the 1740s with the innovations of Jean Antoine Nollet (1700–1770), the electric machine was able to work smoothly, effectively and generate more electricity. Not only was the machine being used to produce light in the glass globe, 'electricians' were able to transfer the electricity to produce sparks like miniature lightning. They even used sparks to ignite alcohol or other inflammable material.[411]

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[409] For a general history of electricity in the seventeenth and eighteenth centuries see: J. L. Heilbron, *Electricity in the 17th and 18th Centuries* (Berkeley: University of California Press, 1979); Roderick Weir Home, *Electricity and Experimental Physics in Eighteenth-Century Europe* (Brookfield: Variorum, 1992); Edward Tatnall Canby, *A History of Electricity* (New York: Hawthorn Books, 1968); Herbert W. Meyer, *A History of Electricity and Magnetism* (Cambridge: MIT Press, 1971); Roderick Weir Home, "Mechanics and Experimental Physics," in Roy Porter (ed.), *The Cambridge History of Science, Volume 4*, pp. 354–374, especially pp. 363–374; Jonathan Shectman, *Groundbreaking Scientific Experiments, Inventions and Discoveries of the 18th Century* (Westport, CT: Greenwood Press, 2003), pp. 80–91, 95–103.

[410] Hauksbee published several papers explaining his experiments with different materials in the spinning glass globe. For his report of experiment with evacuated globes see: Fra. Hauksbee, "An Account of an Experiment Made before the Royal Society at Gresham College, Together with a Repetition of the Same, Touching the Production of a Considerable Light upon a Slight Attrition of the Hands on a Glass Globe Exhausted of Its Air: With Other Remarkable Occurrences," *Philosophical Transactions*, 25 (1706–1707), 2277–2282. It has to be noted that this experiment had its roots in Jean Picard's accidental discovery that a shaken mercury barometer was glowing in the dark (1676). See: Shectman, *Groundbreaking Scientific Experiments*, p. 84.

[411] Home, "Mechanics and Experimental Physics," pp. 368–369.

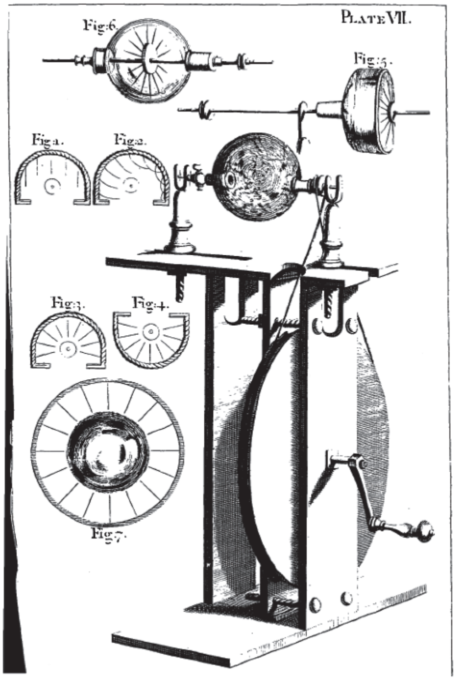

Fig. 6.6 Hauksbee's electric machine, from his *Physico-mechanical experiments on various subjects…* (London: 1709)

The power of the electric machines increased drastically in the second half of the eighteenth century. While a typical machine in the 1740s was capable of generation of less than 5,000 volts with a spark length of about one inch, in 1750 it was able to produce 10,000 volt with a spark length of two inches. These quantities escalated to 30,000 volt and 14 inches in 1773 and 80,000 volt and 24 inches in 1785.[412] This rapid rise in the power of the electric machines was due to remarkable improvements in the design and fabrication of vacuum pumps: the pumps used in Newton's time by Hauksbee or 'sGravesande probably reached to 1/40 or, at best 1/50, atmospheres; however, in the 1770s it reached to 1/165 and a decade later to 1/300 to 1/600.[413]

The luminescence produced in the evacuated glass globes was faint, colorful and hazy. It was not like the sharp sparks produced either by the electric machine or by thunder clouds in the open air. Sir William Watson (1715–1787) in an account of his electrical experiments read before the Royal Society of London in 1752 describes the phenomena of electricity *in vacuo*:

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[412] Heilbron, *Electricity in the 17th and 18th Centuries*, p. 83.

[413] Ibid., p. 82. As we know from modern physics, the intensity of glow in a vacuum tube (or the passage of electricity in it) is related to the pressure of air in the tube or the glass globe.

> […] the electricity, meeting with scarce any resistance, passed from the top to the bottom of the tube […] and it was a most delightful spectacle, when the room was darkened, to see the electricity in its passage […] that is to say, thirty-two inches, and of a bright silver hue. These did not immediately diverge as in the open air, but frequently, from a base apparently flat, divided themselves into less and less ramifications, and resembled very much the most lively coruscations of the *aurora borealis*.[414]

Watson's conjecture was proven in a different way by Benjamin Franklin (1706–1790). In 1752, Franklin discovered that lightning and the sparks produced by the electric machine had the same nature. In a manner similar to that of Newton's discovery proving that the phenomena of the falling of an apple and orbiting of the moon around the earth had the same cause, this discovery showed that electricity was no longer a mere laboratory phenomenon. It was an agent effective at least on planetary scales. Electricity, as one of the most powerful forces in the world, found a new value for philosophers in their explanation of nature.

Franklin's theory of electricity was based on the concept of excess or deficiency of an electric fluid in bodies. Unlike Charles Dufay (1698–1739), who believed that two kinds of electric fluid were responsible for the attraction and repulsion between electrified bodies, Franklin advocated the idea that all electric phenomena were the manifestations of the action of only one fluid. All matter, besides its normal mass, contained an electric fluid in a regular quantity. However, under certain conditions, a body could undergo a loss or gain of the electric fluid and become electrified. Thus, a natural body by gaining an excess of electric fluid became 'positive' and could attract a 'negative' body, which had a deficiency of electric fluid. Equally electrified objects (negative or positive), however, repelled each other.[415]

When the air, and along with it the rarified vapor rising from the oceans between the tropics, moves towards the polar region, it carries the electrical fire (Franklin uses the terms *fluid* and *fire* interchangeably) associated with the vapors. The electrical fire is not visible unless it moves from body to body or from particle to particle through the air. It is also invisible when it moves through dense bodies. That is why when a "wire makes part of the circle, in the explosion of the electric phial, the fire, though in a great quantity, passes in the wire invisibly."[416] However, when the fire passes from a denser body to a lighter one it becomes apparent. It is analogous to

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[414] William Watson, "An Account of the Phenomena of Electricity in Vacuo, with Some Observations Thereupon," *Philosophical Transactions*, 47 (1751–1752), 366–367. In electricity, Watson's fame rests on his theory of charge conservation which states that bodies normally have equal density of electrical fluid or ether. However, if the density of the electric fluid is unequal in different bodies, the fluid will flow and will be seen as an electric discharge. In other words, his theory says that electricity can not be created or destroyed but only can be transferred from one object to another. See: Idem, "A Sequel to the Experiments and Observations Tending to Illustrate the Nature and Properties of Electricity," *Philosophical Transactions* 44 (1746–1747), 704–749, especially p. 742.

[415] Franklin, Benjamin, *Experiments and Observations on Electricity. Made at Philadelphia in America* (London, 1751), pp. 51–55.

[416] Ibid., pp. 45–46.

the flow of water from a tube. When the one end of a water-filled tube is opened, although the water flows from the open end, it actually moves from the closed end towards the open end. In the same way,

> […] the electric fire [which] discharges into the polar regions, perhaps from a thousand leagues length of vaporiz'd air, appears first where 'tis first in motion, *i.e.* in the northern part, and the appearance proceeds southward, tho' the fire really moves northward. This is supposed to account for the *Aurora Borealis*."[417]

Franklin's theory of electricity in general, and his conjecture about the formation of the Aurora Borealis in particular, had an influential role in the application of electrical theories in planetary sciences. In 1753, John Canton (1718–1772), a Fellow of the Royal Society, based on his several electrical experiments and observations of thunder clouds, conjectured that the Northern Lights might be a consequence of some electrical phenomena in the upper atmosphere (Fig. 6.7). He concluded his letter, read in December 6, 1753 before the Royal Society, as follows:

1. May not air, suddenly rarefied, give electrical fire to, and air suddenly condensed, receive electrical fire from, clouds and vapours passing through it?
2. Is not the aurora borealis, the flashing of electrical fire from positive, towards negative clouds at a great distance, through the upper part of the atmosphere, where the resistance is least?[418]

Although Franklin, Canton, and others[419] tried to use the newly developed physics of electricity to explain atmospheric phenomena such as the Aurora Borealis, they mostly concentrated on experimental aspects of electricity. Though there was a tradition assuming cometary tails to be the Aurora Borealis of comets, neither Franklin

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[417] Ibid., p. 46.

[418] John Canton, "Electrical Experiments, with an Attempt to Account for Their Several Phenomena; Together with Some Observations on Thunder-Clouds," *Philosophical Transactions*, 48 (1753–1754), 357–358. Canton, in a letter to the president of the Royal Society, shows how electricity became a focus of interest after Franklin's demonstration of the electric origin of the lightning: "My Lord, as electricity, since the discovery of it in the clouds and atmosphere, is become an interesting subject to mankind; your lordship will not be displeased with any new experiments or observations, that lead to a farther acquaintance with its nature and properties." See: John Canton, "A Letter to the Right Honourable the Earl of Macclesfield, President of the Royal Society, concerning some new electrical Experiments," *Philosophical Transactions*, 48 (1753–1754), 780.

[419] George Matthias Bose (1710–1761), Joseph Priestley (1733–1804) and Giambatista Beccaria (1716–1781) were among those who envisaged a relation between electrical phenomena and the aurora borealis. Priestley says that Beccaria "thinks that the *Aurora Borealis* may be this electric matter performing its circulation, in such a state of the atmosphere as renders it visible, or approaching nearer to the earth than usual"; and "Signior Beccaria adds, that when the *Aurora Borealis* has extended lower than usual into the atmosphere, various sounds, as of rumbling, and hissing, have been heared." See Priestley, *The History and Present State of Electricity*, vol. 1, pp. 410, 436. Priestley himself takes for granted that the aurora had an electric origin: "That the *Aurora Borealis* is an electrical phenomenon was, I believe never disputed, from the time that lightening was proven to be one." Ibid., p. 436. See also Schechner, *Comets, Popular Culture*, pp. 181–187.

nor Canton extrapolated their electrical observations to the cosmic realm. A major problem that had to be solved was the nature of the electrical ether and its relation to the universal ether responsible for gravitation or propagation of light.[420] Thus, electricity was still limited to the boundaries of our planet.

Franklin's theory of electricity introduced a kind of fluid composed of extremely subtle particles that could permeate even the densest metals without receiving any perceptible resistance. The common matter, which is like a kind of sponge to the electric fluid, contains as much electrical matter as is normally possible. If more electric fluid is added, the extra fluid will remain on the surface of the body and create an *electrical atmosphere*.[421] This atmosphere functions as a medium to communicate the short-range forces of attraction or repulsion between the electrified bodies.

Franklin's concern was not to develop a systematic theory of ether; his main project was to explain the electric phenomena and that his electric fluid was able to account for electrification of objects. However, Franklin's electric fluid was a new concept that needed to find its place among other concepts of the ether. It was not like the Newtonian ether, which acted at long-range, nor like the ether that was assumed as the fluid of heat and permeated the whole of a body's volume instead

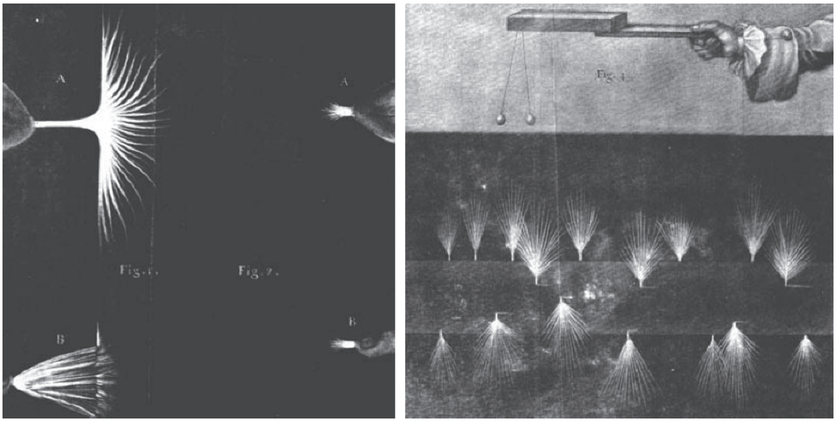

Fig. 6.7 Canton's demonstration of the different shapes that the electrical matter finds during its discharge (From Canton, "A Letter … concerning Some new electrical Experiments, 1754) According to Joseph Priestley, "the most beautiful of all experiments that can be exhibited by the electric light is Mr. Canton's aurora borealis"[422]

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[420] Franklin did not have a well-defined theory of a universal ether. In one of his last papers, he assumed, like Newton, that the ether was a medium where the light-producing vibrations were formed. His ideas about the fluid of heat, electric matter and subtle fluid producing light are discussed in: Cohen, *Franklin and Newton*, pp. 320–343, especially pp. 340–343.

[421] Franklin, *Experiments*, pp. 51–52.

[422] Joseph Priestley, *The History and Present State of Electricity, with Original Experiments*, 3rd ed., 2 vols. (London: 1775), vol. 2, p. 162.

of staying on its surface.[423] Thus, any explanation of interplanetary phenomena (such as cometary tails) based on the electric fluid required a unified theory of ether, or at least a theory capable of demonstrating the function of the electric matter in the presence of a universal ether.

While theorizing such an inclusive theory of electrical ether required further developments in understanding the various aspects of electrical phenomena, natural philosophers tried to construct electric theories of aurora and cometary tails without involving sophisticated problems arising from different concepts of ether. In fact, they tried to isolate the formation of cometary tails or the Northern Lights from the influence of the Newtonian ether and to consider them as local atmospheric phenomena. By this approach, the earth or a comet was treated as an object that could be electrified and this electrification could be manifested in its atmosphere. Hugh Hamilton was one of the first natural philosophers who considered this line of thought.

Hugh Hamilton (1729–1805)

Hamilton, a professor of natural philosophy at the University of Dublin and a Fellow of the Royal Society, generalized Franklin's theory of electrification to the entire solar system. His explanation of the Aurora Borealis and cometary tails was based on two assumptions: first, he assumed that the electric matter existed in the planets as well as comets, and second, he theorized the possibility of electrification of an entire planet or a comet.

In an essay published several times, Hamilton starts his theory by criticizing the Newtonian explanation of the formation of cometary tails in the solar atmosphere. Hamilton denies the existence of such atmospheres; and to show the difficulties in Newton's theory, he assumes that the tail extends into the sun's atmosphere.[424]

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[423] For different models of the ether in the eighteenth century see: Cantor and Hodge, "Introduction," pp. 29–31.

[424] Hugh Hamilton, *Philosophical Essays on the following Subjects. I. On the Ascent of Vapours, the Formation of Clouds, Rain and Dew, and on several other Phœnomena of Air and Waters. II. Observations and Conjectures on the Nature of the Aurora Borealis, and the Tails of Comets. III. On the Principles of Mechanicks*, 2nd ed. (London: 1767), pp. 90–91. It is interesting that Hamilton not only fails to mention the observation of the white glow around the eclipsed sun (the solar corona which was assumed to be the solar atmosphere by his contemporaries), but also is silent about all theories which had been developed to explain the zodiacal light, in all of them the existence of a solar atmosphere (with various extensions) was admitted. Accepting a solar atmosphere would create a major difficulty in Hamilton's theory regarding the possible attraction or repulsion between the solar atmosphere and cometary tails. Although Hamilton does not discuss this specific subject, it seems that by admitting a solar atmosphere he would not be able to explain the shape and orientation of cometary tails in the vicinity of the sun.

He argues that the rarefied vapor of a tail would encounter an immense resistance in the denser atmosphere of the sun. As a result, the tail could not be extended directly opposite to the sun and would have to be seen in the parts that the comet has left. Since observations do not support this assumption, Hamilton concludes first that celestial space is void of resisting matter, and second that the formation of the tails diametrically opposite to the sun (while the comet is moving inside the dense atmosphere of the sun) must have another cause.[425]

Hamilton finds the substance of tails also a major difficulty in Newton's theory. He asks, if the particles of a tail have the capability of reflecting light and growing hot due to the reflection of the sun's rays, why do they not have any effect on stellar rays. A typical tail, with its vast thickness, not only does not diminish the light of the stars behind, it also does not increase their twinkling. From these observations Hamilton deduces that the tail material has no power of reflection and consequently tails are made up of a self-luminous substance. Hamilton comes to the same result by reasoning that cometary tails do not have the power of refraction. If they refracted light, one would see a double image of a star behind the tail of comet, which is contrary to observations (Fig. 6.8). Thus, the material of tails, which has no power of refraction or reflection of light, must be a lucid substance.[426]

In the next step, Hamilton tries to find analogies between cometary tails and the Aurora Borealis. He concludes that the tail, which is thrown off from the dark side of a comet, does not consist of aqueous or other vapors, is not lit by the sun's rays, and does not grow longer due to the density of any circumambient medium. The only phenomenon that resembles it is the Aurora Borealis, and the luminous substance we observe in both seems to be the same. The aurora is seen in the dark hemisphere of the earth, its luminous matter does not have any power of refraction or reflection, and since it is formed diametrically opposite to the sun, it is not lit by the sun's rays. Furthermore, as the tail of a comet appears only in a part of its orbit (right before and after perihelion), the Aurora Borealis also is seen from the autumnal to the vernal equinox.[427]

Having established the similarity between the substances of the Aurora Borealis and cometary tails, Hamilton suggests that the substance is only electric matter that is very rare, subtle, and shining and that its behavior in the evacuated glass globes of electric machines is very much similar to that of cometary tails and the Aurora Borealis. A body electrified in air (in its common state of density) discharges its electric matter suddenly and produces bright sparks of which lightning is the best example. However, when discharging occurs in rarified air (as in the evacuated jars of electric machines) the process takes place steadily and small streams of faint light appear. In the same way, when the vapors carry the electric matter into the higher elevations, where the atmosphere is much rarified, "they must discharge it in continued

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[425] Ibid., p. 92. Hamilton's description of Newton's theory is confusing. He only discusses the tail formation when a comet approaches too close to the sun to enter its so-called atmosphere.

[426] Ibid., pp. 95–97.

[427] Ibid., pp. 100–102.

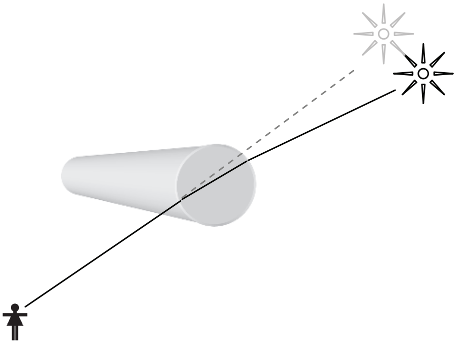

Fig. 6.8 According to Hamilton, if the substance of cometary tails had the power of refraction, the image of stars behind the tail would be doubled

Streams of faint Light, […] and those Streams of Light in the higher Parts of the Atmosphere must exactly represent to us the Appearance of an *Aurora Borealis*." [428]

A similar process may occur in comets. A comet, like the earth, contains electric matter; however, it comes much closer to the sun than the earth and absorbs a great amount of heat. Electrical experiments show that any body, if sufficiently heated, becomes a conductor and lets the electric matter pass through it easily. Thus, when a comet acquires heat in the vicinity of perihelion, it becomes a good conductor and throws off its electric matter, which it may possibly contain in a great amount.[429] Hamilton conjectures that comets do not rotate and, like the moon, they always keep one hemisphere towards the sun. Thus, like the earth where electric matter goes off from the hotter side to the colder side and creates the Aurora Borealis, the electric matter of a comet is ejected towards its colder hemisphere and forms a tail opposite to the sun. Since electrical experiments have shown that the electric matter passes off pointed bodies better than round bodies, the dark hemisphere of a comet possibly is formed so.[430]

Although Hamilton's theory of comets is basically non-Newtonian, it employs a cosmological concept that was essential in Newton's theory of comets. Like Newton, Hamilton believes that comets circulate a spirit in the universe; however, he substitutes electric matter for Newtonian replenishing vapors. As the phenomenon of the Aurora Borealis spreads terrestrial electric matter in the high atmosphere and then in void space, a similar process steadily passes off the electric matter of the other planets. Comets collect and redistribute this electric matter in such a way that the planets, in their courses around the sun, reabsorb their lost electric matter gradually.[431]

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[428] Ibid., p. 105.

[429] Ibid., p. 113.

[430] Ibid., pp. 114–115. Hamilton first points out that a comet, like the moon, to keep its one side towards the sun should be an oblong spheroid.

[431] Ibid., pp. 123–126.

Hamilton's idea of supplanting Newtonian replenishing moisture with electric matter was based on the results of electrical experiments as well as experiments in chemistry, done by Boerhaave and Woodward. This approach marks a turning point in the refutation of Newton's cosmological ideas about comets: while other critics of Newton's theory of comets expressed their ideas in qualitative and philosophical frameworks, Hamilton exploited experimental results to show that the Newtonian idea of the transformation of moistures into earth was not valid, and consequently the role of comets in the circulation of moisture to replenish the earth and the planets was absurd:

> Dr. *Boerhaave* […] affirms from his own Experience, that pure elementary Water cannot, by repeated Distillations, or otherwise, be converted into Earth. […] So that there seems to be no Necessity for supposing a gradual Decay of Moisture in any of the Planets."[432]

Hamilton concludes that the frequency of cometary appearances is not compatible with their acting to compensate the lost moisture of the planets. Although he does not build this idea upon mathematical calculations, he says that if comets were to supply moisture to the planets, none of them would serve more than once. He asks if the sun's heat drives out comets' moisture in their perihelia, where can they obtain a fresh supply afterwards? Thus, the dried comets would move regularly in their orbits without any use and this 'is not agreeable to the Œconomy of Nature."[433] Even if any vapor or effluvia of moisture could arise from the planets, this moisture would not have enough elasticity and heat to be expanded into a large volume and be captured by comets.

Contrary to aqueous vapor, electric matter, because of its subtlety and velocity, can leave the planets and move long distances in interplanetary space.[434] The electric matter moves without encountering any resistance and can glow not by reflecting or refracting of the sun's rays but by itself. All of these properties are compatible with the features of cometary tails and supportive of the idea that a tail cannot be composed of aqueous vapors moving due to its density in a medium. Hamilton concludes that the 'spirit' that Newton referred to as a required substance for life is this electric matter that comets collect and redistribute in the universe.[435]

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[432] Ibid., p. 128. Hamilton also refers to experiments done by John Woodward (1665–1728) which showed something from air or the earth, aside from water, is needed for the nourishment of the planets. For Woodward's results see: John Woodward, "Some Thoughts and Experiments Concerning Vegetation," *Philosophical Transactions* 21 (1699), 193–227.

[433] Ibid.

[434] Hamilton in his description of the aurora seen in March 1716 says that the electric matter rose so high that it was seen from Ireland to Poland and western Russia, or extended at least over 30 degrees of longitude and from the 50th latitude over almost all the north of Europe. According to Hamilton, an imaginary spectator placed at a considerable distance from the earth would see the aurora as a train of light, like a cometary tail, extended from the north pole of the earth. Ibid., pp. 99–100.

[435] Ibid., pp. 129–130. Hamilton refers to Newton's conclusion about the nature of cometary tails in proposition 41 of book 3 of the *Principia*: "Further, I suspect that that spirit which is the smallest but most subtle and most excellent part of our air, and which is required for the life of all things, comes chiefly from comets." See: Newton, *Principia*, p. 926.

Hamilton's theory bridged Newton's theory of comets and Franklin's theory of electricity, and for this reason his theory remained one of the most accepted explanations of cometary phenomena until the first decades of the nineteenth century. In the second half of the eighteenth century, the age of Newton, Franklin appeared as a prominent exemplar of an experimental philosopher, whose discoveries not only opened a new era in electricity but demonstrated the power of Newtonian experimental physics. Although electricity became a discipline in natural science only after Newton's death, it was developed in the framework of Newtonian experimental philosophy. However, contrary to Newton's sophisticated *Principia* or *Opticks* which had little to attract ordinary peoples' attention, electricity had fascinating aspects often demonstrated in public. Among the many useful applications of electrical studies was the invention of the lightning rod by Franklin, which could save buildings, ships, and lives.

Franklin's influence on the development of the physical sciences was not limited to his electrical experiments. He introduced electricity as one of the basic agents in the universe with the same importance as light, gravity, and heat. Consequently, electricity became one of the key concepts in explanation of terrestrial, planetary, and cosmic phenomena. As Cohen wrote, after Franklin's studies, "every experimenter rubbing glass tubes in his laboratory knew that he was studying cosmic forces on a small scale."[436]

Although Hamilton's electrical explanation of cometary tails had its own difficulties, it was not as inconsistent as Newton's theory. He did not delineate the curvature of cometary tails nor did he propose a satisfactory theory for the brightness of the leading edge of a tail.[437] His theory was based on the existence and function of an effluvium; not only were its different aspects demonstrable experimentally, its powerful operation in a planetary scale had been proven by Franklin.

Hamilton employed only general electrical concepts in treating cometary phenomena without applying any specific law or theory developed by the 'electricians' of his time. He found the concept of electric fluid a capable tool to account for cometary tails, but he did not move further to study the possible interactions of celestial bodies as electrified objects. While laboratory experiments, especially those of Benjamin Franklin, had shown in detail the behavior of charged bodies when they met, Hamilton, despite assuming the planets were electrified bodies, did not extrapolate those laboratory results into a planetary scale. Consequently, subjects like the possible impact of comets and planets or attraction and repulsion between the cometary and planetary atmospheres are not discussed in his theory.

Hamilton's theory of tail formation, along with two others – Newton's theory, which admitted solar heat as the driving force of tails, and Euler-Mairan's theory,

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[436] Cohen, *Franklin and Newton*, p. 287.

[437] Although Hamilton mentions that the curvature of a tail is not due to any resisting matter in space and it only appears because of rapid motion of comet's head relative to the extremities of the tail, he attributes the brightness of the leading part of a tail to a condensation in fore parts of a tail due to a slight resistance of subtle ether. See Hamilton, *Philosophical Essays*, pp. 120–131.

which attributed a driving force to the sun's rays – remained the main cometary theories until the first two decades of the nineteenth century. A brief survey of treatises on comets, encyclopedias and general astronomical texts of the late eighteenth century and early nineteenth century shows that in some cases the electrical theory of comets was introduced as the best interpretation of the cometary phenomena.[438]

While the subject of 'comets' in the first edition of the *Encyclopædia Britannica* (1771) was defined completely based on Newton's theory of comets in only two columns,[439] the same entry in the second edition (1778–1783) occupied more than 14 columns, about a third of it concerning Hamilton's theory.[440] The third edition of the *Encyclopædia Britannica* (1797) defines comets in a manner similar to its second edition but contains extra diagrams and explanations about some newly appeared comets.[441] Chambers' encyclopedia treats Hamilton's theory as one of the major contemporary theories of tail formation[442]; Charles Burney (1724–1814) gives a full account of Hamilton's theory along with other theories in his *History of Principal Comets* in 1769[443]; Thomas Vivian (1722–1793) in his *Cosmology* (1791) mentions the analogy between electric phenomena and cometary tails[444]; Samuel Vince (1749–1821) in his encyclopedic work entitled *A Complete System of Astronomy* (1797) describes all three theories[445]; Margaret Bryan (*fl.* 1815) in her popular book of astronomy (1799) portrays tails as the stream of fire coming out of the insulated jar of an electric machine[446]; Charles Hutton (1737–1823) in his *Astronomical Dictionary* (1817) ends his description of cometary tails with Hamilton's refutation of Newton's theory and stresses the affinity of the effluvia of

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[438] This brief survey only covers those writings in English which discuss the physics of comets.

[439] *Encyclopaedia Britannica: or, a Dictionary of Arts and Sciences, Compiled upon a New Plan in which The different Sciences and Arts are digested into distinct Treatises or Systems, And the various Technical Terms, etc., are explained as they occur in the order of the Alphabet*, 3 vols. (Edinburgh: Printed for A. Bell and C. Macfarquhar and sold by C. Macfarquhar, 1771), vol. 1, pp. 444–445. Comets are defined under the general entry of 'Astronomy.'

[440] *Encyclopaedia Britannica,…*, 2nd ed,. 10 vols. (Edinburgh: Printed for J. Balfour, 1778–1783), vol. 2, pp. 761–769.

[441] *Encyclopaedia Britannica,…*, 3nd ed,. 10 vols. (Edinburgh: 1797), vol. 2, pp. 445–470.

[442] Ephraim Chambers, *Cyclopædia, or an Universal Dictionary of Arts and Sciences*, 5 vols. (London: 1778–1788), vol. 1, pp. 905–906.

