Chapter 2

From Ancient Atmospherics to Icy Dirtballs

Identity Crisis

Comets have an identity crisis of historic proportions. Like so much in astronomy, appearances alone can be deceptive. A bright comet in the twilight sky—replete with dazzling head and glowing, sky-spanning tail, its position and appearance changing each night—looks as though it’s making a concerted effort to be the most important object in the night skies. As we’ll find out, that grand, jaw-dropping cometary spectacle is largely the result of celestial ‘smoke and mirrors.’ A great comet is one of nature’s most astonishing special effects.

Complete ignorance may have been acceptable 500 years ago, before the age of scientific inquiry, when nobody knew anything about comets other than they appeared in the skies without warning, they were very far away and they could assume a variety of shapes and sizes. There was also a deep, primeval overlay of fear and superstition—common among varied cultures the world over—that painted comets in a pretty bad light (Fig. 2.1).

Incredibly, hundreds of years of scientific investigation have still not completely vanquished age-old comet phobias; indeed, the use (or should we say misuse) of scientific discoveries and the rise of pseudoscience has seen the perpetuation of comet fears and the appearance of new anxieties. Regrettably, there’s nobody more deceived than the average ‘person on the street,’ whose information about space subjects may be derived from a mixture of cinematic fiction and media sensationalism.

In addition to the convincing illusion of cosmic grandeur and the mire of old and new superstition surrounding comets, another manifestation of the cometary identity crisis is the changing scientific picture of the physical nature of comets and
where they come from. Of course, changing pictures is part and parcel of the essence of science itself. The story of the astronomical investigation into comets, from the speculations of the ancient Greeks, through the work of Edmond Halley to close-up studies by space probes, is truly fascinating.

Cosmic Speculations in Ancient Greece: One Comet Fits All

Philosophers of ancient Greece inquired into the very nature of the cosmos. They were the first to make serious attempts to explain celestial objects and phenomena—from the very small to the very large, from the basic atomic essence of matter to the structure of the universe—without necessarily calling into action the hand of supernatural entities. Comets, too, were the subject of considerable speculation.

There was no overall consensus in ancient Greece on how the cosmos was thought to be arranged. Philosophers were free to speculate, and a number of schools were founded, each dedicated to certain models and ways of thinking. Early Greek mythology fancied that Earth was a circular disk comprising a central landmass surrounded by a great ocean; above was the air, then the cosmic ether, while below Earth lay Hades. Comets were perceived as signs of the gods and portents of
things that were to transpire on Earth, indicators of terrestrial change and signposts to the fate of societies and individuals.

By the fifth century B.C., however, philosophers had largely abandoned this simplistic picture of the universe as civilization flourished and practical problems needed to be addressed by some serious thinking. For example, Greek seafarers navigating by the stars found that new stars appeared above the southern horizon as they voyaged further south. Clearly, Earth was not flat, and the vault of heaven wasn’t just decorated with a fabulous tapestry pinned up by the gods just for mortals to admire.

It’s possible here to cite only a select few ancient Greek speculations on the nature of the heavens and to give just the bones of these theories. Thales of Miletus (c. 624–546 B.C.)—recognized by many to have been the first great Greek philosopher—suggested that everything in the cosmos was made up of ‘moisture,’ a universal substance that can variously manifest itself as air, water, fire, earth and ice.

After traveling widely around the Middle East, a school was founded in Samos by the great mathematician and astronomer Pythagoras (c. 570–495 B.C.). He taught that it was possible to understand the universe through mathematics and held that the circle and the sphere were perfect figures. The number ten was particularly important to Pythagoreans; ten, the tetractys, was the very number of the universe. Early Pythagoreans held that Earth was at the center of the universe. Surrounding it was a nested series of transparent shells—revolving crystalline spheres—upon which celestial objects were attached. Stars were attached to the outermost sphere, beyond which lay an infinite void. Inside lay spheres that carried (in order of decreasing distance from Earth) Saturn, Jupiter, Mars, Venus, Mercury, the Sun, the Comet (a single object like a planet), the Moon and Earth.

An elaborate cosmological model was created by the Pythagorean philosopher Philolaus (c. 470–400 B.C.), who replaced a central Earth with a Central Fire, the powerhouse of the universe. Naturally, there was a total of ten spheres. Antichthon, the ‘Counter-Earth’—a body that was permanently hidden on the other side of the Central Fire—occupied one of these spheres. Antichthon was a peculiar concept introduced to give ‘balance’ to the system, since Earth itself seemed to be such a heavy object compared with the planets. As for the very hub of the cosmos, the Central Fire, Earth revolved so that the hemisphere opposite Greece was always turned towards it. Setting all these objects in their various rates of motion very loosely approximated the real motions of the universe, but the actual motions didn’t hold up against any sort of rigorous comparison with observations. For example, Pythagoreans considered that the Comet was one of the planets, but that it appeared at great intervals of time and only was a little above the horizon; because of this, some apparitions of the Comet failed to be seen owing to their low altitude (Figs. 2.2 and 2.3).

