PART I

Tycho, Gilbert and Kepler

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Tycho Brahe

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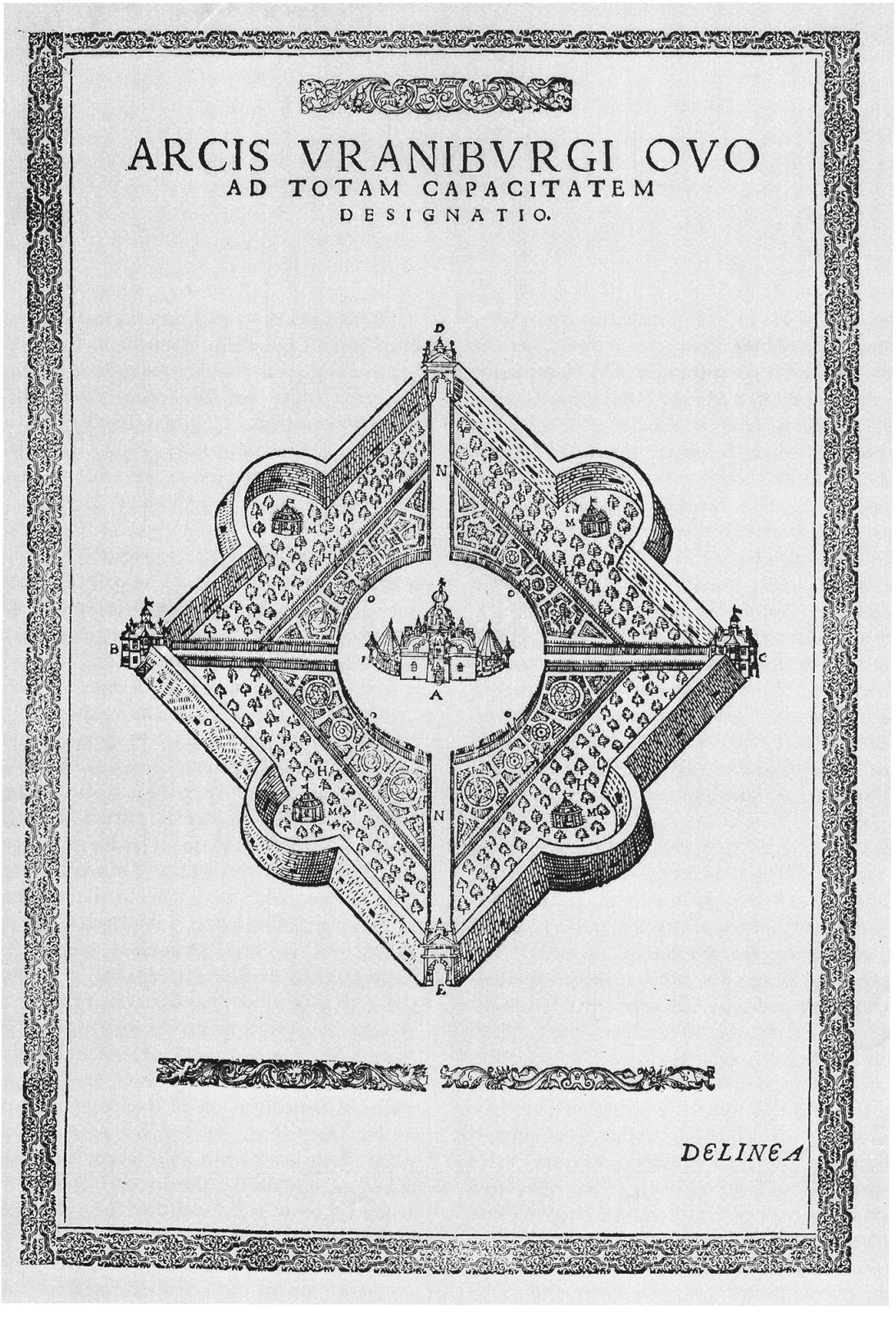
For as long as histories of astronomy have been written, heliocentrism has been regarded as the hallmark of modern astronomy. In accordance with this tradition, Nicholas Copernicus (1473–1543), as the effective originator of heliocentric doctrine, has been hailed as the founder of modern astronomy. In fact, however, except for the motion of the Earth, the revolutionary element in Copernicus's work is very small: in most respects his *De revolutionibus* (1543) follows Ptolemy's *Almagest* so closely that he can equally well be regarded (see Volume 1) as the last great practitioner of ancient astronomy. On this view, it was the seventy-year period following Copernicus's death in 1543 that actually saw the transition to modern astronomy. And insofar as any such development can be attributed to the influence of one person, that transition was wrought by the ideas and efforts of the Danish astronomer Tycho Brahe (1546–1601).

