Chapter 4
Comets in Newtonian Physics

Newton's Introduction to Cometary Astronomy

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

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

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

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

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

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

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

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

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

[209] Ibid., pp. 215–224.

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

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

And, about the motion of comets, Flamsteed states:

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

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

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

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

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

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

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

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

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

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

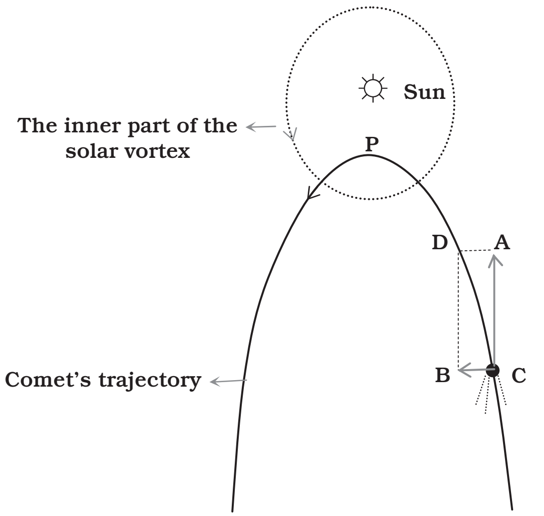

Fig. 4.1 In Flamsteed's theory, the comet C is moving tangentially to the motion of the particles of the vortex (vector A) but, at the same time, the Sun's magnetic attraction (vector B) deflects the comet's path towards D. At P, the sun repels the comet as a magnet attracts one end of a magnetic needle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

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

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

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

Comets in the *Principia*

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

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

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

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

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

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

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

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

[222] Ibid., pp. 891–894.

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

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

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

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

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

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

[225] Ibid., p. 895.

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

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

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

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

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

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

[228] Ibid., p. 918.

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

[230] Ibid., p. 919.

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

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

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

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

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

[231] Ibid., pp. 920–921.

[232] Ibid., pp. 921–922.

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

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

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

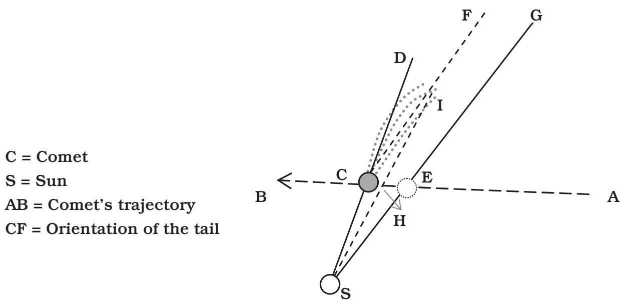

Fig. 4.2 The Comet C is moving along the line AB. Its tail is not exactly antisolar but is curved in such a way that its convex side is towards the direction of motion of the comet. The extremity of the tail, I, was produced when the comet was at E, the intersection of the comet's trajectory with the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

[233] Ibid., p. 922.

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

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

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

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

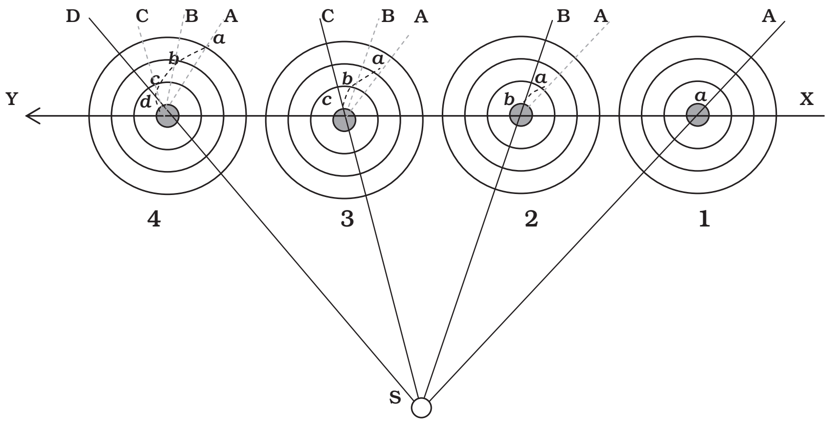

Fig. 4.3 When the comet is at position 1, its tail rises along the direction SA. At position 2, while the extremity of the tail has risen to point *a* (in the middle circle), new vapor rises in the direction SB. At positions 3 and 4, when the comet ejects new vapors in the directions SC and SD respectively,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

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

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

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

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

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

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

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

[237] Ibid.

[238] Ibid., pp. 926–927.

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

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

And further:

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

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

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

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

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[240] Ibid., p. 926.

[241] Ibid., p. 938.

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

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

Comets in the *Opticks* and Later Works

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

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

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

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

[243] Ibid., pp. 939–940.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

And

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

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

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

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

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

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

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

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

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

Physical Properties of Comets According to Newton: A General Assessment

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

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

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

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

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

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

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

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

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

[255] Ibid., p. 937.

[256] Ibid., p. 814.

[257] Ibid.