Hippocrates of Chios (c. 470–410 B.C.), not to be confused with his contemporary Hippocrates of Cos, known as the father of western medicine, wrote one of the first textbooks on geometry and, influenced by the Pythagorean school, speculated on the nature of the cosmos. As an aside, it’s interesting to note that Hippocrates also came up with the striking notion that light rays came from the eyes to illuminate
objects, rather than the other way around, which just goes to show how creative his thinking could be.

Like the Pythagoreans, Hippocrates thought that there was only one Comet, and it was considered to be a planet. He asserted that the Comet’s tail was an optical illusion caused by the deflection towards the observer of sunlight in ‘moisture’ that the comet drew from the Sun whenever the Comet passed the Sun. Odd though it may seem, this explained why the Comet appeared to brighten and develop a long tail whenever it was in the Sun’s vicinity. Hippocrates explained that whenever the Comet approached the Sun from the ‘moister’ northern skies it had no difficulty in drawing off enough moisture to produce a highly reflective tail, whereas if it was seen in ‘drier’ southern skies it did not appear to have a tail at all. He explained that the Comet’s appearance lagged behind the annual revolution of the stars because its path gradually slowed down as it cleared the Sun.

Although these speculations were attempts to explain observed phenomena, it’s easy to pick a number of gaping holes in them. How, for example, could the appearance of two comets at one time (or in very short succession) be explained? What might explain observations of those comets that attained peak brilliance and a large
tail far to the south of the Sun? The fact is that Hippocrates had access only to limited descriptive information about a few great comets that had been seen from his location in Mediterranean climes. Geometry dictates that great comets on high inclination orbits approaching from the north are more likely to be first spotted at night due to sky contrast; they develop lengthy tails as they head sunward, but as they move south their tails may appear to shorten because of the changing angle between Earth and the tail. When they are moving away from the Sun they may only be seen low to the horizon or in twilight conditions, where contrast reduces the brightness of the comet and the visibility of its tail (Fig. 2.4).

Although all original works of astronomer and mathematician Eudoxus of Cnidus (c. 410–347 B.C.) have been lost, we know that he authored a number of works, and it’s possible to glean a great deal about his cosmological theories from secondary sources written around his time. Eudoxus made a number of significant contributions to astronomy. He introduced the celestial globe, built his own observatory in Cnidus and developed sophisticated models of planetary motion; he was also committed to the idea that the sphere and the circle remained perfect figures as befitted the motions of the cosmos.

Eudoxus’ complete picture of the universe was geocentric, placing Earth at the center of a nest of 26 concentric crystalline spheres. To each of these spheres were
attached the Sun, Moon and planets (whose complex motions were determined by multiple associated spheres and whose axes of revolution and speeds differed), while the outermost sphere contained the distant stars that shared its axis with Earth and revolved once a year. It isn’t known whether Eudoxus believed that this was the way things actually were, but the model seemed to explain the way that most celestial objects appeared to move and was the first full-blooded attempt to come to grips with the complexities of the observed motions of the heavens. One notable absence from Eudoxus’ work—an absence doubtless explained by the fact that his ideas have only been partly preserved in the work of other philosophers—is the question of comets (Fig. 2.5).

Aristotle’s Atmospherics

A century later, Aristotle (384–322 B.C.), one-time tutor to Alexander the Great (356–323 B.C.), took on Eudoxus’ model of the cosmos and improved it by adding yet more spheres. His system contained no fewer than 55 of them. Aristotle
considered that the heavens were perfect and unchanging. His cosmological model was that of a universe that was infinite in both past and future. There was only one place to allocate those errant, unpredictable comets. He ascribed them to phenomena that manifested in the upper atmosphere, above the clouds but below the perfect realm of the Sun, Moon, planets and stars.

Incidentally, we have Aristotle to thank for the very word ‘comet.’ It is derived from the Greek word *komē*, which means ‘hair of the head.’ Aristotle described comets as *komētēs* (meaning ‘long hair’), an epithet that derives from the wispy appearance of a comet’s tail. Anyone who has been fortunate to marvel at a great comet—one that is easily visible with the unaided eye at its peak brightness and displays a sizable coma and/or long tail—will know precisely why this description is particularly appropriate. To get an idea, just take a look at, say, an image of Comet McNaught (C/2006 P1) at its best; it looked like a vast plume of hair reefing in the wind, frozen in time (Fig. 2.6).

