

Chapter 2

Of Orbs and Orbits

*O World of Many worlds, O life of lives,
What centre hast thou? Where am I?
O whither is it thy fierce onrush drives?*

Wilfred Owen (1893–1918).
“O World of many worlds” (1913).

Event Awareness

Eclipses are always fascinating to watch. They are always beautiful, and sometimes awesome. As a bonus, they can provide invaluable information unobtainable in any other way. To fully exploit the scientific value of these events, or simply to enjoy watching them, we need to understand what is actually taking place.

Catching a celestial shadow is a matter of pure luck unless its time and place can be predicted beforehand. Besides simply knowing that the interacting bodies exist—that they are above our horizon in both senses of the phrase—our world view needs to accept them as truly physical objects, with the ability to emit, reflect and intercept light. Second, we have to predict the positions of these bodies, including their motion with respect to each other, because we need to forecast not only *whether* an event will happen but also where we need to be and when and where in the sky we need to direct our gaze. There is also the question of what sort of equipment we will need to be successful.

For Your Eyes Only

Before the telescope was first turned on the sky, the human eye was our only optical instrument. Observing any celestial body or event depended on our unaided visual acuity.

Eclipse events involve objects that move and, until the eighteenth century, there were just seven known—the Sun, the Moon, and the five bright planets. (Comets didn’t count since, though moving also, they were believed to be meteorological in nature.) There were only a limited number of events this small coterie of bodies could provide—eclipses of the Sun and Moon, or occultations of stars and planets

by the Moon. The rare transits of Venus across the face of the Sun, though also visible to the unaided (but safely shielded!) eye seen through mists and vapors near sunrise or sunset, could have been made out even in antiquity as a large naked-eye “sunspot” (and records of sunspots are plentiful, especially among the ancient Chinese). However, such an observation would have been a matter of sheer chance; the nature of the spectacle would have been unknown, and there is no evidence that a transit was ever observed in pre-telescopic times. Occultations by planets of naked-eye stars or of one planet by another also can occur; but even an assiduous watcher would be lucky to see one such event in their lifetime. (The most recent occultation of a first-magnitude star by a planet, of Regulus by Venus, occurred in 1959; the next, involving the same two objects, not until 2044.)

The passage of one planet in front of another is even more rare—only 11 have occurred since the invention of the telescope, and of all those, only one was actually observed, by John Bevis (1693/1695–1771), who watched Venus occult Mercury on 1737 May 28. We list the mutual planetary events that, as seen from Earth, take place between 1600 and 2200 in Table 2.1. The table shows that, as luck would have it, we are currently in a drought period for these spectacles; the last previous one took place in 1818 (Venus transited Jupiter), while the next such will be in 2065

Table 2.1 Mutual planetary events, 1600–2200

Date (Gregorian)	Dynamic time ^a (h)	Type of event	Elongation from Sun
1613 Jan 03	22.8	Jupiter occults Neptune	107° W
1623 Aug 15	17.1	Jupiter occults Uranus	009° W
1702 Sep 19	14.1	Jupiter occults Neptune	165° W
1705 Jul 20	23.6	Mercury transits Jupiter	015° W
1708 Jul 14	13.0	Mercury occults Uranus	025° E
1708 Oct 04	12.7	Mercury transits Jupiter	001° E
1737 May 28	21.8	Venus occults Mercury	022° E
1771 Aug 29	19.6	Venus transits Saturn	014° W
1793 Jul 21	05.6	Mercury occults Uranus	024° E
1808 Dec 09	20.6	Mercury transits Saturn	020° W
1818 Jan 03	21.9	Venus transits Jupiter	016° W
2065 Nov 22	12.8	Venus transits Jupiter	008° W
2067 Jul 15	11.9	Mercury occults Neptune	018° W
2079 Aug 11	01.5	Mercury occults Mars	011° W
2088 Oct 27	13.7	Mercury transits Jupiter	005° W
2094 Apr 07	10.8	Mercury transits Jupiter	002° W
2104 Aug 21	01.3	Venus occults Neptune	027° E
2123 Sep 14	15.5	Venus transits Jupiter	016° E
2126 Jul 29	16.2	Mercury occults Mars	009° W
2133 Dec 03	14.2	Venus occults Mercury	004° E

Source: Meeus 2002: 180–181

^aDynamic Time is based on planetary motions, rather than the more irregular rotation of the Earth. The difference between UTC and DT should be under 0.1 h during the period tabulated

(another transit of Jupiter by Venus). In addition, as Mercury and Venus are frequent actors in these dramas, many of them take place unobservably near the Sun.

In order to understand, and perhaps forecast, these celestial encounters one needs to appreciate that they involve physical bodies similar at least in some respects to those familiar to us. If celestial bodies are perceived as deities, spirits, or ethereal manifestations of some sort, they will be capricious and highly unpredictable. If, on the other hand, the Sun and stars resemble lamps, while the Moon and planets are opaque bodies like rocks or clouds, then we can well imagine that the two types of objects can interact in such a way as to produce shadows.

That the Moon, at least, is a tangible mundane object is easy to demonstrate to any person with a naturalistic worldview. Go out in the sunlight when the Moon, as well as the Sun, is visible. (Yes, the Moon is often visible in daylight!) Hold a round object, perhaps a marble, in line with the Moon. Note that the *phase*, the division between light and shadow, of the object in your hand is the same as that of the Moon. If you think this is a mere coincidence, try repeating the experiment on different days with different phases. Your observations will convince you that the Moon displays a sunlit portion and a shaded portion. But if the Moon can shade a portion of its own surface, we might equally expect it to cast a shadow and perhaps register the shadow of another body—the Earth for instance—falling across it. Now a member of a culture that sees a divide between the celestial and the terrestrial, in which both are subordinate to the supernatural, would be unlikely to make such an experiment in the first place, and even more unlikely to interpret it correctly if they did.

Long before we realized the physical nature of these mysterious, moving celestial objects (*planets*, or “wanderers” in Greek), ancient cultures such as the Sumerians and Chinese recorded their movements and their phenomena—visibility periods, conjunctions and eclipses. The Greek philosopher Anaxagoras (*ca.* 500–428 BCE) is credited with asserting that the Moon is illuminated by the Sun, which explains its phases; also that solar eclipses are caused by the Moon’s shadow, and that lunar eclipses happen when the Moon passes into the Earth’s shadow. Subsequently, he went even further—and a step too far for his more conservative contemporaries. He proffered that the Sun was a fiery mass of rock somewhat larger than the Peloponnesus. But the doctrine was deemed impious, and led to his banishment from Athens (Dicks 1970: 58–59).

In trying to uncover who was the first to provide physical explanations for the nature of celestial bodies, we are profoundly handicapped by the fact that so few ancient sources survive. We know the beliefs of many authors only at second or third hand. (If you are a teacher, imagine that future generations might know of your views only from the garbled and uncomprehending notes of your students!) As a matter of fact, even the birth and death dates of many ancient philosophers are uncertain. Given these limitations, historians of science consider either Parmenides (*ca.* 512–450 BCE) or Empedocles (*ca.* 493–433 BCE) as the first person to assert that the Moon is visible by the reflected light of the Sun (Dicks 1970: 52, 54).

Though Anaxagoras’s views shocked his contemporaries, they were already rather blasé by the time of Aristotle (384–322 BCE), who went so far as to assert that all the celestial bodies were spherical (Dicks 1970: 203). This was only a lucky

guess; though often true, or at least a rather good approximation, Aristotle would have had no way of knowing this for any body other than the Moon. Before the telescope, the Sun could have been—as it was for the Egyptians in the time of the “heretic” Pharaoh Akhenaten—a bright disk always turned toward the Earth, while the stars and planets were simply irresolvable points of light.

