2

Earth-Centered World Views in Classical Europe

Two major world views predominated in early European astronomy: the geocentric model, which placed the Earth in the center of the universe, and the heliocentric model, which placed the Sun in the center. There also were hybrid models where some of the planets revolved around the Sun, but the Sun and its retinue and possibly some of the other planets revolved around the Earth (the so-called geoheliocentric world view). All of the stars and even God's heaven surrounded the central Earth or Sun, and there was no real separation between our Sun and planets and the rest of the universe until the 17th Century.

From most of this time, the geocentric world view predominated. In this chapter, we will consider its development in Classical Europe.

2.1 GREEK WORLD VIEWS

2.1.1 Early Greek Philosophers

Writing around 800 BC, Homer viewed the Earth as a flat, circular disk that was surrounded by a great river, Oceanus, which flowed back into itself and produced the other rivers of the world via subterranean channels. Over the Earth was the hemispheric vault of the heavens; below it was the hemispheric vault of hell, Tartarus. According to this view, after the stars and other heavenly bodies set in the west, they floated around Oceanus back to the east, where they rose again the following evening.

Other Greek world views were proposed by Ionian philosophers from the town of Miletus, which set the tone for later Greek thinking. The earliest of these philosophers was Thales (c.624–c.547 BC), who excelled in astronomy, mathematics, politics, and business.

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He described a 365-day year, wrote about the solstices and equinoxes, and predicted a solar eclipse that took place in 585 BC. For him, the primary element was water, from which came the other elements: earth from condensation, air from rarefaction, and fire from heating. He viewed the Earth as a flat disk or cylinder floating on water.

For Thales's student, Anaximander (c.611–c.546 BC), the primordial element was not water or any other known element found on Earth. It was a substance he called the Infinite, from which arose, evolved, and passed away an infinite number of worlds. Our cosmos formed when a hot sphere formed around the cold Earth and separated into rings of fire, becoming the Sun, Moon, and stars. Each of these rings was surrounded by compressed and opaque air with a single circular vent, through which shined the enclosed fire, producing the appearance of a round heavenly body. These rings revolved around a central cylindrically shaped Earth. Some of them were oblique to our planet's axis, forming an area later called the ecliptic. Anaximander thought that the distance to the Moon was about 19 Earth radii and to the Sun about 27 Earth radii.

Anaximenes (c.585–c.528 BC), who was an associate of Anaximander, put air as the primary element, on which was supported a flat Earth. Moisture that arose from the Earth became rarefied, becoming fire and producing the Sun, Moon, and stars. Most of the stars were fixed in place and were seen as being attached to a crystalline sphere. A few were observed to independently float freely on the air. These were the so-called "wandering stars" that had been known since ancient times: Sun, Moon, and five naked eye planets (Mercury, Venus Mars, Jupiter, and Saturn). Anaximenes also proposed the existence of additional dark bodies floating in the heavens that sometimes came between us and the Sun or Moon, accounting for eclipses.

Empedocles of Acragas (c.490–c.444 BC) postulated that there were four primary elements (earth, water, air, and fire) and that all matter was made from their various combinations. He viewed the heavens as being crystalline and somewhat egg-shaped, with the fixed stars being attached to its inner surface. Within this crystalline body revolved two hemispheres, one with fire that was daytime and one with air that was night-time.

Another influential philosopher was Anaxagoras (c.500 BC–c.428 BC), who was born near what we now call Smyrna but later moved and worked in Athens. The famous classicist Sir Thomas Heath credits him with the "epoch-making discovery" that the Moon shines by reflected light from the Sun.[1] This allowed him to correctly propose the mechanisms for solar and lunar eclipses (although he also thought that dark bodies sometimes came between us and the Moon to produce a lunar eclipse). It also allowed him to place the Moon (which he thought to be an Earth-like body, with plains, mountains, and ravines) closer to us than the Sun. He conceived that the world was formed by a vortex in space. In this process, an inner region of air, which through consolidation produced the Earth, was separated from an outer region of rarefied substance called "aether". The whirling action of the aether tore stones from the Earth up into the heavens through centrifugal force and produced the heavenly bodies. The Earth itself was visualized as a flat body that was supported by the surrounding air, and the Sun, Moon, planets, and stars were on fire and were carried around by the revolving aether. Anaxagoras thought that by this same process, there were other worlds that were formed in the universe and that these were inhabited by beings similar to us.