Aristotle made a concerted attempt to explain the nature of comets in the first book of his great work *Meteorology*, where he first explained, and then refuted, a number of speculations by other philosophers about the nature of comets. He rejected the idea that the Comet (singular) existed as an extraordinary manifestation of one of the five classical planets—Mercury, Venus, Mars, Jupiter or Saturn—because sometimes all
five planets plus the Comet could be accounted for. Occasional conjunctions and coalescences of two planets giving rise to a temporary comet, such as had been proposed by Anaxagoras (500–428 B.C.) and Democritus (c. 460–370 B.C.), were of course out of the question.

Aristotle declared that the idea of there being a single Comet was impossible because two comets have often appeared in the sky simultaneously. Hippocrates’ theory of comets was subsequently demolished; such views involved certain impossibilities. He stated that if Hippocrates was correct then some bright comets ought to be visible before they had time to develop a tail, as they drew up reflective vapors as they neared the Sun; early on in their apparition they would appear as a bright point of light just like a planet. This was not so. As for comets only appearing in the north, Aristotle stated that many had actually first appeared in the south. In fact, comets could appear in any part of the sky, including directly opposite the Sun.

**Fig. 2.6** The Great Comet of 2007 had a very ‘hairy’ tail structure. C/2006 P1 (McNaught), imaged by Robin Whittle as it appeared over Mt Macedon, northeast of Melbourne, Australia, on the evening of January 25, 2007. Sony DSC-F707, F2.2, 30 s
In particular Aristotle points to the famous apparition of a bright comet that arose in the west at the time of an earthquake and tidal wave at Achaea. Astronomers have since identified this as the Great Comet of 373–372 b.c., thought to have been one of the greatest comets in recorded history. It was an event that had profound consequences, because in all likelihood Aristotle himself saw this comet when aged 11, igniting his curiosity and perhaps inspiring him to follow the path of science and philosophy.

**Heliocentric Anticipation**

Although the model of an Earth-centered universe remained pre- eminent among thinkers in ancient Greece, it was by no means the only model, as we’ve already seen with Philolaus’ fifth century b.c. theory of a Central Fire around which the Sun, Earth, Counter-Earth and all the planets revolved. In the third century b.c. the great mathematician and astronomer Aristarchus of Samos (310–230 b.c.) proposed a heliocentric model, prefiguring the work of Nicolaus Copernicus (1473–1543) by 1,800 years. Aristarchus proposed that the Sun lay at the center of the universe, and Earth (orbited by the Moon) was one of six planets that orbited the Sun; he even had the planets in their correct order from the Sun. The stars themselves were incredibly far away because they showed no parallax—in other words, the stars always appeared in the same place with regard to each other on the celestial sphere, no matter where in Earth’s orbit we viewed them from. Aristarchus’ views on comets are not known. Since he was bold enough to remove Earth from the center of the universe it would seem odd that he thought of comets as sporadic manifestations in the atmosphere; then again, comets would been impossible to accommodate in a heliocentric universe were they to have followed circular paths.

Despite the fact that Aristarchus’ heliocentric universe was a far more elegant, streamlined and economic theory than any geocentric ones had been (or were to be proposed)—and one that explained some of the complex motions exhibited by the planets in an uncomplicated manner—it never took root. To think that the big, solid Earth was a planet in motion, revolving around both its own axis and the Sun, was to seemingly defy our experience. It was obvious that the heavens revolved around Earth because it looks that way. If Earth were spinning on its axis and zipping around the Sun, then surely, the argument went, we would feel this motion and observe manifestations of phenomena caused by it, such as high winds and no mean degree of dizziness. Besides, to remove Earth from the center of all things was to demote the status of our world and its inhabitants, ranking it alongside all the other objects in orbit around the Sun and retaining just the Moon for geocentric company. Clearly, the philosophical and religious consequences of the heliocentric universe were too unpalatable to bear, and remained so for a very long time indeed.

Ludwig Wittgenstein (1889–1951) took a famous view of this problem when he asked a friend: “Tell me, why do people always say that it was natural for men to assume that the Sun went around the Earth rather than the Earth was rotating?”
“Well, obviously,” said his friend, “because it just looks as if the Sun is going around the Earth.”

The philosopher replied: “Well, what would it look like if it had looked as if the Earth were rotating?”

Ptolemy’s Long-Lived Legacy

Several centuries after Aristarchus, long after the classical period of ancient Greece had ended and the state had been subsumed into the Roman empire, there nevertheless appeared a number of important thinkers on the nature of the cosmos. Claudius Ptolemy (c. A.D. 90–168), of Greek lineage but a citizen of Alexandria in Egypt (a province of Rome), was perhaps the most important of these later philosophers. Ptolemy authored a number of scientific works. One of these, the Almagest, was an encyclopedia of ancient knowledge whose mathematical and astronomical concepts included an Earth-centered universe that attempted to explain the apparent motions of the heavens along the same sorts of lines as those propounded by Aristotle. Almagest is itself an Arabic word and derives from ‘al-majisti,’ referring to its ancient Greek title of The Greatest Compilation. Most of our knowledge of ancient Greek philosophy comes from original ancient texts (most of which have now been lost) that were translated, copied and preserved by Arab scholars in Baghdad during the European Dark Ages.