The Alexandrian astronomer Ptolemæus, who lived in the second century CE and was roughly contemporary with the Roman emperor Marcus Aurelius, produced a distillation of the results of classical astronomy, in which he added a further guess: the disks of the planets and stars have finite size. He attempted to measure them with the sighting instruments that were then available, and grossly overestimated them. His angular diameters were rather too large for the planets, but they were fantastically so for the stars! (Van Helden 1985: 24–25, 51). Nevertheless, his error was not entirely unproductive. By assigning to the planets a real size, Ptolemæus first entertained the idea that Mercury and Venus—being either beyond or below the Sun; he thought below—might occasionally pass between the Earth and the Sun, and so appear in transit (Ptolemæus 1998: 419). Along with other astronomers whose observations he used, he clearly believed the planets to be finite, opaque objects, which could occult stars. (In the case of supposed occultations involving Venus, Mars, and Jupiter, the reported events were illusions caused by the eye’s limited resolving power—they involved the apparent merging of two close objects, not the actual covering of one by the other. The latter is observable only telescopically.)

Tracking the Wanderers

Whatever the seven wanderers might be, it was obviously useful to be able to predict their movements. It is most essential in the case of the Sun, whose annual course determines the seasons, times of planting and harvest, the rainy seasons, the rising of the Nile. The Moon’s cycle of phases is also a helpful timekeeper, providing a natural timescale shorter than the year and longer than the day. The religious calendars of many societies (including our own; consider Easter) depend on celestial movements, while all seven *planets* (Sun, Moon, Mercury, Venus, Mars, Jupiter and Saturn) were assigned astrological roles.

The most direct approach to determining the courses of the wanderers is to observe them over time and note periodicities in their movements. The 24-h diurnal cycle is obvious, the basic natural unit of time. (And, for all practical purposes, regarded as completely constant until clocks became more accurate even than the Earth’s rotation near the turn of the twentieth century.)

The Moon traces out its path in synodic months (also known as *lunations*), which refer to its phases, and hence to the Sun; or in sidereal months, which refer to movement relative to the background stars. Watching the Moon’s motion for just a few months (of either sort) leads to one of our most fundamental discoveries—nature was not evidently designed for our convenience, since neither synodic nor sidereal months contain an even number of days.

Perhaps nature was not designed for our convenience, but to make us better mathematicians. Accepting this awkward incommensurability, we can count the days for a sufficient number of months and still arrive at a good estimate of the *mean* length of a synodic month. (The *mean* month, because no 2 months are exactly the same length.) By the Hellenistic era, Hipparchus was able to calculate a mean length of 29 days 12 h 44 min and $3\frac{1}{3}$ s for the synodic month. This was a tremendous achievement at the time; his result was just 0.4 s longer than the modern value (Sarton 1959: 299).

Moving on to the year, here defined as the tropical year or year of the seasons, we can expect that its length will also be inconvenient. So it is. Again, Hipparchus' value was very good, at 365 days 5 h 55 min 12 s just a bit over 6 min too long by modern standards. (By the way, the Classical-Hellenistic Greeks did not use minutes or seconds for time. Nor did they employ decimals. They used fractions instead. Thus Hipparchus expressed his result as $365 + \frac{1}{4} - \frac{1}{300}$ days.) (Evans 1998: 209).

There are other cycles, also known in antiquity, that are useful for predicting eclipses. The Chaldeans (*ca.* Sixth Century BCE) used, but probably did not discover, a period of 223 synodic months (6585.32 days or 18.029 years) between similar eclipses, whether of the Sun or of the Moon. The modern term for this period is the *saros* (Evans 1998: 316). That annoying leftover one-third day means that two successive eclipses of the same saros will usually not be visible from the same place on Earth. (Although you might see the end of one lunar eclipse and then see the beginning of another in its saros 18 years later.) After three saros periods (54 years and 1 month, called an *exeligmos* in Greek), another eclipse will be seen from the same part of the Earth. Obviously, since solar and lunar eclipses occur far more often than every 18 years, multiple saros cycles are operative at a given time. For example, during the 2000–2025 CE period, no fewer than 40 lunar, and another 40 solar, eclipse saros cycles overlap. (Tallied by Westfall from Espenak and Meeus 2009a: A-161–A-162 and Espenak and Meeus 2009b: A-161–A-162.)

Simply by making use of the saros and other cycles, the Chinese and perhaps the Maya of Central America (who more cautiously gave “eclipse warnings” rather than definite predictions) were able to forecast eclipses. The Chinese may have begun recording solar eclipses as far back as 2137 BCE, but their predictions were often wrong as they never developed a theory of solar motion (Mitchell 1924: 1, 5). Perhaps there is some truth, then, in the old story of the unfortunate court astronomers, Hsi and Ho, supposed to have been beheaded by the Emperor for failing to predict an eclipse.

The art of eclipse prognostication became much more reliable when celestial geometry was taken into account. An eclipse not only can, but *must*, take place when both Sun and Moon are sufficiently near the two critical points in the sky, the lunar nodes, where the paths of the Sun (the ecliptic) and the Moon cross. If the Sun and Moon (at new phase) are both close enough to the same node, a solar eclipse occurs. If Sun and Moon (at full phase) are close enough to opposite nodes, we have a lunar eclipse. (“Close enough” is as much as 18° for solar eclipses and 19° for lunar eclipses; by way of comparison, the Bowl of the Big Dipper spans only 5° .)

By carefully tracking the distance of the two bodies from the fateful intersections of the nodes, predictions become much better. Not only does one rarely either miss upcoming eclipses or forecast ones that never happen, one can pinpoint the dates of these events, and even time of day. A study of Chaldean eclipse predictions made during roughly 700–1 BCE shows that, of 40 predicted lunar eclipses, most happened somewhere on Earth. Of the 61 predicted solar eclipses, all of them actually took place. (Naturally, only a fraction of those eclipses would have been visible from Babylon, but the astronomers can't be faulted for that.) As for event times, predictions of the lunar eclipses were typically accurate to 1 h, the solar eclipses within about two (Steele 1997: n.p.). (Note that it's easier to predict a lunar eclipse than one of the Sun because the former takes place simultaneously wherever the Moon shines; geographical position doesn't affect the event—nor is there any reason it should since, after all, it is taking place on the Moon. A solar eclipse, however, is caused by the Moon's shadow racing across the face of the Earth, and the shadow strikes different places at different times. This makes predicting such events much more difficult—so much so that few astronomical historians credit the legend that one of the “Seven Wise Men of Greece,” Thales of Miletus, in the Sixth Century BCE, predicted the total eclipse of 585 May 28 BCE, which supposedly interrupted a battle between the Lydians and the Medes. Viewing this ill omen, the combatants apparently decided to pick up their war implements and go home. If Thales made a prediction for that date, he was just praeternaturally lucky.)

The Universe in 3-D

So far, we have been considering the sky as two-dimensional, with its objects moving upon or across the concave surface of the dome of the sky. Watch the Moon long enough, however, and one notices it can pass in front of other celestial bodies. It follows that they must be more distant than our satellite. Again, noting that the planets move against the stars, it is logical to suppose that they must be rather closer than the stars, while, since the planets move at different speeds across the sky, the faster bodies are presumably nearer to us than the slower ones.

These observations lead us to consider a three-dimensional model of the movements of the Sun, Moon and planets. Such a model is necessary if we wish to predict not just special events like eclipses, but the positions of these bodies for any chosen time, past, present or future.