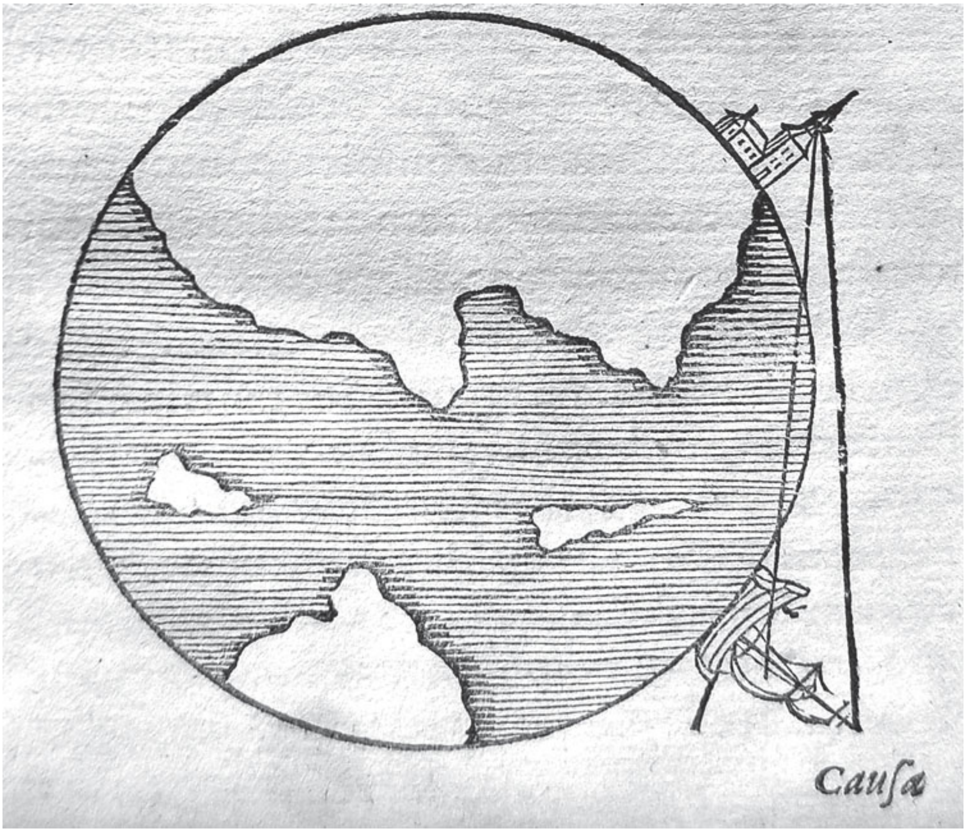

Figure 2.1. An illustration of the sphericity of the Earth, from the 1647 Leiden edition of Sacrobosco's *De Sphaera*. 15.2 × 9.7 cm (page size). Note that it shows how a light in a tower can be seen sooner by an observer at the top of the mast of a ship than someone on the deck, thus proving that the Earth is spherical in shape.

2.1.2 Pythagoras and His Followers

The perception of the Earth as a flat or cylindrical body with a relatively flat surface changed with Pythagoras, who was born around 572 BC on the island of Samos, just off the coast of Ionia. He traveled to Egypt and Babylon, where he is said to have learned mathematics and science. He settled in southern Italy around 535 BC, where he founded his famous school and died around 500 BC.

Pythagoras has been credited as being the first person to view the Earth as a sphere (Figure 2.1). He also thought that the universe was spherical in shape and that the finite heavens revolved around a stationary and central Earth; beyond was a limitless, empty void. He wrote that the planets had motions that were independent from the stars and that the bright "morning" star and "evening" star were the same body (i.e., the planet Venus), ideas he likely learned from the Egyptians or Babylonians. Finally, Pythagoras thought that there was harmony in the universe, both in terms of the sounds that the wandering stars made as they moved along their orbits and in terms of the ratios of their distances from each other, which were similar to the ratios of the notes on a musical scale.

Pythagoras's ideas were very influential, and it is difficult to know for sure which ideas were developed by him and which were developed by one or another of his students. One such student was Parmenides of Elea, who was active around 500 BC. Like Pythagoras, he saw the Earth as being spherical, and he recognized the morning/evening nature of Venus. But unlike the master, he did not believe in the existence of an infinite void, and he thought that the movement of the heavenly sphere was an illusion.