Ptolemy’s model of the universe, expounded in Planetary Hypotheses, differed in one important aspect from that of Aristotle: the introduction of epicycles. Instead of each planetary motion being dependent on the individual speed and movement of several associated spheres, Ptolemy proposed that each planet described a small circular path around a point on a larger circular orbital path around Earth. Epicycles seemed to explain the observed looping movements of the planets—their so-called retrograde motions—while preserving the cosmologically sacred nature of the circle.

Contrary to his mathematical approach to the workings of the universe—and at odds with his generally logical way of thinking—it appears that Ptolemy made little attempt to explain what comets were and in which heavenly realm they appeared. Instead, in his work Tetrabiblos, his cometary speculations delved into the mystical and supernatural, attributing wars, storms and the fates of individuals to them. At the same time, however, he hints at their varied physical appearance, including their occasional resemblance to beams, trumpets and pipes, among other forms. He also indicated that some comets became visible near the Sun during the brief moments of darkness afforded by total solar eclipses. Such Sun-grazing comets have indeed been observed throughout history, most of the more recent ones having been discovered on images taken by the orbiting SOHO satellite (NASA’s Solar and Heliospheric Observatory, operational since May 1996).

The works of Aristotle and Ptolemy were the most influential ever written, and for many centuries served as the main fonts of Western scientific knowledge.
Helped in no small way by assimilation into the dogma of the then-all-powerful Church, Aristotelian science and Ptolemy’s epicyclic model of the workings of the universe came to assume an unchallengeable authority that did little to advance scientific reason, inquiry and progress until the Copernican revolution began in the early fifteenth century (Fig. 2.7).

Before leaving classical antiquity it’s worth noting the remarkably near-the-truth opinions of the Roman playwright and philosopher Lucius Seneca (c. 4 B.C.–A.D. 65), mentor to Roman emperor Nero (A.D. 37–68). In his treatise On Comets Seneca declared the idea of there being but one Comet to be wrong, ruled out the suggestion that comets were illusions caused by planetary conjunctions and also dismissed the notion that comets were merely transient atmospheric occurrences. While taking the view that comets formed in the atmosphere by some sort of condensation of vapors and terrestrial ‘exhalations’ that were expelled into space, they still became real, solid, celestial objects with their own individual orbits. Comets could appear at any point in the sky, and they brightened as they approached the Sun. Although it may be possible to see distant stars through their tails, the heads of comets were opaque and therefore had real substance. He pointed out the great variety of curved celestial paths taken by comets and the varied shapes, sizes and levels of brightness

*Fig. 2.7* In the Far East, comets—known as ‘broom stars’—were regarded as omens, so it was considered vitally important to keep a close watch on celestial events. Thousands of astronomical phenomena are recorded in Chinese annals dating back many centuries. Over an almost continuous period spanning the sixteenth century B.C. to the end of the nineteenth century, Chinese court astronomers were appointed to observe and record changes in the heavens. This legacy of almost 3,500 years’ worth of astronomy provides a rich source of reference material. Shown here is a copy of some of the cometary forms featured in the *Mawangdúi Silk*, a textbook of cometary forms and the various disasters associated with them that was produced in the third century B.C.
that they assumed (he also mentions observer bias), but held that all comets were of the same nature. Following this logic, Seneca wrote: “Innumerable comets revolve in secret, unknown to us, either by the faintness of their light, or the situation of their orbit being such that they become visible only while they reach its extremities.”

It may not come as a surprise to learn that there’s no happy ending to the story of a great but complex man whose life was lived close to a paranoid and superstitious dictator (a trait shared by many dictators through history). Nero’s reign saw the appearance of several bright comets, terrifying the emperor, who thought they were ill omens; Seneca attempted to make political capital by allaying such fears, assuring his leader that they were signs in Nero’s favor. Sadly, the comet of A.D. 65 was to portend Seneca’s demise. Suspecting that Seneca was plotting against him, Nero compelled him to take his own life.