[443] Charles Burney, *An Essay Towards a History of the Principal Comets that have Appeared since the Year 1742. Including a particular Detail of the Return of the famous Comet of 1682 in 1759, according to the Calculation and Prediction of Dr. Halley. … With Remarks and Reflections upon the Present Comet. To which is prefixed, a Letter upon Comets, Addressed to the Late M. de Maupertuis written in the year 1742* (London: 1769), pp. 81–85.

[444] Thomas Vivian, *Cosmology, An Enquiry into the Cause of what is called Gravitation or Attraction, in which the Motions of the Heavenly Bodies, … are deduced …* (Bath: 1791), pp. 103–106.

[445] Samuel Vince, *A Complete System of Astronomy* (Cambridge: 1797), pp. 444–446.

[446] Margaret Bryan, *A Compendious System of Astronomy, in a Course of Familiar Lectures, in which the Principles of that Science are clearly elucidated, so as to be intelligible to those who have not studied the Mathematics…* (London: 1799), p. 126.

tails to that of electric bodies[447]; James Ferguson (1710–1776) in his comprehensive book of astronomy mentions Newton, Mairan, and Hamilton[448]; and finally William Phillips in his general astronomy text (1818) mentions the theory that explains the Aurora Borealis and cometary tails as electrical phenomena.[449]

It is true that in the second half of the eighteenth century the electric explanation of cometary tails was admitted as one of the plausible ways of theorizing tail formation, but it was not the most promising one. Studies in the nature of light and the interaction of light and matter had a direct influence on the theories of cometary tails. While Newton's theory of tail formation was the target of widespread criticism because of its several challenging problems, those theories which attributed a driving force to the sun's rays were gaining more weight. The core concept of these theories – the pressure of light – was a major problem in all theories of light and coincidently was a subject of calculation and experiment by physicists in the second part of the eighteenth century. Any evidence proving that light exerts a force on bodies was a great asset for Euler's or Mairan's theory.

Throughout the eighteenth century there were three major theories of light: (1) The corpuscular theory of Newton that maintained that particles of light traveled from the source to a receptor; (2) an impulse theory, according to which light consisted of impulses transmitted in the ether (this theory which was developed by Huygens had its roots in Descartes' theory of light); (3) and a wave theory, developed by Nicolas Malebranche (1638–1715) and Leonhard Euler, suggested that light was composed of displacement waves in an elastic ether. There were also two other theories, the first maintained a fluid of light, and the second, developed by Roger Boscovich (1711–1787), was a version of Newton's corpuscular theory in which the particles of light had an extended influence in space. All of these theories gave different answers to the problem of the pressure of light.[450]

In Euler's theory, light propagated as vibrations in a medium and even if it was able to transfer a force, the final motion of a particle influenced by these vibrations

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[447] Charles Hutton, *An Astronomical Dictionary Compiled from Hutton's Mathematical and Philosophical Dictionary, to which is prefixed an introduction Containing a brief history of Astronomy, and a familiar illustration of its elementary principles by Nathan S. Read* (New-Haven:1817), pp. 45–48.

[448] James Ferguson, *Ferguson's Astronomy, Explained upon Sir Isaac Newton's Principles, with notes and supplementary chapters by David Brewster*, 2 vols. (Philadelphia: Printer by and for Abraham Small, 1817), vol. 1, pp. 354.

[449] William Phillips, *Eight Familiar Lectures on Astronomy* (New York: James Eastburn, 1818), p. 84.

[450] See: Morton L. Schagrin, "Early Observations and Calculations of Light Pressure," *American Journal of Physics* 42 (1974), pp. 927–929; Home, "Mechanics and Experimental Physics," pp. 363–366. For a review of theories of light in the eighteenth century, see: Casper Hakfoort, *Optics in the Age of Euler: Conceptions of the Nature of Light, 1700–1795* (Cambridge: Cambridge University Press, 1995); Geoffrey Cantor, *Optics after Newton: Theories of Light in Britain and Ireland*, 1704–1840 (Manchester: Manchester University Press, 1983); Eugene Frankel, "Corpuscular Optics and the Wave Theory of Light: The Science and Politics of a Revolution in Physics," *Social Studies of Science* 6 (1976), 141–184.

(such as a particle in a given cometary tail) would be a back-and-forth motion. Mairan, criticizing Euler, maintained that such a vibratory motion could not cause the vast expansion of cometary tails. With the assistance of Charles Dufay (the famous electrician) Mairan tried to devise an experiment to demonstrate that the sun's light could push forward small bodies. They built a very light fan, like a paddle wheel, with six blades and focused light on one of the blades. The fan started to rotate but they soon realized that the fan was rotating due to the convective heat effects rather than light pressure.[451] Although Mairan's experiment failed, his objection to Euler's theory was still valid and the type of motion that light could cause in a tail's particles remained an open question.

Studies on the nature of light had mathematical and computational aspects too. The size of the particles of light, the space between them, and their quantity were among the issues that physicists tried to calculate. Benjamin Martin (1704–1782) attempted to calculate the number of light particles emitted by a candle in one second; Pieter van Musschenbroek (1692–1761), Thomas Melvill (1726–1753), and Partrick D'Arcy (1725–1779) estimated the space between the particles of light; and Samuel Horsley (1733–1806) and John Mitchell (1724–1793) aimed to calculate the momentum of the particles of light.[452]

Although there was widespread enthusiasm for mathematization of the corpuscular theory of light, some fundamental questions about the nature and behavior of these particles were still unanswered. For example, Benjamin Franklin in his article that appeared in 1756 refuted the basic concepts of the corpuscular theory in favor of the theory of a light fluid, though the supporters of the wave theory also benefitted equally. He questioned the magnitude of the force that would be needed to shoot the particles of light from the sun in order to travel the immense intervening space in a relatively short time; he argued that the particles of light should sweep and push forward the fine particles of dust in the earth's atmosphere; and he wondered why the sun had not been diminished and consequently the orbits of planets had not been changed from ancient times.[453]

Franklin's objection was welcomed by supporters of the theory of the imponderable fluids which treated light, electricity, and heat similarly. From the 1760s, and mainly through the studies of Joseph Black (1728–1799) the *igneous* or heat fluid was defined in the same way that electric matter was characterized: The particles of heat fluid (or *caloric* as it was named by Lavoisier in 1787) unlike ordinary matter,

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[451] Schagrin, "Early Observations and Calculations of Light Pressure," pp. 931–932; *Idem*, "Experiments on the Pressure of Light in the 18th Century," *Akten des Internationalen Leibniz-Kongresses…,* Band II (1974), pp. 217–239.

[452] Ibid., pp. 933–935. According to Martin, a candle emits 4.1×10^{44} particles and each particle has a mass of less than 10^{-6} of a grain (one grain = 0.0648 g). The average space between the particles of light was calculated to be in the order of magnitude of 10^{-16} of the size of a hair. For John Michell's innovative ideas on light see: Simon Schaffer, "John Michell and Black Holes," *Journal for the History of Astronomy* 10 (1979), 42–43.

[453] Ibid., p. 934. Franklin first stated his doubts in a letter to Cadwallader Colden in 1752 and read to the Royal society in 1756.

repelled one another but were attracted to the particles of ordinary matter.[454] Lavoisier in collaboration with Laplace included caloric among material bodies in his *Traité élémentaire de chimie* (1789), and Laplace, using the concept of caloric, defined the mass points as the seat of gravitational and other attractive forces surrounded by atmospheres of self-repellent caloric.[455]

At the conclusion of the eighteenth century, none of the three major theories of light could be treated as the most acceptable one and all of them held almost the same status regarding supportive theoretical and experimental evidence. However, from the beginning of the nineteenth century, the theoretical and experimental studies of Thomas Young (1773–1829), Humphry Davy (1778–1829) and Count Rumford (1753–1814) produced enough evidence to show the insufficiencies of caloric theory. They laid down the foundations of a kinetic theory of heat, which led to the development of thermodynamics. The concept of a fluid of light began to be abandoned when Thomas Young, his younger French colleague Augustin Fresnel (1788–1827), and Simoén Denis Poisson (1781–1840) illustrated the wave nature of light in different experiments.[456]

These achievements, however, did not bring cometary scientists closer to a plausible answer regarding the formation of tails. For example, Young and Fresnel to explain the phenomenon of polarization of light, suggested that light waves were transverse, that their vibrations were perpendicular to the direction of propagation. But the only transverse waves known to them were those that propagated in a solid medium. To transmit a transverse wave there must be a kind of resistance in the medium to reposition it to its original status when deformed. Liquids and gases do not have this property. Thus it was required to define the luminiferous ether as a

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[454] Gerald Holton, *Physics, the Human Adventure: From Copernicus to Einstein and Beyond* (New Brunswick: Rutgers University Press, 2001), pp. 234–235; Lissa Roberts, “A Word and the World: The Significance of Naming the Calorimeter,” *Isis* 82 (1991), pp. 198–222.

[455] Bruce R. Wheaton, “Heat and Thermodynamics,” in W. F. Bynum, E. J. Browne, Roy Porter, eds. *Dictionary of the History of Science* (Princeton: Princeton University Press, 1981), pp. 179–182. For a review of chemical physics of heat developed by Lavoisier and Laplace see: Charles Coulston Gillispie, “Laplace, Pierre-Simon, Marquis de,” in Charles Coulston Gillispie, ed., *Dictionary of Scientific Biography*, 16 vols. (New York:Charles Scribner’s Son, 1972), vol. 15, pp. 312–316.

[456] In Young’s double slit experiment, a monochromatic light is passing from two very narrow parallel slits which are cut into a non-transparent sheet. On a screen located at a distance to the slits a pattern of alternating light and dark regions appears. This effect can only be interpreted by a wave theory of light: the interference of waves propagating from the two slit create constructive interference when they reinforce, and cause destructive interference when the waves cancel. Poisson based on Fresnel’s wave theory theoretically concluded that it was necessary for a bright spot to appear at the center of the shadow of a circular opaque obstacle. He expected that this unreasonable prediction would disprove Fresnel’s wave theory, but Fresnel (and then Dominique Arago) showed that there was such a bright spot at the center of the shadow. This effect also could be explained by the constructive interference of the diffracted light from the edge of the circular obstacle. See Holton, *Physics*, pp. 347–348.

highly elastic but very rare solid.[457] The behavior of particles of tails in such a medium required a plausible elaboration.

Indeed, the situation of a theoretician of cometary tails in the early nineteenth century was a complicated one. None of the light theories had persuasive answers for a variety of questions related to the interaction of light and cometary matter and the role and properties of ether. Although during the 1830s and 1840s ray methods in optics were replaced by wave methods in England and France (optical activities were relatively small in Germany in this period)[458] there was not enough evidence to expound a theory of tail formation by employing the new concepts developed in the wave theory of light. On the other hand, corpuscular theory was not able to explain new optical discoveries as consistently as the wave theory. Finally, despite the plausibility of those theories that attributed a self-luminous property to the substance of tails, they not only lacked adequate observational evidence but also were unable to explain some aspects of the cometary phenomena (such as the brightness of the leading edge of tails or the expansion of tails to extremely long distances).

Conclusion

The second half of the eighteenth century was the era of parallel theories of cometary phenomena. Although by the work of Newton it had been established that comets move around the sun and obey the laws of gravitation, many questions about the physical and chemical nature of comets were still open. As Thomas Kuhn

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[457] Holton, *Physics*, p. 349. There are a great number of publications about the early nineteenth century debates on the nature of light. A comprehensive technical history can be found in Jed Z. Buchwald, *The Rise of the Wave Theory of Light* (Chicago: Chicago University Press, 1989); the impact of theories of light on the theories of the ether is discussed in *Idem*, "Optics and the Theory of the Punctiform Ether," *Archive for the History of Exact Sciences* 21(1979), pp. 245–278; for a history of optics in the eighteenth century, with an emphasis of Euler's work see: Caspar Hakfoort, *Optics in the Age of Euler, Conceptions of the nature of light, 1700–1795* (Cambridge: Cambridge University Press, 1995), especially pp. 27–72; an analysis of debates on theories of light in the eighteenth and nineteenth centuries is in Peter Achinstein, "Hypotheses, Probability, and Waves," *British Journal for the Philosophy of Science* 41(1990), pp. 117–147; *Idem*, *Particles and Waves: Historical Essays in the Philosophy of Scienc*e (New York; Oxford University Press, 1991); an analysis of Achinstein's work is in Chris Eliasmith, Paul Thagard, "Waves, Particles, and Explanatory Coherence," *British Journal for the Philosophy of Science* 48 (1997), pp. 1–19; for a review of light theories in the first half of the nineteenth century see Xiang Chen, Peter Barker, "Cognitive appraisal and power: David Brewster, Henry Brougham, and the tactics of the emission-undulatory controversy during the early 1850s," *Studies in the History and Philosophy of Science* 23(1992) pp. 75–101; and Xiang Chen, "The Debate on the Polarity of Light, during the Optical Revolution," *Archive for the History of Exact Sciences* (50)1997, pp. 359–393.

[458] Jed Z. Buchwald, "Waves, Philosophers and Historians," *Proceedings of the Biennial Meeting of the Philosophy of Science association*, 2 vols. (Chicago: Chicago University Press, 1992), vol. 2, p. 206.

refers to the history of electricity in the first half of the eighteenth century as an example of the way a science develops before it acquires its first universally received paradigm,[459] cometology was perhaps experiencing the same phase in the second half of the eighteenth century. Newton's explanation of the formation of cometary tails never attained the status of a commonly accepted paradigm.

The absence of a paradigm implies a variety of approaches to explain a phenomenon. The diversity of cometary theories in the time period covered in the present study is a supportive example. It is critical to note that the theory of comets had two distinctive sides which were developing independently, though one might be affected by the results of the other. On the one side, orbit calculators were seeking a higher accuracy in the calculation of the orbital elements of comets, and, on the other side, physicists were trying to discover the nature of comets. Obviously, they were following two intrinsically different methods in their investigations. While the first group had basic tools – the Newtonian laws, mathematical procedures, and instruments for the positional astronomy – to build their theories, the latter had not attained any method to analyse the physics of the remote objects or to generalize the results of the terrestrial experiments into the celestial realm. The only means to gather facts about the celestial bodies was their light and no technique had been developed to study light as a clue to understanding the physical and chemical constitution of celestial bodies.

In the second half of the eighteenth century, mathematical astronomy and celestial mechanics witnessed a great advancement in Europe. However, due to social and historical factors two different aspects of astronomy developed, with different paces in England and on the Continent. While practical astronomy and instrumentation were the center of attention in England, theoretical astronomy started a golden era on the Continent, especially through the works of the French mathematicians.[460] Perturbation theory, a theory that studies the behavior of three or more bodies

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[459] Thomas S. Kuhn, *The Structure of Scientific Revolutions*, 3rd ed. (Chicago: The University of Chicago Press, 1996), p. 13.

[460] The underlying social factors in development of astronomy were not only different in England and France, but also the diverse approaches of the British and the Continental mathematicians to analysis and mechanics brought about different levels of advancement in the calculus-related parts of mathematics. For the differences between the Newtonian calculus and that of Leibniz (which was maintained by the Continental mathematicians) see: Katz, *A History of Mathematics*, pp. 503–531; Boyer, *A History of Mathematics*, pp. 391–414; D. T. Whiteside, "Patterns of Mathematical Thought in the Late Seventeenth Century," *Archive for the History of Exact Sciences* 1 (1961), pp. 173–388; Curtis Wilson, "The problem of perturbation analytically treated: Euler, Clairaut, d'Alembert," in R. Taton and C. Wilson (eds.), *The General History of Astronomy*, vol. 2B, pp. 89–94;Craig Fraser, "Mathematics," in Roy Porter (ed.), *The Cambridge History of Science, Volume 4: Eighteenth-Century Science* (Cambridge: Cambridge University Press, 2003), pp. 305–327; For a history of mathematics in Britain in the eighteenth century see Niccolò Guicciardini, *The Development of Newtonian Calculus in Britain, 1700–1800* (Cambridge: Cambridge University Press, 1989); For a social history of science in France during the second half of the seventeenth century see: Roger Hahn, *The Anatomy of a Scientific Institution, The Paris Academy of Sciences, 1666–1803* (Berkeley: University of California Press, 1971).

attracting each other based on an inverse-square law, was one of those fields in which striking developments directly affected the theories of comets.

A general solution of the three-body problem appeared in the 1740s when Alexis Claude Clairaut (1713–1765), Leonhard Euler (1707–1783), and Jean le Rond d'Alembert (1717–1783) derived a theory of the motion of the moon from the principles of gravitation. Solving the problem of regular acceleration of Jupiter and regular retardation of Saturn (introduced by Halley in 1695) was another problem that led to new developments in perturbation theory through the work of Joseph Louis Lagrange (1736–1813) and Pierre-Simon Marquis de Laplace (1749–1827). However, the most famous application of the theory was the accurate calculation for the return of the comet whose reappearance in 1758 had been announced by Edmund Halley.[461]

Prediction of the return of a comet was not as easy as the calculation of the perturbation of Jupiter and Saturn. The gravitational influence of each planet on the comet should be calculated for the entire course of the comet during its revolutions from 1531 to 1607 (seventy-six years), 1607 to 1682 (seventy-five years), and finally from 1682 onwards, to find the resultant perturbational effect which might be accelerating or retarding. Clairaut, with the aid of Madame Lepaute, accomplished the cumbersome calculations and found that the combined effect of Jupiter and Saturn would delay the return of the comet 618 days and it would not be observable before April 1759. The return of the comet to its perihelion in March 1759 was a triumph of Newtonian laws, as well as the validity of solution methods of the three-body problem. [462]

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[461] Curtis Wilson, "The problem of perturbation analytically treated," pp. 89–107; Pannekoek, *A History of Astronomy*, pp. 299–303;

[462] Regarding the uncertainties in the planetary masses, the perturbative effects of the undiscovered planets, and the problems in the method of approximation, Clairaut's calculations had a fairly small error. See Yeomans, *Comets*, pp. 111–139; Pannekoek, *A History of Astronomy*, pp. 302–303; Curtis Wilson, "Clairaut's Calculation of the Eighteenth-Century Return of Halley's Comet," *Journal for the History of Astronomy* 24 (1993), 1–15; Craig B. Waff, "Predicting the mid-eighteenth-century return of Halley's Comet," in R. Taton and C. Wilson, eds., *The General History of Astronomy,* vol. 2B, pp. 69–82; Peter Broughton, "The First Predicted Return of Comet Halley," *Journal for the History of Astronomy* 16 (1985), 123–133; For a history of return of Halley's comet in 1759 see: Simon Schaffer, " Halley, Delisle, and the Making of the Comet," in Norman J. W. Thrower, eds., *Standing on the Shoulders of Giants*, pp. 254–298; Craig B. Waff, "The First International Halley Watch: Guiding the Worldwide Search for Comet Halley, 1755–1759," Ibid., pp. 373–411; Idem, Comet Halley's First Expected Return: English Public Apprehensions, 1755–1758," *Journal for the History of Astronomy* 17 (1986), 1–37; Ruth Wallis, "The Glory of Gravity – Halley's Comet 1759," *Annals of Science* 41 (1984), 279–286; Phillip Stewart, "Science and superstition: Comets and the French public in the eighteenth century," *American Journal of Physics* 54 (1986), 16–24.

While mathematical achievements created an accurate picture of cometary orbits, the physical studies of comets did not witness a significant breakthrough. Different theories co-existed and adherents of different schools in physics (regarding the way they were explaining basic physical concepts such as the nature of light or the function of the ether) gathered facts to fit the observed cometary phenomena into their hypothesis. The situation remained the same until the application of spectroscopy in astronomy in the second half of the nineteenth century.

The two parts of cometary studies, thus, developed in different frameworks with different paces. By the beginning of the nineteenth century, mathematical procedures invented by Clairaut, Lagrange, d'Alembert, and Laplace, on the one hand, and improvements in the design of micrometers, on the other hand, increased the precision of predictive astronomy to such an accuracy that not only a major problem like the stability of the solar system could be solved, the mass of a comet, for the first time in history, could be estimated. These achievements will be considered in the next chapter.

Chapter 7
Comets in the Laplacian Cosmos

In 1819, French physicist and astronomer François Jean Dominique Arago (1786–1853) used a newly developed polarimeter (Fig. 7.1) to observe the tail of a brilliant comet that appeared in late June. Ten years earlier, Etienne Malus (1775–1812) discovered that light can be polarized by reflection. He was observing the reflected rays of the sun through a birefringent crystal (Iceland Spar) and found that when he rotated the crystal, the two images of the sun became darker or brighter. Arago observed the same effect when the light of the comet's tail was seen through the polariscope. He observed Capella (which was at the same altitude as the comet) with the same arrangement of telescope-polariscope, but polarization did not happen. Thus, the terrestrial atmosphere was not involved in the observed effect. Capella was a self-luminous object and its light did not show polarization, but the light of the comet (or a part of it) should be reflected light:

> We must conclude from these observations that the cometary light was not entirely composed of rays having the properties of direct light, there being light which was reflected specularly or polarized, that is, coming from the sun. It can not be stated with absolute certainty that comets shine only with borrowed light, for bodies, in becoming self-luminous, do not, on that account, lose the power of reflecting foreign light.[463]

Arago's discovery was the first interpretation of cometary light before the application of spectroscopy in astronomy. It was so significant that a generation later Alexander von Humboldt (1769–1859) mentioned it as "the most important and decisive observations that we possess on the nature and the light of comets."[464] After centuries of cometary observations scientists were able to judge confidently the nature of a comets' light or at least about a part of it.

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[463] François Jean Dominique Arago, "Quelques nouveaux details sur la passage de la comète découverte dans le mois de Juillet 1819, devant le disque du soleil," *Annales de chimie et de physique*, série 2, 13 (1820), 104–110; Also in François Arago, *Oeuvres complètes* (Paris: 1859), Tom 11, pp. 509–524. The translation is quoted from: Alexander von Humboldt, *Cosmos: A Sketch of the Physical Description of the Universe*, translated from the German by E. C. Otté, 2 vols. (New York: Harper, 1850), vol. 1., p. 105.

[464] Humboldt, *Cosmos*, p. 105.

T. Heidarzadeh, *A History of Physical Theories of Comets,*
From Aristotle to Whipple,

Fig. 7.1 The polarimeter which Arago used to demonstrate the laws of light polarized by reflection and refraction, now preserved at the Millington-Barnard Collection, the University of Mississippi, USA

Although this discovery proved that a part of cometary light was reflected, it did not rule out the possibility of the existence of a self-luminous substance either in the atmosphere or in the tail of comets. It was this possibility that attracted Humboldt's attention. Humboldt, like his predecessor William Herschel (1738–1822), believed that comets were composed of a self-luminous matter.[465] They were thinking that a kind of chemical process produced the luminosity of nebulae, comets, and even the stars. Although Herschel's theory, in general, was reminiscent of Hamilton or even Euler, it had a fundamental difference. For Herschel the nebulae observed in the remote spaces were the primary substance from which the planets, stars, satellites, and finally comets were taking form. In this regard, Herschel was an observational astronomer whose data provided direct support for the cosmology of his contemporary Laplace, though their nebular theories were not identical.

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[465] Humboldt believed in a kind of internal process in the planets or comets which might produce light or affect the light they reflect from the sun. He says: "These beautiful experiments still leave it undecided whether, in addition to this reflected solar light comets may not have light of their own. Even in the case of the planets, as, for instance, in Venus, an evolution of independent light seem very probable. The variable intensity of light in comets can not always be explained by the position of their orbits and their distances from the Sun. it would seem to indicate, in some individuals, the existence of an inherent process of condensation, and an increased or diminished capacity of reflecting borrowed light." Ibid., pp. 105–106. Laplace also believed that the sun and stars are encompassed in a layer of self-luminous fluid. See below.

Herschel's Evolving Universe

Herschel in his extensive investigation of the nebulae and nebulous stars, which started in the 1770s and culminated in the 1800s (after he constructed the then largest telescopes in the world), theorized that the nebulae were composed of some luminous matter which "is probably capable of being consolidated, [and] the act of shining proves it to have chemical properties."[466]

By early 1790 Herschel believed that the nebulae were groups of stars which could not be resolved by telescopes; however, by 1791 he declared that nebulae existed by themselves. But an independent nebula had great physical and cosmological implications. Herschel after describing one of those milky patches of light associated with a star wrote:

> But what a field of novelty is here opened to our conceptions! A shining fluid, of a brightness sufficient to reach us from the remote regions of a star of the 8th, 9th, 10th, 11th or 12th magnitude, and of an extent so considerable as to take up 3, 4, 5, or 6 minutes in diameter! Can we compare it to the coruscations of the electrical fluid in the aurora borealis? Or to the more magnificent cone of the zodiacal light as we see it in spring or autumn?[467]

Although Herschel assumes that these nebulae might be formed by the accumulation of an infinite number of the particles of light over a very long time, he says that it is not "of any immediate consequence to us to know the origin of the luminous matter."[468] Herschel holds this notion in most of his writings about nebulae and comets and mainly describes the basic assumptions of his theory rather than explaining the details.[469]

From the existence of extensive collections of scattered nebulae, Herschel concludes that they originate from a "former common stock of nebulous matter."[470] Condensation due to gravitation of different parts of this stock at different rates

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[466] William Herschel, "Astronomical Observations relating to the Construction of the Heavens, arranged for the Purpose of a critical Examination, the Result of which appears to throw some new Light upon the Organization of the celestial Bodies," *Philosophical Transactions* 101 (1811), 333. Like many other natural philosophers in the eighteenth century, Herschel believed in the fundamental role of the active principles – light, electricity, fire and fermentation – in the construction and function of nature. Herschel in his numerous publications considered the nature of the self-luminous nebulae, the structure of the sun, and the action of the sun's rays on matter. During his studies of the sun's rays Herschel discovered the infrared radiation, which was an invisible active emission. For Herschel's theory of light and matter see: Simon Schaffer, "The Great Laboratories of the Universe: William Herschel on Matter Theory and Planetary Life," *Journal for the History of Astronomy* 11 (1980), 81–111

[467] Idem., "On Nebulous Stars, properly so called," *Philosophical Transactions* 81 (1791), 83–84. It is interesting that Herschel does not mentions cometary tails in this analogy.

[468] Ibid., pp. 87–88.

[469] In his famous paper about the construction of the heavens he defines the nebulous matter: " By nebulous matter I mean to denote that substance, or rather those substances which give out light, whatsoever may be their nature, or of whatever different powers they may be possessed." See Herschel, "Astronomical Observations relating to the Construction of the Heavens," p. 277.

[470] Herschel, "Astronomical Observations relating to the Construction of the Heavens," p. 292.

formed the various sidereal bodies. Observation of the celestial bodies, in fact, is the observation of the condensing primary matter in its various phases. For example, a loose nebula is in the beginning of its condensation, but those that are gradually much brighter at the middle are experiencing greater compression which makes the center of condensation more luminous.[471]

Among the broad spectrum of nebular objects that Herschel describes, there are nebulae that have a ‘cometic’ appearance. They are round and their brightness increases towards their central parts. Furthermore, around the brighter central regions, they have a faint chevelure or coma which fades out gradually. Herschel deduces that:

> It seems that this species of nebulæ contains a somewhat greater degree of condensation than that of round nebulæ [...] Their greater resemblance to telescopic comets, however, is very apt to suggest the idea, that possibly such small telescopic comets as often visit our neighbourhood may be composed of nebulous matter, or may in fact be such highly condensed nebulæ.[472]

Herschel in his several accounts of cometary observations follows this line of thought. For example, he describes the nucleus of the comet of 1807 as a solid, planet-like object, encompassed in a nebular matter. He calculates the nucleus to be only 538 miles in diameter, embedded in a coma with a diameter of more than 643,000 miles. But more importantly, he concludes that the nucleus is self-luminous.

Herschel’s argument is simple but thought provoking: if the nucleus is solid and opaque, then it should have phases like the moon or Venus. But his careful observation of the comet with powerful telescopes did not reveal any uneven distribution of light or any change in the brightness of the comet’s nucleus. Thus, “we are authorized to conclude, [Herschel says], that the body of the comet on its surface is self-luminous, from whatever cause this quality may be derived.”[473] He draws the same conclusion with respect to the coma and tail of the comet. Regarding the self-luminosity of the comet’s tail, Herschel reasons further. He doubts that the reflection of the sun’s light from such rare particles can be observable from a distance of more than 240 million miles. Therefore, either the tails must be much thicker (which in that case would obscure the stars behind) or it is self-luminous.[474]

When a comet approaches the sun, the action of the sun’s rays (which is capable of producing light, heat, and chemical effects) decomposes and expands the cometic matter. This nebulous and elastic matter, which had a shining quality and seems to be “of a phosphoric nature,” rarifies and is driven by the impulsive force of the sun’s

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[471] Ibid., pp. 299–305.

[472] Ibid., p. 306.