In the 5th Century BC, successors to Pythagoras developed the idea that the Earth was not the center of the universe but was a revolving planet like the others. The center was occupied by a central fire (the "Watchtower of Zeus"), near which revolved a "counter-Earth" and other unseen bodies. These were always positioned below the horizon and thus could not be seen because the Earth itself rotated on its axis in the same time as it took for it to revolve around the central fire. From the center outwards beyond the Earth revolved the Moon, the Sun, the five known planets, and the sphere of fixed stars. Outside of this finite spherical universe was the infinite void.

2.1.3 Plato

Plato was born around 427 BC and died around 347 BC in Athens. Early in the 4th Century BC, he founded his famous Academy, which was devoted to philosophical research and teaching. His writings contained a number of ideas about astronomy (see especially the *Timaeus* and the *Republic*) and were influenced by Pythagoras.

The Platonic system describes a universe made by a single Creator (sometimes called the "demiurge") who, wishing that all things should be good and perfect, created a blueprint for an orderly and harmonious universe imbued with a cosmic intelligence or soul. In contrast to this perfect world of ideas, our corporeal reality is but a finite and changing reflection of this ideal that consists of four imperfect elements: earth, water, air, and fire. The heavenly sphere is pictured as revolving from east-to-west around a large, spherical, central and immobile Earth. The Sun, Moon, and planets are carried around with the heavens, but in addition each moves in its own circular orbit from west-to-east. The area of the sky in which the Sun, Moon and planets move (i.e., the ecliptic, which contains the zodiac constellations) is called the circle of the Different. This area is obliquely inclined to the area of the sky that represents the equator of the sphere of the fixed stars; this is called the circle of the Same.

In his world view, Plato pictured the Moon as being closest to us, followed in order by the Sun, Venus, Mercury, Mars, Jupiter, Saturn, and lastly the sphere of fixed stars,[2] as shown in Table 2.1. Anaxagoras and many Pythagoreans before Plato likely adopted the same order, as did Eudoxus, Aristotle, and many early Stoics after Plato.[3] This ordering was based on several factors: solar eclipse observations that suggested the Moon moved in front of the Sun; the fact that the Moon occulted not only the stars but also the planets, suggesting that it was close to the Earth; the observation that Mercury and Venus never strayed too far from the Sun in terms of angular separation; and the principle that planetary

Table 2.1. Geocentric World Systems: Planetary Order.

PLATO and his contemporaries	MACROBIUS and other Neoplatonists	PTOLEMY, Late Stoics, Pliny the Elder, Muslims, Byzantines, Middle Age and early Renaissance Europeans
Earth is at the center of the universe and is often shown as four elements: Earth, Water, Air, Fire Moving concentrically out from the Earth are spheres with the following (in order):		
Moon	Moon	Moon
Sun	Sun	Mercury
Venus	Mercury	Venus
Mercury	Venus	Sun
Mars	Mars	Mars
Jupiter	Jupiter	Jupiter
Saturn	Saturn	Saturn
Bounded fixed stars	Bounded fixed stars	Bounded fixed stars
Additional spheres correct the system (e.g., for precession) and include the Primum Mobile. In the Christian Era, God and His retinue are in the last sphere.		

distances were correlated with the time it took for each to return to the same point in the zodiac, so that those with the longest tropical periods (and slowest speed with reference to the background stars) were judged to be the farthest away.[4]

Plato's cosmology was very influential, in two ways. First, his geocentric description of the universe was picked up by later philosophers, such as Aristotle and Ptolemy, whose modified versions led to the model used throughout Islamic and Byzantine lands in the Middle Ages and in Europe during the early Renaissance. Second, his view of a single Creator of the universe was popular with the later Christian clergy, who could point to him as an example of a Classical Greek philosopher whose views of creation were similar to those espoused by the Christian Fathers.

2.1.4 Eudoxus

Eudoxus was born in Cnidus around 400 BC and died around 347 BC. He had attended lectures by Plato but made his own major contribution to Greek astronomy. Although Plato's system accounted for the movement of the planets along the ecliptic from west-to-east, it did not account for the fact that the planets periodically became stationary with reference to the stars, then made a retrograde motion (i.e., went from east-to-west), became stationary again, and then continued with their normal motion in the sky.

