Chapter 2
After Aristotle

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

Non-Aristotelian Theory of Comets

Seneca

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

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

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

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

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

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

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

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

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

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

[53] Ibid., II: 273–275.

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

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

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

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

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

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

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

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

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

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

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

57 Ibid., pp. 6–7, 71–74.

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

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

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

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

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

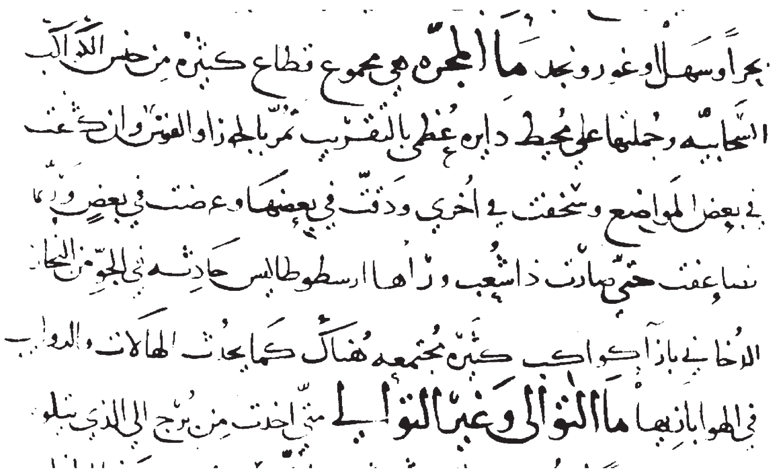

Fig. 2.1 A section of Bīrūnī's *al-Tafhim* (*The Book of Instruction in the Elements of the Art of Astrology*) where he defines the Milky Way: "The Milky Way is a collection of countless fragments of the nature of nebulous stars." Bīrūnī mentions Aristotle's idea that the Milky Way is formed in the atmosphere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

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

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

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

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

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

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

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

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

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

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

> the time comes to speak of the winds. So when there are many comets and they are dense, it is as we say, and the years are clearly dry and windy.[67]

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

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

Comets in the Islamic World

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

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

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

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

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

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

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

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

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

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

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

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

[74] Ibid., p. 810.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

*refers to the types of al-kaid

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

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

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

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

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

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

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

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

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

[90] Ibid., pp. 30–31.

[91] Ibid., pp. 31–32.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Antisolarity of the Tail: A New Chapter in Cometology

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

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

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

[98] Ibid., pp. 117–120.

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

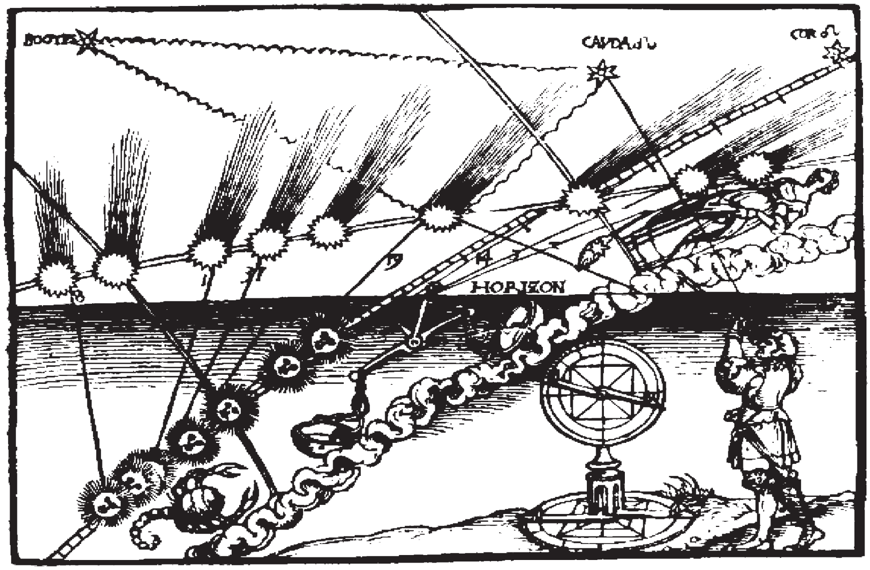

Fig. 2.3 The title page of Peter Apian's treatise on the comet of 1532 (*Ein kurtzer bericht*…, Ingolstadt, 1532) showing the anti-solar direction of the comet's tail. (From Barker, "The Optical Theory of Comets", p. 8)

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

[100] Ibid., pp. 11–13.