[473] William Herschel, “Observations of a Comet, made with a View to investigate its Magnitude and Nature of its Illumination. To which is added, an Account of a new Irregularity lately perceived in the apparent Figure of the Planet Saturn,” *Philosophical Transactions* 98 (1808), 156–157. Herschel also points out that the light of this comet had much greater resemblance to the light of stars than to the mild reflection of the solar rays from the moon.

[474] Ibid., p. 158.

rays. Since only one hemisphere of a comet is exposed to the sun, the rising matter develops in the shape of a hollow cone (Fig. 7.2). The consumed luminous matter of the exposed hemisphere is filled either from the shifting of the same matter from the other hemisphere or by rotation of the comet around its axis. Due to the rotational motion of a comet it is probable that different parts of it which, may have different densities of luminous matter, become exposed to the sun and cause the variation in the branches of light included in the tail.[475]

Herschel finally expresses his cosmological ideas about comets, which recall Newton's thoughts. He compares the comet of 1807 and the second comet seen in 1811 regarding their perihelion distances and the length of their tails. While the first reached within 61 million miles of the sun and had a tail of nine million miles, the second, with a perihelion distance of 36 million miles, developed a tail 91 million miles longer than the former. From this comparison Herschel concludes that the comet of 1807 was more "consolidated" than the latter. And a comet becomes denser and denser only by successive approaches to the sun or *another star*. Thus, either the comet of 1807 was much older than that of 1811 or the latter obtained some fresh nebulous matter (or as Herschel calls it, *unperihelioned* matter) from the deep sky and carried it to our solar system. However, it does not imply that comets are members of our system and journey to the realm of the fixed stars:

> […] from the complete resemblance of many comets to a number of nebulæ I have seen, I think it not unlikely that the matter they contain is originally nebulous. It may therefore possibly happen that some of the nebulæ, in which this matter is already in a high state of condensation, may be drawn towards the nearest celestial body of the nature of sun; and after their first perihelion passage round it proceed, in a parabolic direction, towards some other similar body; and passing successively from one to another, may come into the regions of our sun, where at last we perceive them transformed into comets.[476]

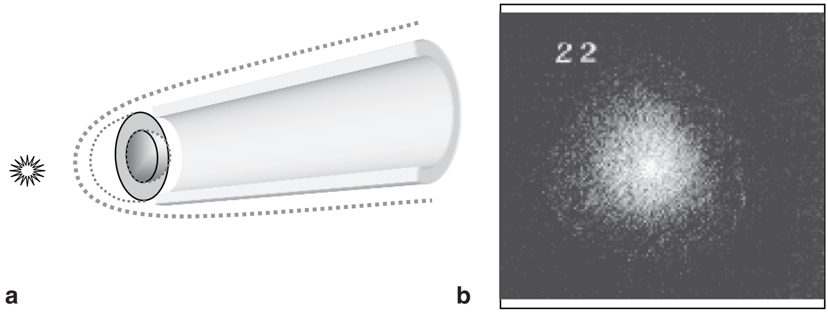

Fig. 7.2 (a) The tail of Herschel's comet is in the form of a hollow cone which is created by the action of the sun's rays on the outer parts of the comet. (b) Herschel's drawing of a cometic nebula, form Herschel's, "Astronomical Observations relating to the Construction of the Heavens," (1811)

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[475] Ibid., pp. 138–140.

[476] Ibid., pp. 142–143.

Herschel's comets are alien. They are not created to refresh or renew the solar system. They are not even as old as the entire universe. Herschel's theory, in fact, is a combination of all major theories from Kepler to Newton in an evolutionary scheme: Nebulae can condense (as the condensation of fatty ether in Kepler's theory), move from one star to another (as Descartes' comets wander between the vortices), transfer nebulous matter (similar to Newton's spirit transporters) and finally be trapped in the gravitational field of a certain star, and even transform to become a planet.

In an article published in 1812, Herschel gives more details about the structural similarities of comets and the planets. By comparing the apparent brightness of the two comets that appeared in 1811, Herschel deduced that the light of the larger comet (1811, II), the nucleus of which had a dimension of about one-third that of the earth, was 'planetary'. By using the term 'planetary' Herschel means that the comet did not have its own luminosity but reflected the sun's rays. His reasoning was based on observational facts: the first comet (the smaller one with a diameter of 428 miles), at a distance of 114 million miles when it was observed with a magnifying power of 600, was seen brighter than the second one (with a diameter not less than 2,637 miles) when it was observed with a magnifying power of 107 at a distance of only 103 million miles.[477] Thus, the second comet, which was larger and closer, should not have as much self-luminous matter.

According to Herschel, the second comet might have some remaining phosphoric matter, suspended in the lower regions of its atmosphere which causes the comet to have a faint tail. Also, comparing these comets with the comet of 1807 indicates that the effect of solar rays depends entirely upon the state of the nebulous matter of the comets. The second comet of 1811 had probably a minor amount of "unperihelioned" matter in its atmosphere and for that reason its coma and tail were dim and were seen mostly due to the reflection of the sun's rays.[478]

These comparisons enable Herschel to arrange the observed comets in an evolutionary pattern. Since the second comet of 1811 was not affected by a perihelion passage more than a planet might have been, it had more affinity with a planet than a comet. It was in a very advanced state of consolidation and contained a very small amount of phosphoric matter in its constitution. The comet of 1807, although it was very condensed, transported a great quantity of nebulous matter, which most probably it had captured from interstellar nebulae in one of

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[477] William Herschel, "Observations of the second Comet, with Remarks on its Construction," *Philosophical Transactions* 102 (1812), p. 234. The brightness of an image seen through the ocular of a telescope or the relative light transmitting capacity of a telescope (which is also the twilight factor) is equal to $d^2\ (D/M)^2$, where d is the diameter of the exit pupil, D is the diameter of the objective, and M is magnification. Thus, when all conditions are the same, using a higher magnification yields dimmer images at the ocular. See: J. B. Sidgwick, *Amateur Astronomer's Handbook* (New York: Dover, 1971), pp. 29–31.

[478] Ibid., p. 235.

its journeys, and finally the first comet of 1811 had a small solid nucleus but a great amount of nebulous matter, which was an indication of its elementary stage of evolution.[479]

Herschel's findings were, in great part, the observational verifications of Laplace's theory of the cosmos. They both were in the same generation and encountered the same problems in astronomy, but regarding their expertise they were at extremes: Herschel's distance from celestial mechanics was the same as Laplace's separation from observational astronomy. However, despite Laplace's highly mathematical approach to astronomy, his final picture of the cosmos was like the image that Herschel was observing through his giant telescopes.

Pierre-Simon Marquis De Laplace (1749–1827)

Laplace's approach to the study of the origin and physical constitution of comets was unique. This was partly due to achievements in the physical and mathematical sciences in the late eighteenth and early nineteenth centuries, but mostly due to his innovations in celestial mechanics and his creativity in the application of mathematics in astronomy. Laplace approached comets from two directions: as a mathematician, he studied their orbits, including the gravitational interaction of the planets and comets, and applied the rules of probability to shed light on the origin of comets; and, as a natural philosopher and cosmologist, he developed a cosmogony in which comets were introduced as new objects, dissimilar to all previous cometary theories.

Laplace discusses the origin and physical properties of comets in four major works, two of them strictly technical, and the other two popular books addressed to general audiences: in "Mémoire sur l'inclinaison moyenne des orbites des comètes, sur la figure de la terre, et sur les fonctions" (1776), he applies the principles of the theory of probability to investigate the origin of the

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[479] Ibid., pp. 236–237. For William Herschel's cosmology see: Michael Hoskin, *William Herschel and the Construction of the Heavens* (New York: Norton, 1964); Idem, "The English Background to the Cosmology of Wright and Herschel," in Wolfgang Yougrau, Allen D. Breck (eds.), *Cosmology, History and Theology* (NewYork: Plenum, 1977), pp. 291–321; Idem, "William Herschel's early investigations of nebulae: A reassessment," *Journal for the History of Astronomy* 10 (1979), 165–176; Schaffer, "The Great Laboratories of the Universe," pp. 81–111; Idem, "Herschel in Bedlam: Natural History and Stellar Astronomy," *British Journal for the History of Science* 13 (1980), 211–239; Idem, "The nebular hypothesis and the science of progress," in J. R. Moore, ed. *History, Humanity and Evolution* (Cambridge: Cambridge University Press, 1989), pp. 131–164; Bernard Lovell, "Herschel's Work on the Structure of the Universe," *Notes and Records of the Royal Society of London* 33 (1978), 57–75; Stephen G. Brush, *Nebulous Earth, The Origin of the Solar System and the Core of the Earth from Laplace to Jeffreys* (Cambridge: Cambridge University Press, 1996), pp. 29–36.

comets; in *Essai philosophique sur les probabilités* (1814) he provides a non-technical account of his theory of probability.[480] In *Traité mécanique céleste* (five volumes, the first four published between 1798 and 1805 and the fifth in 1825), which is a complete course of theoretical and applied celestial mechanics, Laplace, in the section devoted to comets, develops his procedures of cometary orbit determination and theory of perturbation and, for the first time estimates the mass of a comet. And finally in *Exposition du système du monde* (1796) he describes his cosmological theory as well as his ideas about comets.[481]

The Origin of Comets: A Probabilistic Approach

It was known from antiquity that comets were not confined to the same path as were the planets, and later it was discovered that some comets may move opposite to the direction of the motion of the planets. These observations, however, had not been the subject of a quantitative study. Although in several cometary theories those peculiar aspects of comets had been accounted for and were used as evidence to show the different nature of comets and the planets, all explanations had remained qualitative. For Laplace, however, they were meaningful observational data that could be treated mathematically and employed as clues to infer the origin of comets and the planets.

According to Laplace, it is not the effect of chance that the axial rotation of the sun and the planets, and the revolution of the planets and their satellites around the sun are in the same direction and almost in the same plane and that the degree of the eccentricity of their orbits is small. It is a remarkable phenomenon that indicates a general cause that has established all the movements in the solar system.[482] Six planets with their satellites, the sun, and the ring of Saturn altogether perform forty-three co-directioned movements. Laplace calculated that the probability that this phenomenon is not the result of a chance is a bet of more than 4×10^{12} to one. Thus,

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[480] The *Essai*…originally published as the "Introduction" to the second edition of Laplace's *Théorie analytique des probabilités* (Paris: 1812). See Charles C. Gillispie, R. Fox, I. Grattan-Guinness, "Laplace, Pierre-Simon, Marquis de," in Charles C. Gillispie (ed.), *Dictionary of Scientific Biography*, 15 vols. (New York: Charles Scribner's Sons, 1972), vol. 15, p. 388. Laplace wrote the *Essai*… and *Exposition* when he was appointed professor at the new École Normale after the French Revolution in 1789. There, he was asked to deliver lectures on celestial mechanics and probability theory without using mathematics. See Brush, *Nebulous Earth*, p. 20.

[481] Six editions of *Exposition du système du monde* were published from 1796 to 1835. One of the subjects that underwent changes was the theory of comets, which will be considered below.

[482] Pierre Simon Marquis de Laplace, *A Philosophical Essay on Probabilities*, trans. E. T. Bell (New York: Dover, 1951), p. 97.

we can believe with confidence that all planetary motions are the result of a primitive cause.[483]

On the contrary, comets move direct or retrograde on orbits with different degrees of eccentricities and different inclinations with respect to the ecliptic. Laplace found that the number of the retrograde comets was almost equivalent to the number of direct ones. He also calculated from the available cometary data that their mean inclination to the ecliptic was about 45 degrees. Thus, while the ratio of the retrograde to direct comets indicated that the direction of their motion might result from chance, the inclination of their orbits should result from the existence of a cause that had no influence on the determination of the direction of their motions.[484]

These facts led Laplace to conclude that the primeval sun should have been surrounded by a fluid or a nebula, rotating with it like an atmosphere. This atmosphere, because of the excessive heat of the sun, was expanded beyond the orbits of all the planets. But it contracted gradually and, as it cooled at different distances from the sun, local condensations happened which gave rise to the formation of different rings. Condensation of the rings, in turn, formed planets with large atmospheres around them from which the satellites were shaped.[485] However,

> In this hypothesis the comets are strangers to the planetary system. In attaching their formation to that of the nebulæ they may be regarded as small nebulæ at the nuclei, wandering from systems to solar systems, and formed by the condensation of the nebulous matter spread out in such great profusion in the universe. The comets would be thus, in relation to our system, as the aerolites are relatively to the Earth, to which they would appear strangers.[486]

Thus, comets are wandering nebulae from outside of the solar system. When they come closer and enter the ‘sphere of activity’ of the sun, they are forced to describe elliptic or hyperbolic orbits. Since they come from different parts of the sky, they

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[483] Laplace also in different editions of the *Exposition* has calculated the probability of a chance causation of the solar system. In its third edition (1808) which appeared after the discovery of the first four asteroids (Ceres in 1801, Pallas in 1802, Juno in 1804 and Vesta in 1807) Laplace stated that it is more than four thousand billion against one that the arrangement of the solar system is the effect of chance. In a paper written in 1773 (before the discovery of two satellites for Saturn, the planet Uranus, its satellites, and asteroids) Laplace made his calculations for only six planets and ten satellites which were the moon, four satellites of Jupiter and five of Saturn. He used Daniel Bernoulli’s formula in which the chance that n bodies all moved in the same one of two directions is 2^{-n+1} and found the probability to be 2^{-15} or 1/32,768 that at least one of the motions of the planets, satellites (and the ring of Saturn) had been determined by chance. See: Brush, *Nebulous Earth*, p. 21; Stanley L. Jaki, “The five forms of Laplace’s cosmogony,” *American Journal of Physics* 44 (1976), 4–5.

[484] Ibid., p. 98.

[485] Ibid., pp. 99–101. We will return to Laplace’s nebular theory when discussing his *Exposition du système du monde*.

[486] Ibid., 102. Kant also uses a similar analogy to illustrate the stars outside of the plane of the Milky Way: “Those suns which are least closely related to this plane […] so to speak, [are] the comets among the suns. See Kant, *Cosmogony*, p. 47.

move on orbits with different inclinations and different directions. Laplace, then, based on his probabilistic analysis, states that there is a bet of at least 6,000 to one that such a nebula penetrating to the sphere of activity of the sun will move either on an elongated ellipse or a hyperbola. But, the latter, in the observable section of its orbit, will be confined with a parabola.[487] Laplace delineates the same concepts with a sophisticated mathematical language in "Mémoire sur l'inclinaison moyenne des orbites des comètes, sur la figure de la terre, et sur les fonctions" and in *Théorie analytique des probabilités*.[488]

The Mass of Comets

On June 14, 1770, Charles Messier (1730–1817), the French comet and nebula hunter discovered a comet (1770 I), which soon turned out to be one of the most exceptional ever discovered. The comet approached rapidly toward the earth and

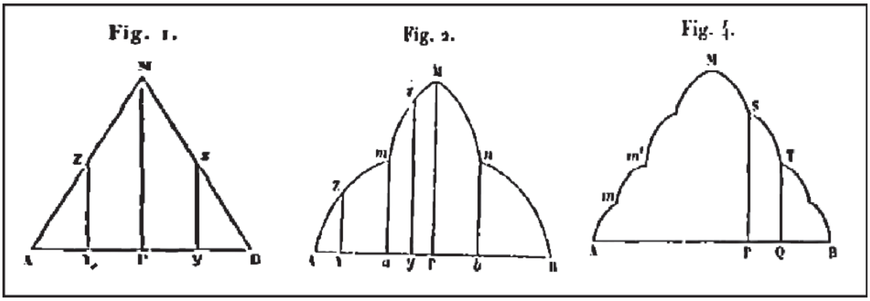

Fig. 7.3 Laplace's analysis of the distribution of cometary orbits: in the left figure, the base, *AB*, of the triangle is 90 degrees and the ordinates are proportional to the probability of the mean inclination of two comets correspondent to each segment on *AB*. The probability that mean inclination lies between *Yy* is equal to the area *YZMzy* divided by *AMB* (the area of the whole triangle). The middle figure illustrates the case when three comets are involved and the probability that the mean inclination confined to certain limits is given by the proportion of the area between those limits divided by the entire area of the shape *AMB*. In the right figure the general rule for *n* comets is given, which states that the probability that the mean inclination of *n* orbits falls between any two points *P* and *Q* equals to the ratio yield from dividing the area between those limits by the entire area of the shape *AMB*.[489] Drawings from Laplace's *Théorie analytique des probabilities* (Paris: 1812)

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[487] Ibid. pp. 103–104. This idea that comets are strangers to the solar system appeared in the fourth edition of the *Exposition* (1813). Before that Laplace assumed comets to originate from the same nebula that condensed to form the solar system. See below.

[488] See Pierre Simon Laplace, "Mémoire sur l'inclinaison moyenne des orbites des comètes, sur la figure de la terre, et sur les fonctions," in Laplace, *Oeuvres complètes de Laplace*, 14 vols. (Paris: Paris: Gauthier-Villars, 1878–1912), vol. 8, pp. 279–321; Pierre Simon Laplace, *Théorie analytique des probabilités* (Paris: Courcier, 1812), pp. 253–261.

[489] Gillispie, et al, "Laplace," pp. 290–292.

passed it on July 1 within a distance of 2,250,000 km (0.015 AU). Many orbit calculators tried to compute the orbital elements and represent the comet's orbit by an appropriate curve. While several attempts to fit a parabolic orbit failed, Andres Johan Lexell (1740–1784) at St. Petersburg discovered that the comet was moving on an elliptical orbit with a period of only 5⅔ years.[490]

The comet's short period implied that it should have been observed several times during its past returns; however, there was no record of its appearance. Further investigations, which all confirmed the validity of Lexell's calculations, showed that the comet's original orbit had been altered due to the perturbative effect of Jupiter.[491] At the beginning of 1767, Lexell's comet approached Jupiter within a very short distance where its strong gravitational influence forced the comet to move on a smaller ellipse (Fig. 7.4). Whatever was the former or the new orbit of the comet, the phenomenon provided a valuable occasion for astronomers to scrutinize the gravitational interaction of the planets and comets, especially the earth and the comet, because of their extremely close approach. In the first years

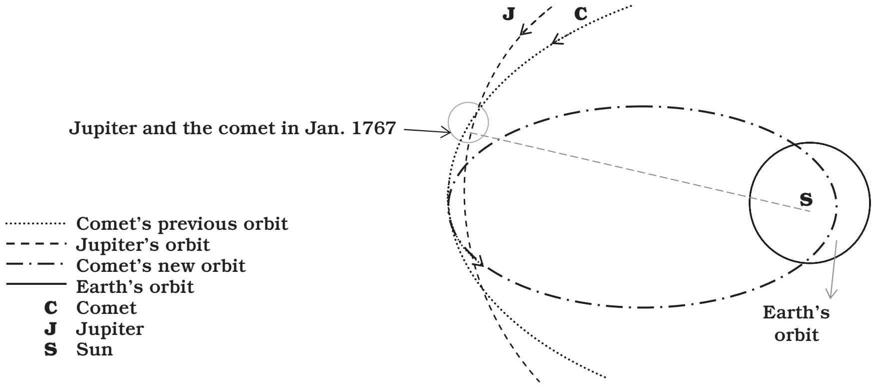

Fig. 7.4 Perturbation due to the action of Jupiter caused Lexell's comet to orbit the sun on a small ellipse (Adapted from Milne's *Essay on Comets* (1828))

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[490] For a history of orbit calculations of Lexell's comet see: Alexander-Guy Pingré, *Cométographie, ou Traité historique et Théorique de Comètes*, 2 vol. (Paris: 1783–1784), vol. 2, pp. 106–107; David Milne, *Essay on Comets* (Edinburgh: 1828), pp. 100–109;Yeomans, *Comets*, pp. 157–160; Gary W. Kronk, *Cometography, A Catalog of Comets*, *vol. 1: Ancient – 1799* (Cambridge: Cambridge University Press), pp. 447–451.

[491] Since Lexell's comet had not been observed before, to verify its calculated period and orbital elements the French National Institute offered a prize for the most complete investigation of the comet's orbital characteristics. The winner was Johann Karl Burckhard (1773–1825), German mathematician and astronomer, whose research yielded almost the same results as those of Lexell. See Milne, *Essay on Comets*, pp. 100–101; Pierre Simon Laplace, *Celestial Mechanics*, trans. Nathaniel Bowditch, 4 vols. (New York: Chelsea, 1966), vol. 4, pp. 429.

of the nineteenth century, Laplace carefully studied the motion of Lexell's comet and published his results in the fourth volume of the *Celestial Mechanics*. Laplace's study of the gravitational actions of Jupiter and the earth on Lexell's comet marked a turning point in cometology and for the first time in history created a quantitative estimation of cometary masses.

Since Lexell's comet passed the earth within a very short distance (almost six times that of the moon), a measurement of orbital inequalities arising from their mutual gravitational attractions would reveal their relative masses. Laplace calculated that the earth's action decreased the time of the sidereal revolution of the comet by 2.046 days. But the more exciting question was to what extent the comet affected the earth's motion. Laplace, solving the problem by assuming the mass of Lexell's comet to be the same as the mass of the earth, found that the increment of the earth's sidereal year (δT) would be $\delta T = 0^{day},11612$. However, the change in the earth's motion was much less. Consequently, Laplace stated that:

> we are certain, from all observations that have been made, particularly from the numerous comparisons of Maskelyne's observations, which were used by Delambre in constructing his solar tables, that the comet of 1770 has not altered the sidereal year 2″, 8″ thus we are sure that the mass of this comet is not 1/5000 part of that of the earth.[492]

Then, having proven the smallness of the mass of comets, Laplace explains the possible effects of a comet-planet encounter, which is drastically different from all previously developed ideas:

> *It not only happens that the comets do not trouble the motions of the planets and satellites, by their attraction; but if, in the immensity of past ages, some of the comets have encountered them, which is very probable, it does not seem that the shock can have had much influence on the motions of the planets and satellites*.[493]

Thus, although Laplace finds it probable that a comet may impact a planet or its satellites, he believes that the result would not be so destructive. He even assures astronomers that the action of comets cannot impair the accuracy of astronomical tables.

Laplace's determination of the cometary masses was one of the most important events in the history of cometology. If Brahe's discovery of cometary distances

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[492] Laplace, *Celestial Mechanics*, vol. 4, p. 436. Nevil Maskelyne (1732–1811) was the fifth Astronomer Royal, who published the first volume of the *Nautical Almanac* in 1766. Maskelyne carried on for almost half a century the tradition of precise observation which Bradley established at the Greenwich Observatory. See: Berry, *A Short History of Astronomy*, pp. 273–274; Hoskin, *Illustrated History*, pp. 180; a complete history of Maskelyne's life and works is in Derek Howse, *Nevil Maskelyne, The Seaman's Astronomer* (Cambridge: Cambridge University Press, 1989).

[493] Ibid., p. 437(Laplace's Italics). Laplace even before publishing the fourth volume of the *Celestial Mechanics* (where he estimated cometary masses) believed that only a direct collision of a comet with the earth produces destructive effects. In the second edition of the *Exposition* (1799) he states: "They [comets] pass so rapidly by us, that the effects of their attraction are not to be apprehended. It is only by striking the earth that they can produce any disastrous effect. But this circumstance, though possible, is so little probable in the course of a century […] that no reasonable apprehension can be entertained of such an event." See: Laplace, *The System of the World*, 2nd ed., trans. J. Pond, 2 vols. (London: 1809), vol. 2, p. 63.

started the first period of modern cometology and Newton's admission of comets in the solar system commenced the second period, there exists no doubt that the estimation of comets' masses by Laplace was the beginning of the third period. After about a century and half of imagining comets as objects comparable to planets in their sizes and masses, Laplace demonstrated that a typical comet is even smaller than the moon.[494] Consequently, the Newtonian picture of comets was replaced by a newer image in which comets were minor bodies that visit the solar system without posing a serious threat to planets or humans. The terror of comets, thus, like the fear of eclipses, became a sign of ignorance:

> The appearance of the comets followed by these long trains of light, had for a long time terrified nations, who are always affected with extraordinary events, of which they know not the causes. The light of science has dissipated these vain terrors which comets, eclipses, and many other phenomena excited in the ages of ignorance.[495]

Laplace in several other occasions also maintains the same idea. He even finds it extremely probable that the earth has been enveloped several times by cometary tails without their effects being observed.[496] However, he admits that a direct impact of a comet on the earth could produce disastrous consequences. But he immediately declares that since an extraordinary combination of circumstances is required in order for two small bodies to collide in such an extremely vast space, the possibility of a collision is so small that there should not be any apprehension.[497] Even in such

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[494] It has to be noted that Laplace calculated the mass of the moon with a higher accuracy. While Newton estimated the moon's mass to be 1/40 of the earth's mass, Laplace using different methods, estimated it at between 1/50 to 1/74, but declared the ratio 1/68.5 as the most likely value. See: Ibid, vol. 3, pp. 336–339.

[495] Laplace, *The System of the World*, trans. Henry H. Harte, 2 vols. (Dublin: 1830), vol. 1, p. 79. Also in Laplace, *Exposition*, in *Oeuvres completes*, vol. 6, 57. Laplace's idea about the role of comets in the history of the earth changed during the time he was developing his cosmogony. In the last edition of the *Exposition* he maintained that cometary impacts can only produce local revolutions. To trace the changing ideas of Laplace on cometary impacts see: Schechner, *Comets, Popular Culture*, pp. 208–214; for a review of the history of geological ideas in the second half of the eighteenth century in which the extraterrestrial considerations are marginalized see: Kenneth L. Taylor, "Earth and Heaven, 1750–1800: Enlightenment Ideas about the Relevance to Geology of Extraterrestrial Operations and Events," *Earth Sciences History* 17 (1998), 84–91.

[496] Ibid., p. 205.

[497] A collision between a comet and a planet may happen if (1) the radius vector of the comet is exactly equal to the planet's distance from the sun; (2) the comet located exactly in the plane of the planet's orbit and (3) the longitude of its ascending or descending node is equal to the heliocentric longitude of the planet. It is very improbable that two objects in the vastness of the space fulfill all of these requirements exactly. See Milne, *Essay on Comets*, pp. 115–116. The French mathematician Dionis du Séjour (1734–1794), in a treatise entitled *Essai sur les comètes en général; et particulièrement sur celles qui peuvent approcher de l'orbite de la terre* (1775), studied the probability of impact of a comet on the earth and showed that from all comets with orbital elements that were ascertained none could pass the earth closer than about twice the moon's distance, and none of them ever passed the earth closer than nine times the moon's distance. See: Denison Olmsted, *Letters on Astronomy* (New York: 1853), p. 344.

a case, the mass of the comet must be comparable to the mass of the earth to create a global deluge or change the axis of rotation of the earth.[498]

The Structure of Comets

Laplace delineated his ideas about the physical structure of comets, their atmospheres and tails mainly in his *Exposition du système du monde* which first appeared in 1796. Four more editions of the *Exposition* were published in 1799, 1808, 1813, and 1824, and a sixth edition appeared posthumously in 1835 but had been largely revised by the author before his death.[499] The *Exposition*, which contains five books, is a survey of astronomy and cosmology without having a single mathematical formula or geometrical figure; but it has been admired as one of the most successful popular works ever published on astronomy.[500]

As has been indicated by Laplace scholars and historians of science, Laplace published five different versions of his cosmogonical theory in successive editions of the *Exposition*.[501] His theory of comets was among those subjects which were altered by the sixth edition. Besides inevitable revisions in his theory of comets due to the discovery of new comets or calculation of cometary masses, Laplace developed a new theory about the structure of comets, which first appeared in the third edition (1813) of his work. The same idea remained intact in the fourth edition (1824) but was omitted in the fifth and the sixth editions. This theory of Laplace, which was maintained by Bessel, has some similarities to the current model of cometary nuclei that Fred Whipple suggested in 1950.[502]

Laplace discusses comets mainly in three chapters of the *Exposition*, together with a general description he gives about the cosmogonic history of comets in his statement of the nebular hypothesis at the end of the work. The first place he talks about comets is in book one in a one-page chapter titled "Of Comets," where he defines comets

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[498] Ibid., vol. 2, p. 49.

[499] Bruno Morando, "Laplace," in R. Taton, C. Wilson, eds. *The General History of Astronomy*, vol. 2B, p. 144.

[500] Humboldt calls it as an 'immortal work" which France possesses (Humboldt, *Cosmos*, p. 48), and François Arago classes it "among the beautiful monuments of the French language" (Morando, "Laplace'," p. 144); also see: Jaki, "The five forms of Laplace's cosmogony," p. 4; Berry, *A Short History of Astronomy*, p. 306.