To solve this problem, Eudoxus produced a geometric model of four concentric spheres moving at the same speed around a central Earth to describe each planet's movement. The rotation of the outermost sphere accounted for the movement of the heavens from west-to-east. The next innermost sphere rotated around an axis perpendicular to the plane of the ecliptic and accounted for the planet's basic east-to-west movement. The third sphere and fourth sphere (which carried the planet) were oriented in different planes depending on the specific planet being modeled. The combined motion of the third and fourth spheres made the planet move in a figure-of-eight curve through the sky called a "hippopede" (thought by most historians to be named for the shape of the shackles that were placed on the legs of horses to restrain them, although Dreyer states that the term was based on the figure produced by riding school horses while cantering[5]). Combined with the second sphere, this reproduced the stationary and retrograde movements of the planet. Eudoxus also described the motions of the Sun and Moon but used a simpler system of three concentric spheres.

Eudoxus's world illustrates two characteristics that were to become typical of Greek astronomy: the creation of speculative geometric models for explaining the movement of heavenly bodies (which may or may not represent reality but still managed to "save the phenomena") and the testing of these models through the use of observation and principles of spherical geometry.

2.1.5 Aristotle

Aristotle was born in 384 BC in Macedonia, where his father was the physician to the king. At the age of 17, he went to Athens and studied for two decades at Plato's Academy. After Plato's death, Aristotle went to Asia Minor, where he founded his own academy, then was summoned by King Philip of Macedonia in 342 BC to tutor his son, Alexander (the Great). After Philip conquered Greece in 338 BC, Aristotle moved back to Athens, where he founded his Lyceum. Throughout his life, Aristotle wrote essays on various aspects of philosophy, and he articulated an influential cosmology that he described in his treatises *On the Heavens (De Caelo)* and *Metaphysics*. He died in 322 BC.

Like Plato, Aristotle hypothesized a geocentric cosmos with a large, spherical, and immobile Earth surrounded by a spherical universe. But unlike Plato, who believed that reality existed not in the world of the senses but in the world of ideas, Aristotle promulgated a more physical universe that could be understood and described through observation and logic. He minimized the role of a Creator and tried to understand nature in purely natural terms, but he believed that a "Prime Mover" was responsible for keeping the heavenly spheres in motion.

Aristotle viewed that part of the universe below the sphere of the Moon as being changeable and corrupt and composed of the elements of earth, water, air, and fire, which could intermix and transform into one another. These elements had tendencies to move in a straight line, with earth moving strongly downward, water weakly downward, air weakly upward, and fire strongly upward. Comets and meteors were produced in the hot and dry fiery realm. Beyond this region were the unchangeable heavenly bodies, each of which was embedded in a sphere. The bodies and spheres were all made of aether, a crystalline-like substance that was smooth, pure, changeless, and divine. Objects made of aether had a tendency to move in a circle. Being continuous and without beginning or end, the circle (or its three-dimensional counterpart, the sphere) was seen as the most perfect form, which was appropriate for the heavens. This universe contained everything; beyond the sphere of the stars was nothing.

Like Eudoxus, Aristotle tried to account for the movement of the heavenly bodies through a system of revolving homocentric spheres. But unlike his predecessors, who devised models based on mathematics, Aristotle transformed his world view model into a mechanical system, where material spherical shells physically acted upon one another. Fifty-five shells were needed, some moving the planets forward, some allowing them to retrograde, and some neutralizing or decoupling the effects of one planetary sphere to allow another to move independently. The ordering of his planetary shells around the central Earth essentially followed that of Plato (see Table 2.1).

2.1.6 Eratosthenes and the Alexandria Library

Eratosthenes was born around 276 BC in Cyrene. He studied in Alexandria, Egypt, and in Athens, acquiring a name for himself as a scientist, mathematician, geographer, historian, poet, and philosopher. He wrote treatises in many of these areas. Although never the best in any field, he was nicknamed "beta" (after the second letter of the Greek alphabet) by his colleagues, since he was usually the second best in everything he studied. Consequently, around 235 BC, he was summoned to become the head librarian of the famous library in Alexandria, one of the world's major centers for literary scholarship and scientific studies. He maintained his post as head librarian until his death around 195 BC.