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

Parallax

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

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

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

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

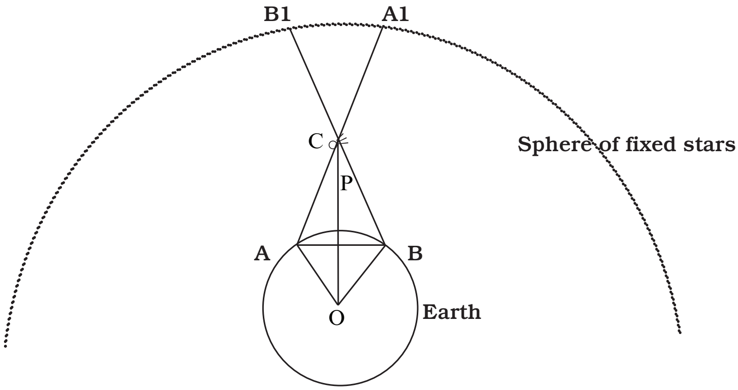

Fig. 2.4 Observers at A and B will see the object C at different positions. Angle P is called the parallax of the object C

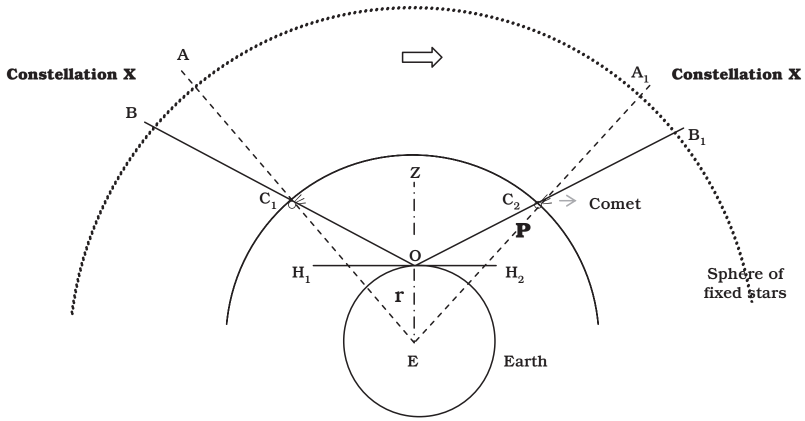

Fig. 2.5 An observer at O observers the object C_1 among the background stars at B. After several hours, due to diurnal motion of the celestial sphere, the same object is seen at B_1. However, an imaginary observer at the center of the earth, E, will see the same object at A and A_1 respectively. The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

from a fixed position can make two observations with an interval of several hours. In the intervening time, the rotation of the earth displaces the observer (in four hours, the displacement of an observer on the equator is equal to the Earth's radius), but the observer supposes that the celestial sphere rotates around the center of the earth (Fig. 2.5) and C1 moves to C2 which is seen at B1 among the stars of the constellation X. By measuring the angles $\angle H_1OC_1$ and $\angle H_2OC_2$, or more practically the angles $\angle ZOC_1$ and $\angle ZOC_2$, or measuring the position of C_1 and C_2 relative to the position of the nearby stars (when their positions are accurately known), the amount of the angular displacement of the comet can be found. Since r (the earth's radius) and $\angle AEA_1$ (the angle of rotation of the celestial sphere between the two observations) are known, using the law of sines we have

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

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

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

Tycho Brahe and the Comet 1577

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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[109] Ibid., p. 135.

[110] Ibid., p. 137.

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

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

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

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

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

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

[115] Ibid., p. 62.

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

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

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

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

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

Brahe's Optical Theory of Comets

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

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

[116] Ibid., p. 63.

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

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

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

Tycho's Contemporaries

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Conclusion

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

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

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

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

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

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

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

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

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

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

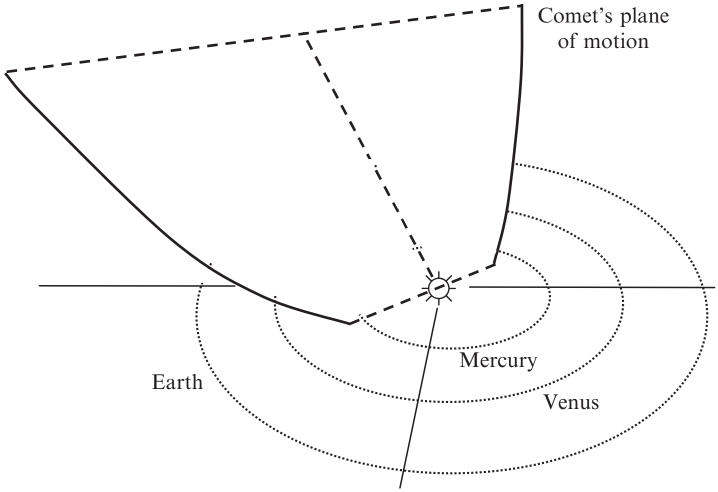

Fig. 2.6 The orbit of the comet 1577 was highly inclined. That was the first time that astronomers were calculating the motion of a body moving on such an oblique 'circle'. (Adopted from Robert S. Westman, "The Comet and the Cosmos," p. 18)

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

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

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