There could be no more appropriate rounding-off to our brief survey of classical antiquity and the status of comets within its various cosmologies than to quote Seneca in *On Comets*:

The day will yet come, when the progress of research through long ages will reveal to sight the mysteries of nature that are now concealed. A single lifetime, though it were wholly devoted to the study of the sky, does not suffice for the investigation of problems of such complexity. And then we never make a fair division of the few brief years of life as between study and vice. It must, therefore, require long successive ages to unfold all. The day will yet come when posterity will be amazed that we remained ignorant of things that will to them seem so plain. The five planets are constantly thrusting themselves on our notice; they meet us in all the different quarters of the sky with a positive challenge to our curiosity.

The man will come one day who will explain in what regions the comets move, why they diverge so much from the other stars, what is their size and their nature.

Many discoveries are reserved for the ages still to be when our memory shall have perished. The world is a poor affair if it does not contain matter for investigation for the whole world in every age…Nature does not reveal all her secrets at once. We imagine we are initiated in her mysteries. We are, as yet, but hanging around her outer courts.

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**New Observations Alter Old Theories**

**Copernican Revolution**

Even though Aristarchus, in third century B.C. Greece, had proposed that the Sun, not Earth, lies at the center of the Solar System, the modern acceptance of the heliocentric theory begins with Nicolaus Copernicus (1473–1543). Copernicus, a mathematician and astronomer born in Poland but widely traveled around Europe, was inspired to inquire into the workings of the universe after learning about Ptolemy’s theories. By combining brilliant insight with observations, he discovered that Ptolemy’s theory of the Moon’s motion was simply not good enough, planting
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seeds of doubt in his mind about the whole geocentric theory. Copernicus had access to many astronomical and mathematical works written in antiquity, and he doubtless became aware of Aristarchus’ heliocentric theory.

Around 1510, Copernicus produced several handwritten copies of a manuscript, the Little Commentary, a work intended to be a private preparatory sketch (passed among friends) for a planned book detailing his proposed heliocentric theory. Although that planned book took many years to finally appear in print, Copernicus’ heliocentric views were no great secret. In 1533 his theory was even heard by Pope Clement II and his cardinals in a lecture given in Rome by papal secretary Johann Widmannstetter. Indeed, Widmannstetter was so impressed that he later urged Copernicus to publish his theory, along with the data that backed it up.

Interestingly, the fourth decade of the sixteenth century also saw a remarkable succession of bright comets, much to the excitement of European astronomers who had endured a dearth of comets over the course of several preceding decades. Comets appeared in 1531, 1532, 1533, 1538 and 1539, drawing so much interest and attention that a flurry of tracts on comets appeared, written by contemporary astronomers such as Peter Apian (1495–1552), Gemma Frisius (1508–1555) and Girolamo Fracastoro (1478–1553) (Fig. 2.8).

Copernicus is sure to have marveled at the sight of these comets, and we know that he made a special study of one of them, the Great Comet of 1533, since he published a treatise on it. Incredibly, it appears that Copernicus failed to make the leap (at least in print) of realizing that comets were in orbit around the Sun. At the very least, he simply ignored the problem. In keeping with his contemporaries

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**Fig. 2.8** An illustration from Peter Apian’s book *Astronomicum Caesareum* (1540) depicting the comet of 1531 (now known as Halley’s Comet); it shows that a comet’s tail points away from the Sun (Courtesy of the Royal Astronomical Society)
Apian, Frisius and Fracastoro, Copernicus considered that comets were ‘sublunary’ phenomena of the upper atmosphere, just as Aristotle had thought eighteen centuries before, and the notion of the ‘perfect’ celestial path being bound to the form of the circle held firm. This may seem odd, given that Copernicus had made such a great leap in making Earth a mere planet. It is also puzzling, since a series of observational studies of comets, made a century before by the Italian mathematician and astronomer Paolo Toscanelli (1397–1482), provided ample material from which to arrive at the correct conclusion.

In the fifteenth century Toscanelli made what is considered to be the first modern attempt to study the paths of comets across the skies, his folios recording his observations of the apparition of a number of comets. The first, the comet of 1433, consisted of a simple drawing of the comet’s path against the background stars, presented as a smooth curve without precise positional data. Later comets—those of 1449–1450, 1456 (Halley’s Comet), the spring and summer comets of 1457 and that of 1472—were given a more thorough observational treatment in which careful positional observations with regard to stars and planets were made with the aid of naked-eye sighting devices, while timings were made using a clock.

Although these later studies show unevenness in the cometary paths due to slight observational errors in position, they are the more honest and scientifically valuable of Toscanelli’s observations (indeed, they have remained useful to astronomers to the present day). Toscanelli’s notes on his observations are, however, scant, and those which remain are mired in astrological babble. Although there is a hint in one of his diagrams that he attempted to measure the distance of comets by means of parallax, or at least understood the concept, there is nothing in his writings following this up; instead, he made little scientific use of his observations and fell back on the age-old default position of thinking that comets were high atmospheric phenomena (Fig. 2.9).

