# How the Sun was Misplaced for 1,700 Years

## After Aristarchus of Samos proposed a heliocentric Solar System in 250 BCE, other scholars moved Earth back to the center, where it remained until Copernicus.

### By Samuel M. Wilson

Ancient Greek astronomers had two vexing questions about what they were observing in the firmament. The first had to do with the objects that moved against the backdrop of a seemingly unchanging field of stars. When the motion of these “travelers” was charted from night to night and season to season, the astronomers could see that the objects did not move along consistent paths. One object—the planet Mars—might on one month move steadily across the constellations of the zodiac, but it could also speed up and slow down, and every two years or so it would reverse course and go in the other direction for a few weeks. If the universe, as the astronomers envisioned it, was a series of spheres nested within one another—with Earth at the center and the Sun, Moon, planets, and fixed stars occupying their own spheres—then why wasn’t the motion of these moving objects regular and orderly?

The second big question was: Why wasn’t the timing of key celestial events consistent and even? The intervals between the winter and summer solstices, and the spring and fall equinoxes, were not the same. If one assumed that the Sun was going around Earth in a perfectly circular path on its own crystalline sphere, the distance from solstice to equinox should always be the same. In other parts of the world, earlier observers of the heavens may have also wrestled with these questions when they built finely calibrated observatories, such as Stonehenge in England, the Taosi observatory in China, or the astronomical-sighting devices of the people of Africa and the Americas. Wherever there is a standing “henge” of stones or stakes, we may assume that there were people making records and, possibly, scratching their heads about the reasons for the uneven seasons of the year and the movement of the planets. The differences between the solstices and the equinoxes vary from eighty-eight to ninety-four days. If the night sky is orderly and Earth is at its center, they should always be the same.

For some, these anomalies were not an issue. Plato (c. 427–c. 347 BCE) and some others of his time believed that what we perceive as “reality” was a poor secondary reflection of an ideal reality that could only be understood by one’s intellect. In this view, the information we take in via our senses was a flawed version of the ideal. Therefore, Plato was not troubled by inconsistencies in the time between solstices and equinoxes.

Others strongly disagreed, including Plato’s student, Aristotle (384–322 BCE). He and others believed that our senses give us access to the world as it truly is, and the way to understand the nature of things is to make observations and then try to make sense of these observations. Aristotle and other like philosophers were deeply intrigued by the inconsistencies in the night sky and sought better and better models to account for them. Despite its flaws, they adhered to a standard model of the cosmos; it was reasonably powerful and intuitively accessible.

However, one scholar for whom the model of the celestial spheres was particularly troubling was Aristarchus of Samos (c. 310–c. 230 BCE), who was born about twelve years after Aristotle died. Recognized for his mastery of astronomy, mathematics, geometry, and music, he was referred to as Aristarchus the Mathematician, though very little more is known about his life. He was firmly in Aristotle’s camp regarding the use of empirical data but had a novel model of the universe, as described by the scientist, philosopher, and mathematician Archimedes (c. 287–c. 212 BCE):

> [Aristarchus’s] hypotheses are that the fixed stars and the Sun remain unmoved, that Earth revolves about the Sun on the circumference of a