Interpreting liberally his statements about celestial “whorls” in the *Republic*, we might credit Plato (*ca.* 427–347 BCE) with the invention of the geocentric model of the universe. The outermost “whorl” or sphere holds the “Fixed Stars”; then, located successively inward, come the spheres of Saturn, Jupiter, Mars, Mercury, Venus, the Sun, and finally the Moon (Dicks 1970: 109–114). Other philosophers, such as Plato's sometime pupil Eudoxus of Cnidus (*ca.* 408–355 BCE), moved some of the spheres around relative to one another (Dicks 1970: 177–179) to produce a result that might have been similar to that shown in Fig. 2.1. By the time of Aristotle,

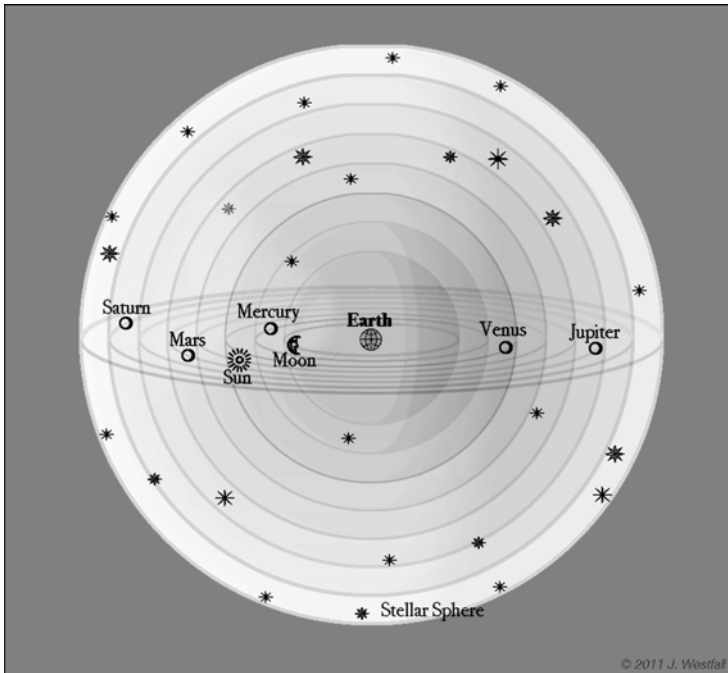


Fig. 2.1 One interpretation of the earth-centered universe of concentric spheres described (vaguely and ambiguously) by Plato and modified by Aristotle in the fourth century BCE. Note the central Earth, with the seven *planets* in a plane, circling around it (Diagram by J. Westfall)

Venus's sphere had ended up just inside the Sun's, and Mercury's was situated between those of Venus and the Moon. The three planets "above" the Sun, Mars, Jupiter and Saturn, became known as *superior planets*, while the two "below" the Sun, Venus and Mercury, were known as *inferior planets*. The spherical Earth, suspended in the midst of space, sat motionless in the center of the eight concentric spheres. Not only was the Earth without a motion of translation, but also it couldn't rotate, which meant that all the spheres around it had to turn, at varying speeds, in order to produce the observed motions relative to the fixed stars and to each other (Dicks 1970: 196–202). For example, the Sun's sphere rotated once in 24 h (the solar day), that of the stars in 23 h 56 min (the sidereal day), and the lunar sphere in about 24 h 50 min. Also, it was stipulated that each sphere had to rotate with uniform circular motion. The last requirement, doctrinaire though it seems to us today, was faithfully carried over to later, more complicated, models for centuries.

As we watch the sky over the space of a year or two, this simple model unravels. Mercury and Venus oscillate on either side of the Sun, and never stray far from it. Mars, Jupiter, and Saturn move eastward over the long term, but periodically stop and then loop backward to the west (i.e., move retrograde) for a while until they return to their regular eastward courses. Figure 2.2 shows an example of a retrograde

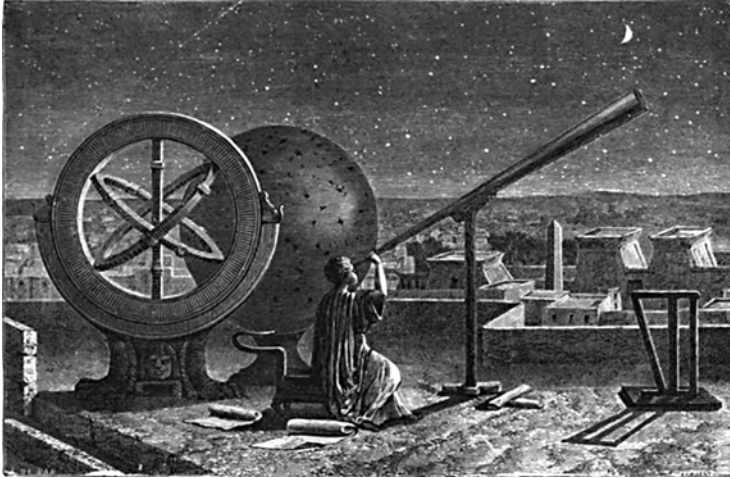


Fig. 2.3 A widely reproduced nineteenth-century engraving said to show Hipparchus, who, we hope, is looking through a hollow viewing tube (used to exclude scattered light) and not through an actual telescope, eighteen centuries too early! An armillary circle, used to determine celestial coordinates, stands behind him. We must point out, though, that Hipparchus was born in Nicaea (in modern Turkey) and apparently lived and observed in Rhodes, not Egypt (Figuier 1877: f. p. 284)

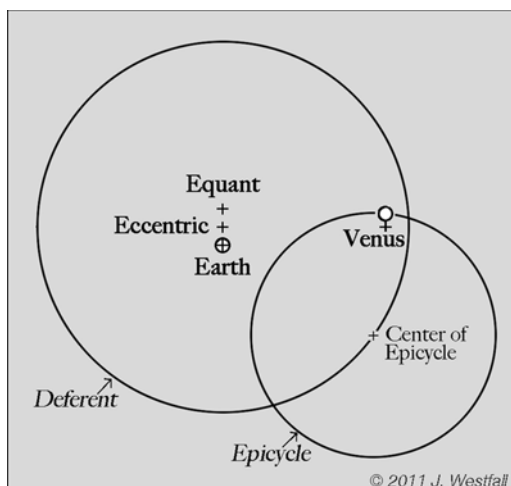
Hipparchus created a mathematical model of the motions of the Sun, the Moon, and planets, which apparently was worked up into a mechanical model, for there appear to be Hipparchan resonances in the remarkable Antikythera mechanism, found in a wrecked ancient ship discovered in 1900 by sponge fishermen off the coast of Antikythera, between Kythera and Crete. The wreck contains vases in the style of Rhodes, suggesting the ship was en route from Rhodes, where Hipparchus is known to have been active, when it sank, and has been dated from the first century BCE—i.e., the century after Hipparchus' time. The Antikythera mechanism is the most complex computing device we know from antiquity; it consists of at least 30 interlocking metal gear-wheels used to compute and display the motions of the Sun, Moon, and planets. Some of the wheels appear to be firmly based on Hipparchus' theory of the motion of the Moon. Thus, one wheel moves around once every 9 years, the period in which the Moon's perigee—the point of its orbit closest to the Earth—completes one complete swing around the Earth. To this wheel are fixed a pair of small wheels, one almost centered on the other; the bottom wheel has a pin sticking up from it which pushed the top wheel around, and because the two wheels are not exactly centered, the pin moves back and forth and causes the movement of the upper wheel to speed up and slow down, just as the Moon actually does. The device could have been used to predict the times of eclipses. Since the Antikythera mechanism lay on the bottom of the sea for over two millennia, it is in a rather degraded state, but a number of plausible reconstructions have been proposed, and it remains the subject of active research (Marchant, 2009).

