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,*

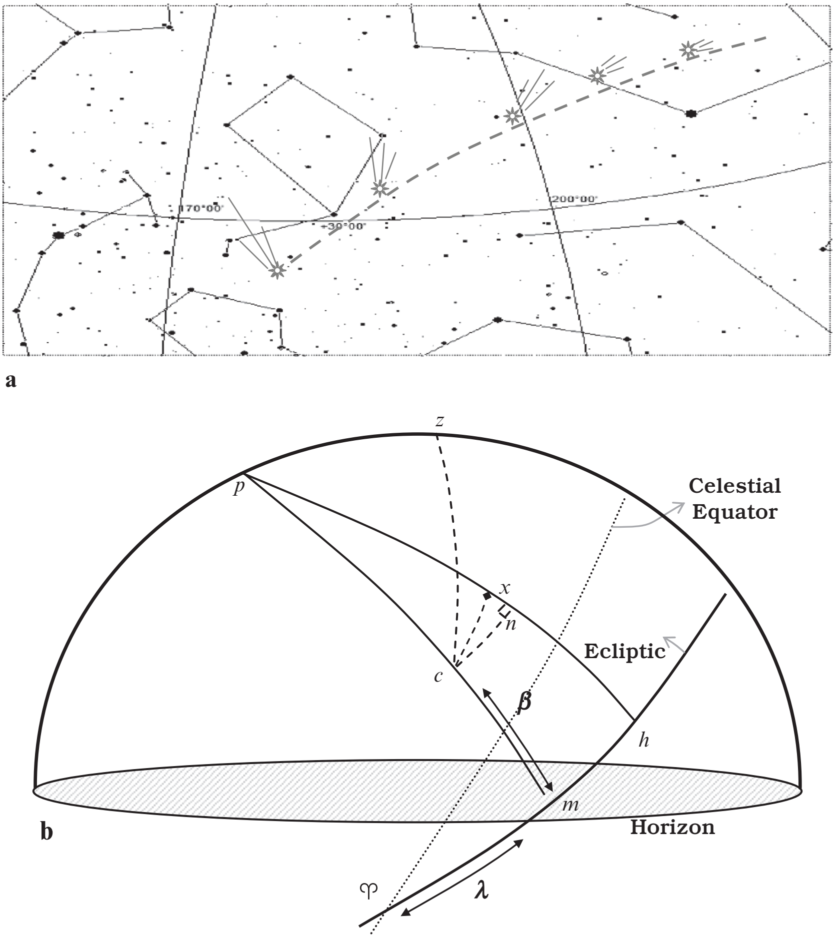

Fig. 3.1
z = Zenith
p = Ecliptic pole
c = Comet
γ = Vernal Equinox/First point of Aries
x = Reference star
λ (comet) = γh - mh
β (comet) = hx - nx

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

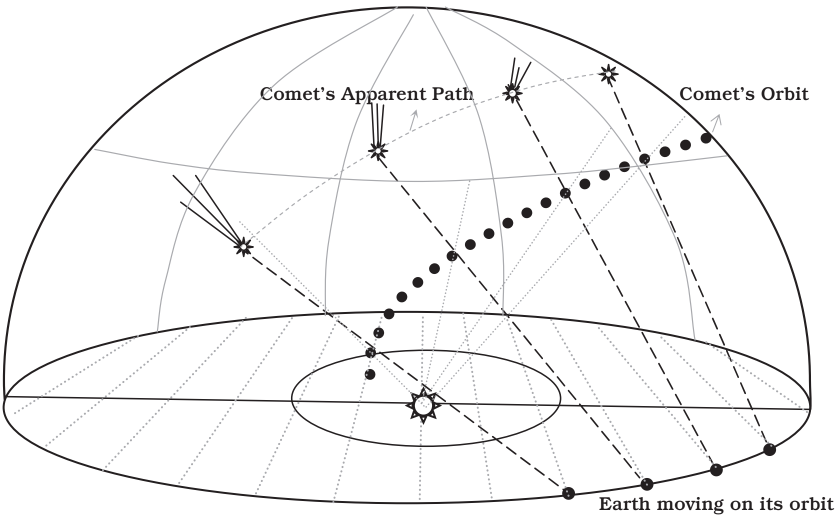

Fig. 3.2 A comet's apparent path among the stars is a projection of the real trajectory of the comet on the celestial sphere. The apparent path is affected by the obliquity of the comet's orbit (here, perpendicular to the plane of the ecliptic), the comet's proper motion, and the position and the revolution 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.