[501] Jaki, "The five forms of Laplace's cosmogony," pp. 4–11; R. Stolzle,"Die Entwicklungsgeschichte der Nebularhypothese von Laplace, Ein Beitrag zur Geschichte der Naturphilosophie," in Geburtstag Georg Freiherrn von Hertling, *Abhandlungen aus dem Gebiete der Philosophie und ihrer Geschichte: eine Festgabe zum 70* (Freiburg: Herder, 1913), 349–369; Charles Allen Whitney, *The Discovery of Our Galaxy* (NewYork: Knopf, 1971), pp. 133–154; B. J. Levin, "Laplace, Bessel, and the Icy Model of Cometary Nuclei," *The Astronomy Quarterly* 5 (1985), 113–118; Brush, *Nebulous Earth*, pp. 20–23; Schechner, *Comets, Popular Culture*, pp. 208–214

[502] Levin, "Laplace, Bessel," pp. 114, 117.

briefly as bodies that move in every direction and are accompanied by a nebulosity (or coma) and a long rare tail.[503] In book two, in a chapter named "Of the figure of the orbits of the comets, and of the laws of their motion about the sun" Laplace explains the motion of comets at length and where he discusses their perihelion passage, he elucidates the physical structure of cometary nuclei, the coma, and tails.[504] In book four also, he devotes a chapter to the perturbation of the elliptic motion of the comets, which discusses the gravitational interactions of the planets and comets; and finally, at the conclusion of the work, he investigates the origin of comets. In this latter part, though he does not describe the structure of comets, he tries to find whether comets were formed as a part of the solar system or whether they belong to other systems.

Laplace's discussion of comets in book two of the *Exposition* is the only place that he illustrates the structure of comets in detail.[505] There Laplace first describes the motion of comets, the orbital elements, and the procedure by which the periodicity of comets is distinguished by examining those elements. Then, he explicates the physical conditions that a comet encounters in the sun's vicinity and investigates the possible changes that a typical comet may undergo in such circumstances. To portray the influence of the sun's heat on a comet, Laplace employs a concept that he and Antoine Laurent Lavoisier (1743–1794) had studied in 1780s.[506]

Laplace applies the laws of change of state to the nuclei of comets. This approach, which marks one of the first steps in the astrophysical study of comets, analyzes the structural changes of comets in the light of laboratory experiments and extends the application of the newly-born physical chemistry to the realm of sidereal objects. Laplace investigates the latent heat of evaporation of comets, which were the only known celestial objects that experienced a tremendous change of temperature.

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[503] This chapter – of Comets – which is chapter X of book one in the first three editions and chapter XII in the last three, remained intact in all editions.

[504] This is the chapter where Laplace introduces his theory of cometary nuclei in the third and the fourth editions but omits it in the fifth and the sixth editions. Due to revisions in different editions of the *Exposition,* the chapter numbers are varied. The chapter (of the figures…) is numbered VI in the first, second and third editions, but is number V in the other editions. See: Laplace, *Exposition du système du monde*, 1st ed., 2 vols. (Paris: 1796), vol. 1, pp. 165–172; Idem, *Exposition…*, 2nd ed (Paris: 1799), p. 119–124; Idem, *Exposition…*, 4th ed (Paris: 1813), p. 127–134; Idem, *Exposition…*, 5th ed, 2 vols. (Paris: 1824), vol.1, pp. 225–236; Idem, *Exposition…*, 6th ed., in Laplace, *Oevres complètes de Laplace*, 14 vols. (Paris: 1878–1912), vol. 6, pp. 135–141.

[505] Laplace in other publications also discusses the structure of comets; however, his description in book two of the *Exposition* is more complet. For example see: Laplace, "Sur les comètes," read in 1813, reprinted in Laplace, *Oeuvres complètes de Laplace*, 14 vols. (Paris: 1878–1912), vol. 13, pp. 88–97; Idem, *A Philosophical Essay*, p. 99.

[506] In 1783 Laplace and Lavoisier published their studies on the nature of heat and introduced the famous ice calorimeter they had devised to measure any change in the amount of heat during the change of state. Their treatise entitled *Mémoire sur la chaleur,* in four parts, discusses the nature of heat, the determination of specific heats of various substances, theory of physical chemistry, and finally methods of study of combustion and respiration. See Gillispie, et al, "Laplace," pp. 312–316; Roberts, "A Word and the World," pp. 199–222; Henry Guerlac, "Chemistry as a Branch of Physics: Laplace's Collaboration with Lavoisier," *Historical Studies in the Physical Sciences*, 7 (1985), 193–276.

Laplace admits that the nebulosity around the comets is formed by the action of the sun's heat. The particles surrounding a comet which are congealed in the immense cold of aphelion rarify in the perihelion, and assuming the intensity of heat to be proportional to the intensity of the sun's light, a comet receives more heat when it comes closer to the sun. For example, since the perihelion distance of the comet of 1680 was 166 times less than the distance of the earth from the sun, the heat it received at the perihelion was 27,500 ($\approx 166^2$) times greater than what we receive on the earth. This intense heat, which could not then be produced artificially, can volatilize a great number of terrestrial substances.[507]

The tremendous solar heat, thus, can change the state of the matter of which a comet is made. Obviously, the intensity of heat has a key role in, for instance, the vaporization of a liquid or sublimation of a solid; however, many comets have been observed that have produced tails even at the distance of the earth from the sun. Thus, a comet must be composed of such a volatile matter that its state changes even if it is not extremely close to the sun.

Laplace explains his theory of state change in comets for the first time, in the third edition of the *Exposition* and repeats it in the fourth edition as well. However, he omits in the fifth edition a relatively long passage from the chapter five of book two, where he delineated the theory in detail.[508] The deleted part was not restored in the sixth edition, and as a result, the succeeding printings of the *Exposition* (which were based on the last – the sixth – edition) did not contain the aforementioned passage.[509] Since this omitted passage illustrates the line of reasoning that led Laplace to theorize the physical structure of comets, it is pertinent to quote it completely even though it is comparatively long:

> Whatever be the nature of heat, we know that it dilates all bodies. It changes solids into fluids, and fluids into vapours. These changes of form are indicated by certain phenomena

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[507] Laplace, *The System of the World* (1830), p. 200.

[508] Laplace also omitted three chapters of book four of the *Exposition* in the fifth edition, in order to develop their contents in a separate treatise concerning the phenomena dependant on molecular action. Since he did not prepare the treatise, the deleted chapters were restored in the sixth edition which appeared after Laplace's death. See: Levin, "Laplace, Bessel, and the Icy Model," p. 114. It is not known why Laplace deleted the passage regarding the change of state of comets from the fifth edition.

[509] The omission of this passage was pointed out for the first time by B. J. Levin. He emphasized that "in both French editions of Laplace's collected works and in all translations into other languages, the text of the *Exposition du système du monde* is given according to the sixth Paris edition, and therefore the excluded passage on comets remained practically lost to astronomy" (Levin, "Laplace, Bessel, and the Icy Model," p. 115). Obviously, he did not have access to Henry Harte's English translation of the *Exposition* which was published in 1830 and contained the whole omitted passage. Levin's unawareness of this translation caused him to ask a French speaking astrophysicist (Armand H. Delsemme) to translate the omitted passage. However, Harte's translation itself is a mystery: it is a translation of the *fifth* edition of the *Exposition,* but it contains the omitted passage without any explanation of the translator. Harte added several explanatory notes to his translation but neither in those notes nor in the introduction does he give a clue about the original text he chose for translation. The original text could not be the fourth edition (1813) because it contains Laplace's discussion of the observation of Enke's comet in 1818 and 1819.

> which we will trace from ice. Let us consider a volume of snow or of pounded ice in an open vessel submitted to the action of a great heat. If the temperature of this ice be below that of melting ice, it will increase up to zero of temperature. After having attained this point, the ice will melt by new additions of heat; but if care be taken to agitate it, until all the ice is melted, the water into which the ice is converted, will always remain at the same temperature, and the heat communicated by the vessel will not be sensible to the thermometer immersed in it, as it will be entirely occupied in converting the ice into water. After all the ice is melted, the additional heat will continually raise the temperature of the water and of the thermometer till the moment of ebullition. The thermometer will then become stationary a second time; and the heat communicated by the vessel will be entirely employed in reducing the water into steam, the temperature of which will be the same as that of boiling water. It appears from this detail, that the water produced by the melting of ice and the vapours into which boiling water is converted, absorb at the moment of their formation a considerable quantity of caloric, which reappears in the reconversion of aqueous vapours to the state of water, and of water to the state of ice; for these vapours, when condensed on a cold body, communicate much more heat to it than it would receive from an equal weight of boiling water; besides we know that water can preserve its fluidity, though its temperature may be several degrees below zero; and that in this state, if it is slightly agitated, it is converted into ice, and the thermometer, when plunged in it, ascends to zero, in consequence of the heat given out during this change. All bodies which we can make pass from a solid to a fluid state, present similar phenomena; but the temperatures at which their fusion and ebullition commences, are very different for each of them.
>
> The phenomenon which has been just detailed, although very universal, is only a particular case of the following general law, "*in all the changes of condition. which a body undergoes from the action of caloric, a part of this caloric is employed in producing them, and becomes latent,* that is to say, insensible *to the thermometer; but it reappears when the, system returns to its primitive state*." Thus when a gas contained in a flexible envelope is dilated by an increase of temperature, the thermometer is not affected, by the part of the caloric which produces this effect, but this latent part becomes sensible when the gaz [*sic*] is reduced by compression to its original density.
>
> There are bodies which cannot be reduced to a state of fluidity, by the greatest heat which we can produce. There are others which the greatest cold experienced on earth is unable to reduce to a solid State: such are the fluids which compose our atmosphere, and which, notwithstanding the pressure and cold to which they have been subjected, have still maintained themselves in the state of vapours. But their analogy with aeriform fluids, to which we can reduce a great number of substances by the application of heat, and their condensation by compression and cold, leaves no doubt but that the atmospheric fluids are extremely volatile bodies, which an intense cold would reduce to a solid state. To make them assume this state, it would be, sufficient to remove the earth farther from the sun, as it would be sufficient in order that water and several other bodies should enter into our atmosphere, to bring the earth nearer to the sun. These great vicissitudes take place in the comets, and principally on those which approach very near to the sun in their perihelion. The nebulosities which surround them, being the effect of the vaporisation of fluids at their surface, the cold which follows ought to moderate the excessive heat which is produced by their proximity to the sun; and the condensation of the same vaporised fluids when they recede from it, repairs in part the diminution of temperature, which this remotion ought to produce, so that the double effect of the vaporisation and condensation of fluids, makes the difference between the extreme heat and cold, which the comets experience at each revolution, much less than it would otherwise be.[510]

Laplace in the first half of this passage, explains the theory of latent heat had had been worked out by Joseph Black (1728–1799) in 1760s. Laplace himself carried

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[510] Laplace, *The System of the World*, trans. H. Harte, pp. 200–203.

out extensive research on the nature of heat with the collaboration of Lavoisier in the early 1780s (Fig. 7.5). In their theory, heat or the element of caloric was treated as a material entity which could flow from an object after it was heated or rubbed by another object. However, from the beginning of the nineteenth century, this idea of the heat was being challenged by the theory of Benjamin Thomson, Count Rumford (1753–1814) who demonstrated that heat was a mode of motion in matter.[511]

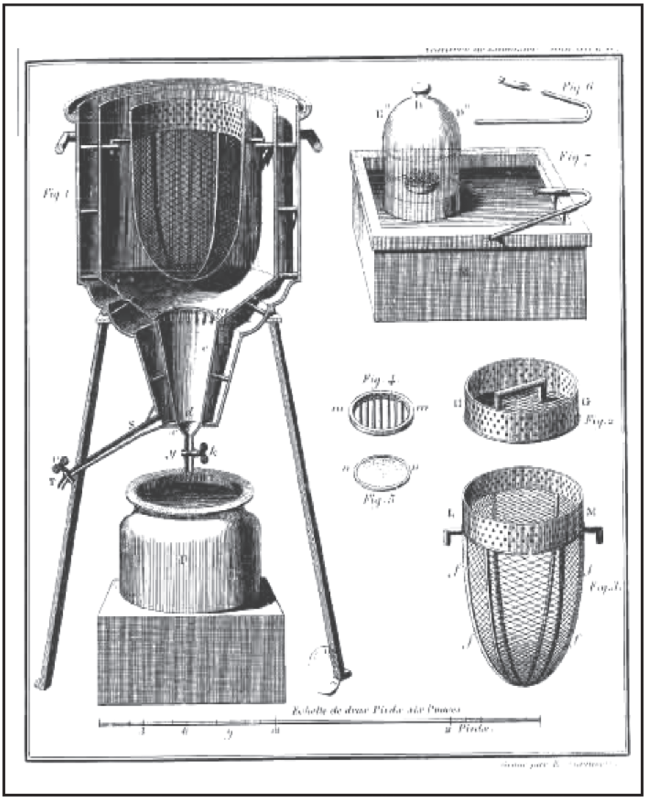

Fig. 7.5 Ice calorimeter designed by Laplace and Lavoisier to measure caloric and fixed air (carbon dioxide) during a chemical combustion or animal respiration. Left: the calorimeter contained three concentric chambers. In the inside chamber a burning object or a respiring animal was producing caloric, which could melt a specific quantity of ice held at the middle chamber. The outer chamber was filled with snow as an insulator. The quantity of the melted ice in the middle chamber was proportional to the heat produced in the inside chamber. From Lavoisier's *Mémoires de chimie et de physique* (Paris: 1862)

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[511] Holton, *Physics*, pp. fo234–239; Douglas McKie, Niels H. de V. Heathcote, *The Discovery of Specific and Latent Heats* (London: Edward Arnold, 1935), pp. 222–249; R. J. Morris, "Lavoisier and the Caloric Theory," *British Journal of the History of Science* 6 (1972), 1–38; Luis M. R. Saraiva, "Laplace, Lavoisier and the Quantification of Heat," *Physis* 34 (1997), 99–137. Laplace met Rumford (and William Herschel) in 1802. All three scientists visited Napoleon Bonaparte when he was the First Consul. See: Whitney, *The Discovery of Our Galaxy*, pp. 123–124.

Whatever was the nature of heat, Black's discovery of latent heat had a very important lesson: it revealed that heat and temperature are two different concepts. A body can absorb heat without showing an increase in its temperature. When a liquid, such as water, absorbs heat to undergo a change to the vapor state, a thermometer placed in it does not show any increase beyond the boiling point. In fact, the extra heat is expended to create a change of phase or state in the liquid.

Laplace employs this newly discovered concept of latent heat to theorize the influences of severe heat and cold on the structure of comets. He admits that an intense cold can even change the state of atmospheric fluids (gases) to a solid. Therefore, when a comet moves toward aphelion, its atmospheric fluids solidify, and in contrast, when it approaches the perihelion its liquids are changed to the vapor state. The critical point is that the latent heat of vaporization prevents the mass of the comet from being entirely destroyed. Just as a mass of snow does not melt immediately when the temperature rises high above the freezing point, or a kettle of water does not vaporize at once when it reaches to the boiling temperature, a comet also does not undergo a change of state entirely when it approaches the sun.[512]

Laplace has doubts about the telescopic observation of the cometary nuclei. Because the masses of comets are very small, the diameters of their nuclei must be indistinguishable through the telescope. Thus, he defines the visible nucleus of a comet as the "densest strata of the nebulosity" that surrounds its solid body. In the vicinity of the sun the most volatile particles of this nebulosity are excited by the heat of the sun and are driven by the action of the solar rays in the opposite direction. The shape, length, and intensity of a tail are affected by differences in the volatility, density, and magnitude of the molecules from which the tail is made. In addition, effects which may arise from the rotation of the cometary nuclei, combined with annual parallax, define the shape, curvature, and unique appearances of cometary tails.[513]

A comet in each revolution around the sun will lose a part of its nebulous matter and finally, the entire atmosphere surrounding it will be exhausted. In that case, the naked nucleus, which is small, will be invisible. The short-period comets reach this stage sooner than the long-period ones. The phenomenon also can explain the disappearance of comets whose orbital elements are known. For example, the comet of 1770 which was calculated to reappear after 5½ years had not been observed since its first appearance.[514]

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[512] Friedrich Wilhelm Bessel (1784–1846) in a paper published in 1836 suggested that the nucleus of a comet is not a solid body like the earth or the moon. He theorized that the matter of cometary nuclei must change to a vapor state easily. Inspired by Laplace's theory Bessel wrote: "The fact volatility shows first on the surface side right under the sun, and its action is stronger, and extended to an always larger fraction of the surface, by a closer proximity of the sun and by a longer duration, fits well with the observations. The fact that the vaporization and its latent heat must be protected from destruction, has been, if I am not mistaken, noticed first by Laplace." According to Levin Bessel apparently read the above-mentioned passage in the third or the fourth edition of the *Exposition*, and unable to find it in the later editions expressed his uncertainty in referring the idea to Laplace. See Levin, "Laplace, Bessel, and the Icy Model," p. 114.

[513] Laplace, *The System of the World* (1830), pp. 203–205.

[514] Ibid., pp. 206–207.

Comets and the Nebular Hypothesis

Laplace in the concluding part of the *Exposition* proposed his theory of the formation of the solar system, which gave the publication a permanent reputation. There, he theorized that the members of the solar system – all the planets and their satellites – were formed contemporaneously with the sun from a swirling nebula which surrounded the sun as an atmosphere.[515] While most of the fundamental concepts of Laplace's hypothesis remained unchanged in all six editions of the *Exposition*, the details were altered by the last edition. The origin of comets, however, was one of the subjects that changed drastically.

By the fourth edition of the *Exposition* (1813), Laplace supposed that comets were formed outside the primitive solar atmosphere. He argued that if comets were formed within the primitive solar atmosphere they would have plunged into the sun because of the retardation of their motions. Comets that are present today were formed at the extremities of the solar nebula and moved towards the sun after its atmosphere had shrunk significantly. The great eccentricity of cometary orbits, the variety of the inclination of their orbits, and the long period of their revolutions about the sun confirm that they were not produced in the solar atmosphere.[516]

In between the third (1808) and the fourth (1813) editions of the *Exposition* Herschel published his famous paper about the construction of the heavens (1811), in which he described in detail the different forms of isolated nebulous matter in interstellar space, among them a type he called cometic nebula. Herschel's paper, in fact, provided an evolutionary scheme of the cosmic nebulosity and demonstrated the nebulae in different stages of their development. Thus, based on Herschel's observational evidence, one could arrange the nebulae from their expanded phases to condensed stages, as if one witnessed the formation of the solar system based on Laplace's nebular hypothesis.

Laplace in the fourth edition of the *Exposition* declared the alien origin of comets. Herschel's name appeared for the first time in this edition of the *Exposition*. Laplace pronounced that comets were small nebulosities that formed by the condensation of the nebular matter and moved from one solar system to another until captured by one of the suns.[517] In this way, he was able to account for the irregular properties of comets

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[515] Laplace's nebular hypothesis has been the subject of several studies. Here we mainly concentrate on the situation of comets in this hypothesis. For Laplace's cosmology and its evolution see: Jaki, "The five forms of Laplace's cosmogony," pp. 4–11; Brush, *Nebulous Earth*, pp. 20–29; Roger Hahn, "Laplace and the vanishing role of God in the physical universe," in Harry Woolf (ed.), *The Analytic Spirit: Essays in the History of Science in Honor of Henry Guerlac* (Ithaca: Cornell University Press, 1981), pp. 85–95, Ronald L. Numbers, *Creation by Natural Law, Laplace's Nebular Hypothesis in American Thought* (Seattle: University of Washington Press, 1977), pp. 3–13, 124–132; Jacques Merleau-Ponty, "Laplace As a Cosmologist," in Wolfgang Yourgrau, Allen D. Breck, eds., *Cosmology, History, and Theology* (New York: Plenum Press, 1977), pp. 283–291.

[516] Laplace, *Exposition*, 1st ed., vol. 2, p. 302; Idem, *The System of the World*, 2nd ed, pp. 363–364.

[517] Laplace, *Exposition*, 4th ed., p. 436. Laplace did not give any clue about the stellar systems and the average distance between the stars.

easily. While it was difficult to explain comets as by-products of the condensation of solar nebula, Herschel's discovery of small nebulae provided the missing segment of the Laplacian puzzle of cosmogony. Laplace repeated Herschel's discoveries and his evolved theory of alien comets in his *Philosophical Essay on Probability*, which was published in 1819, between the fourth and the fifth editions of the *Exposition*.[518]

Laplace's physical theory of comets, however, was in contradiction with his other planetary theories and was unable to answer some important questions that had been left unanswered since the beginning of modern cometology. The nature of cometary atmospheres is one of those questions that Laplace never tries to discuss in detail. While he is explicit that a "thin, transparent, compressible, and elastic fluid [the atmosphere]… surrounds every celestial body,"[519] he does not explain why tails are not formed by planets like Venus and the earth, which are located in an appropriate distance from the sun.

The formation of a thick coma around the small body of a comet is also one of the ambiguous issues in Laplace's theory. Admitting that the mass of a comet is only a fraction of the mass of the moon, Laplace does not delineate how the weak gravitational attraction of such a minor body can hold an agitated atmosphere while moving with an incredible speed in the ether. The problem gets more complicated if one attributes a rotation to comets, as Laplace finds possible.

Conclusion

The role of comets in the Laplacian cosmology is completely different from their roles in all other cosmologies founded on Newton's physics. The key factors in this transformation of cometary thought were Laplace's solution of the problem of the stability of the solar system and his calculation of the cometary masses. In fact, it was after these achievements of Laplace that comets were finally freed from all the forms of cosmological roles attributed to them. Comets were introduced neither as refueling or renewing agents, nor as a probable cause of instability in our system of planets; rather they were found to be minor bodies threatening only in direct impacts.

The stability of the solar system was one of the challenging problems of celestial mechanics after Newton. The system of the planets and their satellites is considered stable if none of them escape or collide. However, it was known that the orbital elements of the moon and some of the planets are changing. Three phenomena that were very difficult to answer with Newton's rules of the two-body problem were the progression of the moon's apse, the secular acceleration of the mean motion of the moon, and the acceleration in the mean motion of Jupiter and deceleration in Saturn's

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[518] Laplace, *The Philosophical Essay*, p. 102.

[519] Laplace, The System of the World (1830), vol. 2, p. 136.

motion. Another problem was the possible gravitational effect of comets on planetary motions, a subject that needed elaborate analytical procedures to be solved.

During almost a century of theoretical and observational studies, on the one hand, the difference between secular and periodic perturbations was distinguished, and on the other hand, mathematical procedures were developed to approximate the behavior of an *n*-body system with higher precision. Laplace's mathematical treatment of the perturbation, which was a culmination of works done by Euler, Clairaut, Delambre, and Lagrange, demonstrated that the calculation of the perturbations of the major bodies of the solar system did not contain secular terms. In other words, he stated that the inequalities in the orbital elements of the planets and their satellites are not accumulating to make the solar system unstable, rather those inequalities are periodic.[520]

Laplace's role in the establishment of a new physics of comets, however, was unique. After his estimation of the cometary masses, astronomers and physicists realized that they were dealing with a mere small body and had to rethink all previously established theories of comets, which assumed them to be at least as large as the earth. If Brahe revolutionized our understanding of comets by drastically increasing their distances, Laplace did the same by radically decreasing their masses.

Laplace's calculation of cometary masses, which was verified by measuring only a negligible alteration in the length of the year (due to the encounter of Lexell's comet), was confirmed observationally by William Herschel. Herschel's figures for the sizes of cometary nuclei were at least ten times less than the then established size of a typical comet and were in agreement with Laplace's theory. Consequently, the idea of the smallness of comets was accepted without any confrontation. In his prize winning essay on comets (1828), David Milne explicates the role of this Laplacian achievement in the transformation of cometary ideas in Europe:

> These fears concerning the *moral* influences of Comets, the production of a weak and debasing superstition, have long since been rooted out from the faith of enlightened Europe: But they have disappeared only to be succeeded by others, respecting their *physical* influence, […].[521]

And,

> LA PLACE, to whose opinion the highest respect is due […] infers, that either no comets have ever come in contact at all with the planet or such comets only, as, from the smallness of their mass, were not capable of deranging the primitive elements of their orbits.[522]

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[520] For the eighteenth century developments on the perturbation theory see: Jeff A. Suzuki, "A History of the Stability Problem in Celestial Mechanics, from Newton to Laplace," PhD. diss., Boston University, 1996. Suzuki elaborates technically the main problems and developments in the perturbation theory and shows the critical role of Lagrange and his superiority to Laplace in some fields. Also see: Berry, *A Short History of Astronomy*, pp. 289–321; Morando, "Laplace," 131–142; Curtis Wilson, "The problems of perturbation analytically treated," pp. 89–107; Idem, "Perturbation and Solar Tables from Lacaille to Delambre: the Rapprochment of Observation and Theory, Part I," *Archive for the History of Exact Sciences* 22 (1980), 189–296; Gillispie, et al, "Laplace," pp. 322–333; Florin Diacu, Philip Holms, *Celestial Encounters, The Origin of Chaos and Stability* (Princeton: Princeton University Press, 1996), pp. 127–157.

[521] Milne, *Essay on Comets*, p. 109.

[522] Ibid., p. 120.

A generation after the death of Laplace, H. N. Robinson, professor of mathematics and astronomy at the United States Naval College, in his textbook of astronomy 'designed for schools, academies and private students' wrote:

> From their singular and unusual appearance, they were for a long time objects of terror to mankind, and were regarded as harbingers of some great calamity. […] It is but little more than half a century since these superstitious fears were dissipated by a sound philosophy; and comets, being now better understood, excite only the curiosity of astronomers and mankind in general.[523]

In some astronomical texts the danger of a possible cometary impact was so underestimated that it looks unrealistic, even judged by contemporary physical knowledge. Robinson, discussing the probability of a cometary encounter, quotes the ramifications of such an impact from Ezra Otis Kendall, a distinguished professor of mathematics in the University of Pennsylvania:

> Another source of apprehension, with regard to comets, arises from the possibility of their striking our earth […]. If such a shock should occur, the consequences might perhaps be very trivial. It is quite possible that many of the comets are not heavier than a single mountain on the surface of the earth. It is well known that the size of mountains on the earth is illustrated by comparing them to particles of dust on a common globe.[524]

In the same way, Denison Olmsted, professor of astronomy at Yale, in his encyclopedic work on astronomy wrote that comets "are like insects flying, singly, in the expanse of heaven", and cannot be assumed as threats. Criticizing William Whiston and David Gregory for their belief in comets' destructive influences on the earth and the life on the earth, Olmsted stated that such "notions are too ridiculous to require a distinct refutation."[525]

From Laplace's calculation of the cometary masses in 1805 to the first spectroscopy of comets in 1864 by Giovanni Battista Donati (1826–1873), nothing considerable was added to physical knowledge of comets. The accepted picture of a comet, then, was of a very small body from which a tail was emanating due to the driving force of the sun's rays. This picture did not have any Newtonian element within it. In the century from the death of Newton (1727) to the death of Laplace (1827) nothing had changed in Newtonian astronomy as drastically as the physics of comets.

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[523] H. N. Robinson, *A Treatise of Astronomy, Descriptive, Theoretical and Physical* (New York: 1857), p. 54.

[524] Ibid., p. 160, quoted from Ezra Otis Kendall, *Uranography, or, A Description of Heavens* (Philadelphia: 1845).

[525] Olmsted, *Letters on Astronomy*, pp. 345–346.

Chapter 8
Comets in the Post-Laplacian Era

By the first quarter of the nineteenth century, when the fifth and the last volume of Laplace's *Traité de mécanique céleste* was published, astronomers were highly confident that the trajectory of planets and comets and the perturbational effects of the members of the Solar System were accurately calculable based on the computational procedures developed by d'Alembert, Lagrange, Legendre, Delambre, and Laplace. Among all those figures, however, Laplace had a special position. He, according to Asaph Hall, not only "gathered up and presented in a complete and practical form the whole theory of celestial mechanics", he also created innovative work on the gravitational theory that in Gauss' words were "the finest chapters ever written on the theory of attraction."[526]

Laplace's method of cometary orbit calculation was functional and, as Alexandre Guy Pingré concluded in his *Camétographie*, was the best available.[527] However, it was unwieldy. In 1797, Heinrich Wilhelm Matthäus Olbers (1758–1840), a physician and an amateur astronomer, developed a simpler method to calculate five elements of the six needed to determine an orbit. Olbers' method was so practical and straightforward that it soon became the popular way of determining cometary orbits. In fact, by the turn of the nineteenth century, the two common procedures of orbit computation were those of Olbers and Laplace. However, in 1801 Giuseppe Piazzi (1746–1826) of Palermo, one of the *Celestial Police*, who were searching for the missing planet between Mars and Jupiter, observed a small segment (a geocentric arc of only 3 degrees) of the motion of an object whose orbit was not accurately calculable even by Olbers' method.[528] Even though a number of giants in mathematics, including Laplace, were alive and productive, the problem was solved elaborately by

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[526] "Ein schönes Document der feinsten analytischen Kunst," cited in Asaph Hall, "Address of Professor Asaph Hall," *Science* 1 (1880), 123.