Much of what we know of Hipparchus' work we must infer from the *Almagest* of Ptolemæus, written three centuries later. Though standing on the shoulders of his predecessors, Ptolemæus was a clever mathematician in his own right. As the last great proponent of the geocentric system in ancient times, the latter has come to be known as the Ptolemaic System (Jeans 1948: 91–93).

In the Ptolemaic system each planet, including the Sun and Moon, moved uniformly around the center of a circle called the epicycle. In turn, the center of the epicycle swept around a larger circle called the deferent. So far as this went, Ptolemæus was just following the scheme of earlier astronomers, dating back to the third century BCE. However, Ptolemæus needed two more complications to satisfy the planetary observations available in his time. First, he centered the deferent not on the Earth, but on a point called the eccentric, and he also made the *rate* of angular motion uniform not on the center of the eccentric but about another point, the equant. We needn't go into all the details here. As a calculating device, Ptolemæus's scheme was rather marvelous, but obviously it honored the principle of uniform circular motion more in the breach than in the observance, and displaced the Earth from being the physical center of anything, as shown in Fig. 2.4 (Crowe 1990: 32–44). Still, it was as far as the ancient Greek tradition in astronomy could go; when Ptolemæus died, the classical tradition was clearly exhausted. The geocentric model—with epicycles and deferents—was set to reign unchallenged for over a thousand years.

It is rather hard to believe that anybody actually believed in the physical reality of this model. Its physical reality, however, was a secondary consideration; the important point was that it “saved the phenomena”—it served to reproduce the apparent motions of the Sun, Moon and planets, and in its highly refined form, did so to the accuracy of the instruments of the day. Serious problems remained; for instance, the model forecast a far greater variation in the Moon's distance (and

Fig. 2.4 The working components of the “Ptolemaic” Solar System, developed by Hipparchus, for the planet Venus. The planet moves with constant speed along its epicycle, with the epicycle itself moving along its deferent. The deferent is centered, not at the Earth, but at its eccentric. The epicycle of Venus moves uniformly about its equant, rather than its eccentric. The epicycle and deferent are drawn to scale (Diagram by J. Westfall)



hence its apparent diameter) than was actually observed, and also it didn't do very well in predicting the brightness changes of the planets, particularly of Mars. But we must give credit where credit is due, and admit that it was good enough to furnish useful predictions of lunar and solar eclipses and of occultations of stars and planets by the Moon. It could also predict conjunctions of the planets with each other and with the fixed stars, though it wasn't accurate enough to predict true occultations of stars by the planets—though no one at the time would have been aware of this, as the planets' disks are at best at the very limit of, or smaller than, what the unaided eye can resolve.

The Sun Takes Center Stage

Though it has been fashionable (at least as far back as the thirteenth-century King Alfonso X of Spain) to ridicule the Ptolemaic system as a “crank machine,” it was certainly ingenious, and above all *it worked*. Admittedly, the calculations required to predict planetary positions were tedious, but they were well within the capability of ancient and medieval mathematics to handle. Indeed, the coefficients involved—quantities such as the radii of deferents and epicycles—were refined during the Middle Ages by Muslim astronomers, while the laboriousness of the calculations was mitigated by the publication of tables, such as the *Toledan Tables* (compiled by Gerard of Cremona, 1114–1187) (Evans 1998: 400–401) and the widely used *Alfonsine Tables* (published at the behest of the aforementioned Alfonso X *ca.* 1270) (Gingerich 1992: 61–62). With such tables in hand, one need simply add up table entries to obtain planetary positions.

Then too, prior to the invention of the telescope, there was no way to prove the geocentric approach wasn't correct. A fixed Earth was intuitively correct. Likewise, were the Earth off-center, and thus in motion, to the stars ought to show an annual parallax (or else be unimaginably distant), and none was observed.

Still, some implications of the geocentric system were rather odd. Why did those annoying retrograde loops require epicycles for every superior planet when they could all be explained in a single stroke by letting the Earth, our point of observation, provide the motion? Likewise, as it was recognized that the visible universe was far larger than the Earth, wouldn't it be more economical for the Earth to be in rotation (provided, of course, that it could remain fixed in position) rather than the entire Universe be turning at enormous velocity?

The counterproposal, that the Earth could move and perhaps also rotate, had early roots. As early as the Fifth Century BCE, the Pythagorean School held that the Earth and other planets moved about a central fire (but not the Sun) (Dicks 1970: 65–66). Martianus Capella (Fifth Century CE) had Mercury and Venus circling the Sun, but the Sun itself, with the superior planets, circling the Earth (Crowe 1990: 130). Much earlier, Aristarchus of Samos (*ca.* 310–230 BCE) had placed the Sun at the center of a complete Solar System, and given the Earth both a rotational motion on its axis and an orbital motion about the Sun (Jeans 1948: 88–89).

Notwithstanding these developments, throughout both ancient and medieval times the geocentric universe remained dominant. The swing away from the old system began only with the publication of the *magnum opus* of Nicolas Copernicus, which its author held in his hands only on his deathbed. Although this tome, *De Revolutionibus Orbium Coelestium* (On the Revolutions of the Celestial Orbs) initiated the demise of the earth-centered universe, geocentricism struggled on for a century and a half, supported by the authority of the Church, even though staggered by successive blows from Galileo and Kepler. It finally received the *coup de grâce* from Isaac Newton (1643–1727) (Jeans 1948: 124–134).

Copernicus's heliocentric idea was not entirely new; it had been advanced long before, notably by Aristarchus, but the musings of its advocates had survived only in brief second- and third-hand paraphrases. Copernicus's tome presented a fresh angle of attack, explaining the concept at length, and including the mathematics needed to apply it. Though formally much of the Copernican system resembled the Ptolemaic System—it came into the world swaddled in the same old deferents, epicycles, eccentrics and equants. But the decisive step had been taken: the Sun had been moved to the center of the Universe, and this had the profound result of making the Earth a planet and, reciprocally, the planets bodies more or less like the Earth.

The Sun-centered model was more elegant than its predecessor in two ways. First, retrograde motion became a natural consequence of the model. It was now the result of the Earth's annual circuit about the Sun rather than of a planet's motion in its main epicycle. Second, Mercury and Venus, whose motions had always posed severe problems for the geocentric system—they required giant epicycles to make them oscillate about the Sun, which implied enormous geocentric distance variations and changes in brightness changes far greater than any seen—could now be treated in more straightforward fashion. In the Copernican Model, the two inferior planets always moved inside Earth's orbit, and swung naturally back and forth from side to side of the Sun (Crowe 1990: 96–101).

Despite these simplifications, predicting planetary movement the Copernican way required calculations of the same lengthy and tedious sort as had the Ptolemaic. An early convert, Erasmus Reinhold (1511–1553) reduced Copernicus' mathematics to tabular form, publishing the *Prutenic Tables* in 1551 (Evans 1998: 422). Ironically, Reinhold's Copernican tables proved only slightly more accurate than the old, geocentric-based, *Alfonsine Tables* (Gingerich 1992: 128). Clearly, more work was needed, both to convert the doubters and to forge a model that could more accurately describe the courses of the Moon, the Sun (whose course was now reframed as a reflection of the motion of the Earth), and the Sun-circling planets.

An Elliptical Path

A better solar-system model needed better observations as well as a fresh approach. There was no Hipparchus on the scene, a single person able to provide both. This time the observations and the theory were furnished by two separate persons.