Eratosthenes devised an ingenious method of finding the circumference of the Earth by measuring the angle of the shadow made by the Sun with reference to a vertical pole in Alexandria at the time it was high noon in Syene (where there was no shadow cast). The angles was about seven degrees (or 7/360 of a circle) and, since the distance between the two cities was known, he could calculate the total circumference of the Earth. His value was close to our modern value.

2.1.7 The Eccentric Model

Given their expertise in spherical geometry, the Greeks discovered that movements in the sky could be modeled in two ways that still allowed them to adhere to the basic assumptions of their philosophically perfect heavens; that is, the Earth was at the center of the universe, and heavenly bodies moved with constant speed in perfectly circular paths around the Earth. The first model was to place the center of the sphere carrying an orbiting body away from the Earth, making it eccentric. This worked well to describe the motion of the Sun. For example, it was well known to the Greeks that the time from the autumnal equinox to the spring equinox (a little over 178 days) was shorter than the time from the spring equinox to the autumnal equinox (187 days). How could one model this observation (i.e., save the phenomena)?

The solution was to theorize that the Sun went around the Earth in an off-center eccentric orbit. This is illustrated in Figure 2.2. The large ecliptic circle with the colored zodiac areas on the periphery represents the entire cosmos, with the Earth at its center. The smaller inner circle that is eccentric to the other represents the orbit of the Sun. Note that the line labeled *Aequinoctialis Seu Colurus Aequinoctiorium* runs left to right through the center of the Earth, and as can be seen there are fewer days of the Sun's orbit below than above this line, accounting for a shorter autumnal to spring equinox time. Thus, the phenomena were saved without violating the basic assumptions alluded to above.

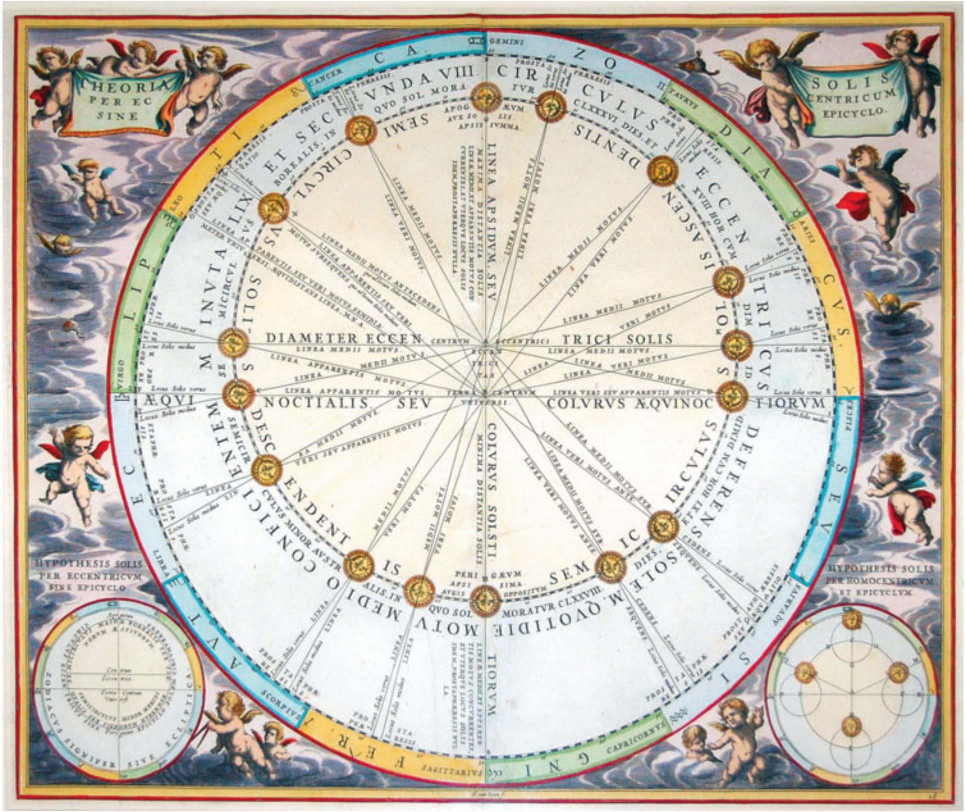

Figure 2.2. A plate showing the orbit of the Sun around the central Earth according to Hipparchus and adapted by Ptolemy, from Cellarius's *Harmonia Macrocosmica*, c.1661. 42.1 × 50.4 cm, 38.5 cm diameter hemisphere. Note that the eccentric orbit accounts for the unequal period of time between the equinoxes, with the lower part (autumn to spring) being shorter than the upper part (spring to autumn).