Given the evidence available to Copernicus it seems improbable that the idea that comets were in orbit around the Sun could have failed to enter his mind; we have no record of this, but an admission that their orbits were clearly not circular or centered on Earth may have presented him with an obstacle too great to take on in print. It was only towards the end of Copernicus’ life, after having built up a great deal of knowledge and amassed considerable observational data, that Copernicus considered the time was right to publish his great work *On the Revolutions of the Heavenly Spheres* (1543).

*On the Revolutions* threw out the very fundamentals of Ptolemy’s geocentric view of the universe. Copernicus stated that the stars are at an immense distance, compared to the distance from Earth to the Sun. He was convinced that the Sun, not Earth, lay near the center of the universe, and that the apparent daily rotation of the stars is caused by Earth’s rotation. Copernicus went on to explain that the apparent annual circuit of the Sun around the ecliptic is caused by Earth revolving around the Sun, and the apparent retrograde motion of the planets is caused by the motion of Earth along an orbit inside that of the outer planets. His explanation of the phenomenon of retrograde motion dispensed with the need to introduce epicyclic planetary motions and is perhaps the most insightful and original of Copernicus’ points.
Fig. 2.9 Naked-eye observations of the comet of 1449–1450, shown moving from Ophiuchus through Corona Borealis, as depicted in the notebook of Paolo Toscanelli (top), and the author’s simulation of the view on October 17, 1449.
Comets are mentioned only once in *On the Revolutions*, where Copernicus wrote:

It is said that the highest region of the air follows the celestial motion. This is demonstrated by those stars that suddenly appear. I mean those stars that the Greeks called comets. The highest region is considered their place of generation, and just like other stars they also rise and set. We can say that this part of the air is deprived of the terrestrial motion because of its great distance from the Earth.

**Cosmic Conundrums**

Tycho Brahe (1546–1601), regarded as the last and greatest astronomer of the pre-telescopic era, was a hot-headed Danish nobleman with a deep interest in mathematics and astronomy. Although he admired the elegant geometry of Copernicus’ heliocentric theory the fact that he could not discern any stellar parallax owing to Earth’s orbit around the Sun implied that the stars were at an unimaginable distance from us. He found this idea untenable. At the same time, Tycho was unwilling to dispense entirely with the geocentric Ptolemaic system because of the religious-philosophical connotations of removing Earth from the center of the universe.

Tycho set about constructing his own scheme of the universe, a geo-heliocentric model known as the Tychonic system, in which the Sun and stars orbited Earth while the other planets orbited the Sun. In this scheme, Earth remained at the center of the universe; the stars were fixed to a vast, all-encompassing Earth-centered globe, removing the problem of stellar parallax.

As early as 1563, when aged 17, Tycho had been painfully aware of the inaccuracy of current maps of the heavens, writing:

> I’ve studied all available charts of the planets and stars and none of them match the others. There are just as many measurements and methods as there are astronomers and all of them disagree. What’s needed is a long term project with the aim of mapping the heavens conducted from a single location over a period of several years.

Realizing the need for more accurate positional data about the movements of the planets to get to the truth, Tycho began to make precise measurements with the aid of naked-eye quadrants and cross-staffs. However, Tycho’s careful astronomical observations went on to provide plenty of evidence against age-old Aristotelean notions of an Earth-centered universe (Fig. 2.10).

Purely by chance, a vital piece of evidence against Aristotle’s picture of ‘unchanging heavens’ came in the form of a brilliant ‘new star’ that suddenly appeared in the constellation of Cassiopeia in November 1572. Now known as SN 1572, the event was a Type Ia supernova—the catastrophic explosion of a white dwarf star—which, after initially rivaling Venus in brilliance, gradually faded but remained visible to the unaided eye into 1574. SN 1572 was one of the most important single astronomical phenomena in history, because careful positional measurements by Tycho and his contemporaries showed that it displayed no discernible parallax; its observed position in the skies when viewed from different locations and times remained the same.
No conclusion other than that the new ‘star’ lay in distant starry realms was possible; but it was a conclusion that struck at the fundamental Aristotelian notion of eternal celestial immutability. In 1573 Tycho published his observations of the supernova in Concerning the New Star, metaphorically striking the first nails into Aristotle’s cosmic coffin. Tycho’s account of the phenomenon—the first scientifically studied supernova—was published in Copenhagen in 1573 and was the basis for his subsequent reputation as a first-class astronomer (Fig. 2.11).