The observations were the contribution of a Danish nobleman, Tycho Brahe (1546–1601). (For more detail, see Chap. 9.) Tycho supplied the more accurate data of planetary movements needed as the basis of a better theory. An avowed anti-Copernican (at least in part because he could not believe the stars could be as large as Copernicus’s views implied), Tycho contrived his own system, in which the planets did indeed revolve about the Sun, but the Sun itself revolved about the Earth! He had his faults, but observationally, he was without a peer. His talents were recognized by the Danish king, who granted him an island, Hven in the Öresund (between modern Denmark and Sweden), for his estate, and from the magnificent observatory Tycho set up there he recorded stellar and planetary positions, whose errors averaged under a minute of arc. They were an order of magnitude more accurate than any Ptolemæus possessed (Jeans 1948: 134–137).

Proving a better astronomer than landlord, Tycho eventually abandoned Hven, and after an unsettled period landed in Prague as the Imperial Mathematician of the Holy Roman Emperor Rudolf II. In 1600 Tycho encountered the young Johannes Kepler (1571–1630). Kepler was a brilliant mathematician, of a moody, and rather mystical, temperament, and left with weak eyesight from an early attack of smallpox. Tycho invited Kepler to Prague to serve as his assistant, but only grudgingly—and on a need-to-know basis—shared with him his precious observations of the positions of Mars. For years, Kepler labored over the Mars data, a process he called his “war with Mars.” Considering both the different lengths of our seasons and the small but measured annual variation of the apparent size of the Sun, Kepler realized that our distance from the Sun varies, as does the Earth’s velocity in its orbit. Likewise, the velocity and solar distance of Mars fluctuate. Going further, he found that each planet’s angular rate of motion was inversely proportional to its distance from the Sun. This relationship, implying that *the line between a planet and the Sun sweeps out equal areas in equal times*, is now known as Kepler’s second law, even though it was the first discovered. (We hasten to point out that Kepler himself did not refer to laws at all. The term “Kepler’s laws of planetary motion” was first introduced by Voltaire only in the eighteenth century.)

Kepler required several more years to decide upon the *shape* of Mars’s orbit. It was, by the way, fortuitous—or providential, as Kepler himself would have said—that Tycho had assigned him to work on the motion of Mars, since whatever shape one takes for its orbit, it is clearly not a circle.

The way that Kepler plotted Mars’s orbit is spelled out in detail in his book. He first applied a most useful corollary of the Copernican system—if the Earth moves, its different positions at different times can be used as triangulation stations (Gingerich 1989: 59–69). Here’s how this works. Suppose we observe Mars’s position, then wait 687 days and measure its position again. Since 687 days is the sidereal period of the planet about the Sun, Mars will have returned to the same position in space. Yet the Earth will not be where it was before, because 687 days is not a whole number of 365-1/4-day years. We now plot out our two sightlines, taking into account Earth’s location at the two dates. Mars will then lie at their intersection. Repeating the process for different pairs of dates, the members of each pair separated by 687 days, we lay out a series of Mars-points around the Sun, and trace out

TRIANGULATING THE ORBIT OF MARS, 2012 - 2015

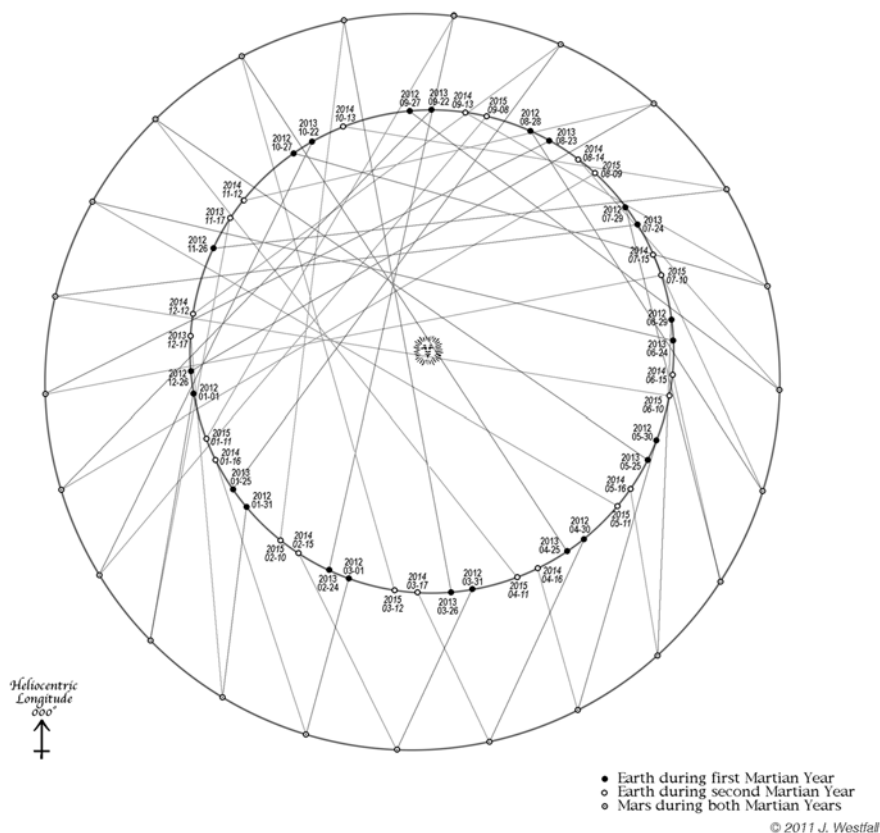


Fig. 2.5 How Kepler said that he determined the elliptical shape of Mars' orbit from Tycho's sightings. (Some claim that he found the elliptical shape by other means, and then plotted the Mars measures to fit.) Here, the triangulation method is applied to Mars' direction as seen from the Earth at 30-day intervals from 2012 to 2015. The geocentric direction of Mars is drawn from 2012 Jan 01 to 2013 Oct 22. Then the process is repeated, starting one Mars year (687 days) after 2012 Jan 01—from 2013 Nov 17 to 2015 Sep 08. This results in 23 pairs of sightlines intersecting at 23 positions of Mars, tracing out an ellipse (Diagram by J. Westfall)

the form of its orbit as shown in Fig. 2.5. Note that to do all this we have to know the Earth's changing heliocentric position, both as an angle (expressed in celestial longitude along the ecliptic, measured from the March Equinox) and relative distance (which Kepler took to average 100,000 arbitrary units—decimals were not yet in vogue, so large integers were frequently used in trigonometry). We also have to know the sidereal period of Mars, but that was easily computed from its synodic period (the apparent period as seen from Earth) and the length of Earth's year.

Kepler could see that this was an oval of some sort, but the exact form eluded him. He kept trying different ovals, but nothing quite worked. At one point, he even

confided to a friend, David Fabricius, just how easy things would be if the orbit were the mathematically simplest oval, the ellipse, which had already been discovered (along with the other conic sections—circle, parabola, and hyperbola) by Menaechmus (*ca.* 380–320 BCE) and was addressed in a celebrated treatise on the subject by Apollonius of Perga (*ca.* 262–190 BCE). He repeated the calculations time and time again. Eventually, in a sudden flash of insight, it dawned on him that the shape truly was an ellipse after all, with the Sun in one focus. The result held true not only for Mars, but also for the other planets, and is now known as Kepler's first law of planetary motion: *each planet moves in an ellipse with the Sun at one focus*. Both of Kepler's "laws" first appeared in the manuscript of his book, *Astronomia Nova*, which he finished writing in 1605 (but, owing to lack of funds, it was not actually published until 1609).