2.1.8 Apollonius and the Epicycle Model

Although reasonably accurate in accounting for the locations of some heavenly bodies in the sky, the eccentric solution was not perfect, and a second model was called for which has been attributed to the great Greek mathematician Apollonius. Born in Perga around 240 BC, he spent much of his life in Alexandria, where he probably died around 190 BC. He is credited as being the first person to use deferents and epicycles in explaining irregularities in planetary movements that could not be accounted for by the eccentric theory alone. In this model, a heavenly body revolves around a small circle called an epicycle, the center of which itself moves around the Earth in a circular orbit called a deferent. By adjusting the size, rotational speed, and rotational direction of the epicycle and its deferent, a model for each heavenly body could be made that fairly accurately accounted for its location in the sky.

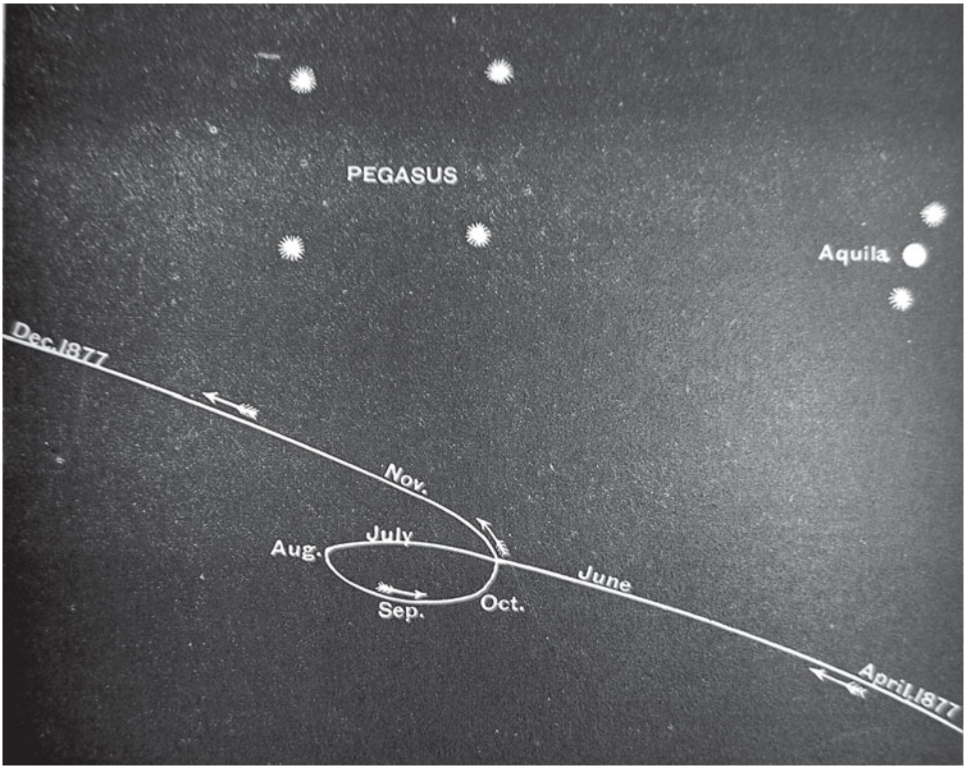

Figure 2.3. A figure from Sir Robert Ball's *The Story of the Heavens*, published in 1897. 23 × 15.3 cm (page size). Note the appearance of Mars in the heavens in the latter part of 1877, when it made its retrograde loop.

This model also explained the apparent retrograde motion of a planet as it moved along its path. An example of this is shown in Figure 2.3, where the path of Mars is plotted for most of the year 1877. Note that it makes a big looping pattern from August to October, where it retrogrades backwards toward the west. The explanation for this using epicycles and deferents is shown in Figure 2.4, using a diagrammatic style popularized by Georg Peurbach's *Theoricae Planetarum Novae*.[6] Here, a planet is shown revolving around the Earth ("a") counter-clockwise along its epicycle ("f-b-d-e-c"), whose center is in turn moving counter-clockwise along its deferent ("c-b"). When the planet goes from "c" through "f" and on to "b", it appears to move toward the left (toward the east) as seen from the Earth. It then appears to slow down and becomes stationary at "d". As it goes from "d" to "e", it actually appears to be going retrograde (toward the west) before becoming stationary again at "e". As it moves beyond this point, it starts to go away from the observer and retraces it eastward approach.