[527] Brian G. Marsden, "Eighteenth- and Nineteenth-Century Developments in the Theory and Practice of Orbits Determination," in Taton and Wilson (eds.), *The General History of Astronomy*, vol. 2B, p. 183.

[528] The object observed by Piazzi was the first asteroid discovered, and named Ceres after the patron goddess of Sicily. See Hoskin, *The Cambridge Illustrated History of Astronomy*, pp. 186–191.

T. Heidarzadeh, *A History of Physical Theories of Comets,*
From Aristotle to Whipple,

a 26 year old German mathematician named Carl Friedrich Gauss (1777–1865), who was later granted the prestigious title of the "prince of mathematics".[529]

Gauss' method enabled astronomers to calculate the six required orbital elements even if the observed arc of the object's trajectory was short. It provided a great opportunity for the calculators of comet orbits and also for the hunters of the newly discovered class of objects in the Solar System – the asteroids – to find the actual orbits of those objects whose long-term observation was not guaranteed because of technological limitations or the specifications of their trajectories.

A decade after the publication of Gauss' work on orbit calculation, the German mathematician and astronomer Johann Franz Encke (1791–1865), who was a student of Gauss in the 1810s, discovered the second periodic comet. Using Gauss' method, Encke determined the orbits of comets of 1786 I, 1795, 1805 and 1819, and concluded that all of them were in fact four apparitions of the same comet returning every 3.3 years. He predicted that the next perihelion passage of the comet would occur on May 24, 1822. The comet returned as had been predicted and later bore the name of the calculator of its orbit.[530] The most interesting feature of Encke's comet was the shortness of its period. In each return, accurate measurement of the comet's orbital elements could reveal the perturbational effects.

Encke's accurate calculations of the comet's perihelion passages revealed that the comet's period had increased slightly. What brought this result to the center of attention was the non-gravitational origin of the comet's acceleration. According to Encke, the observed increase in the mean motion of the comet was due to the retarding effect of a resistant medium that had filled the interplanetary space.

The idea of the existence of an interplanetary resisting medium was not new. Starting with Newton, it had been speculated by several physicists and astronomers that the attribution of even an extremely infinitesimal density to the ethereal medium would result in a secular retardation in the motion of the heavenly bodies. Even Alexis Claude Clairaut (1713–1765) estimated the possible effect of such a resisting medium on the return of Halley's Comet in 1759.[531] However, despite the assumption that the zodiacal light or the glowing haze around the eclipsed sun (the solar corona) was to be a hindrance in the motion of the comets, there was no direct evidence exhibiting the effect of an interplanetary resisting medium.

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[529] Gauss worked for many years on his techniques for calculating planetary and cometary orbits and in 1809 published a long paper called "Theoria motus corporum coelestium in sectionibus conicis solem ambientium" ("Theory of the motion of the heavenly bodies moving about the sun in conic sections") which contained the refined form of his method of orbit determination. Yeomans, *Comets*, pp. 144–149; Brandt, John C., and Robert D. Chapman, *Introduction to Comets* (Cambridge: Cambridge University Press, 2004), pp. 17–18.

[530] Yeomans, *Comets*, pp. 169–170.

[531] Clairaut, Alexis Claude, *Recherches sur la Comete des années 1531, 1607, 1682 et 1759* (St. Petersbourg: de l'Imprimerie de l'Academie Imperiale des Sciences, 1762), pp. 38–42. For a technical summary of Clairaut's calculations on the 1759 return of Halley's Comet see: Wilson, Curtis, "Clairaut's calculation of the 18th century return of Halley's Comet," *Journal for the History of Astronomy* 24 (1993), 1–15.

Despite considering the gravitational effect of the planets, Encke still found that the perihelion passage of this short-period comet had been shortened to about two and a half hours in each return. Analyzing the observed acceleration, Encke wrote:

> The first calculations of perturbations applied to the periods 1805–1819 and 1795–1805, led to this surprizing conclusion, which has since received further confirmation, that the magnitude of the semi-major axis of the orbit, cleared from perturbations and reduced to a given instant, is obtained smaller from the later revolutions than from the earlier. […] The observations of 1786, 1795, 1805, 1819, were strictly examined, and their greater or less uncertainty might perhaps amount to 1 or 2 minutes, but not to so much that there could have been a possibility of errors as great as must have found place if a uniform period of revolution had been assumed.[532]

Then he concluded:

> The most natural and in fact almost the only explanation which this phenomenon admits of, appears to me, (an opinion in which Olbers concurs) to be afforded by the hypothesis that the comet experiences a resistance in its course, which (as the existence of a perfect vacuum is improbable) may be exercised by the medium extending through all space.[533]

According to Encke, the effective resistance of the medium was proportional to the density of the medium and the square of the linear velocity of the comet. On the other hand, the density of the medium was proportional to the inverse square of the distance from the sun.[534]

The existence of an interplanetary resisting medium with an increasing density towards the sun would have more of an effect on the cometary and planetary motions than on the physical constitutions of comets. Thus, while Encke's controversial hypothesis initiated a wave of careful reviewing of the orbital data of several comets, the possible influence of such a medium on the shape of comets and the formation of their tails was not deliberated adequately even by Encke.[535]

While Encke's hypothesis was still an unresolved question for astronomers, two cometary apparitions impacted the ongoing debates and directly influenced astronomers' modeling of the cometary structure and tail formation. In 1835, Comet Halley in its closest approach passed within a distance of 0.187 AU from the earth and provided an opportunity to observe it with instruments more improved than those employed seventy-five years ago. In 1826, the second short period comet was discovered which during its return in 1845/6 surprisingly split up into two separate comets and initiated more speculations about the constitution of comets.

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[532] Encke, Johann Frantz, "On Encke's Comet, Encke's Dissertation Contained in no. CCX and CCXI of the *Astronomische Nachrichten*," trans. G. B. Airy (Cambridge: Printed by J. Smith, 1832), pp. 20–21.

[533] Ibid., p. 21.

[534] Ibid., p. 23.

[535] After Encke (died in 1865), Friedrich Emil von Asten (1842–1878) at the Pulkovo Observatory studied the acceleration of Encke's Comet and after his death, Oskar Andreevich Backlund (1846–1916) from Sweeden continued the work. Backlund discovered that during the years 1871–1881 the magnitude of the acceleration became half of the amount calculated by Encke. Since such an acceleration was not found in the motion of the other comets, the observed anomality was assumed to be a peculiar behavior of Encke's Comet.

Comet Halley was visible from August of 1835 to early May of 1836, except for about one month (mid-November to mid December) when it was close to the Sun. Among the troop of astronomers observing the comet was Friedrich Wilhelm Bessel (1784–1846) at Königsberg Observatory, where a newly made 6¼ inch heliometer had been mounted (Fig. 8.1). The telescope, which was one of the masterpieces of Joseph Fraunhofer (1787–1826) and was completed after his death, was the one that enabled Bessel in 1838 to measure the first stellar parallax.

Bessel's Jet Theory

Bessel not only was interested in the dynamics of comets, the physical aspects of comets were under his careful scrutiny. His vigilance concerning the changes in the shape, color, direction, and dimensions of cometary parts is best demonstrated in an article he published after the observation of the comet Halley in 1835. This article entitled "Beobachtungen über die physische Beschaffenheit des *Halley*'schen Kometen und dadurch veranlasste Bemerkungen", also contained a completely new theory of tail formation, and on the other hand, shed a light on possible interactions between the formation of a tail and the motion of a comet.

Bessel first gives the details of his observations of Halley's Comet for almost the entire October of 1835, when on the second day of this month he noticed the appearance of an emanation of luminous matter from the nucleus of the comet approximately in the direction of the sun (Fig. 8.2). His careful observation of this strange phenomenon in the following nights revealed that not only the size, shape, and brightness of the emanation was changing, but also its axis was oscillating with respect to the direction of the sun.[536] Based on the variation of the measured angles between the axis of the emanation and the radius vector of the comet, Bessel proposed two hypotheses about the possible motions of the emanation: either the cone of the emanation was performing an oscillatory motion in the plane of the comet's orbit or it was rotating about the comet's radius vector at a constant angle.[537]

Bessel preferred the first hypothesis, which was mostly in agreement with the observational data. But, in either case, the main question was the cause of such a motion, which apparently was not gravitational. After a careful study of the available data and consideration of the other cometary reports, Bessel came to this conclusion that the magnitude of the repulsive force that caused the emanation was almost twice the magnitude of the normal attraction and, without any doubt, it was the sun that induced such a repulsive force.[538]

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[536] Friedrich Wilhelm Bessel, "Beobachtungen über die physische Beschaffenheit des *Halley*'schen Kometen und dadurch veranlasste Bemerkungen," *Astronomische nachrichten* 13 (1836), 191–192. The article also has been translated in English for NASA, which is cataloged as " Observations concerning the physical nature of Halley's Comet and resultant comments," trans. Kanner (Leo) associates, 1976, NASA TT F- 16726.

[537] Ibid., pp. 197–198.

[538] Ibid., pp. 228–229.

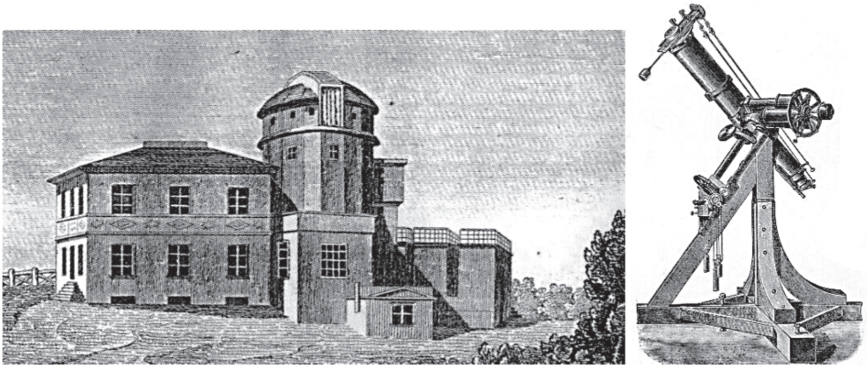

Fig. 8.1 Königsberg Observatory, and the 6¼ inch heliometer made by Joseph Fraunhofer

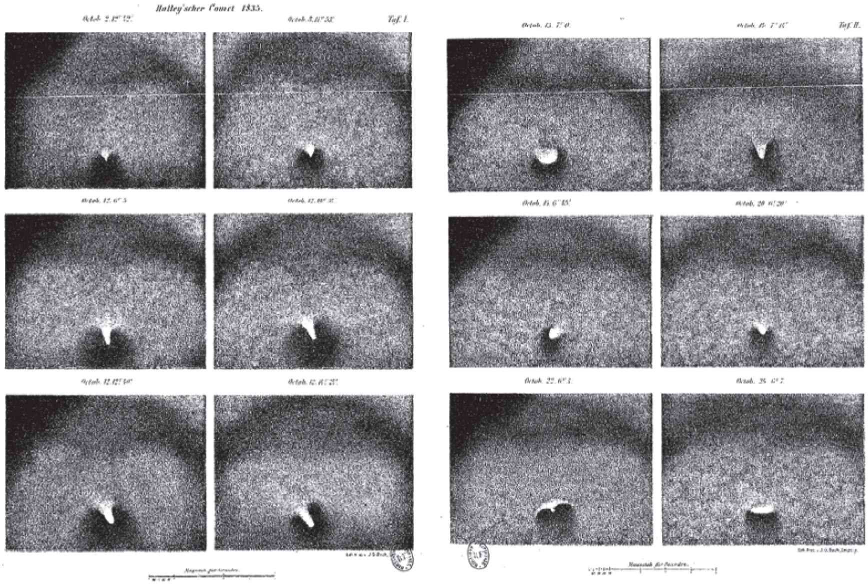

Fig. 8.2 Bessel's drawings of the comet Halley, 2–25 October 1835 (Bessel, Friedrich Wilhelm, "Beobachtungen über die physische Beschaffenheit des *Halley*'schen Kometen und dadurch veranlasste Bemerkungen," in *Abhandlungen von Friedrich Wilhelm Bessel*, Rudolf Engelmann (ed.), 3 vols. (Leipzig: Verlag von Wilhelm Engelmann, 1875–1876), plates I & II (between p. 56 and p. 57))

According to Bessel, the action of a body on another can be divided into two steps. While in the first step all parts of the other body are affected equally from a long distance, in the second step (when the distance between them decreases), different effects of the first body on the different parts of another become appreciable. In the case of a comet, in the first step evaporated particles of it polarized in such away that they move away from the sun. However, in the second step, the comet itself becomes polarized and an emanation towards the sun takes form. Such an emanation, which appears as a rocket having its jet towards the sun, must have the same effect on the comet's motion.[539]

In fact, the cometary particles which are being expelled in the direction of the sun create a recoil acceleration that, depending on their angle of ejection with respect to the radius vector of the comet may increase or decrease the comet's orbital period. In other words, the formation of a tail can influence the dynamics of a comet. This very important point, which was absent in all previous theories of comets, could explain the observed anomalies in the motion of Encke's Comet. Although, based on our present knowledge of cometary physics, Bessel did not differentiate the polarized jets from the vaporization of ices on the cometary nuclei, his idea of nongravitational acceleration of comets was correct.[540]

Despite the plausibility of Bessel's jet theory in explaining the retardation of Encke's Comet, the hypothesis of resisting medium still was more acceptable in the scientific community. The attributed properties of this medium were different from those of the universal ether; and because there were a few other phenomena in the vicinity of the sun that might be related to the existence of a kind of atmosphere around the sun, Encke's hypothesis had supporters even in the second half of the nineteenth century.[541]

Bessel's conclusion about the constitution of comets' nuclei illustrates his careful observation of the cometary phenomena as well as his employment of the contemporary achievements in physical sciences. In his description of a typical cometary nucleus Bessel wrote:

> I consider it probable that a comet's nucleus is not a really solid body; i.e. not a solid body of the same kind as the Earth, the Moon and the planets. It must be able to go easily through a state of volatility, whereas the above-mentioned bodies do not possess this property, or at least possess it to a lesser degree: the fact that its surface does not show a sharp boundary suggests that it is in such a condition; the almost incredibly large space filled by the tail of many comets, associated with the apparent extreme smallness of their masses, also shows that the matter of comets has the property to expand unlimitedly. But, the mass (nucleus) of the comet cannot originally have this property; at least, it cannot be a material which has no density when it is under no pressure, since such a material would obviously be completely vanished. However, I

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[539] Ibid., p. 231.

[540] Steven R. Chesley, and Donald K. Yeomans, "Nongravitational Accelerations on Comets," *Dynamics of Populations of Planetary Systems, Proceedings of IAU Colloquium #197*, 31 August–4 September, 2004, Belgrade, Serbia and Montenegro. Edited by Z. Knezevic and A. Milani (Cambridge: Cambridge University Press, 2005), pp. 289–290.

[541] For example, Amédée Guillemin in his general book of astronomy (1871) wrote: "It is possible that the nebulous ring which forms the zodiacal light can be the medium which accelerates the period of Encke's comet?," Amédée Guillemin, *The Heavens: An Illustrated Handbook of Popular Astronomy* (New York: G. P. Putnam, 1871), p. 248, or in an article in *Science*, probably written by its editor, it says: "The possibility there is an exceedingly rare atmosphere around the sun is well worthy the attention of astronomers and physicists. The zodiacal light, the motion of the perihelion of Mercury, and the acceleration of Encke's comet, all point this direction," "Encke's Comet, and the Resisting Medium," *Science* 69 (1884), 660. However, by the end of the nineteenth century, Encke's hypothesis was loosing supports, at least regarding the influence of the resisting medium on cometary motions, as Agnes Clerke describes it in 1885: "The hypothesis, then, of a resisting medium receives at present no countenance from the movements of comets, whether of short or of long periods." Agnes M. Clerke, *A Popular History of Astronomy During the Ninteenth Century* (London: A. and C. Black, 1902), p. 94.

> do not see any problem in assuming that comets consist of parts which become volatile when under the influence either of heat or of some other repulsive property.[542]

Although a similar idea had been expressed by Laplace (whose priority was also acknowledged by Bessel[543]), Bessel's deduction was based not only on theories of latent heat and phase change but also benefited from the meticulous observation of cometary features, especially the expansion of the coma and formation of jet streams.

The Mystery of Comet Biela

Almost a decade after the sole apparition of the Comet Halley in the nineteenth century, an unexpected cometary phenomenon in 1846 brought the science of comets to the center of attention of not only scientists but also the public. For astronomers it was even more exciting than the great comet of 1843, which appeared with a tail as long as two astronomical units, passed the sun within 830,000 km, and was observable during daylight.[544] The comet of 1846 was, in fact, had been seen in its several returns since 1772. However, it was in 1826 that Wilhelm von Biela (1782–1856) from Austria, Jean Felix Adolphe Gambart (1800–1836) from France, and Thomas Clausen (1801–1885) from Denmark calculated its orbit. The period of the comet was 6.75 years, which made it the second short period comet then discovered, and because Biela was the first to announce his discovery, the comet bore his name.[545]

In the third return after calculation of its orbit, comet Biela was observed on November 26, 1846 as a faint diffused object. However, after about a month the nucleus of the comet was seen as a pear-like elongated object, and by mid January 1847, surprisingly, two nearby comets appeared in the eyepieces of telescopes, both moving in equal degree and retaining their relative positions (Fig. 8.3). Thereafter, several astronomers from North America, Europe, and Russia centered on recording all relative data of this extraordinary appearance.[546]

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[542] Bessel, "Beobachtungen über die physische Beschaffenheit …," p. 208.

[543] Levin, "Laplace, Bessel…," pp. 113–114.

[544] Gary W. Kronk, *Cometography: A Catalogue of Comets*, 2 vols. (New York: Cambridge University Press, 1999–2003), vol. 2, pp. 129–137.

[545] Yeomans, *Comets*, pp. 181–182. In some contemporary texts the comet also called after Gambart.

[546] Ibid., pp. 182–188; Clerke, *A Popular History of Astronomy*, pp. 95–96; Kronk, *Cometography*, vol. 2, pp. 156–161. There are a great number of technical reports containing data about the positions of the Biela's twine nuclei, the orientation of their tails, and their motion. For example see: Hind, J. R., "Ephemeris of Biela's comet," *Monthly Notices of the Royal Astronomical Society* 11 (1845), 3; "Observations of Biela's Comet," *Monthly Notices of the Royal Astronomical Society* 12 (1845), 21; "Biela's Comet," Astronomische Nachrichten 24 (1846), 135–146; C. H. F. Peters, "Beobachtungen des Biela'schen Cometen auf der Sternwarte von Capodimonte bei Neapel," *Astronomische Nachrichten*, 24 (1846), 249–256; Dawes, W. R., "Estimated positions of Biela's comet," *Monthly Notices of the Royal Astronomical Society* 7 (1846), 39; "On the duplicity of Biela's Comet," *Monthly Notices of the Royal Astronomical Society*, 7 (1846), 73; Rümker, C., "Mean Places of Stars in Parallel of Biela's Comet," *Monthly Notices of the Royal Astronomical Society* 7 (1846), 84; Challis, J., "On the duplicity of Biela's comet," *Monthly Notices of the Royal Astronomical Society* 7 (1846), 90; Idem, "On the duplicity of Biela's comet," *Monthly Notices of the Royal Astronomical Society* 7 (1846), 99.

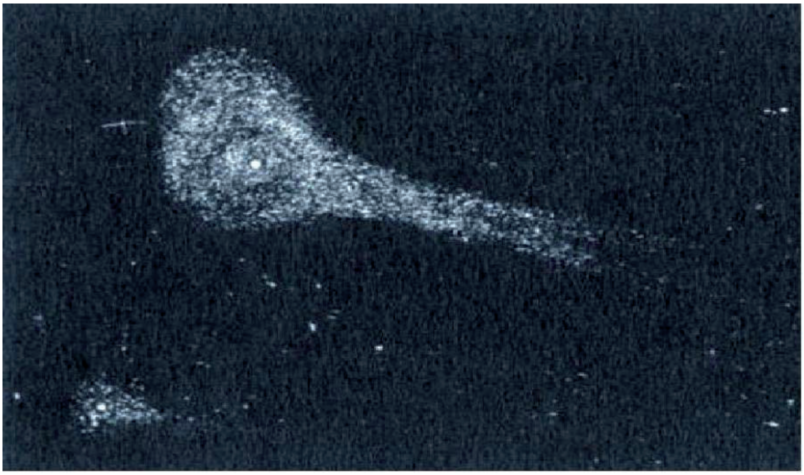

Fig. 8.3 The two components of Comet Biela as drawn by Otto W. Struve

Duplicity was not the only unusual aspect of the 1846 appearance of Comet Biela. By February 10, 1847 when the two nuclei were separated by an interval of about 9 arc minutes, both had short tails parallel in direction; and now, the companion comet which was very small and dim when first discovered in mid January, was as bright as the main comet. On the 14th and 16th of February the companion comet became brighter than the main one and presented a sharp nucleus. After two days, however, the main comet became twice as bright as the companion and showed a star-like nucleus. Meanwhile, a kind of tail formation appeared as a bridge between the two nuclei and for a few nights the comet was seen with three faint tails, one of them extending from the main nucleus to the companion.[547]

Comet Biela's duplicity raised several questions related to comets' physical constitution and the possible causes that initiated such a breakdown. At the same time, study of the behavior of its companions, both in 1846 and 1852 apparitions of the comet helped astronomers to sharpen their ideas about the size and mass of the cometary nuclei. According to Agnes M. Clerke the smallness of the mass of their nuclei "could not have received a more signal illustration than by the fact that their revolutions round the sun were performed independently; that is to say, […] that at an interval of only 157,250 miles their attractive power was virtually inoperative."[548]

Although evidence such as the enormous expansion of the coma or the undetectable gravitational effect of a comet on the planets had already proven that the mass and

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[547] John Herschel, *Outlines of Astronomy* (London: Longmans, Green, and Co., 1878), pp. 390–391.

[548] Clerke, *A Popular History of Astronomy*, p. 96.

density of a typical nucleus were very low,[549] the division of Comet Biela supported the idea that cometary nuclei were not as strongly built as the planets or satellites. At the same time, development of theories about the volatile nature of cometary material – which had been observed in the emanation of jet streams from the nucleus – caused astronomers to consider that *internal* forces also might have been responsible for the destruction of the comet. Elias Loomis, in his calculation of the time of the comet's division, concluded that the separation of the two parts of comet Biela "probably took place in the latter part of the year 1844. This separation may have been caused by the operation of some internal force like that which causes the tails of comets, or perhaps by collision with some other body like one of the asteroids."[550]

Comet Biela was seen for the last time in 1852, when the distance between its dim and inconspicuous binary nuclei was about 200,000 miles. In its next predicted return in 1865–1866, all efforts to detect the comet failed; however, in the following expected return of 1872, a very populated meteor shower was seen on November 27. The hourly rate of the shower was about 3000 and its radiant point was located in the constellation Andromeda. Soon, astronomers calculated that this meteoric swarm was moving in the orbit of the missing comet Biela.[551] Then, a new entry was added to the list of meteoric showers, whose their connection to some periodic comets had been established since 1860s.[552] The idea that comets can be disintegrated into myriads of tiny pieces now was gaining new support.

During the time between the last apparition of comet Biela and the first observation of the Andromedid meteor shower, theories of Bessel and Olbers regarding the formation of tails had found more observational support when Donati's comet appeared in 1858. The comet, which was visible with the naked eye for about four months and by telescope for nine months, was a bright comet with some extraordinary features. It developed a luminous head with three tails and two of them were string-like appendages forming a tangent to the main tail's curve in the direction of the sun (Fig. 8.4). According to Clerke, "Olbers' theory of unequal repulsive forces was never more beautifully illustrated. The triple tail seemed a visible solar analysis of cometary matter."[553]

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[549] Also, observation of stars *through* the nucleus of comets inclined astronomers to believe that cometary nuclei were merely made of nebulous matter. For example, the comet discovered by Maria Mitchell in 1847 passed centrally over a star of fifth magnitude, however, the stars light did not fad even when the center of the nucleus was overlapped the star. See Herschel, *Outline of Astronomy*, p. 373; Clerke, *A Popular History of Astronomy*, p. 106.

[550] Elias Loomis, *A Treatise on Astronomy* (New York: Harper, 1868), p. 273.

[551] J. R. Hind, "On the Radiant Point of the Meteors of November 27, 1872," *Monthly Notice of the Royal Astronomical Society* 33 (1872), 98; R. A. Proctor, "On the Origin of the November Meteors," *Monthly Notice of the Royal Astronomical Society* 33 (1872), 45–47; A. S. Herschel, "Meteor-Shower of November 27, 1872," *Monthly Notice of the Royal Astronomical Society* 33 (1872), 73–78; Yeomans, *Comets*, pp. 184–185.

[552] A. S. Herschel, "Observation of Meteor Showers, supposed to be connected with Biela's Comet," *Monthly Notice of the Royal Astronomical Society* 32 (1872), 355–359; Anonymous, "Progress of Meteoric Astronomy in 1872–1873," *Monthly Notice of the Royal Astronomical Society* 33 (1873), 252–260; Clerke, *A Popular History of Astronomy*, pp. 334–338. The connection between comets and meteoric showers will be discussed below.

[553] Clerke, *A Popular History of Astronomy*, p. 324.

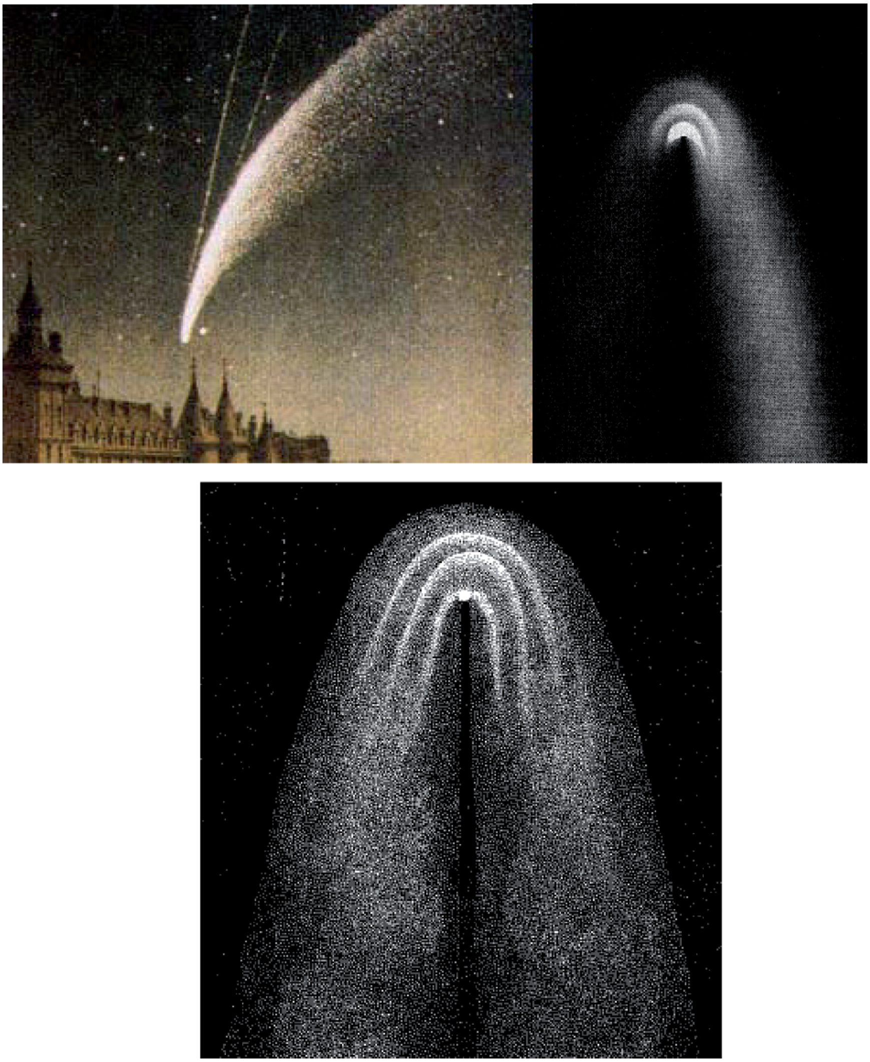

Fig. 8.4 Donati's Comet: different drawings of its tails and envelops.

Through the telescope, it appeared that successive envelopes were building up around the comet's head in a way that each envelope was separated from the other with a dark zone. These sunward envelopes, which apparently were formed by ejected material from the nucleus, finally faded out into the main train of the comet's tail and moved away from the sun. George Phillips Bond (1825–1865) from the Observatory of Harvard College, in his comprehensive account of the comet, which was based on hundreds of reports from various observatories in the world, described the development of seven envelopes from September 20 to October 20 of 1858.[554]

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[554] G. P. Bond, *Account of the Great Comet of 1858* (Cambridge: Welch, Bigelow, and Company, 1862), pp. 169–322, especially p. 199.