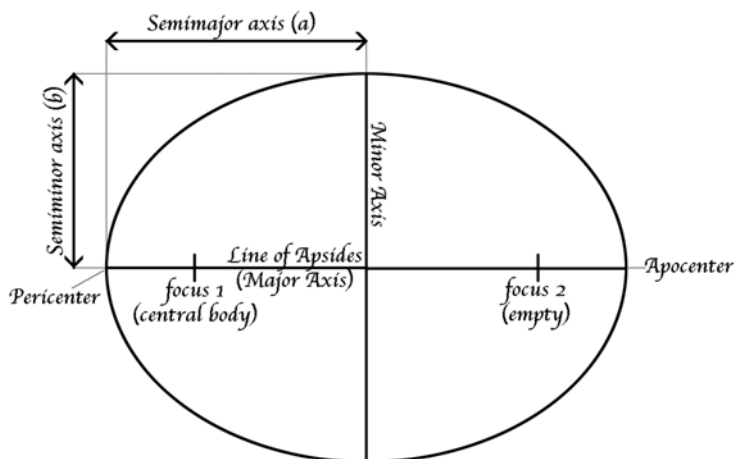
Whereas we can completely describe a circular orbit by its radius, the position of its center, and the spatial orientation of its plane, pinning down an ellipse is more complicated. The various elements of a Keplerian orbit are as shown in Fig. 2.6. Analogous to the circle's radius, the ellipse has a major axis, its maximum dimension, and an eccentricity, a measure of its degree of flattening or ellipticity. (An eccentricity of 0.0 defines a circle; as the eccentricity becomes larger the ellipse becomes more elongated, and with an eccentricity of 1.0 the ellipse turns into a parabola—an open-ended figure.) Also, instead of a single center, as in a circle, an ellipse has two foci, one of which is occupied by a body like the Sun or a planet and the other of which is vacant (Green 1985: 162–164). (Note that a circle is in fact a special case of an ellipse in which the two foci coincide in a single point.)

Four other quantities, each determined by the major axis and the eccentricity, can be defined for any ellipse. The minor axis is the narrow dimension of the ellipse; the semimajor axis is simply one-half the major axis; the pericenter the closest point to the central body (if it's the Sun, the term is perihelion); while the apocenter is the farthest point (aphelion when orbiting the Sun) (Green 1985: 162–164).

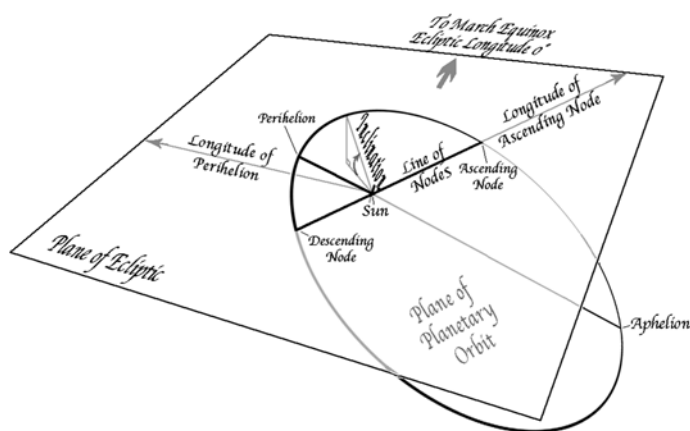
Just as with a circle, an ellipse lies in a plane, whose specific orientation in space needs to be defined. For every orbit in the Solar System except the Earth's, the orbital plane has a tilt, or inclination, to the Earth's orbital plane (the plane of the ecliptic). The line in space where the two orbital planes intersect is called the line of nodes, whose orientation is defined by the ecliptic longitude of the ascending node, the point on the orbit where the body crosses the plane of the ecliptic, moving from south of the ecliptic to the north. The final angle we need to specify an elliptical orbit is the orientation of the major axis in space, which is defined by the ecliptic longitude of perihelion. All of these are readily identified in the figure.

In addition, in order to calculate the planet's position for any time, we need to know the period it takes to complete each circuit of the Sun. The sidereal period is the period in reference to the stars, the synodic period that relative to the Sun as seen from Earth. The relationship of the sidereal period to the semimajor axis was the subject of Kepler's third law (or harmonic law), published in 1619—the *square of the orbital period of a planet is directly proportional to the cube of the semimajor axis of its orbit* (Jeans 1948: 167).

THE ELLIPSE: SIZE AND SHAPE (UNIVERSAL EXAMPLE)



THE ELLIPSE: ORIENTATION (SOLAR-SYSTEM EXAMPLE)



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Fig. 2.6 The various Keplerian elements of two ideal elliptical orbits. (*Upper*) This ellipse could be anywhere in the universe, depending which central body lies at the first focus. The ellipticity of the ellipse is equal to the difference between the two axes (major minus minor), divided by the major axis. (*Lower*) An elliptical orbit within the Solar System, showing angular relationships. The plane of the ecliptic is the plane of the Earth's orbit, usually the standard for spatial orientation (Diagram by J. Westfall)

Knowing the values of a planet's orbital elements, plus an actual position of a planet at a specified date (*epoch*), we can both plot its orbit and predict the positions and movements of the planet as it moves around it. By way of example, in Fig. 2.7 we have plotted the orbits of the three innermost planets—Mercury, Venus and the Earth—while in Table 2.2, below, we provide the mean elements of the eight major

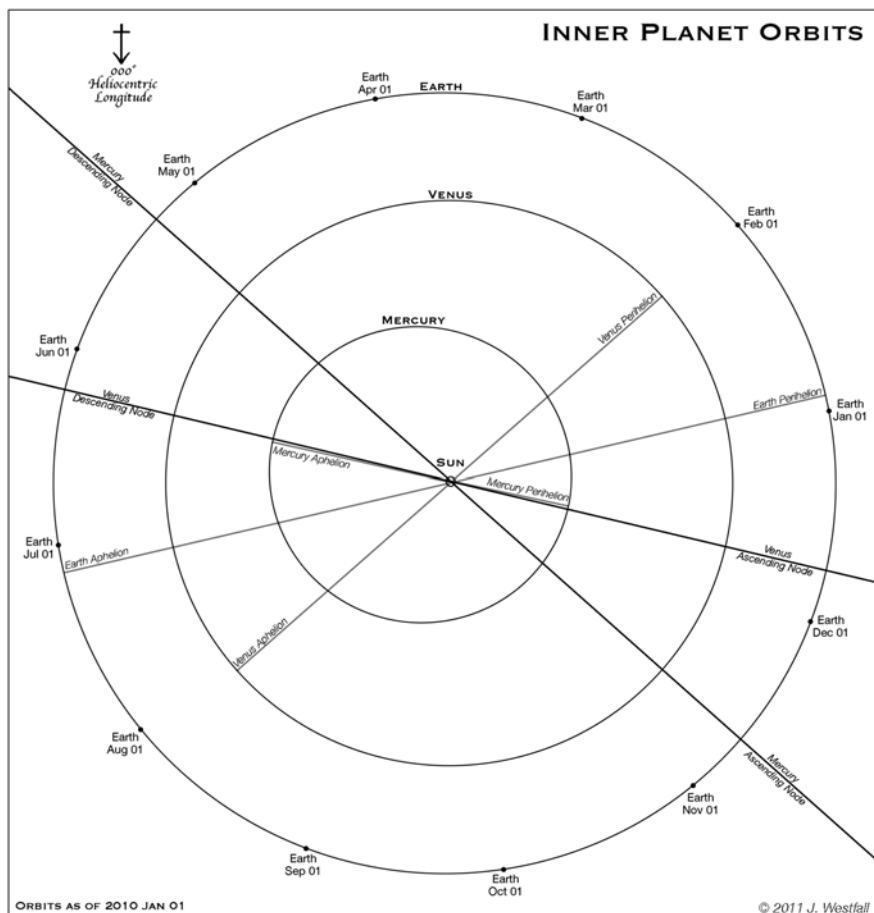


Fig. 2.7 The heliocentric orbits of the three inner planets drawn to scale and seen from the north, including their lines of nodes (connecting their ascending and descending nodes) and lines of apsides (connecting their perihelia and aphelia), with the position of the Earth at monthly intervals. The orbits are drawn to scale but those of Mercury and Venus are projected onto the plane of the ecliptic (Venus's orbital inclination is actually 3.4° and that of Mercury is 7.0°) (Diagram by J. Westfall)