Interestingly, the simple eccentric model and the simple epicycle model could produce equivalent results, simply by adjusting the relative parameters of the epicycle/deferent

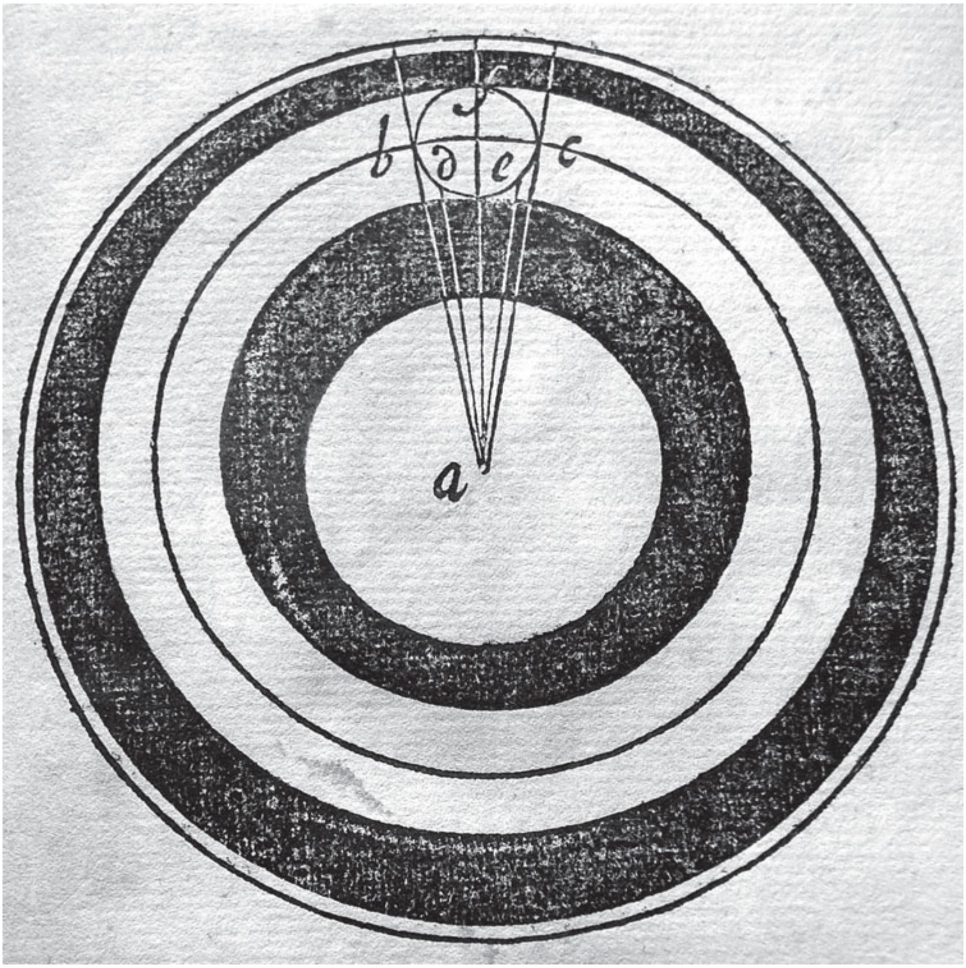

Figure 2.4. An illustration (influenced by Peurbach's *Theoricae Planetarum Novae*) explaining the retrograde motion of an outer planet in the sky, from the 1647 Leiden edition of Sacrobosco's *De Sphaera*. 15.2 × 9.7 cm (page size). See text for details.

combination in terms of speed and direction of rotation or the relative size of the epicycle and deferent. This is shown in the diagram from the lower right corner of Figure 2.2, where if one connects the four images of the Sun as oriented in its epicycle as it moves around its deferent, a circle is defined that is eccentric to the central Earth. Different astronomers picked different epicycle/deferent combinations. Some even combined the models by using eccentric deferents.

Although the deferent/epicycle model worked reasonable well in saving the phenomena in terms of plotting the location of heavenly bodies in the sky, it sometimes produced clearly nonsensical observations. A case in point is found in Figure 2.5, which shows the

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