Only a few facts are necessary to establish the background of Tycho's career as an astronomer. The first is that he was born into the small oligarchy of families that had controlled political, economic, and social power in Denmark for at least 200 years: had he lacked the status conferred by birth into this privileged class, any work he might have done as an astronomer would have been carried out on a completely different basis. The second is that, except for the rather bizarre circumstances of being raised as a fosterson by his father's brother, Tycho simply would not have been given enough freedom to develop predilections for astronomy: his four younger un-fostered brothers were esquired into castles in their early teens and knighted before they were twenty. Third, Tycho's education in astronomy was essentially a private affair (as it was for any sixteenth-century astronomer), and a very extended one. Long after he could have begun to make his mark in society, this oldest son and oldest grandson of Councillors of the Realm was still drifting from one university circle to another. Only in his twenty-fifth year did Tycho take up his residence in Denmark. And then it was not at court, but at his maternal uncle's provincial Abbey of Herrevad – where he soon generated more controversy by forming a permanent liaison with a commoner.

Tycho's influence and reputation stems from achievements that fall into three quite distinct categories. The one that was most important during Tycho's life and for the fifty years following it was cosmological in character. It was initiated in 1572 by the appearance of what has come to be called Tycho's nova (now classified as a supernova), and raised to the dimension of a crusade by the appearance of the even more spectacular comet of 1577. During the ensuing decade Tycho composed lengthy monographs on each phenomenon. These would form the great bulk of his life's literary output, and would include the discovery which he himself undoubtedly regarded as the outstanding achievement of his career – the so-called Tychonic system of the world. Although Tycho naturally sought to endow his cosmological writings with the authority so justly due to observations made with his best instruments, the New Star and comet were both observed with instruments that were primitive by Tycho's standards. The mature instruments – as well as all of the other remarkable facilities associated with Tycho's name – were products of the second strand of Tycho's career, and appeared only during the decade following 1576, when Tycho was granted the island of Hven and provided with annual stipends to underwrite his work there. By 1585 he had established the modern prototype of the scientific research institute (Figure 1.1), featuring housing, instrument-mak-



ing works, instruments, observatories; a collection of artisans, students, unpaid assistants, and salaried co-workers to staff his manifold activities; and even papermaking and printing shops to publish his results. Only with the completion of these facilities could he proceed to the third facet of his work – technical studies of the celestial motions that would culminate in nothing less than the complete renovation of astronomical science.

Tycho's cosmological activities

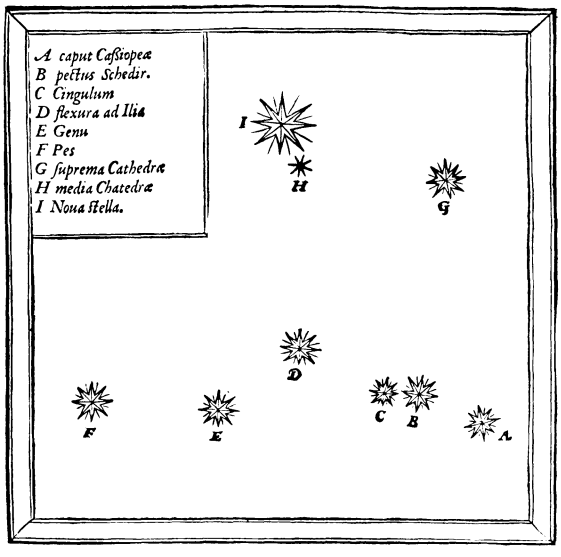
The event that signalled the formal beginning of Tycho's career as an astronomer occurred on 11 November 1572, a month before his twenty-sixth birthday. As he was returning from his alchemical laboratory that evening for supper, he noticed an unfamiliar star-like object in the sky – one that was not only clearly alien to the constellation in which it appeared, but was also brighter than any star or planet he had ever seen. Its appearance seemed to deny that it could be a comet, and a few nights of observation revealed that it was not only too stationary to be a comet, but too stationary even to be associated with the realm below the Moon to which comets were supposed to be restricted.