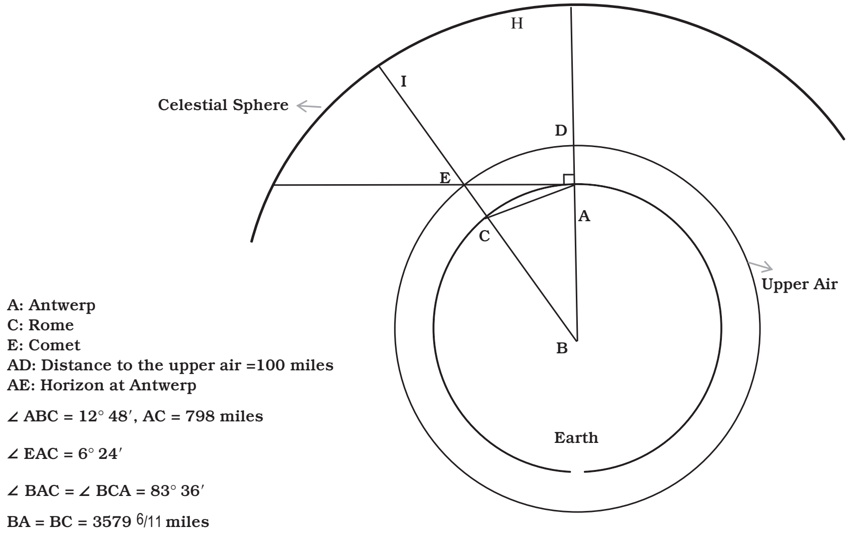

Fig. 3.3 Grassi's initial data for estimating the distance of the third comet of 1618

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.

[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

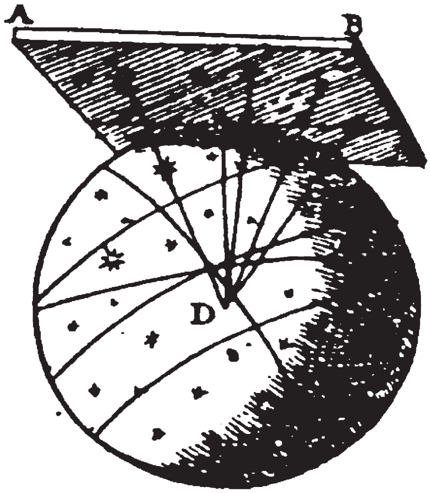

Fig. 3.4 According to Grassi, the apparent straight path of a comet is the stereographic projection of the comet's real trajectory, where the rays of projection are radiating from the earth, located at D, the center of the world. (From Grassi's anonymously published treatise, 1619)

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

[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

[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]

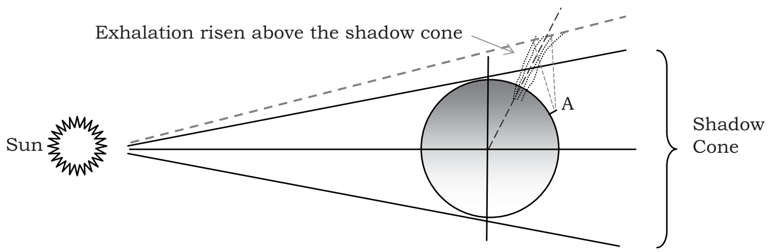

Fig. 3.5 Galileo's theory of the Aurora Borealis: rarified vapor rises above the shadow cone of the earth and reflects the sun's rays to the observer A

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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.