For Bond, the succession of the envelopes and the appearance of dark zones between them was a "clear indication of the intermittent nature of the forces by which they are thrown off from the nucleus."[555] On the other hand, Bond's extensive study of the features on the envelopes led him to conclude that

> It is obvious that, in order to keep the vortices of the envelopes constantly interposed between the Sun and the nucleus, there must be a rotation in the plane of the orbit equal in amount to the heliocentric motion of the Comet. […] It follows that the nucleus must have had a rotation in the plane of the orbit corresponding in amount with the change of direction of the radius vector. If this be admitted […] it shows that the Sun exercises a controlling directive force, and is so far in accordance with Bessel's theory of the polarization of the nucleus.[556]

Donati's comet was one of the very few comets in the history that was observed by a great number of professional astronomers for a long time. The outcome marked one of the most important achievements about comets' nature in the pre-spectroscopic era. Donati's comet not only supplied more evidence in agreement with the eruptive nature of the process of the tail formation (which in turn was an indication of the volatility of the cometary matter), it also became the first observational data to attribute an axial rotation to comets' nuclei.

New Electrical Theories of Tail Formation

The light from comet Donati's tail and head, like that of other comets that were observed after 1819 with the polarimeter, was partially polarized. Now, having more evidence about the volatility of cometary matter, astronomers were seeking the possible mechanisms that could relate the influence of the sun's light and heat to the evaporation of comets' matter and the consequent process of light emission. Although it was not too complicated to visualize the evaporative effect of the sun's radiation on the volatile matter of a comet (whatever was its nature), the resulted propagation of light was an open question.

A possible answer to this central question was worked out during the time that Donati's comet was still observable by the telescope. However, the answer was not an outcome of a pure astronomical investigation. The new theory to explain the tail phenomenon was inspired from a novel discovery in the field of electricity and led to the development of a new brand of electrical theory of tail formation different from those eigtheenth century theories, which were based on the manifestations of the static electricity.

In the final years of the 1830s, Michael Faraday (1791–1867) performing a series of experiments on electrical discharges, discovered that when a discharge happens in a low-pressure tube, a non-luminous zone appears near the cathode of the discharge tube.[557] Faraday's device, however, contained a primitive vacuum tube. The technology of evacuating of the tubes, installing the metallic plates inside them and sealing the openings was

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[555] Ibid., p. 357.

[556] Ibid., p. 361.

[557] Sogo Okamura (ed.) *History of Electron Tubes* (Tokyo: ISO Press, 1994), p. 8.

in the early stages of development. A breakthrough came in 1855 when Johann Heinrich Wilhelm Geissler (1815–1879), a German scientific instrument maker, constructed an efficient vacuum pump and improved the techniques of placing of the electrodes and sealing the tube. Using a Geissler tube, German physicist Julius Plücker (1801–1868) discovered that, when the pressure inside the tube decreased, the tube became darker but a glow extended around the cathode. The length of the luminescence created by the cathode on the wall of the tube was inversely proportional to the tube's pressure.[558]

A Geissler tube connected to a Ruhmkorff coil, which had been in use from the 1850s, created a better display. Heinrich Daniel Ruhmkorff (1803–1877) developed a powerful induction coil which produced very high voltages, suitable for experiments with the discharge tubes. As Adolph Ganot described in his popular physics textbook, "when the two platinum wires [at the two ends of a Geissler tube] are connected with the ends of a Ruhmkorff's coil, magnificent lustrous striæ, separated by dark bands, are produced all through the tube. These striæ vary in shape, colour, and luster with the degree of the vacuum, the nature of the gas or vapour, and the dimensions of the tube."[559] The bright and dark lines which appeared within the low-pressure medium of a Geissler tube due to the action of electricity could be exhibited in the rarified tail of a comet if a source of electricity stimulated it (Fig. 8.5).

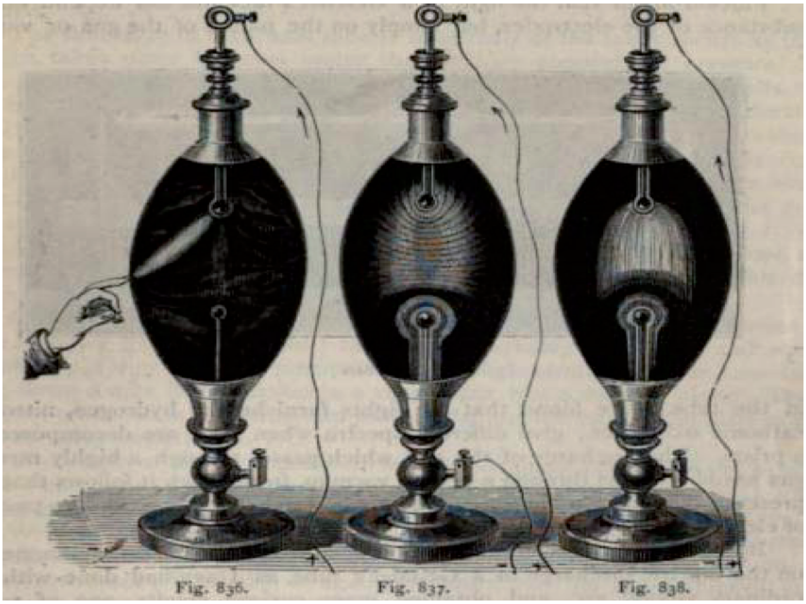

Fig. 8.5 Various displays of light in the Geissler tube. In the middle tube, successive bright and dark lines are conspicuous. From Ganot's *Elementary Treatise on Physics*, ninth ed., 1879, p. 825

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[558] Holton, *Physics*, pp. 380–381.

[559] Ganot, Adolph, *Elementary Treatise on Physics, Experimental and Applied*, trans. E. Atkinson, sixth ed. (New York: William Wood, 1875), p. 773.

While some astronomers referred to similarities between the emission in a Geissler tube and the phenomena of cometary tails, Osborne Reynolds (1842–1912), the famous British physicist and fluid mechanics pioneer, explored the possible electrical effects of a comet on the interplanetary medium. In his article about the tails of comets, the solar corona, and the aurora, Reynolds elaborated this idea that a tail might be merely the effect of an electrified comet on the medium in which it moved and not a real appendage to a comet's nucleus. Reckoning several dynamical difficulties with tails as appendages – such as their extremely rapid emission from the nucleus and rejection by the sun's (or other) repulsive force – Reynolds asks:

> Do we know, or can we conceive, any physical state, into which any substance which can be conceived to occupy the space traversed by comets could possibly be brought, so as to make it present the appearance exhibited by comets?[560]

And,

> I think the answer must be in the affirmative […]. For electricity is a well-known state, and gases are well-known substances; and when electricity under certain conditions, as in Dr Geissler's tubes, is made to traverse exceedingly rare gas, the appearance produced is similar to that of the comets' tails; the rarer this gas is, the more susceptible is it of such a state; and, so far as we know, there is no limit to the extent of gas that may be so illuminated. Hence, we may suppose the exciting cause to be electricity, and the material on which it acts, and which fills space, to have the same properties as those possessed by gas. What is more, we can conceive the sun to be in such a condition, as to produce that influence on this electricity which should cause the tail to occupy the direction it does; for such an electrical discharge will be powerfully repelled by any body charged with similar electricity in its neighbourhood.[…]
>
> The appearances of the comet in detail, such as the emission of jets of light towards the sun, and the form of the illuminated envelope, are all such as would necessarily accompany such an electrical discharge.[561]

Reynolds' theory of tail formation was an elaborated form of Norton's electrical theory, which was developed in the 1840s. William A. Norton, a professor of mathematical and natural sciences at Newark College, Delaware (and then at Brown University and Yale College), based on his observations of Donati's comet in 1843 as well as his study of other cometary data, worked out a theory of cometary structure in which the formation of the tail was attributed to a repulsive electrical force emanating from the sun. According to Norton, since the driving force of the tail particles cannot be emanating from the comet's nucleus (in that case the particles would expand in all direction), a repulsive force propagating from the sun that gives impetus to those particles. However, Norton argues that the tail and head of a comet are not from one connected mass, revolving as one body around the sun. Instead, the tail of a comet is made up of particles which continually are being detached from the head, and a collection of those particles within a specific time interval is seen as a tail. In fact, at the end of any such interval a completely new tail is observed.[562]

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[560] Reynolds, Osborne, *Papers on Mechanical and Physical Subjects*, 3 vols. (Cambridge: Cambridge University Press, 1900–1903), vol. 1, p. 8.

[561] Ibid., p. 9.

[562] Norton, William August, "On the Mode and Formation of the Tails of Comets," *American Journal of Science and Art* 46 (1844), 106–109, 123–124.

Since experiments to detect any impulsive force of the sun's rays had failed, Norton named the tail- forming agent "the repulsive force of the sun".[563] He calculated the limits of this repulsive force using the method employed by Olbers and Bessel. In this method, they applied the common equations of motion to the particles of the tail and tried to determine the constant that represented the force exerted by the sun, assuming that the force acted based on the inverse square law. Norton's limits for the sun's repulsive force were between −2.73 and +0.46 (plus sign is for an attractive and minus for repulsive force), and the nature of the force was assumed to be magnetic or electrical.[564] In an article written after the introduction of the spectroscopy in the cometology, Norton explains his electrical theory in detail as:

> […] the direct effect of the action of the sun on the side of the nucleus exposed to the solar rays, is to form an envelope of gaseous carbon dioxide extending a certain distance from the nucleus. This envelope, consisting of a diamagnetic gas, is traversed by the ideal lines of magnetic force proceeding from the nucleus, which are also lines of electric conduction through the diamagnetic gas. The electricity set free by the ascending currents of the gas, by reason of the diminished gaseous pressure, is propagated along these lines; and the impulsive force of the electric currents detaches streams of successive molecules of the gas, in the direction of the lines of contraction. De La Rive's well-known experiment of transmitting electricity through an attenuated gas or vapor surrounding a magnet, showed that the lines of force in the magnetic field were also lines of electric conduction, rendered luminous by the propagated electricity.[565]

Reynolds' electrical theory, in one aspect, was similar to Tyndall's theory of comets. In the late 1860s, the Irish physicist John Tyndall (1820–1893), who is also famous for his explanation of the color of the sky, developed a theory in which the formation of a tail was attributed to the interaction between the cometary vapor and two kinds of forces. According to Tyndall, a comet is composed of a kind of vapor that is decomposable by the sun light. Also, the head and tail of a comet are made up of an actinic cloud resulting from the decomposition of the cometary matter. The tail, however, is not projected matter, it is the matter that precipitated on the solar rays passing through the cometary atmosphere. The tail is antisolar because two antagonistic powers are acting upon the cometary vapor: an actinic power, tending to produce precipitation, and a calorific power, tending to effect vaporization.[566] Thus, like Reynolds, Tyndall does not assume the tail to be an appendage to the head of a comet; it is considered as a rainfall of actinic vapors which is seen in different directions due to the displacement of the comet.

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[563] Ibid., p. 109.

[564] Ibid., pp. 113–125; also see Asaph Hall, "Comets and Meteors," *The Analyst* 1 (1874), 20–21.

[565] W. A. Norton, "Coggia's Comet – its Physical Condition and Structure. Physical Theory of Comets," *The American Journal of Science and Arts*, 3rd series, 15 (1878), 167. Here, Norton states that "From the bright bands observed [in the spectrum of the comet Coggia] we may infer that the coma consisted in a large measure of matter in the gaseous state; […] The light of incandescence of the gaseous particles, which furnished the bands, must have been of electric origin; since the heat of the sun could not have been sufficient to ignite the most inflammable vapor". Ibid., p. 162.

[566] John Tyndall, *Contributions to Molecular Physics in the Domain of Radiant Heat* (London: Longman Green, and Co., 1872), pp. 443–444.

Despite the plausibility of such mechanical theories in the lack of an acceptable theory about the electrical properties of the sun, theories based on the involvement of a repulsive electrical force in the formation of cometary tails were more attractive in the second half of the nineteenth century, especially after the introduction of spectroscopy in the cometology. The most elaborate of such electrical theories of comets, which lasted even in the first decades of the twentieth century, were worked out by Johann Carl Friedrich Zöllner (1834–1882) and Fyodor Aleksandrovich Bredikhin(1831–1904).[567]

Zöllner, a professor of physics and astronomy at University of Leipzig, in his important article of 1871, drew attention to the fact that unlike gravity, which depends on the masses of the interacting objects, the attractive or repulsive force of electricity depends on the surface of the body acted on. In other words, the shape and size of a typical tail not only are affected by the mass of the tail particles, they are changed based on the surface size of those particles.[568] Therefore, by assuming that the sun and the comet are similarly electrified, if the particles of cometary matter diminish, the gravitational interaction decreases and the net electrical repulsive force increases. According to Zöllner, whenever a comet approaches the sun, rapid evaporation and disturbance in its atmosphere creates electrical phenomena of enormous strength. This electrification, on the one hand, is responsible for a part of the comet's light, and on the other hand, initiates the formation of its tail. The produced light, then, is not due to incandescent cometary particles but to electrical phenomenon.[569]

Zöllner's electrical theory was expanded and developed by Bredichin, who studied the process of formation, shape, direction and other physical features of more than fifty cometary tails. Bredichin in a series of articles not only suggested an electrical theory of tail formation, but also laid down the basis of a modern typology of cometary tails. According to Bredichin, when a comet approaches the sun, a part of its matter is broken into very small parts – molecules – which no longer adhere together and therefore act like a vapor. These particles are swept away by the repulsive forces of both the comet's nucleus and the sun in the direction opposite to the sun (Fig. 8.6). The velocity of those particles is a function of their masses: the heavier the particle the slower its motion. Each particle, then, moves on an orbit determined mainly by three forces, namely the attraction of the sun, the repulsion of the sun, and the repulsion of the comet (comet's gravitational attraction to the particles is negligible).

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[567] In Russian Фёдор Александрович Бредихин. It is also transliterated as Fedor Alexandrovich Bredichin. In most of the European sources his last name is spelled as Bredichin.

[568] Carl Friedrich Zöllner, "Über die Stabilität kosmischer Massen und die physische Beschaffenheit der Cometen," *Berichte der Königlich Sächsischen Gesellschaft der Wissenschaften* 6 (1871), p. 174, reprinted in idem, *Über die Nature der Cometen, Geschichte und Theorie der Erkenntniss* (Leipzig: Verlag von Wilhelm Engelmann, 1872), pp. 115–124.

[569] Zöllner, *Über die Nature der Cometen*, pp. 110–113; R. Jaegermann, *Prof. Th. Bredichin's Mechanische Untersuchungen über Cometenformen* (St. Petersburg: 1903), pp. 112–116. Osborne Reynolds also studied comets' atmospheric turbulences and their possible electrical consequences. See Reynolds, *Papers on Mechanical and Physical Subjects*, vol.1, pp. 15–21.

Since the velocity of the tail particles is a function of their masses, the lightest particles – molecules of hydrogen[570] – are driven faster and further; and heavier molecules such as carbon and iron cannot move far away. Therefore, based on the composition of a comet not only different kinds of tails may develop, but also each tail may have been composed of different parts. Bredichin, by investigating the process of formation of a multitude of tails, and employing available spectroscopic data, divided cometary tails into three main types. In his typology of tails the initial determining factor for each type was the magnitude of the non-gravitational (repulsive) force of the sun $(1-\mu)$, and the characteristic value for each type was[571]:

Type I, $1-\mu = 11.0$ $g = 0.15$ or 4,500 m per 1^s
Type II, $1-\mu = 1.4$ $g = 0.03$ or 900 m per 1^s
Type III, $1-\mu = 0.2$ $g = 0.01$ or 300 m per 1^s

(g is the velocity of emission of particles, based on observation of the dimensions of comet's head)

Since at any moment the net value of the solar repulsive force is unvaried, the reaction of each cometary particle is determined by its mass. Therefore, based on the constitution of the particles, different tails would be formed. In Bredichin's scheme, the first type of tail is composed of the lightest particles – mainly hydrogen molecules – which move faster and create long and straight tails. The second type is made up of slightly heavier particles – hydrocarbons – which appear as curved and plume-like tails. In Donati's comet, the main tail was a type II tail, and the narrow tangent rays diverging from the body of the former belongs to the first type. The third type contains much heavier matter, such as iron vapor, whose particles cannot move faster and further by the action of the repulsive force [572] (Fig. 8.7).

The theory of tail formation based on the action of a repulsive force, which was developed by Bessel and extended sophisticatedly by Bredichin, did not cover in a technical approach the nature of the acting force. In fact, there was not any physical evidence or observational fact to provide a clue about the physical character of the force. Electricity, however, seemed to be the most probable force to cause the observed cometary phenomena. No other agent than the electricity was known to produce luminosity in the rare media and propagate enormously in a short interval of time. Even Bredichin was in quest of further research to obtain a clear idea about the nature of the repulsive force:

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[570] Spectroscopy had been already introduced into cometology when Bredichin studied cometary tails.

[571] Jaegermann, *Bredichin's Mechanische Untersuchungen*, pp. 273–278; Anonymous, "Prof. Bredichin's Researches on the Tails of Comets," *Monthly Notices of the Royal Astronomical Society* 41 (1881), 234–235; Yeomans, *Comets*, pp. 231–233. For a brief technical account of the major researches on the shape of comets from the 1820s to the 1880s, see François Tisserand, *Traité de mécanique céleste*, 5 vols (Paris: Gauthier –Villars et fils, 1889–1896), vol. 4, pp. 245–276.

[572] Th. Bredichin, "Sur la constitution probable des queues des comètes," *Astronomische Nachrichten* 95 (1879), pp. 27–30; Jaegermann, *Bredichin's Mechanische Untersuchungen*, pp. 475–483; Charles A. Young, *A Text-Book of General Astronomy* (Boston: Ginn, 1889), pp. 414–416; Yeomans, *Comets*, pp. 231–232.

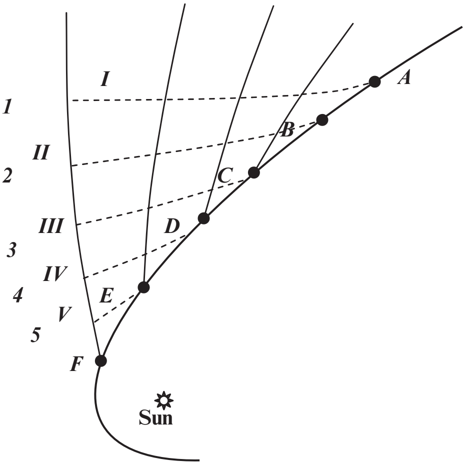

Fig. 8.6 Formation of a comet's tail according to Bredichin: The comet's nucleus on its orbit expels particles *I, II, III…* at *A, B, C,…* which are seen at positions *1, 2, 3,…* when the nucleus is at *F* (Adopted from: George C. Comstock, *A Text-Book of Astronomy* (New York: D. Appleton and Company, 1901, p. 285))

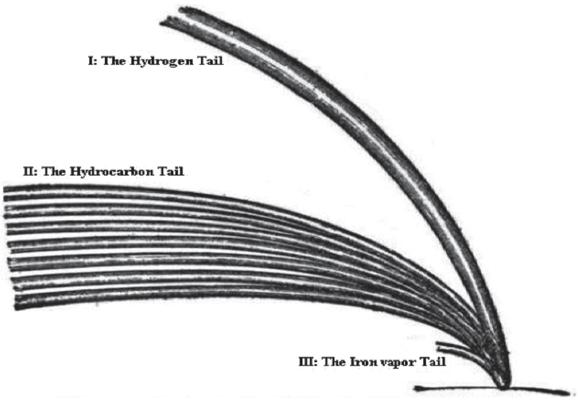

Fig. 8.7 The three types of cometary tails according to Bredichin (Adapted from Francis Rolt-Wheeler (ed.), *The Science-History of the Universe*, 10 vols. (New York: The Current Literature, 1909), vol. 1, p. 244)

> J'emploie la dénomination de l'électricité pour l'énergie, qui émane du soleil et agit diversement sur les différents éléments chimiques des comètes, parceque cette dénomination est déjà introduit dans les théories physiques des comètes; mais il est bien possible, que les recherches ultérieures préciseront mieux la dénomination et les qualitiés de cette énergie.[573]

Bredichin made this statement six years after the publication of *A Treatise on Electricity and Magnetism* by James Clerk Maxwell (1831–1879) in which for the first time the pressure exerted by the incident radiation on a surface was calculated in the framework of the electromagnetic field theory. Maxwell stated that "in a medium in which waves are propagated there is a pressure in the direction normal to the waves, and numerically equal to the energy in unit of volume."[574] After calculating

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[573] Jaegermann, *Bredichin's Mechanische Untersuchungen*, pp. 483–484, cited from *Annales de l'observatoire de Moscou*, 2 (1879), 139.

[574] James Clerk Maxwell, *A Treatise on Electricity and Magnetism* (Oxford: Clarendon Press, 1973), vol. II, p. 391.

the pressure of sunlight falling on a surface of one square foot area, Maxwell discussed the effects of the radiation on surfaces suspended in a vacuum:

> It is probable that a much greater energy of radiation might be obtained by means of the concentrated rays of the electric lamp. Such rays falling on a thin metallic disk, directly suspended in a vacuum, might perhaps produce an observable mechanical effect.[575]

The Pressure of Light

A year after the publication of Maxwell's work, William Crookes (1832–1919) performed a series of experiments to demonstrate the attractive and repulsive force of radiation. After discussing the various results of these experiments and their implications, Crookes concluded that the observed effect of solar radiation may provide a key to answer some unsolved problems in celestial mechanics, among them: "In the sun's radiation passing through the quasi vacuum of space we have the radial repulsive force, possessing successive propagation, required to account for the change of form in the lighter matter of comets and nebulae."[576] Although Maxwell admired Crookes' observations and results he did not adopt the radiation-pressure explanation for the tail formation.[577]

During the time from Crookes' conjecture about the involvement of the solar radiation pressure in the formation of cometary tails to the establishment of the theory of tail formation based on the light pressure, several brilliant comets appeared and were well observed all over Europe and North America. However, for most astronomers the electrical theory of tail formation still seemed more plausible, especially due to the works of Norton, Zöllner, and Bredichin. To employ Maxwell's theory in problems like cometary phenomena, developments in two areas were necessary. First, a detailed calculation of the action of the solar radiation on cometary particles was required, which in turn needed knowledge of the possible combinations and sizes of those particles; and second, accurate observational tools were essential to confirm experimentally the validity of Maxwell's results either in the laboratory or in the astronomical phenomena. The latter was specifically important after the studies of Crookes and Reynolds, which created confusion between the effects of light pressure, and the thermal and convective influences.[578]

The first of these unsolved problems was elucidated less than a decade after Crookes' work. In May 1882, between the apparition of the two Great Comets of 1881 and 1882, George Francis Fitzgerald (1851–1901) calculated the pressure of

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[575] Ibid., pp. 391–392.

[576] William Crookes, "On the Attraction and Repulsion Resulting from Radiation," *Philosophical Transactions* 146 (1874), 527.

[577] Elizabeth Garber, Stephan G. Brush, C.W.F. Everitt (eds.), *Maxwell on Heat and Statistical Mechanics* (London: Associated University Press, 1995), p. 68.

[578] S. G. Brush, C. W. F. Everitt, "Maxwell. Osborne Reynolds, and the Radiometer," *Historical Studies in the Physical Sciences* 1 (1969), 105–125.

the sun's rays on the particles of cometary tails and concluded that the repulsive force emanating from the sun could account for comets' tails. Fitzgerald assumed that the molecules of cometary tail particles were spherical and composed of complex hydrocarbons that absorbed a considerable proportion of the incident radiation. He pointed out that since some comets had more than one tail, a different acceleration should be involved in different kinds of cometary matter. The repulsion of the sun, then, depended on the surface era and the absorbing power of cometary particles and was not proportional to the mass of the particles.[579]

The second difficulty – problem associated with the experimental verification of light pressure – was solved in 1898 by Russian physicist Pëtr Nikolaevitch Lebedev (1866–1912) who, with a highly sensitive torsion apparatus free from the influence of convective effects, detected and measured the pressure of light. He concluded that (1) light exerts pressure both on reflecting and on absorbing surfaces; (2) the pressure of light is directly proportional to the energy of the light beam and not to its color; and (3) the observed forces of light pressure, considering the range of observational errors, are equal to the quantities calculated by Maxwell and Bartoli.[580]

Following the works of Fitzgerald and Lebedev in the first years of the twentieth century, Svante Arrhenius (1859–1927) studied a version in which the particles repelled by the light pressure were assumed to be condensed or solid corpuscles instead of being gas molecules. Based on Arrhenius' calculation, in the vicinity of the sun, a spherule of the same density as water should have a diameter of 0.0015 mm to attain a balance between the sun's gravitational attraction and its light pressure.[581] Arrhenius, employing the newly discovered conducting effects of radiation on gasses by Charles Thomson Rees Wilson (1869–1959), explained the non-polarized light emission from comets. As Wilson showed in his cloud chamber experiments in 1896, Röntgen rays (discovered in 1895), Cathode rays and ultraviolet light could ionize gasses and transform them into conductors of electricity. Arrhenius theorized that the ultra violet radiation of the sun partially ionizes the cometary gasses and since negative ions are capable of condensing vapors upon themselves, the motions of the negative and positive ions are due to light pressure and consequently become separated. If the opposite charges are accumulated in high degrees then electric discharges may ensue and the gases become luminescent despite their low temperature.[582]

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[579] Joseph Larmor (ed.), *The Scientific Writings of the Late George Francis Fitzgerald* (London: Longman, Green & Co., 1902), pp. 108–110.

[580] P. N. Lebedev, "Experimental Examination of Light Pressure," translated from Russian by Soloviev V., *Annalen der Physik* 6 (1901), 457–458. Adolfo Bartoli (1851–1896) was an Italian physicist and chemist whose experimental and theoretical studies on Maxwell's theory of light pressure had influence on the succeeding studies of the matter. See: Bruno Carzza, Helge Kragh, "Adolofo Bartoli and the problem of radiant heat," *Annals of Science* 46 (1989), 183–194.

[581] Svante Arrhenius, *Worlds in the Making: the Evolution of the Universe*, trans. H. Borns (New York: Harper & Brothers Publishers, 1908), p. 97.

[582] Ibid., pp. 98–99.

A few months after Arrhenius' work, Karl Schwarzschild (1873–1916) pointed out that to consider the light pressure as the driving force of tail particles – as Arrhenius had concluded – the size of particles must be very small, in a magnitude comparable to the wavelength of light. Schwarzschild, including the effects of diffraction of light in his calculations, showed that when the dimensions of the exposed particles are either smaller or larger than the wavelength of the falling light the magnitude of the repulsion of light is smaller than the gravitational attraction of the sun. However, the sun's light can exert pressure, on particles with moderate dimensions, twenty times more than the sun's gravitational attraction.[583] In Schwarzschild's calculations the newly developed radiation law by Wilhelm Wien (1864–1928) was employed to particles that were assumed to be perfectly conducting spheres.[584]

By the first decade of the twentieth century, there existed profound developments in the study of the interaction of light and matter and there existed more spectroscopic information about the nature of cometary material, which together opened a new chapter in the history of cometology. In 1903, Ernest Fox Nichols (1869–1924) and Gordon Ferrie Hull (1870–1956), equipped with the data produced by Arrhenius, Lebedev, and Schwarzschild imitated cometary tails in an interesting experiment. In the search for an appropriate powder to play the role of tail particles, they discovered that the spores of the fungus *Lycoperdon* were nearly spherical with average diameter of two microns. They calcined spores by heating to redness and produced sponge-like charcoal spheres with a density of about one-tenth that of water. They mixed these particles with some emery sand particles and placed them in an evacuated long hour-glass. When the tube was held vertically and a fine stream of powder started to fall down, a beam of light with approximately known intensity was directed horizontally to the stream. While the sand particles were falling vertically, the spores were deflected from the stream by the light pressure [585] (Fig. 8.8).

From the three long-lasting cometary problems – their motions, tail formation, and physical nature – two were solved successfully within about three centuries after Brahe's elevation of comets to the celestial region: By the end of the seventeenth century Newton explained comets' motion; by the end of the eighteenth

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[583] Karl Schwarzschild, "Der Druck des Lichts auf kleine Kugeln und die Arrhenius'sche Theorie der Cometenschweife," *Sitz. Ber. Math. Phys. Classe d. Kgl. Bayer. Akad. d. Wiss*, 31 (1901), 293–338, reprinted in Karl Schwarzschild, *Gesammelte Werke*, edited by H. H. Voigt, 3 vols. (Berlin: Springer Verlag, 1992), vol. 1, pp. 317–322; Anonymous, "Recent Researches on the Theory of Comets' Tails," *Monthly Notices of the Royal Astronomical Society* 64 (1904), 347–349; Arrhenius, *Worlds in the Making*, pp. 97–98.