By 1572 the Aristotelian dichotomy between the earthly sphere of *change*, and the heavenly spheres beyond the Moon, where things were assumed to retain forever a pristine perfection unimaginable to anyone living on Earth, had been accepted by philosophers from Greek, Moslem, and Christian cultures over a period of nineteen centuries. The primary reason for the longevity of Aristotle's cosmology, of course, was the fact that, in general, it fitted the evidence. With respect to comets it was seriously erroneous, but even there it was considerably less vulnerable than might be expected. The accepted nature of comets as atmospheric phenomena placed them outside the domain of astronomy; and their motions must have produced enough phantom parallaxes to mislead or discourage the few sceptics who sought to investigate them prior to Tycho's day. Nor, indeed, was the situation greatly different in 1572. For most of Tycho's contemporaries, change was not only theoretically but, by virtue of the weight of scientific terminology, almost *logically* restricted to the world below the Moon. Most of them were so compelled by the logic of Aristotelian cosmology that it did not occur to them to doubt that there would be parallax in a body so manifestly 'generated', and thus so obviously associated with the terrestrial sphere of change. Many others actually obtained observational results through which they satisfied themselves that the new star was indeed below the Moon where it was theoretically expected to be, while some insisted on calling it a comet even though they could find no measurable parallax for it. Even men who were willing to accept observations that placed the 'star' above the Moon could remain mired in the rest of Aristotle's doctrine: the Landgrave of Hesse-Kassel, John Dee (1527–1608), and Thomas Digges (*c.* 1546–95) assumed that any change of brightness of the 'star' must be purely apparent, and therefore the reflection of a change in its height. But despite the fact that even the very terms available for discourse on the subject implied commitments to the Aristotelian world view, Tycho succeeded in detaching himself sufficiently from his preconceptions not only to test the object for parallax, but to believe the negative results he obtained.

By the beginning of 1573, Tycho had decided that the object was indeed nothing less than a new star, and had written a manuscript that attempted to rationalize its origin and interpret its astrological significance. Early in the summer these reflections, along with a description of the progressive decline of the star (to the brightness of Jupiter in December, and down to that of a second magnitude star by May), and computations of the lunar eclipse predicted for 8 December 1573, appeared as a small book published in Copenhagen.

From the standpoint of sixteenth-century thought, Tycho's nova (Figure 1.2) had implications in principle as radical as those of heliocentrism. The net of Aristotelianism encompassed everything: once it started to unravel, the whole world would fall apart. But in fact nothing so serious happened in 1572, and what little perturbation of opinion there was owed little to Tycho's obscure volume. Only in conjunction with the

1.1. Tycho's observatory on Hven, Uraniborg, viewed from the east. The observatory building itself is at the centre, and it is surrounded by ornamental gardens and a protective wall. At the southern corner is the printing house, and at the northern the quarters for the servants.



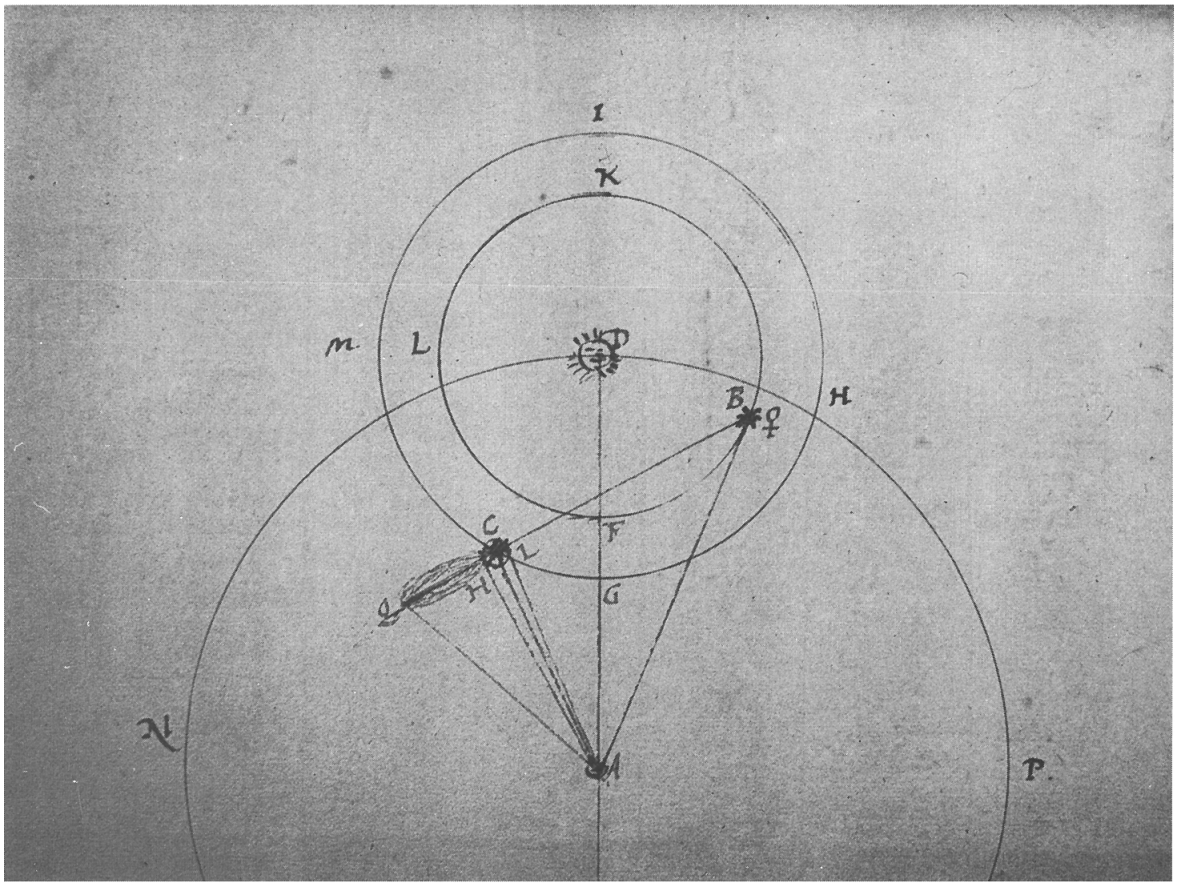
1.2. Tycho's nova (*I*) shown in relation to nearby stars of Cassiopeia.