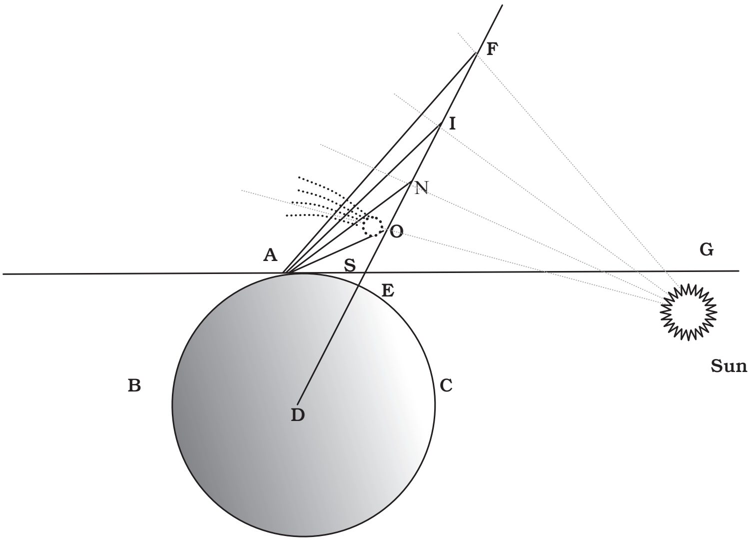

Fig. 3.6 Galileo's theory of comets: A cluster of exhalation moves uniformly along a straight line, into the celestial region, and the observer A sees it under progressively decreasing angles. Therefore, the comet appears steadily smaller and slower, while moving on a rectilinear trajectory

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

[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

[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.

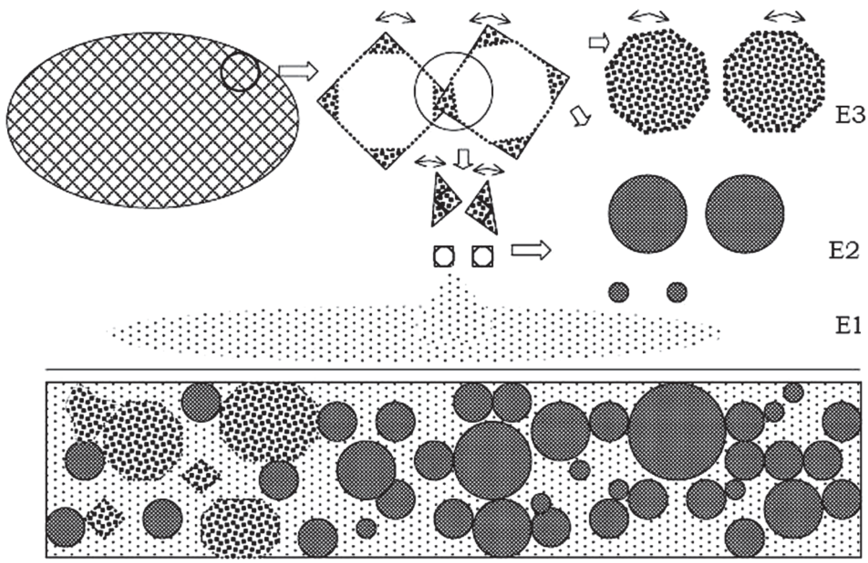

Fig. 3.7 Descartes' cosmos, at the beginning, was filled by non-spherical particles of the primary matter. When the Creator gave motion to the cosmos, most of those non-spherical particles became spherical due to friction and rubbing. In this process, a great amount of scrapings (first element, E1) was 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

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

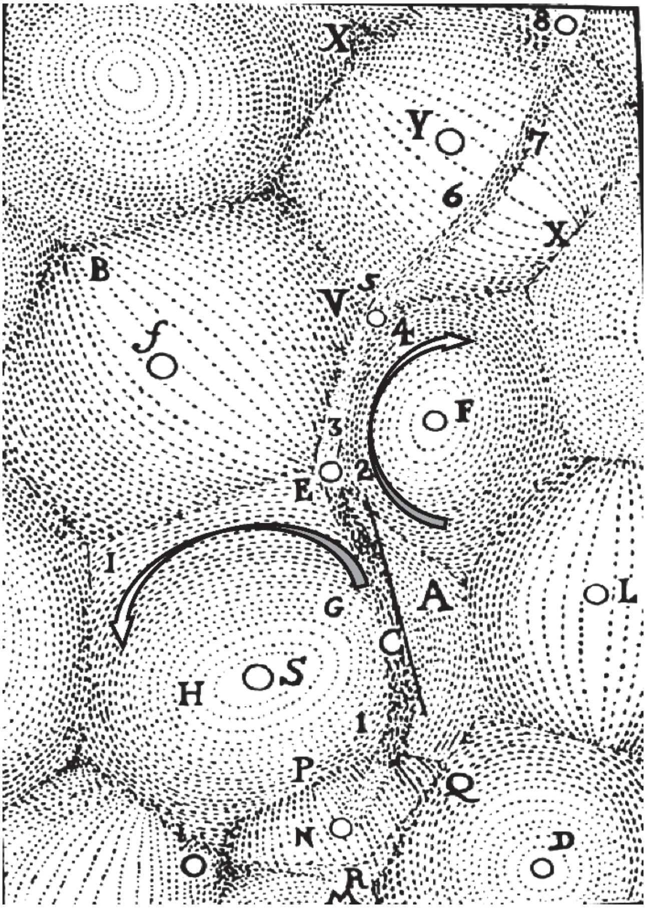

Fig. 3.8 The Cartesian vortices are swirling particles circling around central stars S, F, Y, *f* and so on. The vortices consist of the second element (E2), the stars are made of the first element (E1) and planets and comets are composed of the third element (E3) (From Descartes' *Principles of Philosophy*,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

[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.