planets of our Solar System, the first dwarf planet, Pluto, and of our own Moon. Why the *mean* elements? Sadly, as hinted earlier, even an ellipse does not perfectly describe the motion of an actual planet. An elliptical orbit would perfectly reproduce the orbit of an object only in the ideal case, where the object is infinitesimal in mass, orbiting a spherical central body, and the two bodies alone in the Universe (and also, we would need to ignore General Relativity). If you look up the orbital elements of the planets in a source such as the annual *Astronomical Almanac*, you will find a table of osculating elements (literally, “kissing” elements), the elliptical elements that describe a planet’s motion at a specified moment in time.

Table 2.2 Mean orbital elements of selected solar-system bodies (epoch 2000.0)

Element	Mercury	Venus	Earth	Mars	Jupiter
Semimajor axis (au)	0.38710	0.72334	1.00000	1.52371	5.20289
Eccentricity	0.20564	0.00678	0.01671	0.09339	0.04839
Inclination (°)	7.00498	3.39468	−0.00002	1.84969	1.30440
Longitude of ascending node (°)	048.33077	076.67984	–	049.55954	100.47391
Longitude of perihelion (°)	077.45780	131.60247	102.93768	336.05637	014.72848
Sidereal period (Julian years)	0.38710	0.72333	1.00000	1.52368	11.85653
Synodic period (days)	115.8775	583.9214	–	779.9361	398.8840
Element	Saturn	Uranus	Neptune	Pluto	Moon
Semimajor axis (au)	9.53668	19.218916	30.06992	39.48212	0.00257
Eccentricity	0.05386	0.04726	0.00859	0.24883	0.05490
Inclination (°)	2.48599	0.77264	1.77004	17.14001	5.14540
Longitude of ascending node (°)	113.66242	074.01693	131.78423	110.30394	125.12395
Longitude of perihelion (°)	092.59888	170.95428	044.96476	224.06892	083.18635
Sidereal period (Julian yr)	29.42352	83.74741	163.72320	248.0208	27.32166d
Synodic period (days)	378.0919	369.6560	367.4867	366.7207	29.53059

Sources. Planets, excluding periods: Jet Propulsion Laboratory, Solar System Dynamics 2011a, 2011b. Planetary periods and eccentricity for the Moon: Seidelmann 1992: 704. The Moon, excluding eccentricity: United States, Nautical Almanac Office 1999: D2

Notes: Even mean elements change over time, but current values can be found at the JPL website (see above), and in the most recent *Astronomical Almanac* or *Observer’s Handbook* of the Royal Astronomical Society of Canada. The quantities for the Moon change particularly rapidly, and the eccentricity and angular values are given here as examples only. The Moon’s quantities refer to its orbit around the Earth, rather than around the Sun; note that both its sidereal and synodic periods are given in days. The au, or astronomical unit, is 149,597,870.7 km; for practical purposes the mean distance of the Earth from the Sun

The Solar System Takes Shape

Not surprisingly, the early modern scientific community did not unanimously or immediately embrace the Copernican–Keplerian hypothesis—such major paradigm shifts take time. The fixed stars continued to appear, well, *fixed*, implying that the Earth was fixed as well. A number of other developments were required to dislodge our world from the center of things. One of the developments was the publication of Isaac Newton’s *Philosophiae Naturalis Principia Mathematica* (“*Principia*”—*The Mathematical Principles of Natural Philosophy*) in 1687. Here, Newton demonstrated that any object in orbit about a central body, subject to the inverse-square law of gravitational attraction, would necessarily trace out a conic section; were its orbit closed this would necessarily be either a circle (implying a perfect balance of velocity and gravitation) or, more generally, an ellipse (Newton 1995: 50–55).

For some time after Newton the stars continued to appear unmoving, implying a universe that was either geocentric or awfully big. James Bradley (1692–1762), the second Astronomer Royal at the Greenwich Observatory, sought to detect stellar parallax with a vertical telescope of unprecedented precision. In 1729, he detected motion—but in the wrong direction. Indeed, the stars followed ellipses with a 1-year period and, as one would expect for parallactic motion, those on the ecliptic oscillated along lines and those at other celestial latitudes traced out ellipses. But they were wobbling the wrong way—clockwise north of the ecliptic and counter-clockwise to its south—while parallactic motion should do just the opposite. Worse yet, every star moved the same amount. Were the stars all at exactly the same distance, a reversion to the stellar sphere of ancient times? The solution came to Bradley in a moment of inspiration—the apparent direction of a star was displaced by the combination of the motion of starlight (be it waves, particles or whatever) and our own motion. Naturally the shift due to this phenomenon, called aberration, was small—the Earth is moving far more slowly than light itself—but due to the gradually greater refinement in celestial measurement, it was now within reach. (The modern value for the constant of aberration is 20.5 arc sec, about one-third of the limit of Tycho’s accuracy of slightly over a century earlier.) This newly discovered effect could only be explained by Earth’s motion (Maunder 1900: 75–79).

After Bradley, it was very hard to argue against Copernicanism, and the more accurate measurement techniques also showed that, not only did the Earth move about the Sun, but the distance between the two bodies varied in just the annual pattern that it would if the Earth were moving in a Keplerian ellipse. The ultimate proof came with the detection and measurement of the annual parallaxes of the stars Alpha Centauri, Vega and 61 Cygni in the 1830s (Clerke 1902: 35–37).

The Copernican–Keplerian model, now embraced by the astronomical community, combined with improved instruments and mathematical techniques, led to ever-better ephemerides. In 1705, Edmond Halley (1656–1742), who realized that at least some comets move in elliptical paths, predicted the return of Comet 1682 (now Comet P1/Halley) in 1758, adjusted to late 1758–early 1759 in his posthumous *Astronomical Tables* (published in 1749). The German farmer-amateur astronomer Johann Georg Palitzsch (1723–1788) spotted the object on Christmas Eve, 1758, a triumphant demonstration of the predictive powers of the new science of celestial mechanics (Gingerich 1992: 149–151; Yeomans 1991: 111–139). A generation later, the discovery of the first new planet in history, Uranus, was made during a systematic survey of the skies by William Herschel—no celestial mechanics involved. The ongoing succession of minor planet discoveries, commencing in 1801, was also the result of sky surveys or, in some cases, pure serendipity. However, the discovery of Neptune, the eighth planet, in 1846, was made possible by the prediction of closely agreeing positions calculated independently by John Couch Adams (1819–1892) and Urbain Jean Joseph Le Verrier (1811–1877), based on the suspected planet’s perturbations of the motion of Uranus. The model of planetary motions developed by Copernicus, Kepler and Newton, refined and elaborated by the computations of generations of their successors, predicted not only the movement of known celestial bodies but led to the discovery of a hitherto unknown one.