Aware of Tycho’s importance in upholding the status of Denmark as a progressive nation that nurtured the advancement of science, King Frederick II granted Tycho a large estate on the island of Hven in Copenhagen Sound (the island now belongs to Sweden), along with generous funding to establish an observatory there. Before long, the astronomer had set about creating the most modern observatory of
the day. Between 1576 and 1590, a large castle-styled observatory known as Uraniborg (from its dedication to Urania, the muse of astronomy) grew at the island’s center. Astronomical observations were made using a variety of skillfully fabricated instruments, including a mural quadrant, revolving wooden and steel quadrants, astronomical sextants and equatorial armillary spheres, many of them featuring novel designs of Tycho’s invention (Fig. 2.12).

From Uraniborg, Tycho’s meticulous naked-eye observations were to strike yet more nails into Aristotelian and Ptolemaic cosmology. He kept a meticulous 10-week observational record—some 24 measurements made between November 1577 and January 1578—of the track of a comet that he had first sighted in November 1577, carefully following it as it traversed the northern skies. Ten years later he published his work on the comet (now designated C/1577 V1) in Concerning New Phenomena in the Ethereal World, in which he pointed out that his observations of the comet’s tail disproved Aristotelian notions:

[A]t all times this comet had its tail turned directly away from the sun, as all other comets, those observed many years ago by Regiomontanus, Apian, Gemma Frisius, and Fracastoro, have also done: all have turned their tails away from the Sun. From this, it appears that the tail of a comet is nothing but the rays of the Sun which have passed through the body of the comet…Therefore, Aristotle and all those who follow him cannot maintain their opinion, namely that the tail of a comet is a flame of the rare fattiness which is burning above the air, for if that were true, these flames would not have a relationship to the Sun, and always turn themselves away from it.

Far from being an object high in Earth’s atmosphere, Tycho was certain that the comet lay much further away than the Moon because simultaneous observations made with a confederate in Prague, 660 km south of Uraniborg, showed that it displayed a great deal less parallax than the Moon. He went on to plot the comet’s path, placing part of its orbit near that of Venus. Tycho suggested that cometary

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**Fig. 2.11** Tycho’s observation of the supernova of 1572, compared with a simulation of what it would have looked like in the sky (Illustration © by the author)
orbits may not keep to circular paths and also remarked on the fact that the comet’s
tail always pointed in a direction away from the Sun, regardless of the comet’s
motion through space. There wasn’t any doubt that this comet was located in true
planetary realms, a place where Aristotle had claimed that “nothing new could be
born.” Tycho’s 400-year-plus observations of C/1577 V1 have since been used to
pinpoint its likely current location, some 300 au from the Sun, far above the plane
of the Solar System.

Yet all was not tempered by hard data, mathematics and reason; despite finding
evidence to support the idea that Earth, along with planets and comets, were in orbit
around the Sun, Tycho remained highly skeptical of the idea. He clung to the old
notion of an Earth-centered universe whose motions would eventually be explained
as soon as the right mathematical model was found. Added to his scientific insight,
Tycho, like so many of the era, attached a useless layer of astrological significance to comets. However, these startling discoveries were among the first of what was to become a flurry of thin ends of wedges that were to be driven into the once-solid edifice of dogmatic belief in ancient cosmological ideas during the sixteenth and seventeenth centuries (Fig. 2.13).

Towards a Deeper Understanding: The Laws of Planetary Motion

As a young boy Johannes Kepler (1571–1630) had marveled at the sight of the great comet of 1577, an object that had proven so difficult for Tycho Brahe to admit into his scheme of the universe. However, his curiosity about the skies was never destined to be realized in as practical a manner as that of Tycho, since his ability to perform the tasks of observational astronomy was impaired by limb weakness and poor eyesight consequent to childhood smallpox. It is a little-known fact, however, that Kepler used a telescope in his later years, and in September 1618, he became the first person to have ever observed a comet telescopically—comet C/1618 Q1 (see below).

Instead, Kepler’s genius lay in the use of mathematics to achieve a firm grasp on the movements of the heavens and the motions of the Moon and planets. Profoundly religious, he was convinced that the universe had been created in accordance with certain mathematical rules, and that knowledge of these rules was within human comprehension. His work inspired yet greater understanding among later generations of astronomers, and indeed his legacy remains potent to this day.
Perhaps the great comet of his childhood had imbued within Kepler a deep sense of the transcendent and mystical, since, in addition to astronomy, he was a firm believer in astrology—a subject that we now consider to be the unscientific art of attempting to reconcile planetary movements with Earthly phenomena. It is strange to think that any rational person could give any credence to astrology, but in Kepler’s time the lines between scientific logic and ill-founded superstition were somewhat blurred, particularly when it came to the subjects of astrology and astronomy. It was actually through the practice of astrology as a student at the University of Tübingen in Germany that Kepler first developed an understanding of the apparent motions of the planets. In later life, while at Prague, Kepler’s chief role as imperial mathematician to Rudolph II was to provide astrological advice.