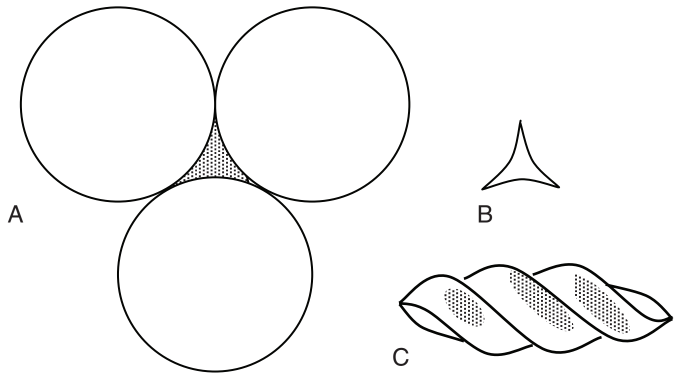

Fig. 3.9 The cross-section (B) of a grooved particle (C) is triangular with concave sides. It is slightly smaller than the space between three adjacent spheres of the second element (A). The grooved particle is twisted like a screw which makes it easier to move among the particles of the second element

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]

[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.

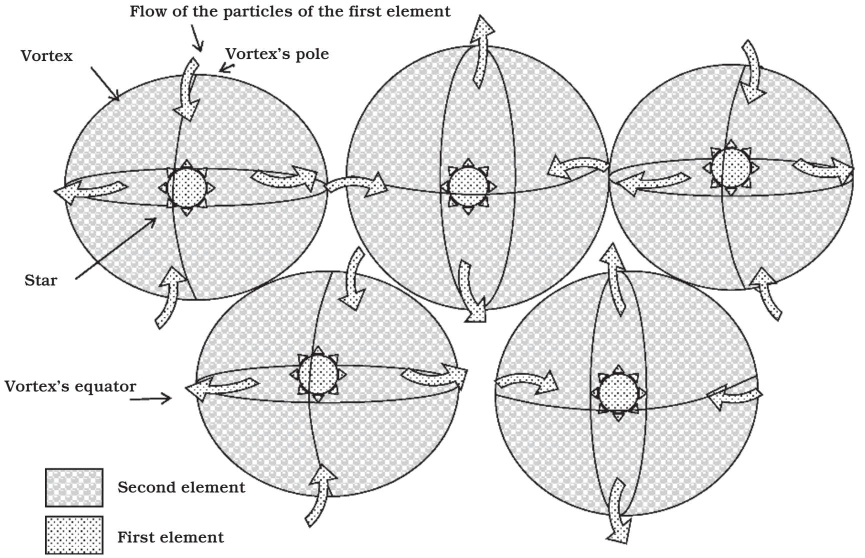

Fig. 3.10 Flow of the particles of the first element among the vortices. Vortices are attached to each other, but the poles of a vortex do not touch the poles of another one

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-

[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.

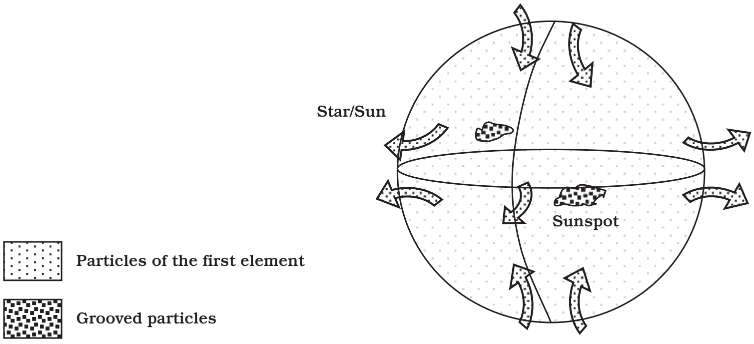

Fig. 3.11 The low-speed grooved particles attach together and appear as sunspots on the surface of the sun or other stars

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).

[171] Ibid., III, pp. 59–62.