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

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

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

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

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

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

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

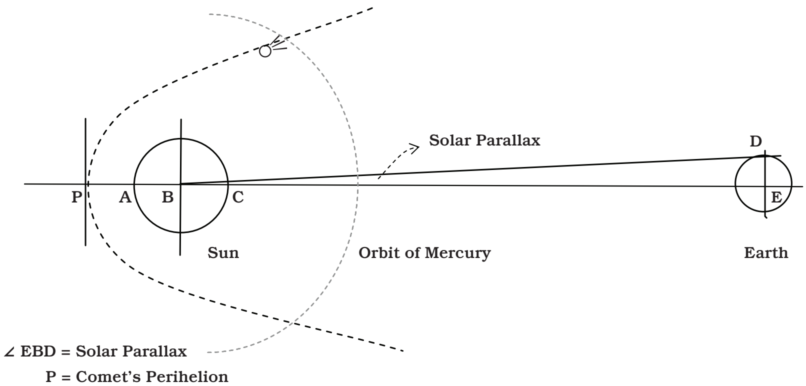

Fig. 4.4 According to Newton, the ratio of distances of the comet of 1680 at its perihelion from the sun to the distance of the earth from the sun was PB/BE = 6/1000, and PA was less than 1/6 of AC. Obviously, adopting different values for the solar parallax affects the ratios. With a solar parallax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

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

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

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

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

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

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

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

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

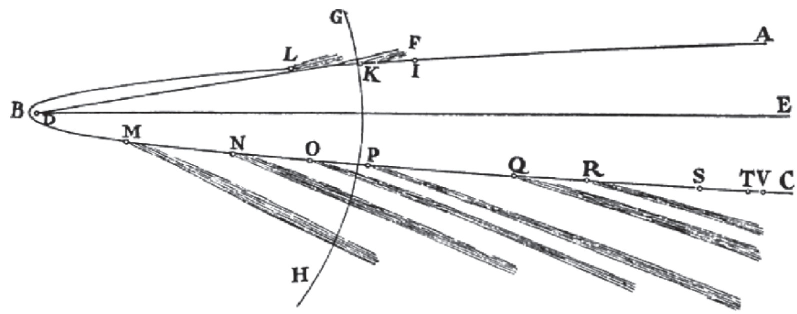
[264] In the *Principia*, Newton simply says that the distance of the comet from the sun was less than one sixth of the sun's diameter. Since usually all distances between the celestial objects are given as distances between their centers, Newton's account should be read as 'comet's distance from the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

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

And in query 11:

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

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

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

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

[277] Ibid., pp. 343–344.

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

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

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

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

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

And,

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

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

[279] Ibid., pp. 341–342.

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

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

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

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

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

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

[283] Ibid., p. 922.

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

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

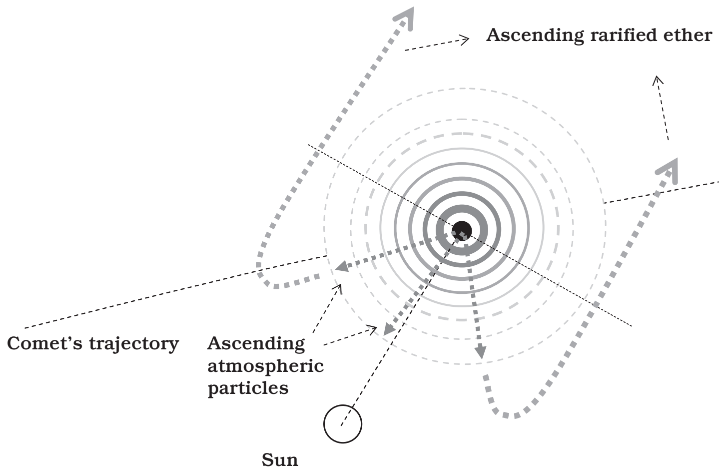

Fig. 4.6 Newton's comet is engulfed in a thick atmosphere (or coma) with a radius about ten times the radius of the nucleus. Although the rarified exhalation and vapor of the atmosphere of the comet rise vertically with respect to the surface of the nucleus, the ether rarified by the heat of the atmospheric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

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

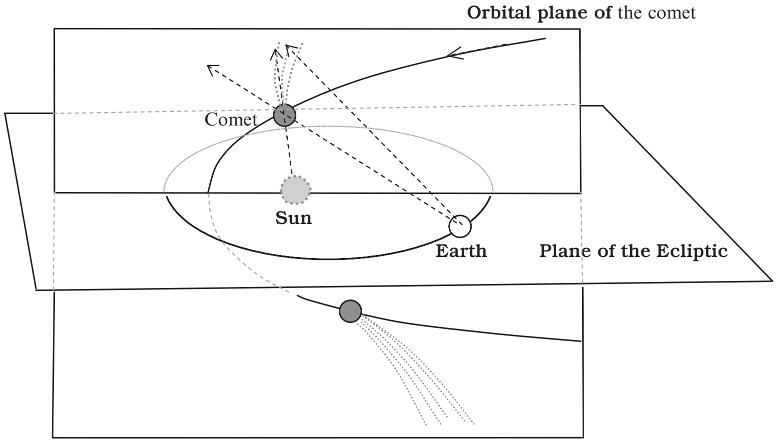

Fig. 4.7 Rarified particles of the ether, while moving away from the sun in the plane of orbit of the comet, carry along the particles of the outer atmosphere of the comet and produce a tail. The tail of the comet of 1680, just after its perihelion (12 December 1680) was about 70 degrees. This would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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Conclusion

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

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

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

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

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

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

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

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

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

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

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

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

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

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