comet of 1577 would the New Star, and Tycho, begin to have some impact.

Already in his publication on the New Star, Tycho suggested implicitly that comets might also turn out to contradict the Aristotelian view of the cosmos. His first chance to test this hunch proved every bit as interesting as he anticipated. The comet of 1577 was as bright as Venus and attended by a tail 22° long. It attracted so much attention as to seem almost made to order for Tycho's purposes. Of course, it guaranteed an audience for everyone else's opinion, too; and Tycho's experience with the literature on the New Star gave him a very good idea as to how closed-minded and muddle-headed those opinions would be, and how difficult it would be to prevail against them among a public who tended to share these intellectual handicaps. Accordingly, he seems to have conceived from the beginning a book considerably more ambitious than his ineffective work on the New Star – one that would stand out from its competitors in rigour, in detail, in sheer weight, if nothing else. And so he presented his findings in a detail that was unprecedented in the history of astronomy. Starting from observed distances between the comet and various reference stars whose coordinates he re-determined himself, Tycho painstakingly determined successive positions for virtually every one of the thirty non-cloudy nights of the comet's duration. He then rationalized these positions into a trajectory which he defined in both ecliptic and equatorial coordinates, by determining its intersection with and inclination to both the ecliptic and the equator. While his results are not especially interesting, his methods certainly are. For, by making – and reporting – seven trials of each element, rather than the single determination that any of his predecessors would have offered, Tycho inaugurated the modern scientific practice of using redundant data and admitting scatter in his results.

After ninety pages of preparatory computations the actual task of proving that the comet "ran its course high above the sphere of the Moon in the ether itself" was almost anticlimactic. Several of Tycho's determinations showed no parallax at all. But for reasons of candour and partly of hunch, Tycho chose for his most detailed presentation a determination that showed the comet to have been some four times as far away as the Moon, and generalized his various results to estimate a minimum distance for the comet of about 300 Earth-radii (five times as far as the Moon).

While Tycho was labouring over such aspects of his analysis as re-determining the coordinates of his reference stars, his contemporaries rushed to comment on the comet. By the time he was struggling to prove such things as his contention that through some kind of optical illusion, the tail of this comet appeared to be directed away from Venus rather than away from the Sun (Figure 1.3), well over a hundred publications had descended on the reading public of Europe. Relatively few of them were concerned with the questions that interested Tycho, and fewer still handled them with any kind of competence. If Tycho was to prevail against these odds, he knew he would have to make a special effort. Accordingly, he struck on the strategem that was probably to be responsible for the impact both of his book on the comet and of the great volume he subsequently published on the New Star – that of appending to his own analysis, critical reviews of the results of his competitors. Aggregating to a length exceeding the 200 pages of his own text, these reviews involved point-by-point analyses of the efforts of eight authors, and curt but reasoned dismissals of the results of eleven others. The principal goal, of course, was to expose the errors of those who had derived a measurable par-



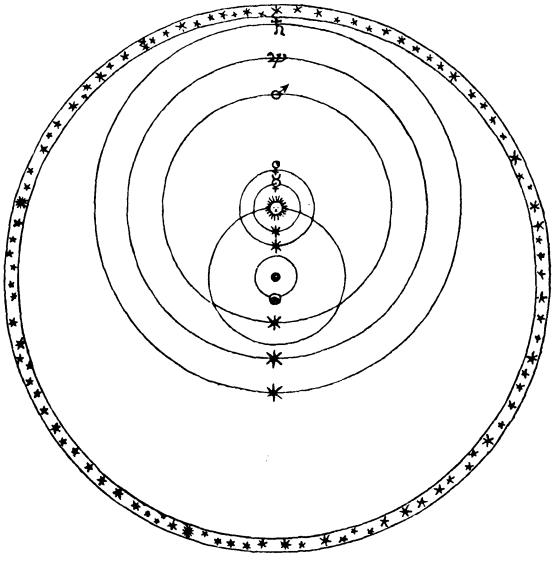
1.3. Tycho's placement in 1585 of the comet of 1577 in a geoheliocentric framework. Earlier Tycho had followed Apian and others in supposing that the tail pointed away from the Sun, but by 1585 his calculations were showing that the tail was directed opposite to Venus. Later still, as indicated in the text, he concluded that this effect was an illusion.