[584] In 1896 Wien showed that the distribution of energy with wavelength is as: $\lambda_{\max} \times T = A$, where λ is wavelength (cm), T is temperature (K), and A is a constant. In the last years of the nineteenth and early years of the twentieth centuries the validity of this relationship was the subject of experimental and theoretical investigations, especially by W. A. Michelson, Frederick Paschen, S. P. Langley and many others. See: Robert D. Purrington, Physics in the Nineteenth Century (New Brunswick: Rutgers University Press, 1997), pp. 152–153.

[585] E. F. Nichols, G. F. Hull, "The Application of Radiation Pressure to Cometary Theory," *Astrophysical Journal* 17 (1903), 352–360. Nichols and Hull also developed a sophisticated method to demonstrate experimentally the pressure of light. See: Idem, "The Pressure due to Radiation," *Astrophysical Journal* 17 (1903), 315–351.

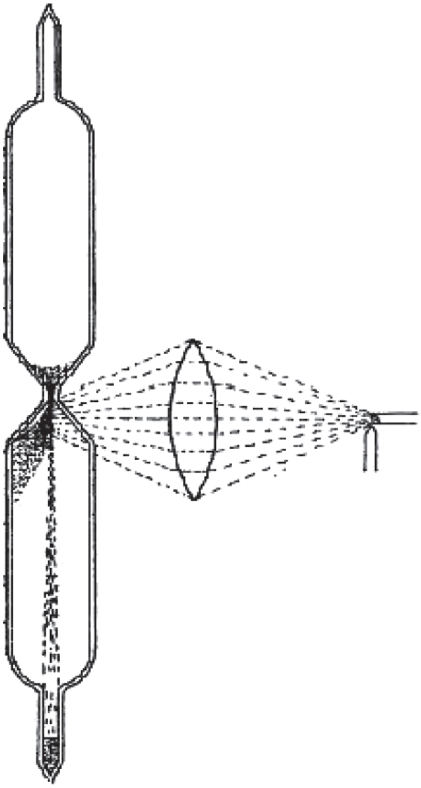

Fig. 8.8 Simulation of the formation of cometary tails by Nichols and Hull. The stream of an extremely fine powder in the hour-glass deflected when exposed to a concentrated artificial light (From Nichols and Hull, "The Application of Radiation Pressure," p. 358)

century Laplace estimated their masses, and by the end of the nineteenth century, the mystery of tail formation was revealed. The nature and physical constitution of comets; however, were still under scrutiny, though the introduction of the spectroscopy in the second half of the nineteenth century had revolutionized the field.

Spectroscopic Study of Comets

Almost half a century after the introduction of spectroscopy in astronomy, Giovanni Battista Donati (1827–1873) made the first visual spectroscopic observation of a comet in 1864. Donati observed the comet I, 1864, and described its spectrum as being similar to the spectra of metals. The dark portions of the spectrum seemed to be broader than the luminous parts, and the spectra were composed of three bright lines.[586]

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[586] Annonymus, "Report of the Council to the Forty-fifth Annual General Meeting of the Society," *Monthly Notices of the Royal Astronomical Society* 25 (1865), 114. At the end of a short quotation from Donati about the comet's spectra, the author adds: "So far, then, there is reason to presume the existence of some close relation between nebulous and cometary matter. Thus another step is gained in our knowledge of Sidereal Physics."

Two years after the publication of Donati's simple report of cometary spectra, William Huggins (1824–1910) and Angelo Secchi (1818–1878) produced detailed descriptions of what they observed in the spectra of Tempel's comet, which appeared in January, 1866.

Huggins who had started spectroscopic studies of nebulae and stars from 1864, and made spectroscopy his life-time discipline, had a remarkable contribution in the spectral analysis of comets. In his first report of cometary spectroscopy, Huggins concluded that the light of comet Tempel's coma was the reflection of the solar light but its nucleus was self-luminous and its matter was in the state of ignited gas. He also compared the spectra of the nucleus with those recorded from the nebulae. Huggins found that the bright line of the nucleus was corresponding in refrangibility with the spectra of many nebulae which gave a spectrum of one line only. Since this nebular bright line corresponded in refrangibility with the brightest lines of nitrogen, Huggins come to this conclusion that the cometary matter might be consist chiefly of nitrogen or a more elementary substance existing in nitrogen.[587] Secchi, however, observed three bright lines, the brightest situated half-way between *b* and F of the solar spectrum.[588]

Huggins in May of 1868 studied the spectrum of Brorsen's comet and also found three bright bands; however, the brightest band was in a small degree less refrangible than the line of nitrogen, and the position of lines seemed to indicate a chemical constitution different from those nebulae that produce a spectrum of bright lines (Fig. 8.9). He also noticed that the luminous matter were not expelled immediately to the outer parts of the coma and the tail. They formed a dense luminous cloud in front of the nucleus and for a while the characteristics of its light were not distinguishable from those of the nucleus.[589]

A month later, Huggins studied the spectrum of comet II, 1868, and announced that the "spectrum of the comet appeared to me to resemble some of the forms of the spectrum of carbon which I had observed and carefully measured in 1864."[590] Then, in the 1871 return of Encke's comet the observation of a band coincident with the third band in the carbon spectrum was confirmed, but Huggin's observations to detect polarized light in the comet led him to conclude that probably "no considerable part of the comet's light is polarized."[591] Three years later, the appearance of

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[587] William Huggins, "On the Spectrum of Comet 1, 1866," *Proceedings of the Royal Society of London* 15 (1866–1867), 5–6.

[588] Angelo Secchi, "Spectre de la comète de Tempel," *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences* 62 (1866), 210; Heinrich Scellen, *Spectrum Analysis in its Application to Terrestrial Substances and the Physical Constitution of the Heavenly Bodies*, trans. Jane and Caroline Lassell (New York: D. Appleton and Company, 1872), p. 395.

[589] William Huggins, "On the Spectrum of Brorsen's Comet, 1868," *Proceedings of the Royal Society of London* 16 (1867–1868), 387–389.

[590] Idem., "Further Observations on the Spectra of some of the Stars and Nebulae, with an Attempt to determine therefrom whether these Bodies are moving towards or from the Earth, also Observations on the Spectra of the Sun and of Comet II., 1868," *Philosophical Transactions of the Royal Society of London* 158 (1868), 557.

[591] Idem., "Notes on the Spectrum of Encke's Comet," *Proceedings of the Royal Society of London* 20 (1871–1872), 47.

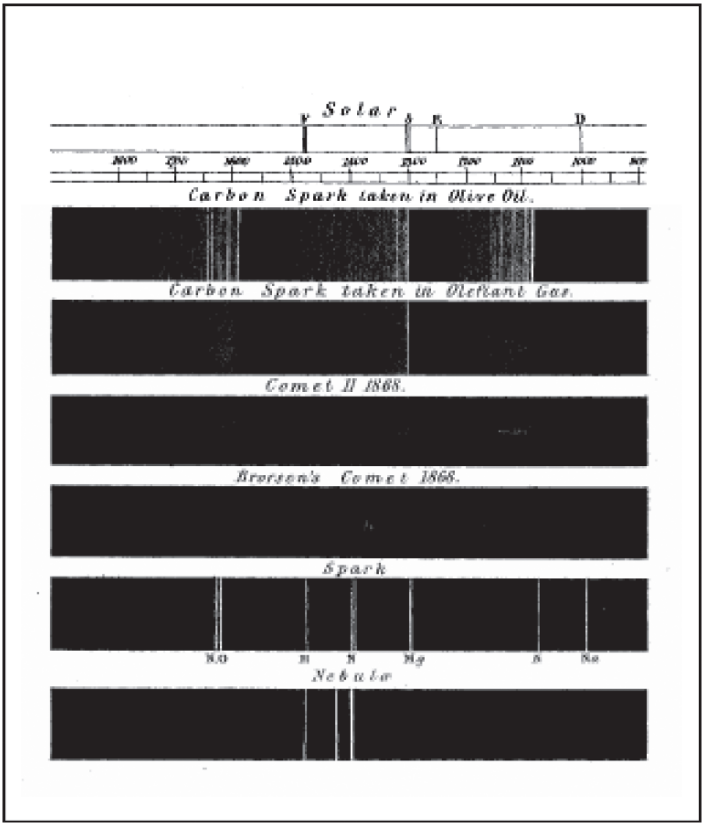

Fig. 8.9 Comparison of the spectra of Comet II, 1868 with those of the sun and carbon spark (From Huggins, "Further Observations," p. 565)

Coggia's comet in April, 1874 provided an opportunity to study the spectrum of a bright comet by several astronomers, among them Secchi, Heinrich Ludwig d'Arrest (1822–1875), Hermann C. Vogel (1841–1907), Arthur Cowper Ranyard (1845–1894), and Huggins. Their results more or less were the same: they observed three bands from which the brightest cometary band was seen on every occasion, they could detect the polarization in the coma and tail, and the resemblance of the bright band to the spectrum of carbon was established.[592] Huggins extended his inquiries to investigate the possible physical state of carbon in comets. From the fact that the majority of comets did not acquire adequate heat to produce luminous vapor of carbon and from the connection between the orbits of comets with those of meteor showers and the presence of hydrocarbons in many meteorites, Huggins suggested the probability of presence of carbon in comets in combination with hydrogen.[593]

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[592] Kronk, Cometography, vol. 2, pp. 410–411; William Huggins, "On the Spectrum of Coggia's Comet," *Proceedings of the Royal Society of London* 23 (1874–1875), 154–159.

[593] Huggins, "On the Spectrum of Coggia's Comet," p. 156.

The connection between meteor showers and comets had just been established. After the long study of the radiant points of several meteor showers that had been conducted since the beginning of the nineteenth century, in 1866 Giovanni Virginio Schiaparelli (1835–1910) concluded that the orbits of meteor showers coincided with the trajectory of comets. The parent comets of some meteor showers were identified: comet Swift-Tuttle (1862, III) for the Perseids, comet Tempel-Tuttle for the Leonids, and comet Biela for the Andromedids. The prediction of the Bielid shower of November, 1872 clearly confirmed the comet-meteor shower relationship.[594]

To find experimental evidence for the comet-meteor relationship, Arthur W. Wright of Yale College, obtained the spectrum of a newly recovered stony meteorite. He found that the characteristic gas in such a meteorite is carbon dioxide and this along with a small proportion of carbon monoxide make almost ninety percent of the gas extracted from the meteorite at the temperature of boiling water. Wright, by passing an electric arc through the collected gas, revealed that the three bright bands in its spectrum coincided in position with the bands in the spectra of comets.[595] Inspired by Wright's results and employing calculations made by Faraday and Pouillet, W. A. Norton proposed that solid carbonic acid might be accumulated at the surface of comets. Michael Faraday (1791–1867) had experimentally shown that carbon dioxide condenses into liquid at 80°C below the freezing point at the pressure of one atmosphere. Claude Servais Mathias Pouillet (1790–1868) estimated that the temperature of the outer space to be −140°C. Norton concluded that the physical condition was appropriate to create liquid carbon dioxide at the surface of cometary nuclei.[596]

The three bright bands in cometary spectra were seen in yellow, green, and blue parts of the spectrum (Fig. 8.10). In 1856, Scottish physicist William Swan (1818–1894) investigated the spectral bands of carbon radical C_2, which are called Swan bands. The cometary bright bands that were observed by Huggins and others usually coincided with two or three Swan bands at the approximate wavelengths of 4737, 5165, and 5635 Ångström.[597] These bands were located in the visual portion of the spectrum, and the photographic plates also were mainly sensitive to that

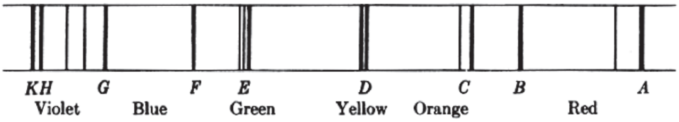

Fig. 8.10 Fraunhofer lines (From Holton, *Physics*, p. 428)

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[594] Yeomans, *Comets*, pp. 188–202; Brandt, *Introduction to Comets*, pp. 19–21.

[595] Arthur W. Wright, "Spectroscopic Examination of Gases from Meteoric Iron," *American Journal of Science and Arts* 9 (1875), 294–303; Idem., "Examination of Gases from the Meteorite of Feb. 12, 1875," *American Journal of Science and Arts* 10 (1875), 44–49;

[596] Norton, "Coggia's Comet," p. 163.

[597] Yeomans, *Comets*, p. 204.

Table 8.1 Relative speed of photographic surfaces (From Brand, *Lines of Light*, p. 73)

Date	Sensitive surface	Exposure
1839	Daguerre-Niepce (I_2)	30 min
	(Br_2,Cl_2)	3 min
1841	Talbot	3 min
1851	Wet plate	10 s
1878	Gelatin plate	1 s

portion. However, by the1880s improvements in photography not only increased the speed of photographic surfaces but also expanded their sensitivity to non-visual portions of the spectrum (Table 8.1). In 1878, the invention of dry plates – a suspension of silver halide in gelatin – opened a new era in photography and made scientific photography routine. Dry plates had a long shelf time and worked effectively in the non-vacuum ultraviolet.[598]

In 1881, for the first time since the application of spectroscopy and photography in astronomy, astronomers were able to examine the invisible portion of a comet's spectrum at its blue end. Huggins found two bright lines in the ultra-violet region of comet 1881 b, with wavelengths of 3883 and 3870 Ångström. The lines apparently belonged to the spectrum of carbon, possibly in combination with hydrogen.[599] However, the result of observations made by G. D. Liveing and J. Dewar was different: the comet's spectrum indicated the presence of cyanogen, a compound that necessitated the presence of nitrogen in the comet.[600] In 1882, spectroscopic observation of comet Wells added a new element to the list of cometary constituents. Astronomers discovered that the yellow line of sodium in the spectra of comet coincided with the D line of the solar spectrum.[601] After a few months, the Great comet of 1882 exhibited many more lines. R. Copeland and J. D. Lohse published a list of lines with their probable origins, which covered elements Fe, Mn, Pb, and Mg.[602] By the beginning of the twentieth century, the list of cometary elements and compounds derived from the interpretation of the spectral lines mainly consisted of CN, C_3, C_2, CH, and Na, with some other indistinguishable lines that might have had metallic origins.

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[598] John C. D. Brand, *Lines of Light, The Sources of Dispersive Spectroscopy, 1800–1930* (Amsterdam: Overseas Publishers Association, 1995), p. 73.

[599] William Huggins, "Preliminary Note on the Photographic Spectrum of Comet b 1881," *Proceedings of the Royal Society of London* 33 (1881–1882), 1–3.

[600] G. D. Liveing, J. Dewar, "Note on the Reversal of the Spectrum of Cyanogen," *Proceedings of the Royal Society of London* 33 (1881–1882), 3–4.

[601] B. Hasselberg, "Uber das Spectrum des Cometen Wells," *Astronomische Nachrichten* 102 (1882), 259–26; Henry E. Roscoe, *Spectrum Analysis* (London: Macmillan, 1885), pp. 327–328.

[602] Norman Lockyer, "Appendix to the Bakerian Lecture, Session 1887–1888," *Proceedings of the Royal Society of London* 45 (1888–1889), 178–179. The work of Copeland and Lohse was criticized later by some astronomers, see: M. W. Burke-Gaffney, "Copeland and Lohse and the Comet, 1882 II," *Journal of the Royal Astronomical Society of Canada* 62 (1968), 49–51.

In 1907, Henri Deslandres and A. Bernard obtained a clear spectrogram of comet Daniel's tail and revealed several weak bands which they attributed to hydrogen or carbon gas in a special vibratory mode. They observed the tail of comet 1908 III and identified bands due to CO^+ and a band at 3194 Å, which was later attributed to N_2^+.[603] The same bands were also observed by Pluvinel and Baldet at Paris, which they attributed in part to carbon monoxide, nitrogen, carbon and cyanogens. They also observed some faint bands and failed to identify them.[604] Again, in 1910 almost the same compounds, namely cyanogens, carbon monoxide, N_2^+ and CH, were detected in Halley's comet.[605]

In the last decade of the ninetieth century and the beginning years of the twentieth century, spectroscopy experienced major developments both in technical and theoretical aspects. In 1882, Henry A. Rowland (1848–1901) invented the concave grating and the device to produce parallel grooves on the grating with higher accuracy. Rowland's dividing engine, when maintained at a constant temperature, was capable of producing cuts on the grating with errors at no point exceeding 1/100,000th of an inch.[606] Rowland's grating not only increased the accuracy of the wavelength measurement but also greatly facilitated the process of astronomical spectroscopy. In the theoretical realm, Bohr's atomic theory (1913) provided a theoretical basis to interpret the spectral lines correctly. At the same time, developments in molecular spectroscopy revealed the nature of the spectral bands. It became clear that the observed bands were in fact a multitude of close lines which were not resolvable in small apparatuses. Consequently, astronomers found that the Swan spectrum was not related to hydrocarbons, it was produced by the carbon molecule C_2; the fainter light of cometary tails was mainly due to carbon monoxide (CO^+); and fainter bands were produced by molecules of CH, CH_2, OH, NH and N_2^+.[607] In 1926, French astronomer Fernand Baldet (1885–1964) illustrated the distribution of the major molecules and ions in a typical comet as follows: CN and C_2 in the coma or head only (the extension of CN molecules is larger than that of C_2 molecules) and CO^+ and N_2^+ in the tail [608] (Fig. 8.11).

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[603] Yeomans, *Comets*, pp. 219–220.

[604] A. de La Baume Pluvinel, F. Baldet, "Spectrum of Comet Morehouse (1908 c)," *The Astrophysical Journal* 34 (1911), 89–104.

[605] J. Evershed, "Halley's Comet and its Spectrum, Observed at Kodaikénal," *Monthly Notices of the Royal Astronomical Society* 70 (1910), pp. 605–611; Charles P. Butler, "The Spectrum of Halley's Comet," *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 84, 573 (1911), 523–526. For a comprehensive review of the reports, spectra and photographs of the 1910 return of Halley's comet see: Nicholas T. Bobrovnikoff, "Halley's Comet in its Apparition of 1909–1911," Publications of the Lick Observatory, 17, Part 2 (1931), 1–482.

[606] W. Marshall Watts, *An Introduction to the Study of Spectrum Analysis* (New York: Longmans, Green and Co, 1904), p. 120; Davis Baird, *Thing Knowledge, A Philosophy of Scientific Instruments* (Berkley: University of California Press, 2004), pp. 73–74.

[607] Pannekoek, *A History of Astronomy*, pp. 426–427; Yeomans, *Comets*, pp. 203–204.

[608] Karl Wurm, "On the Interpretation of the Spectra of Comets and Their Forms," *Astrophysical Journal* 89 (1939), 314.

Fig. 8.11 Distribution of the emitting molecules in comets according to Baldet (From Karl Wurm, "On the Interpretation of the Spectra," p. 315)

Comet	**Nucleus**	**Head**	**Tail**
	Some emission	CN	CO^+
	Not yet	C_2	N_2^+
	Identified	CH	

Modern atomic theory also shed a new light on the process by which light pressure acts on particles. Instead of visualizing the process as the impact of electromagnetic waves on small spherical particles of gas or dust, as Schwarzschild had theorized, it was understood as the transfer of photons' momentum to particles whenever they are absorbed or scattered. In fact, when a photon strikes an atom and is absorbed by it, the atom ascends to an excited state but returns to its original state by emitting a photon in a random direction. As a result, it recoils in the direction opposite to the emission of the photon. However, after repeated performances of this absorption-emission process the net changes in the atom's momentum is in the same direction of the incident photons.[609]

Although deciphering some long-lasting riddles of the chemistry of comets opened new windows to understand cometary phenomena, it raised new questions. One of the key questions that Karl Wurm brought forth in the 1930s was about the origin of radicals and ions in comet spectra. He theorized that since the identified lines belong to unstable radicals and ions, they must be originate in the action of the solar radiation upon some stable molecules existing within comets:

> Hence, the appearance of particles which we cannot expect to be freed from the solid nucleus directly, such as C_2, CO^+, N_2^+ and perhaps others, must be formed by one of the two processes […] namely by ionization or by dissociation by light absorption of another particle, which we may call the "parent-molecule."[610]

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[609] Pannekoek, *A History of Astronomy*, p. 427; Dina Prialink, *An Introduction to the Theory of Stellar Structure and Evolution* (Cambridge: Cambridge University Press, 2000), pp. 42–23.

[610] Wurm, "On the Interpretation of the Spectra," p. 317. For Wurm's other cometary articles see: Karl Wurm, "Über die Größe des selektiven Strahlungsdruckes auf die Moleküle in den Kometenschweifen," *Zeitschrift für Astrophysik* 10 (1935), 285; Idem., "Beitrag zur Deutung der Vorgänge in Kometen. II," *Zeitschrift für Astrophysik* 9 (1934), 62; Idem., "Beitrag zur Deutung der Vorgänge in Kometen. I," *Zeitschrift für Astrophysik* 8 (1934), 281–291; Idem., "Zur Deutung des Anregungsmechanismus von Kometen-, Polar-und Nachthimmellicht," *Zeitschrift für Astrophysik* 8 (1934), 96–101.

Any knowledge about the chemical and physical conditions of these parent molecules and their relative abundances would enlighten astronomers about the constitution of comets and their possible structure. In the 1940s, Polydore F. Swings (1906–1983), following Wurm's approach, not only introduced several stable molecules as the possible parents molecules but also showed how comets' spectra can be affected by comets' motion and the consequent interaction between the sun's radiation and cometary molecules.

Swings' first achievement in cometary science was the discovery of a phenomenon which now is called the *Swings' effect*. It was known that the intensity distribution in the molecular bands obtained from comets is different from those produced in the laboratory. The intensity distribution not only varies in different comets but also it changes in the same comet by the comet's heliocentric distance. In 1941, Swings explained that due to the motion of comets a Doppler shift of the Fraunhofer lines happens with respect to the lines in cometary spectral bands. Consequently, a line in a cometary band may appear brighter or fainter based on its position relative to a strong Fraunhofer line in the sun's spectrum. In other words, Swings showed that because of the variable velocity of a comet around the sun the frequency of radiation that a cometary molecule absorbs depends upon this velocity due to the effect of Doppler shift.[611]

Swings' spectral analysis bridged the gaps between the observational and physical features of comets. A few years before the publication of Swings' studies about comet Encke (1947), Nicholas Theodore Bobrovnikoff (1896–1988), a leading figures in cometology, in his evaluation of the spectral studies of comets since the first observation of a comet's spectrum wrote: "Since that time [1864] the spectra of 108 comets have been observed. There is no exaggeration in saying that the study of the spectra of comets has not helped in elucidation of cometary phenomena. On the contrary, a host of new and baffling problems has been introduced."[612] One of these problems was to find the nature and proportion of the parent molecules in a comet before the formation of its tail.

Swings' studies of comets' emission bands led him to conclude that the following occluded compounds must have existed in the cometary solids: H_2O, NH_3, CH_4, C_2N_2, N_2, CO or CO_2.[613] Thus, water, methane, ammonia, carbon dioxide, carbon monoxide and nitrogen were the molecules that under the influence of the sun's radiation dissociated to those "daughter molecules" observed in the spectra of comets. These substances maintained at a frozen state before the nucleus reached a specific heliocentric distance.[614] Also, the existence of $CH_{4,}$ CO_2, and N_2 in the spectra of meteorites implied a possible relationship between comets and meteorites.

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[611] Yeomans, *Comets*, pp. 221–224; Brandt, *Introduction to Comets*, pp. 31–33; K. S. Krishan Swamy, *Physics of Comets* (River Edge, NJ: World Scientific, 1997), pp. 70–71.

[612] N. T. Bobrovnikoff, "Physical Theory of Comets in the Light of Spectroscopic Data," *Review of Modern Physics* 14 (1942), 164.

[613] P. Swings, "The Physical Chemistry of Comets," *Popular Astronomy* 51 (1943), 414.

[614] Idem., "Le Spectre de la Comète d'Encke, 1047 I," *Annales d'Astrophysique* 11 (1948), 124–136; Yeomans, *Comets*, pp. 242–243; M. C. Festou, H. Rickman, R. M. West, "Comets," *The Astronomy and Astrophysics Review* 4 (1993), 368.

According to Swings "it might not be entirely legitimate to identify the two types of objects; yet a comparison is very useful."[615]

Due to the relation between comets and meteoric showers some astronomers were suspicious if the nucleus of a typical comet was of meteoric nature. Discovery of compounds such as methane, water and ammonia in comets which should be in a frozen state before approaching the sun, implied a coexistence of both types of an intrinsically solid and frozen material in comets. In order to develop a plausible structural model, a quantitative knowledge, even rough, was needed concerning the proportion of those constitutional compounds, the average size of building blocks, and the rate of evaporation of volatile material. These should be in harmony with the visual and spectral observations to enable astronomers to answer questions such as the problem of regeneration of cometary surfaces, duration of comets, development of jets and envelopes in cometary nuclei, formation of different types of tails and other questions.

In 1946, Boris Vorontsov-Velyaminov (1904–1994) from Sternberg Astronomical Institute, Moscow, developed a quantitative model to reconcile the available data of gas liberation with the mass of cometary nuclei. To elucidate his model, Velyaminov even suggested a new cometary jargon to avoid any misinterpretation. He differentiated between the *photometric* nucleus (the apparent luminous condensation in a comet), the *stellar* nucleus (which sometimes is seen inside the photometric nucleus), the nucleus as the *origin of the Fraunhofer spectrum*, the nucleus as the *origin of the continuous spectrum*, the nucleus as the *source of the gasses*, and the nucleus as a *bearer of the comet's mass*. For the nucleus as the bearer of the comet's mass he assigned an upper limit of approximately 10^{23} gm and a lower limit of about 10^{13}–10^{15} gm. In Velyaminov's model, a typical solid nuclei was an object 25–60 km in diameter, with a mass of 3×10^{19} gm, composed of blocks some 160 m in diameter which were nearly in contact. For example, he illustrated the nucleus of Halley's comet as a dense cluster of meteoric blocks, whose distances from each other were approximately at the same magnitude of their dimensions. The nucleus was 30 km in diameter with a mass of 3×10^{19} gm. The liberation of gasses proceeded inside the fragmentary nucleus, with a higher rate in the sunlight side.[616]

Whipple's Theory of Comets

The idea of the fragmentary cometary nuclei was recast in a highly detailed and consistent format by Fred Lawrence Whipple (1906–2004) of Harvard College Observatory. Whipple, by publishing two articles in 1950 and 1951, introduced a model in which the nucleus was assumed to be an icy conglomerate of volatile and

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[615] Swings, "The Physical Chemistry of Comets," p. 414.

[616] B. Vorontsov-Velyaminov, "Structure and Mass of Cometary Nuclei," *Astrophysical Journal* 104 (1946), 226–233.

meteoric material.[617] This model, mostly known as the *dirty snowball* model, soon turned out to be the most acceptable cometary theory and showed its capability in solving a variety of problems associated with comets.[618]

Whipple's starting point was to explain the nongravitational acceleration of comet Encke, which had been remained unsolved since the 1820s. Although the observed effect of retardation did not have the same magnitude in Whipple's time as it had when first discovered, it was still there. A key question, which was almost as old as the discovery of this effect, was about its non-uniform action. If there were retarding ether filling the interplanetary space and shortening the orbit of the comet Encke, why did it act in an opposite way on comet Halley by enlarging its orbit? Whipple's approach to solve this difficulty was genuine: in Nigel Calder's words, he made a "jet engine out of a snow ball" to attribute the non-gravitational accelerations not to the encompassing medium but to the comet itself.[619] It was a twentieth century version of the notion that held the nature and motion of comets are two sides of a single coin!

In Whipple's model a comet's nucleus was envisaged as "a conglomerate of ices, such as H_2O, NH_3, CH_4, CO_2, CO (C_2N_2?), and other possible materials volatile at room temperature, combined in a conglomerate with meteoric materials, all initially at extremely low temperatures (<50°K)".[620] Although, there was no record of any meteorite having originated from a comet, Whipple, considering theoretical and observational facts, assumed that the meteoric pieces in a comet were small, with a size ranging from a few centimeters in radius to particles in molecular scale. In Whipple's terminology, "ices" were used to refer to substances with melting point below 300° C and "meteoric material" to those with higher melting points.

When a comet approaches its perihelion, the ices on or close to the surface of its nucleus vaporize. The evaporation of these ices causes meteoric material below a certain size to be dispersed. The largest particles or matrices remain on the surface of the nucleus and form an insulating layer. This layer, in a relatively short time,

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[617] Whipple has nurtured his cometary model for several years and published an abstract of the model in 1949, see: Fred L. Whipple, "Comets, Meteors and the Interplanetary Complex," *Astronomical Journal* 54 (1949), 179–180. Swings also mentions Whipple's idea about the duration of Encke's comet (which was important in the development of Whipple's theory) in his publication in 1948, see: Swings, "Les Spectre," p. 136.