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

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

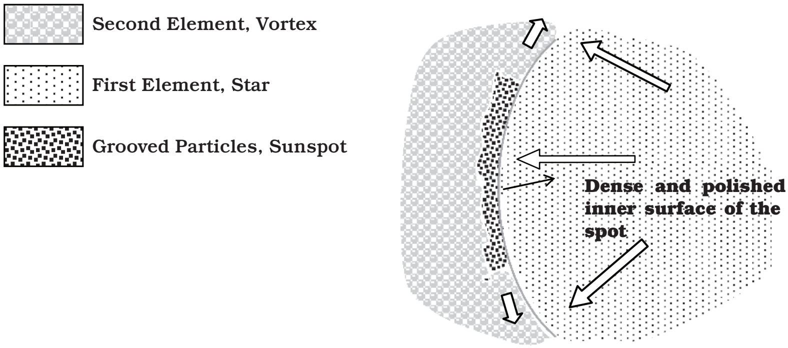

Fig. 3.12 Spots on the surfaces of a star block the flow of the particles of the first element into the vortex. As a result, the star-vortex equilibrium undergoes a disturbance which triggers the collapse of the entire vortex

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

[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.

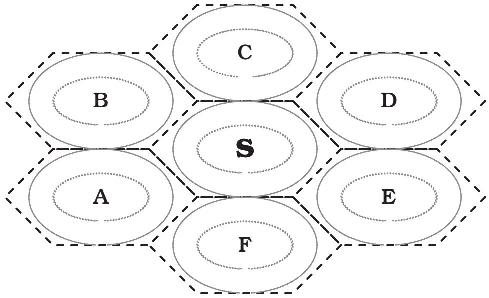

Fig. 3.13 The six vortices encompassing S maintain a state of equilibrium between themselves and S. When the central star of S is covered by spots, its vortex shrinks until nothing remains of it except the central star. The star, finally, will be carried by one of the neighboring vortices which expands. 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

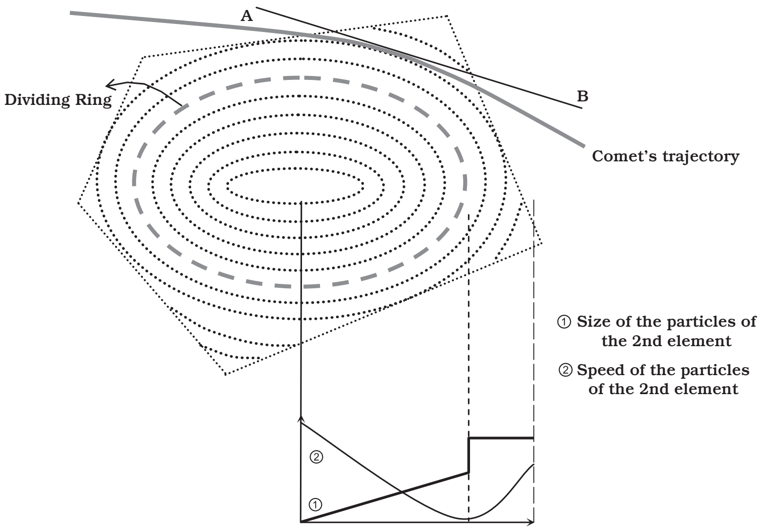

Fig. 3.14 The pattern of variation in size and speed of the particles of the second element in a vortex. Since there is no quantitative explanation in Descartes' account, the slope of the lines are taken arbitrarily

[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.

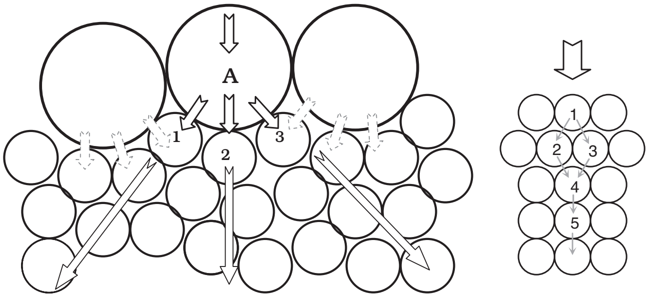

Fig. 3.15 Left: the pressure of sphere A is distributed between three smaller spheres and therefore, propagates in three different directions. If all the spheres were equal in size, the pressure would be exerted in one direction (right)

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.