allax. But even those (such as Michael Mästlin) who had obtained results showing the comet to be above the Moon found their instruments, their observing procedures, and even their computations subjected to rigorous examination. And in the case of the Landgrave of Hesse-Kassel, who had neglected to derive any conclusions from his observations, Tycho converted the raw data into a minor treatise on the detection of parallax.

Tycho's arguments were finally circulated from his private press in 1588 as *De mundi aetherei recentioribus phaenomenis*. He contemplated but never completed another volume generalizing his result by means of observations of several succeeding comets. In fact, however, little room remained for intellectually respectable dispute concerning the astronomical – as opposed to meteorological – status of comets; and after the volume was officially published in 1603 and again in 1610, the issue was essentially settled.

The Tychonic system

Closely associated with Tycho's challenge to Aristotelian cosmology was a parallel challenge to the world systems of Ptolemy and Copernicus. As early as 1574, in guest lectures given at the University of Copenhagen, Tycho had expressed the ideal of avoiding both the mathematical absurdity of Ptolemy's equant and the physical absurdity of Copernicus's moving Earth. Nor was the ideal original with him. Already in the first generation after Copernicus, Erasmus Reinhold (1511–53) and Gemma Frisius (1508–55) had made statements that suggest that they understood fully the



1.4. The Tychonic world system. The Earth is at rest at the centre, encircled by the stars. The five planets orbit around the Sun, while the Sun and the Moon orbit around the Earth.

geometrical possibility of utilizing Copernican models for a geostatic cosmology. By 1578, Tycho's readings and ruminations on the subject had led him as far as the so-called Capellan system, with the inferior planets in motion around a revolving Sun: and by 1584 he had envisaged applying the conception to the superior planets as well. But in an age in which practically everyone believed that some kind of solid sphere carried each of the planets on its appointed rounds through the heavens, the resulting intersection of Mars's orbit with the Sun's (Figure 1.4) at first prevented Tycho from taking the scheme seriously. He was finally induced to so by the implications of the comet of 1577.

When Tycho first saw the comet, it was moving rapidly away from the Sun in the evening sky. After the first week the elongation increased less quickly, until, after reaching a maximum of almost 60°, it actually began to diminish again. During all this time the comet had progressively faded, suggesting that it was moving away from the Earth. These data virtually cried out for a (retrograde) orbit circling the Sun, and that is how Tycho accounted for them already in 1578 (Figure 1.5). This geometry could be used to deduce distances for the comet – distances (from the Earth) that ranged from a small fraction of the 1150 Earth-radii attributed to the Sun's 'altitude', to well above the Sun, when it finally disappeared. Only some years later, however, does Tycho seem to have realized that if the comet had thus gone right through the Ptolemaic spheres of Venus and Mercury, there could be no solid spheres, and no reason why the orbit of Mars could not intersect the orbit of the Sun.

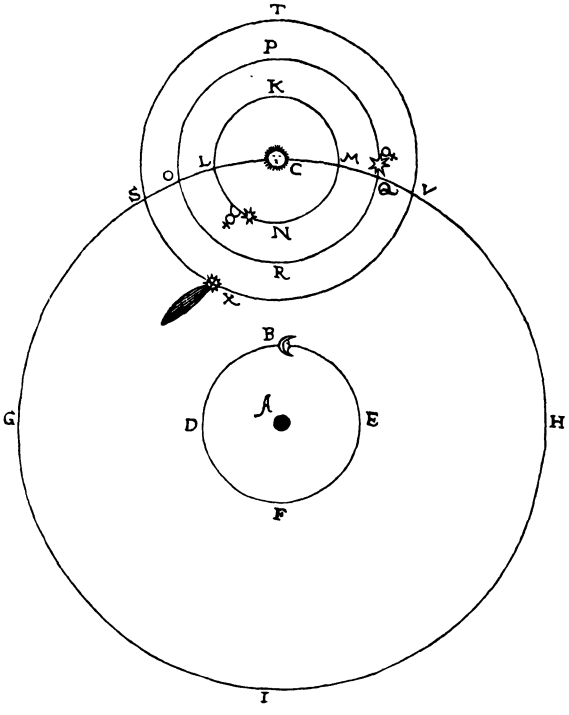
The Tychonic system was published in 1588, as a hastily inserted (eighth) chapter of *De mundi*. There can be little doubt that Tycho regarded it as his most significant achievement, and in the short term it surely was. As a geometrical equivalent of the Copernican system, it was capable of representing every aspect of the astronomical phenomena without demanding allegiance to a moving Earth, for which there would be no proof until much later. During the seventeenth century, therefore, after telescopic discovery of the phases of Venus and Mars rendered Ptolemaic cosmology untenable, professional favour tended to shift either to Tycho's scheme or to the so-called semi-Tychonic version of his disciple Longomontanus (1562–1647) and others involving a rotating Earth (see Chapter 3).