[618] Boris Yu. Levin in 1943 and Ray Lyttleton in 1948, proposed similar theories of comets and envisioned the cometary nucleus as a sandbank – a gravitiontionally bound swarm of minute particles and absorbed gases – moving around the sun. Although Whipple's model was successful in explaining different acpects of cometary phenomena, the debate between the supporters of both models continued for decades. See: Paul R. Weissman, Erik Asphaug, Stephan C. Lowry, "Structure and Density of Cometary Nuclei," in M.C. Festou, H. U. Keller, and H. A. Weaver (eds.), *Comets II* (Tucson: The University of Arizona Press, 2004), p. 338; R. A. Lyttleton, "On the Origin of Comets," *Monthly Notices of the Royal Astronomical Society* 108 (1948), 465–475.

[619] Nigel Calder, *Comets: Speculation and Discovery* (New York: Dover, 1980), p. 89.

[620] Fred L. Whipple, "A Comet Model. I. The Acceleration of Comet Encke," *Astrophysics Journal* 111 (1950), 375.

Table 8.2 Properties of certain molecules (from Whipple, "A Comet Model. I", p. 377)

	MOLECULE				
	CH_4	CO_2	NH_3	C_2N_2	H_2O
Melting point (° K)	90	217	198	239	273
Heat of fusion (cal/gm)	50	45	108	–	80
Boiling point at 1 atm. (° K)	111	195	240	252	373
Heat of vaporization from solid (cal/gm)	188+	138+	435+	103++	670+
Vapor pressure at 191°K (atm.)	45.8	0.74	0.038	8.0×10^{-3}	3.7×10^{-7}

will reduce the loss of gas from the nucleus. If a comet is composed of non-volatile solids (as in the case of Encke's comet), the temperature of the nucleus will reach about 140° K at perihelion and consequently CH_4 would melt and vaporize rapidly, but the ices of other substances in Table 8.2 would vaporize gradually. Finally, all substances listed in Table 8.2 will be gaseous at perihelion, and from the base of meteoric layer, ices will be layered based on their vapor pressure. Thus, the first layer will consist only of H_2O ice and meteoric material; the following layer will include C_2N_2, in addition (if it exists); and layers continue through the remaining molecules.[621]

While the outer icy layers of the nucleus reach a quasi-equilibrium state based on the vapor pressure of the ices at low temperatures, its deep interior remains very cold because of two reasons. First, the heat conductivity from the surface to the interior is very low, and second, the available heat is being used in vaporization. Continuous vaporization gradually makes the outer layers weak, but since the surface gravity is very low, a weak and fragile structure may remain for a while. However, they may collapse at irregular intervals and cause the heated pieces to fall on the ices and vaporize them fast. In such a process, dust and small particles blow out, making the outer insulator layer even weaker. When a pit is made by one of those collapsed structures, solar radiation will cause more vaporization until it arrives in an equilibrium state. On the other hand, if a cluster of ice with a low melting point is trapped in ice with a high melting point, it will cause the embedded ices to explode or make a crack in the encompassing ice and create jets of outgoing gas.[622]

The importance of all of these heating-vaporization processes is the mechanism by which the heat transfers from the outer to the inner parts of the nucleus. With the outermost icy layers of a nucleus evaporated and a matrix of non-volatile insulating meteoric material exposed, the mode of heat transfer plays a critical role in comet behavior. Quantitative and qualitative studies show that in thin meteoric

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[621] Ibid., p. 377.

[622] Ibid., p. 378.

layers in vacuum, heat transfers mainly by radiation. Thus, in our model nucleus, the heat transfer is inversely proportional to the effective number of those layers and it takes a while for heat to penetrate to the inner parts of the nucleus. It means a considerable time lag in heat transfer for a rotating nucleus. In other words, the "day" hemisphere of the nucleus gains heat but its evaporating effect will be materialized when it turns to be "night" (Fig. 8.12). The thrust produced by the evaporation of ices and formation of jets directly affects the comet's motion:

> Because of the time lag, such a cometary nucleus rotating in the "forward" sense will emit its vaporized ices with a component toward the antapex of motion. The momentum transfer from the kinetic velocity of the emitted gas will propel the nucleus in the forward sense, reduce the mean motion, and increase the eccentricity of the orbit. Such orbital effects occur for Comet D'Arrest; […] Retrograde rotation can produce an acceleration in motion and a decrease in eccentricity, as observed for Comet Encke.[623]

Whipple's theory was not only able to elucidate the physical and chemical features of comets but also plausibly explained the origin and function of the non-gravitational forces acting on comets. To illustrate briefly the importance of Whipple's publications in 1950, 1951, and 1955, one can say that, he explained the processes occurring at the surface of comets, which are responsible for a majority of cometary phenomena, and he established a physical connection between cometary phenomena, meteor streams and the zodiacal light.[624] Furthermore, he outlined how our knowledge of cometary nuclei might shape our understanding of primitive solar system environments.[625]

It will not be an exaggeration to say that a revolution occurred in cometology in 1950–1951. Four major developments, of which Whipple's work was only one, established the modern science of comets. Right after Whipple's first announcement

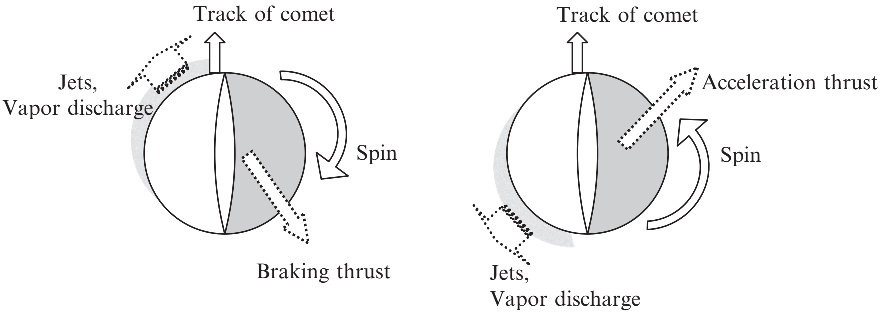

Fig. 8.12 The influence of vapor production on comes' motion (Adopted from Calder, *Comets*, p. 90)

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[623] Ibid., 375; 386–392.

[624] Fred L. Whipple, "A Comet Model. III. The Zodiacal Light," *Astrophysical Journal* 121 (1955), 750–770.

[625] Michael J. S. Belton, "Whipple's Comet Model," *Astrophysical Journal* 525 (1999), 393.

of the *icy conglomerate* model, Jan Hendrik Oort (1900–1992) theorized that a reservoir of comets existed in a distance of 50,000 to 150,000 AU which acted as the source of comets. Then, Gerard Peter Kuiper (1905–1973) suggested that a closer reservoir of comets lay just outside of the solar system, composed of the leftovers of the cloud from which our planetary system was formed; and finally, Ludwig Biermann (1907–1986) explained the process of the formation of cometary tails through the interaction of the solar wind with cometary gases.[626]

Oort and Kuiper did not develop a physical theory of comets; however, they opened a new chapter in the study of the source and origin of comets. Oort, based on the dynamics of the long-period comets, concluded that the "new" long-period comets originate in a general cloud of comets surrounding the sun in a distance from 50,000 to 150,000 AU. This accumulation of comets which is called the *Oort cloud* is estimated to contain 10^{11} comets of observable size. The entire mass of the *Oort cloud* is about 1/10 to 1/100 of that of the earth. Time to time, the gravitational action of a nearby or passing star on the members of this cloud causes a perturbation which directs new comets towards the sun, because its gravitational influence is dominant in this range.[627]

Kuiper tried to theorize about the source of the short-period comets. He suggested that in a distance starting from the orbit of Neptune and extending as far as 50 AU a great population of comets is distributed in a flattened disk which acts as the source of the short-period comets. This distribution of comets, called the Kuiper belt, contains probably 10^7 to 10^9 comets larger than 5 km in size.[628] According to Kuiper, when the solar nebula was still in existence (before the transformation of proto-planets to full grown planets) the temperature of the outer solar system – from 38 to 50 AU – was about 5–10° K, which increased to about 40° K after the formation of the planets. During this time interval, condensation of H_2O, NH_3, CH_4, and other volatile substances led to the formation of a larger aggregation of icy material of 1 km or more in size. These conglomerations form the main reservoir of the short-period comets.[629]

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[626] Festou, et al, "A Brief Conceptual History of Cometary Science," p. 5; Burnham, *Great Comets*, p. 17.

[627] J. H. Oort, "The Structure of the Cloud of Comets Surrounding the Solar System, and a Hypothesis Concerning its Origin," *Bulletin of the Astronomical Institutes of the Netherlands* 11 (1950), 91. Since the present work is mainly focused on the physical theories of comets, we will not discuss the works on the origin of comets in depth. For further studies on Oort's theory and its background see: J. H. Oort, "Origin and Development of Comets," *The Observatory* 71 (1951), 129–144; Yeomans, *Comets*, pp. 302–331; Brandt, *Introduction to Comets*, pp. 44–50; P. R. Weissman, "Dynamical History of the Oort Cloud," in Laurel L. Wilkening (ed.), *Comets* (Tucson: The University of Arizona Press, 1982), pp. 637–658; Lyttleton, "On the Origin of Comets," pp. 465–475; J. J. van Woerkom, "On the Origin of Comets," *Bulletin of the Astronomical Institutes of the Netherlands* 10 (1948), 445–472.

[628] John D. Fix, *Astronomy: Journey to the Cosmic Frontiers*, 3rd ed. (New York: McGraw-Hill, 2004), p. 359.

[629] Gerard P. Kuiper, "On the Origin of the Solar System," *Proceedings of the National Academy of Sciences* 37 (1951), 13.

If Whipple's model revolutionized our understanding of the structure and constitution of cometary nuclei, Biermann's contribution was to solve one of the long-lasting problems related to cometary tails. Even after the discovery of the radiation pressure and development of tail theories based on the pressure of the sun's light, there were left several comets whose rapid increase of tails was not explainable by the new theory. In some cases, the type I tail in the Bredichin's scheme was developed in such a speed that it required the repulsive force to be more than 100 times stronger than the gravitational attraction of the sun. Biermann suggested that a continuous flow of high-speed particles from the sun accelerates the ions (mainly CO^+) in a comet's tail through the momentum transfer.[630] This flow of particles, which is called the *solar wind*, though it has a very low density (~10^{-23} g cm^{-3}), travels at the high speed of about 500 km/s.[631] Biermann's discovery of the solar wind, besides its important consequences in the study of the stellar astrophysics, formation of the solar system, and the solar-planetary relationships, successfully explained the physics behind the formation of the ion tails.

Due to the action of the high speed particles of the solar wind, ionized molecules of cometary substance form a tail that is aligned almost with the radius vector of the comet's orbit. This tail which is distinguished by its extended length, straightness and bluish color is called the *plasma* tail. Its blue color is from the ionized carbon monoxide, which emits strongly in the blue part of the spectrum. On the contrary, the second type of cometary tail, the *dust* tail, is composed of dust particles swept from the nucleus and is distinguished by its white to yellow color, relatively short length, and curved shape. In 1957, Hannes Alfvén (1908–1995) suggested that when the cometary plasma encounters the solar magnetic field lines (dragged by the solar wind) they wrap around the comet's ionosphere and stretch in the antisolar direction, which affect the formation and shape of the plasma tail (Fig. 8.13). Alfvén's theory was a further step in explanation of the fine structure of the plasma tail and the narrow streams seen in this type of cometary tail.[632]

At the dawn of the space age, the physical science of comets was in the process of establishment of an encompassing theory capable of explaining the observational, chemical, physical, dynamical, and cosmogonical aspects of comets, a great orchestration in which the performance of "several" first violinists harmonized by Whipple's genuine conducting. As several comet scientists have stated, the modern era of understanding of cometary phenomena started with Whipple's classic series of papers.[633] Whipple introduced some key concepts that have become a part of the

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[630] L. Biermann, "Kometenschweife und solare Korpuskularstrahlung," *Zeitschrift für Astrophysik* 29 (1951), 274–286; Yeomans, Comets, pp. 235–237; Brandt, Introduction to Comets, p. 42.

[631] Erika Bohm-Vitense, *Introduction to Stellar Astrophysics*, 2 vols. (Cambridge: Cambridge University Press, 1989), p. 204.

[632] Susan Wyckoff, "Overview of Comet Observations," in Wilkening (ed.), *Comets*, p. 40; Brandt, *Introduction to Comets*, pp. 42–43; Fix, *Astronomy*, pp. 356–357.

[633] Weissman et al., " Structure and Density of Cometary Nuclei," p. 338; Festou, Keller, Weaver, "A Brief Conceptual History of Cometary Science," in Festou et al., *Comets II*, p. 5; Brandt, *Introduction to Comets*, p. 37; Robert Burnham, *Great Comets* (Cambridge: Cambridge University Press: 2000), p. 17; Belton, "Whipple's Comet Model," p. 393.

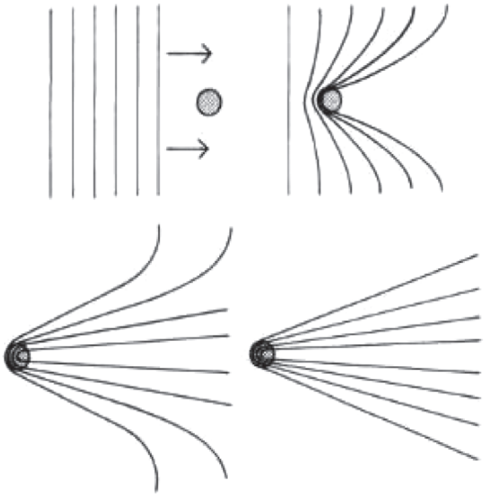

Fig. 8.13 Interaction of the solar magnetic field (dragged by the solar wind) and a comet according to Alfvén: Magnetic lines wrap around cometary plasma and pulled into the ion tail (After H. Alfvén, "On the Theory of Comet Tails," *Tellus* 9 (1957), 92)

standard bases of modern cometology. These concepts, besides the "rocket" effect – responsible for non-gravitational accelerations – include the formation of cometary nuclei at very low temperatures, their low density, their porous structure and low strength, and their low albedo and low thermal conductivity.[634] Whipple's theory remained nonparallel till the approach of the periodic comet Halley in the 1980s, at which time new data from detailed observations both from the earth and space led to the introduction of new models for cometary nuclei (Fig. 8.14). Although these models propose a different structure for a comet's nucleus, they are based on the key concepts proposed by Fred Whipple in the 1950s.[635]

Summary and Concluding Remarks

Physical investigation of comets has been one of the most dynamic enterprises in the history of modern astronomy. The extraordinary nature of comets was a strong source of motivation for astronomers and natural philosophers to scrutinize every aspect of comets and theorize about their physical constitution, their formal and structural changes, and their origin and end. In this endeavor, they extrapolated earth-bound physical and chemical knowledge into the realm of the sidereal objects. From this perspective, modern cometology (especially in the eighteenth and early nineteenth centuries) can be considered the first stage in the astrophysical study of celestial objects.

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[634] Weissman et al., "Structure and Density of Cometary Nuclei," p. 338.

[635] Ibid., pp. 337–340.

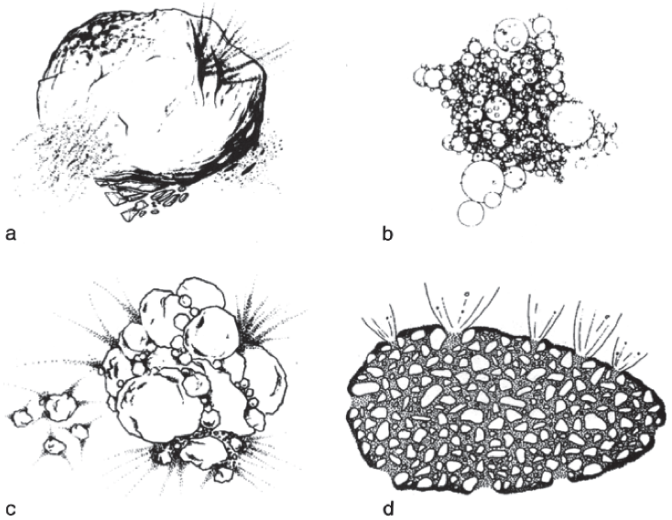

Fig. 8.14 Sketches of cometary nuclei based on (a) Whipple's *icy conglomerate* model; (b) B. Donn, P. A. Daniels, and D. W. Hughes's *fluffy-aggregate* model; (c) Paul Weissman's *primordial rubble pile* model; and (d) T. I. Gombosi and H. L. F. Houpis's *icy-glue* model. The basic concept in models (b) and (c) is that the nucleus is an aggregation of smaller icy planetesimals jointed together randomly at low velocities. Model (d) proposes that a nucleus is composed of porous boulders with compositions similar to outer main-belt asteroids, stick together with a kind of icy glue (After Weissman et al., "Structure and Density of Cometary Nuclei," p. 340)

From antiquity to the introduction of spectroscopy in the mid-nineteenth century, the history of physical theories of comets can be divided into three distinctive periods. In the first period, which culminated in the works of Aristotle, comets were thought to be meteorological objects. According to Aristotle, comets were exhalations that originated from the earth due to the action of the sun's heat, and the scene of their demonstrations was the upper part of the terrestrial atmosphere, right below the sphere of the moon. Although in Aristotle's theory comets were only heralding hot and dry weather, a notion of astrology of comets was developed by the end of the Hellenistic period. Then, the Aristotelian theory of comets combined with a mainly Ptolemaic interpretation of the astrology of cometary appearances which was sustained in Medieval Europe, Islamic culture, and even in the Renaissance.

From the late fifteenth to the mid-sixteenth centuries, measurements on comets, which broke from tradition, led to the discovery of the antisolarity of cometary tails in the 1530s. This discovery showed a direct link between the sun and the orientation and formation of cometary tails, which had not been explained by Aristotle. As a result, the first non-Aristotelian theories of comets appeared by the mid-sixteenth century. Cometology then grew as a subject of quantitative study and became a center of widespread attention by astronomers and natural philosophers.

The second period of cometology began with Brahe's discovery of the celestial origin of comets in 1577. This discovery not only changed the foundations of cosmetology, it created a crack in the structure of the Aristotelian cosmos. Comets, then, were considered as celestial bodies moving in unknown trajectories. Brahe's discovery introduced a new category of celestial objects whose nature and behavior were different from those of the planets and stars. Although astronomers and natural philosophers stayed mainly silent about the nature of the planets and stars or admitted the traditional explanations of the stellar or planetary phenomena, they needed a new theory to introduce comets as celestial objects. Because the main established criterion to distinguish a phenomenon as celestial was the reducibility of its apparent motion to a uniform circular motion or a combination of circular motions, the post-Tychonic cometology in large part was the study of the motion of comets.

This period which lasted almost a century – from Tycho's estimation of cometary distances in 1577 to the publication of Newton's *Principia* in 1687 – saw groundbreaking developments in the physical sciences. Standing on the shoulders of the giants of this period, Newton was able to take advantage of major progress in the fields of observational and theoretical astronomy, mathematics and natural philosophy to revolutionize cometology by introducing comets as members of the solar system.

In this interval, the invention of the telescope and the micrometer not only altered the human perspective of the universe but also changed the procedures practiced in astronomy. For the first time, astronomers were able to see the surfaces of the sun, the moon and some of the planets, which enabled them to develop ideas about the physical condition of celestial objects. At the same time, use of the micrometer, either on the positional astronomy devices such as the sextant or in combination with the telescope, increased the accuracy of observations drastically. While the accuracy of Copernicus' observational instruments was around 1/8 degree, astronomers at the conclusion of the seventeenth century could measure positions of the celestial bodies as accurately as 15 arc seconds.[636] Invented in 1657, Huygens's pendulum clock also provided a reliable device for time measurement in the observatories.

Telescopes opened a new window to the universe and demonstrated that the number of celestial bodies was exceedingly larger than what had been assumed for centuries. Besides the discovery of sunspots, phases of Venus, rings of Saturn, and the resolution of the Milky Way into clusters of faint stars, within only seventy five years from 1610 to 1684, nine new objects were discovered in the solar system.[637] The surface of the moon was found to be similar to the mountains and deserts on the earth and evidence of the existence of a kind of atmosphere around some planets was discovered. Detection of the planetary atmospheres planted the seeds of an idea which admitted comets as special planetary bodies covered by thick atmospheres. Comets, of course, were sighted by telescopes, although nothing besides their hazy coma was detected.

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[636] Chapman, "The Accuracy of Angular Measuring," pp. 134–135.

[637] Four satellite of Jupiter: Io, Europa, Ganymede, and Callisto were discovered in 1610, and five satellite of Saturn: Titan, Iapetus, Rhea, Tethys, and Dionis in 1655, 1671, 1672, 1684, and 1684 respectively. See: Illingworth, *Macmillan Dictionary of Astronomy*, p. 427.

Despite admitting comets as celestial objects there was no evidence of their circular motion. Even Kepler did not include comets in his laws of planetary motions. In the same manner, Descartes thought that the non-periodic motions of comets occurred in some slightly curved trajectories in the outer parts of the stellar vortices. Descartes' theory was the first cometary theory since Aristotle in which comets were defined as a part of a consistent theory of nature and were deprived of any influence on the earth or the living things upon it.

In Descartes' cosmos, matter was devoid of any active principle or quality. As a result, any action between bodies in the universe was reduced to a mechanical impact between particles of different types. However, concentrating on the basic physical concepts of his cosmology, Descartes did not elaborate on the details of the planetary and cometary motions. As a widely accepted theory before the Newtonian era, Descartes' theory of comets contained a major difference from the all previously stated ideas: Descartes admitted comets as planetary bodies which due to their compactness and momentum, were moving in different trajectories far from the planetary zone of the vortices.

The third period in our account of physical cometology begins with Newton's theory of comets. In contrast to Descartes, Newton based his theory of planetary motions on the mutual attraction of the sun and the planets. Comets were introduced as members of the solar system, obeying the same law of gravitation. They could approach the sun and the planets and they might even impact. Although this notion gave comets a more terrifying role than any traditional idea, Newton attributed to comets a unique cosmological function and presented them as the Creator's aid to reform and refresh the unwinding clock-work of the cosmos. In Newton's theory, the latter thought was emphasized more than the destructive role of comets.

Newton's theory of comets, however, was inconsistent. First, it did not explain clearly and in detail the nature of the cometary vapor that was supposed to refresh the planets, as it was not clear about the nature of the vapor that supposedly was leaving the planets. Secondly, based on his description of the density of cometary tails, there ought to have been an extremely great number of comets to compensate the vapor-loss of the planets. Thirdly, the theory became incoherent in explaining tail formation when it suggested that rarified particles of the ether drove the heavier particles of the cometary tails. Finally, and most importantly, it was incompatible with some of the other theories of Newton, delineated in his *Opticks*. If one applied Newton's theory of fire (as it appeared in the *Opticks*) to his theory of comets, one would conclude that the coma and tails of comes would turn into flames in the vicinity of the sun.

By the mid-eighteenth century, Newton's theory of comets enjoyed a wide reception in England; however, its inconsistencies were not hidden. Several astronomers and natural philosophers criticized different aspects of Newton's theory of comets; but, amazingly, none of them referred to those contradictions that existed between the comet-related concepts in the *Principia* and the *Opticks*. Furthermore, while a careful study of Newton's cometary theory would reveal its problems, it took almost half a century for Newton's critics to create a complete list of difficulties in his theory of comets. This was either due to Newton's authoritative role or simply because there was no comprehensive study of his works.

On the Continent, however, different approaches were taken in the reception of Newton's theory of comets. In general, the physical and mathematical sciences developed in a different framework on the Continent in the eighteenth and the nineteenth centuries than in England: Leibnitzian calculus attracted more attention than that of Newton. Scrutiny of ethereal theories of gravitation and attempts to reconcile them with Newton's inverse-square law stimulated a remarkable progress in solving the perturbational problems. Different wave theories of light were developed in contrast to Newton's corpuscular theory. The inert notion of matter was maintained and developed on the Continent, which freed physicists and mathematicians from dealing with the ultimate composition of matter. And finally a new mathematical tool – the theory of probability – was developed which was not only employed as an epistemological method, but also helped scientists increase the accuracy of results by deliberately processing observational and experimental data.[638]

In such an intellectual atmosphere on the Continent, where the mathematical solution of physical and astronomical problems was more emphasized than the methods of experimental philosophy, cometary theories evolved in a different way. Because the Cartesian interpretation of nature was still compelling, the introduction of Newtonian physics on the Continent, especially in France, was not a straightforward task. In the first half of the eighteenth century several scholars attempted to reconcile the two rival notions of nature or at least add a Cartesian touch to Newton's theories.

In the physical theory of comets, Newton's explanation of tail formation was unwelcome on the Continent from its first day of introduction. Instead, an Eulerian theory, based on the attribution of a driving force to the sun's rays, was accepted and lasted for sometime. Even the electrical theories of tails were not paid adequate heed. Nevertheless, comets became the subject of a sophisticated mathematical study to examine their perturbational effects. In fact, the second half of the eighteenth century was the period of development of celestial mechanics on the Continent (mainly by French neo-mechanists) which equipped astronomers with highly accurate procedures of orbit determination. Clairaut's prediction of the return of Halley's comet and Laplace's determination of the mass of Lexell's comets were two of many important results brought about by Continental progress in celestial mechanics.

Empirical verification of the perturbation theory and orbit determination procedures, however, required precise observational instruments. This was the front on which British instrument makers were the real conquerors. By the end of the eighteenth century, instrument makers in England, who now were being treated as astronomers, some of them Fellows of the Royal Society, reduced the accuracy of the micrometer to ½ arc second, or about thirty times more than the accuracy of instruments that astronomers had been using at the beginning of the century.[639] The

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[638] Peter Hanns Reill, "The Legacy of the Scientific Revolution," in Roy Porter (ed.), *The Cambridge History of Science, Volume 4: Eighteenth-Century Science* (Cambridge: Cambridge University Press, 2003), pp. 32–33; Wilson, "The problem of perturbation," pp. 90–91; Boyer, *A History of Mathematics*, pp. 391–414, 454–456.

[639] Chapman, "The Accuracy of Angular Measuring," p. 135.

fourth period of cometology began when accurate instruments were available to measure the magnitude of the change that Laplace had predicted as the perturbational effect of Lexell's comet on the earth's revolution. Based on Nevil Maskelyne's tables Laplace declared the validity of his calculation and started a new era in cometology in which comets were treated as physically insignificant bodies in the solar system.

A glance at the nineteenth century and early twentieth century history of astronomy, in general, and the history of theories of comets, in particular, reveals distinct revolutionary changes that differentiate this period from the previous era. Among the list of these changes – from genuine formulations of the planetary motion and perturbational effects to the invention of achromatic lens and employment of large-scale telescopes – one can depict the introduction of the spectroscopy and subsequent birth of astrophysics as the most prominent astronomical event of the nineteenth century. Spectroscopy, on the one hand, enabled physicists and astronomers to analyze the building components of the terrestrial, planetary, and stellar material, and on the other hand, provided an effective tool to understand the structure of matter in the molecular and atomic levels. Cometology, like other branches of astronomy, benefited from all of these developments.

The introduction of spectroscopy, which coincided with the invention of photography,[640] revealed the chemical components of comets; however it did not lead to the immediate discovery of the structure of cometary nuclei. It took almost a century from the mid-eighteenth century on to overcome the theoretical difficulties in rendering the observed spectra to the actual chemical and physical conditions that existed in the observed subjects. This task was reserved for the development of modern physics in the first decades of the twentieth century.

Although the major developments in spectroscopy, modern physics and observational and theoretical astronomy took place in Europe during the nineteenth century and the commencement of the twentieth century, the center of weight of research in physical sciences, including astronomy, was gradually shifting towards the United States. By the first decade of the twentieth century, astrophysics had developed into the leading branch of astronomy in the United States.[641]At the same time, solar system astronomy became another major field of study in the

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[640] Photography with telescopes in addition to providing detailed pictures of the planetary and solar features found an influential role in recording the spectra. In the early 1840s, J. W. Draper obtained daguerreotypes of the solar spectrum. However, early astrophotography had major limitations imposed by the low sensitivity of the photographic plates, and telescope mounts and drives which made the long-exposure photography very difficult. It was by the invention of the 'fast" dry plates in the 1870s that spectroscopy benefited from the high potentials of the photography. See Clerke, *A Popular History of Astronomy*, p. 438; Daniel Norman, "The Development of Astronomical Photography," *Osiris* 5 (1934), 560–594; E. E. Bernard, "The Development of Photography in Astronomy (I.)," *Science*, New series, 8, 194 (1898), 341–353.

[641] Ronald E. Doel, *Solar System Astronomy in America: Communities, Patronage, and Interdisciplinary Research, 1920–1960* (Cambridge: Cambridge University Press, 1996), p. 5.

American universities and observatories, which gained more attraction by Percival Lowell's Martian studies and reached its culmination by the discovery of Pluto by Clyde Tombaugh in 1930. Pluto, the first planet discovered in the twentieth century, was a completely American addition to the solar system. It was in such an atmosphere that Whipple synthesized the modern theory of comets employing diverse theories, observations, and conjectures from both European and American resources.

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