In October 1604—just 32 years after Tycho’s supernova—another ‘new star’ flared into being. This time, the supernova occurred in the constellation of Ophiuchus and peaked at around the brightness of Venus. Kepler thought that the supernova affirmed the fact that the heavens could no longer be regarded as changeless and immutable. The new star was undoubtedly in stellar realms because, like other stars, it displayed no measurable parallax.

Kepler also interpreted the 1604 supernova astrologically, believing that it represented the beginnings of an important new phase of terrestrial events. Although his astrological predictions and horoscopes may have possessed little scientific merit (a quality shared by all astrological forecasts), Kepler’s painstaking analysis of Tycho’s observations was to produce one of the most important scientific insights of all time. Tycho had originally directed Kepler to investigate Mars’ orbit using a mathematical tool known as an equant, helping solve some of the problems observed in planetary motions introduced by the geo-heliocentric Tychonic system. Kepler eventually created a model that agreed with observations to a point, but still produced discrepancies between observation and theory of up to 8 arcminutes (almost one-quarter the Moon’s apparent diameter) (Fig. 2.14).

In 1600 Kepler visited Tycho in order to analyze the great astronomer’s meticulous observations—measurements of the motions of Mars in particular—in order to discover whether a set of fundamental laws about planetary motions could be determined. Using Tycho’s extensive records—the most accurate and consistent set of naked-eye measurements ever made—he was to refine Copernicus’ heliocentric theory and place it on a firm scientific footing.

After analyzing Tycho’s observations of Mars from 1587 to 1595 he dispensed with perfect circles and equants and went to work on the basis of the idea that Mars traveled an ovoid (egg-shaped) path around the Sun. He discovered that the planets move faster when nearest the Sun, and the radius vector (the line connecting a planet to the Sun) sweeps out equal areas in equal times, a concept now known as Kepler’s second law of planetary motion.

Kepler’s next discovery came with his insight into the shape of Mars’ orbit when he hit upon the idea of an ellipse, a shape formed by cutting through a cone at an oblique angle. He realized that for years he had been attempting to fit an ovoid into an oval slot. It made sense that all planetary orbits must be ellipses of varying degrees—that of Mars being particularly eccentric among the planets—and the Sun is located at one focus of this ellipse. This is known as Kepler’s first law of planetary
motion. Describing this ‘eureka’ moment, Kepler wrote: “I awoke as from a sleep, and new light broke upon me.”

Yet, even in Kepler’s new scheme, this ‘new light’ was yet to fall upon comets. After studying the path of a bright comet that appeared in 1607 (which, unbeknown to him was the periodic visitor Halley’s Comet), he came to the curious conclusion that comets moved freely through the Solar System, more or less in straight lines. However, it appears that the observational data available to Kepler were not good enough for him to compute an orbit accurate enough to betray the comet’s curved path. Kepler’s astrological inclinations caused him to believe that comets were omens, guided through space by an intelligent, often seemingly malevolent supernatural spirit; they influenced terrestrial events by disrupting nature itself.

Nevertheless, Kepler did come to some reasonable conclusions about comets, their physical properties and phenomena. He speculated that comets were spontaneously created from impurities or ‘fatty globules,’ in the ether; they were as numerous as fish in the sea, but we see only a small selection of them during our short time on Earth. Explaining cometary tails, he wrote:

The direct rays of the Sun strike upon it [the comet], penetrate its substance, draw away with them a portion of this matter, and issue thence to form the track of light we call the tail…In this manner the comet is consumed by breathing out its own tail…the head is like a con-globulate nebula and somewhat transparent; the train or beard is an effluvium from the head, expelled through the rays of the Sun into the opposed zone and in its continued effusion the head is finally exhausted and consumed so that the tail represents the death of the head.
Four years after their discovery, the first two laws of planetary motion featured in his book *New Astronomy* (1609). The book also contains ideas about gravity (many decades before Isaac Newton’s theory of gravitation) and speculation that the Sun’s own position in space was far from being stationary. It wasn’t until 1619 that Kepler’s third law of planetary motion appeared in his book *Harmonies of the World*; it states that the ratio of the length of the semi-major axis of each planet’s orbit (cubed), to the time of its orbital period (squared), is identical for all planets. Known as the ‘harmonic law’ this is perhaps better expressed by stating that the square of a planet’s orbital period is proportional to the cube of its mean distance from the Sun.

Kepler’s three laws of planetary motion could be applied to any object orbiting any other object under the influence of gravity. The laws appeared to explain the motions of all objects in the Solar System—including comets—and they delivered a means by which the scale of the Solar System could be deduced. Kepler’s laws enabled Isaac Newton to lay out his theory of gravitation in his *Principia* (1687), which demonstrates that Keplerian orbits are the most simple of two-body orbits.
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