Tycho's conception of the rest of the physical world was, likewise, a sensible compound of tradition and innovation. For the most part, he subscribed to the account of its workings synthesized by Aristotle and adapted by medieval Christendom. But his studies of the (non-)parallaxes of comets led him to doubt either that there was any kind of sphere of fire just below the Moon (from which comets and meteors were supposed to be generated), or that the universe beyond the Moon was partitioned off by solid spheres into individual domains for each of the planets. For him, rather, the Aristotelian sphere of air extended essentially up to the Moon, thinning gradually from a thick layer filled with impurities (which produced refraction) up to a completely free aether-filled universe beyond the Moon. The planetary portion of this universe, of course, was essentially Copernican, even as far as scale, since Tycho retained through his lifetime the 3′ parallax adopted by Copernicus from the ancients. But the stellar portion remained Ptolemaic. Although Tycho could find no parallax for the stars, he had no doubt that they were situated just beyond Saturn. No small part of his unwillingness to consider Copernicanism stemmed from his

inability to imagine that God would have created a universe containing as much wasted space as was implied by the calculated Copernican distance to Saturn combined with the absence of stellar parallax. In addition, stars whose (pre-telescopic) angular diameters (1′ for third magnitude) implied quite reasonable sizes (four times the Earth's diameter for first magnitude) at a distance just beyond Saturn's, had to be 700 times as large, or comparable to the size of the Earth's *orbit*, if their parallax were as little as 1′. Tycho did not believe that all the stars were necessarily at precisely the same distance, however. He conceived of them as ordered in a thin shell, fixed into constellations and alignments that were still identical to descriptions given in Antiquity, but probably rotating axially to produce the phenomenon of scintillation.

Tycho's astrological views

So involved in his cosmology as to be virtually part of it was Tycho's attitude toward astrology. That the universe was an articulated unit created by God as a home for man was the foundation of Tycho's metaphysics. Again, it was a traditional theme strongly influenced by certain recent ideas due to Paracelsus (1493–1541) which linked man to the physical world even more closely than did Aristotle's doctrines. The notion that all aspects of the natural world were mutually interconnected provided Tycho with life-long motivation to elucidate the consequences of heavenly events and the effects of earthly substances on human beings. Experiments in medical alchemy earned him early recognition as an adept, and enabled him to dispense medications whose effects were highly valued and whose recipes were circulated long after his death. His investigations into the effects of celestial influences were less rewarding. Empirical attempts to relate weather to the cyclings of the planets induced him to record daily conditions for fifteen years, and circulate (under the names of two of his disciples) publications on weather forecasting in 1586 and 1591. Studies of the horoscopes of famous men proved even less instructive, and during his lifetime Tycho steadily lost confidence in the accuracy of 'personal' forecasts. The belief that the free will of an individual could counter astral influences assumed progressively greater prominence in his prognostications, and by 1587 was provoking Tycho to express serious reservations about the