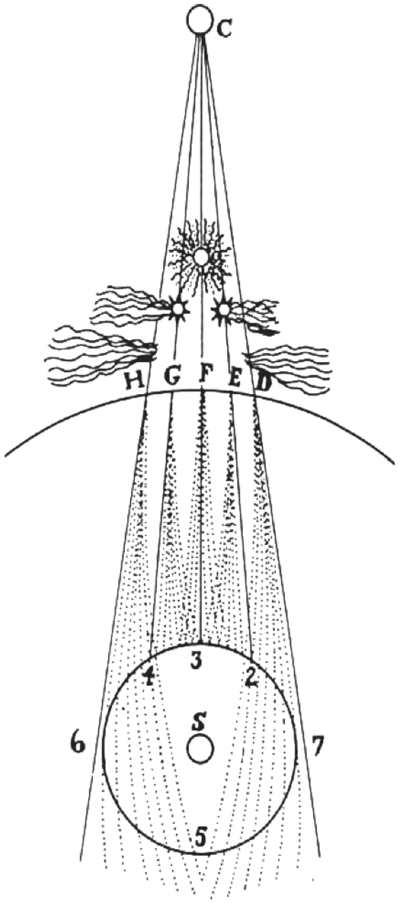

Fig. 3.16 S is the sun, 2 3 4 5 is the orbit of the earth, DEFGH is the dividing ring, and C is a comet. The reflected ray CH when it reaches the smaller particles of the inner part of the vortex, not only continues to 6, but also is deflected towards 4. In the same way, deflection of CG covers 4-3, 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

[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

[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.

[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.

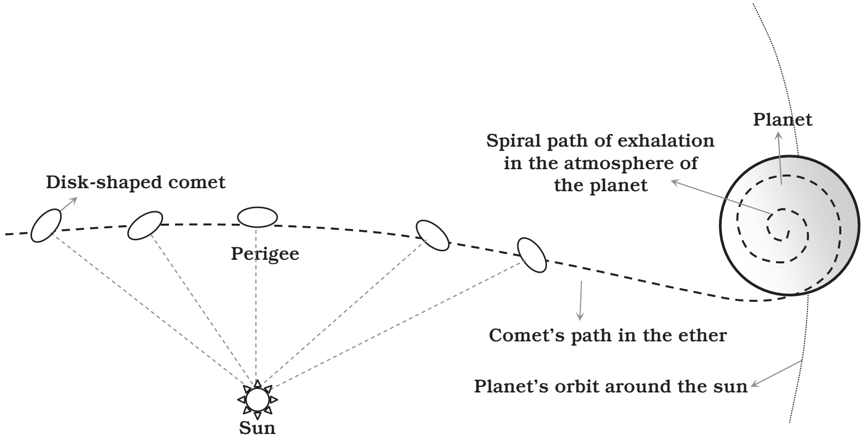

Fig. 3.17 In Hevelius' theory, comets are disk-shaped objects, composed of the solar and planetary exhalations. A magnetic mechanism always keeps one side of the comet perpendicular to the sun's rays

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.

[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

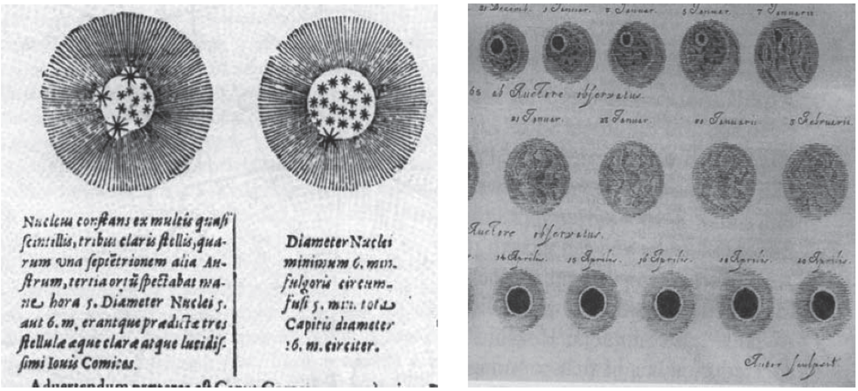

Fig. 3.18 Right: John Bainbridge's sketch of the comet of 1618 (From Johann Baptista Cysat, *Mathemata astronomica de loco, motu, magnitude, et causis cometae* (Ingolstadt, 1619), copied from Schechner Genuth, *Comets, Popular Culture*, p. 110). Left: A part of Hevelius' drawings of the comets of 1664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