Seeing the Universe with New Eyes

The science author Willy Ley (1906–1969) described three eras of astronomy—naked-eye, telescopic and spaceflight (Bonestell and Ley 1949: 55–56, 95). Tycho’s work was the high-water mark of the first era, while the career of Kepler straddled the transition between the naked-eye and telescopic eras (indeed, despite having poor eyesight himself, Kepler applied his knowledge of optics to invent a form of eyepiece that we still use today). A necessary tool in the improvement of celestial mapping was the telescope, invented by one (or more) of a group of claimants in the first decade of the 17th century, and first turned to the sky in 1609. The increasingly greater accuracy of celestial measures was due to the telescope’s ability to magnify. But this phenomenon of enlargement, combined with the new instrument’s capability to gather more light than the unaided human eye, meant, not only that previously known objects would appear bigger and brighter, but that objects yet unknown would be brought into human ken (Bell 1981: 10).

Galileo Galilei (1564–1642) was not, it seems, the first scientist to turn this new device to the sky. A few months before Galileo observed, Thomas Harriot (*ca.* 1560–1621) in England had sketched a rough telescopic lunar map (Whitaker 1989: 120–123). But Galileo had a better telescope and experience in drawing and (rather hurriedly) published his findings in his famous *Sidereus Nuncius* (“Starry Messenger”; March 1610), thus becoming the true inaugurator of the telescopic era. During a single week—January 7–13, 1610—the Italian observer detected and then monitored four “stars” circling the planet Jupiter, concluding they must be planets in their own right, circling the giant planet just as the planets (including Earth) circle the Sun. (It was Kepler, by the way, who introduced the term “satellites” for these bodies.) With these four new objects, the first new bodies recorded since history began, Galileo inaugurated the process of “inventorying” the Solar System (Débarat & Wilson 1989: 144). The task continues even today.

Galileo was a committed Copernican, and the heliocentric hypothesis was significantly strengthened by the discovery that objects could circle a body other than the Earth. A few months later, he was able to further rattle the Ptolemaic universe. The orthodox geocentric model placed the planet Venus “below” the Sun—oscillating between the Sun and the Earth—which would cause it to perpetually exhibit a crescent phase. Yet, as the planet rose higher into the evening sky during summer and fall, 1610, Galileo witnessed it at nearly full phase. Of course, the placement of the planet in the geocentric solar system was somewhat arbitrary—were it “above” the Sun, then it would always show a gibbous or full phase. Yet, as 1610 drew to a close, Venus grew in size, as it was expected to have done even according to the Ptolemaic system; but then it diminished to half phase in mid-December, before becoming a waning crescent. Indeed, Venus eventually passed through all the phases that our moon does. As there was no way the geocentric system could place Venus *both* below and above the Sun, Venus provided yet another victory to the Copernican system (Gingerich 1992: 98–104).

The lens of Galileo's telescope was a single piece of glass, and single-element lenses have the inherent problem of producing fuzzy images, blurred by spherical and chromatic aberration. The latter was the more serious fault, due to the lens's inability to bring light of different wavelengths to a common focus. Both problems could be alleviated by increasing the focal length of the lens, and so, during the century after Galileo, telescopes increased in length even more rapidly than their lenses increased in diameter, leading to awkward behemoths sometimes scores of meters in length (Bell 1981: 11–19).

Another way around the problem of lens aberrations was a totally new design, a telescope using one or more mirrors rather than a lens. James Gregory (1638–1675) proposed one form of reflecting telescope in 1663, but never built it, while Isaac Newton came up with a more convenient scheme and, beginning in 1668, produced at least three working models (Bell 1981: 19–22). For various reasons, not least that mirrors were long made of easily tarnished speculum metal, the reflector was slow to be adopted, however, and did not become fully dominant until the twentieth century. Meanwhile, experiments were made with achromatic lens designs using two components of different forms of glass. Such a refracting telescope was designed and commissioned by an English lawyer and amateur mathematician, Chester Moor Hall (1704–1771) in 1733 but the invention was not immediately taken up by others (Bell 1981: 27–28). It took another quarter-century before achromats began to replace the unwieldy “long refractors” in the form designed, patented (1758) and manufactured by Hall's countryman, John Dollond (1706–1761) (Bell 1981: 28–30).

The subsequent 250 years of telescope development can be summarized as instruments growing ever larger (thus increasing both their light-gathering and resolving power), yet made more efficient in use by means of equatorial mountings to follow diurnal motion, leading ultimately to computer-operated mountings. In the last third of the nineteenth century photographic plates began to replace the human eye at the telescope, and about a century later electronic sensors rapidly replaced chemical photography. The last great refracting telescope was the 40-in. (1.02-m) of Yerkes Observatory, installed in 1897 (Andersen 2006: 34), unless one counts the short-lived horizontal 1.25-m refractor of the 1900 Paris Exposition (Manly 1991: 180–182). Subsequently, reflectors soon became dominant as was clear by 1908 with the “first light” of the 60-in. (1.52-m) Mount Wilson reflector (King 1955: 330).

As earth-based instruments were growing ever larger and more efficient—they are now mostly located on mountaintops and armed by CCD (charge-coupled device) or CMOS (complementary-metal-oxide-semiconductor) sensors—the third era of astronomy began with the images of the “back side” of the Moon that were returned by the unmanned Soviet *Luna-3* spacecraft in October 1959. Since then, the manned American *Apollo* expeditions circled and landed on the Moon (1968–1972), while several nations have launched scores of unmanned probes that by now have investigated several comets and asteroids close-up, along with all the major planets from Mercury to Neptune, including many of their satellites.

Space probes have not replaced telescopes, which continue to grow and develop, while more and more instruments (including telescopes) are being placed in earth orbit. The parallel developments of earthbased and orbital telescopes, along with

Table 2.3 Inventory of the Solar System; number of objects with known orbits

Date (January 1)	Planets	Natural satellites	Asteroids	Periodic comets	Total objects
1600	5	1	0	0	6
1650	5	5	0	0	10
1700	5	10	0	1	16
1750	5	10	0	1	16
1800	6	14	0	5	25
1850	7	16	13	12	48
1900	7	22	463	30	522
1950	8	31	1,568	61	1,668
2000	7	69	62,428	162	62,666
2010	7	170	229,914	217	230,308
2013	7	182	382,394	295	382,878

Notes: The Earth and Sun are not included and Earth's Moon is included under natural satellites. Comets that are also listed as asteroids (five currently) have been considered as asteroids only; in addition, several periodic comets have either disintegrated or have failed to be recovered at their predicted returns—the actual count of all extant or extinct periodic comets, as of January 1, 2010, was 232. Also, starting in 2000, the “dwarf planets,” including Pluto have been counted as asteroids. The eight satellites of dwarf planets have been included, but not the approximately 300 known satellites of asteroids

Sources: Asteroids, 1850–1950—Cunningham 1988: 28

Asteroids, 2000 and 2010—International Astronomical Union, Minor Planet Center 2011, 2013

Periodic Comets—Yoshida 2011, 2013

Satellites—Yeomans 2012

planetary probes, have led to an exponential growth in the number of known objects. Equally significant in relation to predicting and interpreting eclipse phenomena, the number of objects with accurately known orbits has grown over time—the greater the number of bodies with known paths, the more opportunities for predictable eclipses, transits and occultations. Table 2.3 shows the staggering increase, since the invention of the telescope, in the number of solar-system objects whose orbital elements have been pinned down well enough to predict eclipse events.

Among these numerous objects, two of the planets and some of the asteroids and comets can at times transit the Sun, while planetary satellites can be eclipsed or occulted by each other or by their parent planet, which they can also transit. Any objects near the ecliptic will sometimes be occulted by our Moon. Moreover, all the bodies on the list are potential occulters of stars. There is a surfeit of potential eclipse events to watch for, and literally no end to the work that is to be done.

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