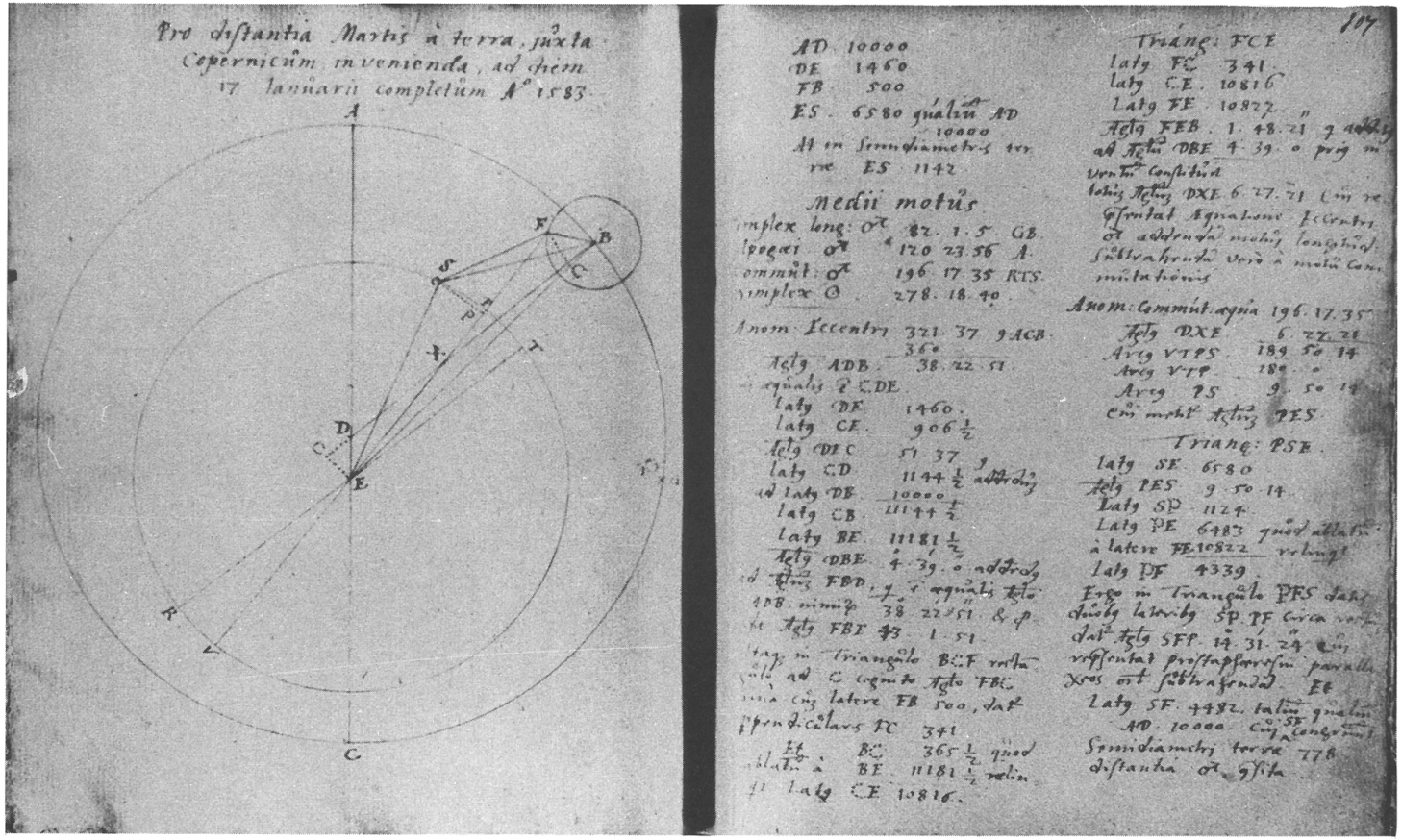


1.5. The comet of 1577 in relation to the inner bodies of the Tychonic system. Mercury, Venus, and the comet orbit the Sun, while the Sun and the Moon orbit the Earth.

whole horoscope enterprise. Yet Tycho could never quite shake off his feeling that in a created universe, the constituent parts would have to harmonize sufficiently to make some kind of astrological prediction possible. So, while the gulf between the intellectual allure of astrology and its operational value provided such mixed reaction that Tycho often managed both to denounce and defend it in virtually the same breath, his denunciations usually touched either the practice of the art or the state of the art, rather than the essence of the art itself. At bottom, he seems to have remained convinced that the weak link in the system was the science on which it was founded – astronomy.

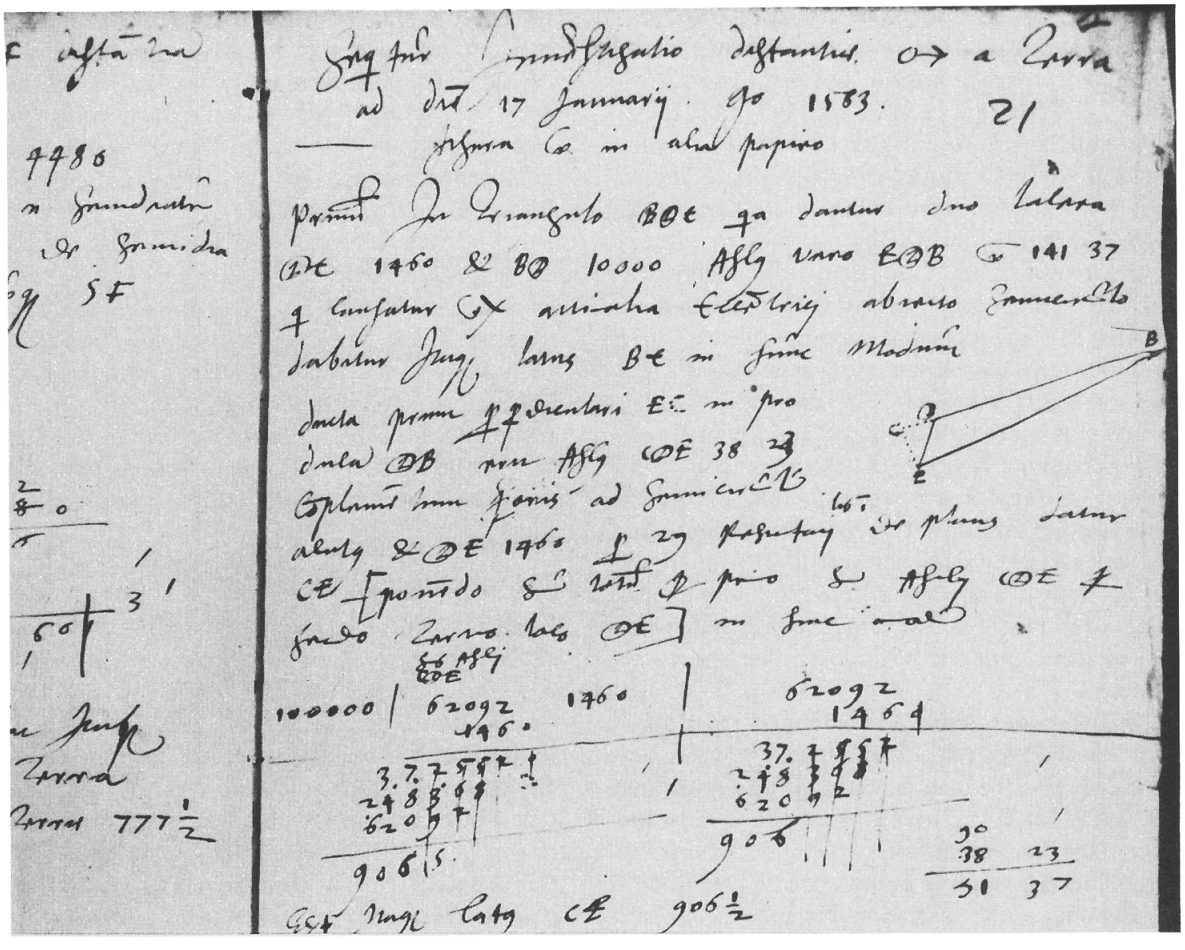
The renovation of astronomy

According to Tycho, the conviction that nothing less than a renovation from the ground up would solve the problems of technical astronomy was a product of his student days. Only with his enfiefment on the island of Hven at the age of thirty, however, was he able to begin serious progress



1.6. A diagram for determining, on the basis of the Copernican system, the distance of Mars from the Earth on 17 January 1583, with calculations in the hand of one of Tycho's assistants. The Earth–Mars distance (*SF*) is shown to be less than the Earth–Sun distance (*SE*); the same would be true in Tycho's geoheliocentric system.

According to Kepler (*Astronomia nova*, p. 64), Tycho often affirmed that from the observations of 1583 he had found the parallax of Mars to be greater than that of the Sun. But using Tycho's observational data Kepler found the parallax of Mars to be indetectable. He conjectured that Tycho's assistants had merely determined the Earth–Mars distance on the assumption of the Copernican system, as in the above diagram, and that Tycho had taken their result as a genuine empirical determination of parallax. But Kepler adds that he does not know whether this mistaken trust in his assistants' calculation was the sole basis for Tycho's pronouncement on the parallax of Mars.



1.7. In Tycho's own hand, calculations corresponding to the diagram in Figure 1.6. Thus, as J.L.E. Dreyer showed, Tycho cannot have been ignorant of the basis of the calculation performed by his assistants, and Kepler's conjecture is wrong. In his *Progymnasmata* (I, 414), Tycho states that with a very exact instrument, measuring to parts of a minute, he has diligently and precisely measured the parallaxes of Mars when in opposition, and that in a more convenient place he will set forth his results – a promise that was never fulfilled. The parallax of Mars when in opposition to the Sun can rise to about 23″, but for the solar parallax Tycho always retained the ancient value of 3′; hence his pronouncements concerning the Martian parallax must be judged to be without foundation.

towards this goal. And then it was nearly five more years (late 1580) before he moved into his still-unfinished home/observatory (Uraniborg), and began to see instruments issue from his shop. As the size and number of these instruments overflowed the space available in Uraniborg, he built a separate underground observatory named Stjerneborg in 1584. Still, the results were worth the wait. Prior to the establishment of his own shop, he had to depend on instruments designed by and commissioned from commercial artisans. They were good enough to ensure that his observations of the New Star and the comet were as accurate as any ever made in Europe – perhaps to within 4′, rather than the 10′–15′ which was the best most earlier astronomers had been able to achieve. (There are some exceptions: the mean relative error in Bernhard Walther's observations, made about the end of the fifteenth century, is about 5′, once the error in the position of the reference body is removed.) From his own facilities, however, he turned out a succession of instruments capable of measuring