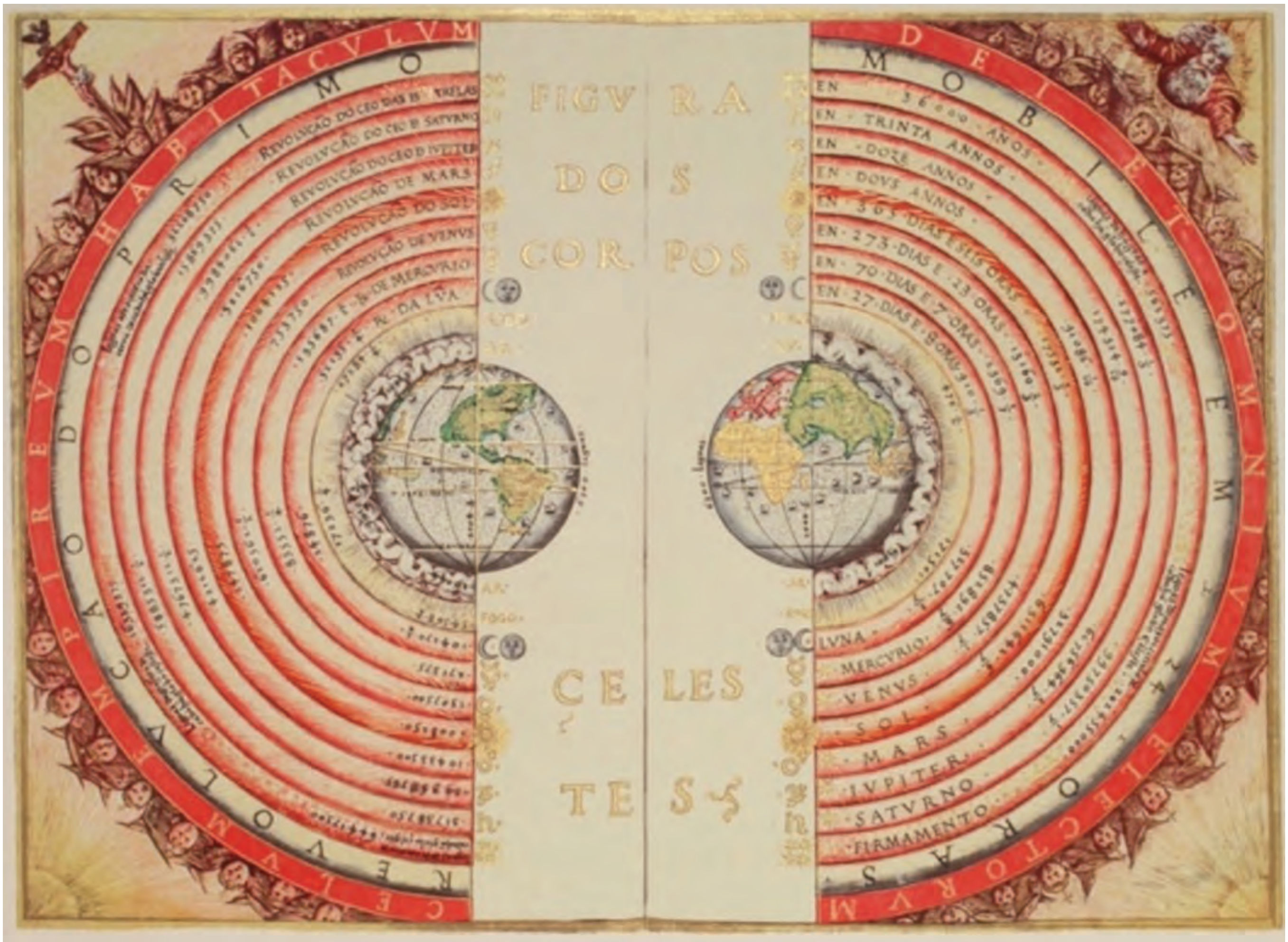


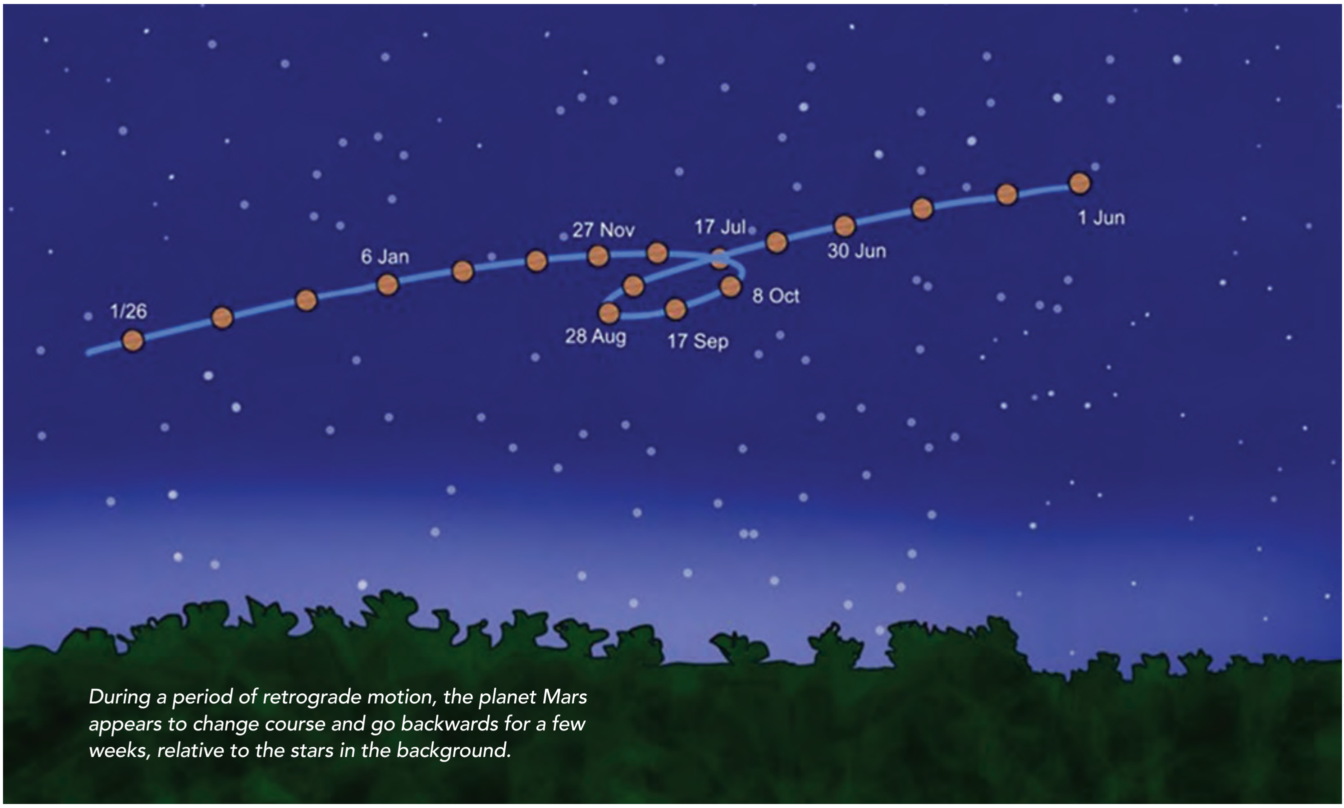
*Illustration of the Ptolemaic geocentric system by Portuguese cosmographer and cartographer Bartolomeu Velho (d. 1568)*

> circle, the Sun lying in the middle of the orbit, and that the sphere of fixed stars is situated about the same center as the Sun . . .

These ideas resolved several issues. They offered an explanation for the way the planets exhibited this vexing "retrograde" motion. If all the planets are circling the Sun, and if Mars, for example, is farther away from the Sun than is Earth, perhaps Earth would appear to speed past Mars in certain configurations making it appear that Mars reverses course in the night sky, which is exactly what happens; with Mars's orbit about 687 days long and more elliptical than Earth's, our perspective of the more-distant planet shifts.

But Aristarchus's model had two shortcomings. It did not account for Earth's lopsided seasons. And, although it made intuitive sense to those who had studied the issue, the mathematics describing the motion of the planets had not been fully worked out. Aristarchus could not point to a column on a table and show where Mars had been or predict where it would be (if Aristarchus did calculate such a table, it was lost, because only one of his written works remains). Eventually, these unresolved issues were enough to keep Aristarchus's theory from supplanting Aristotle's idea of nested spheres.

Aristarchus's hypotheses about a Sun-centered universe were widely known to scholars of his time and after. As mentioned, Archimedes, arguably the most influential of the classical Greek scientists, took Aristarchus seriously. Seleucus of Seleucia (c. 190–c. 150 BCE), supported Aristarchus's ideas and tried to build on them. Seleucus lived in the strongly Greek-influenced Seleucid empire, centered near modern Baghdad, which indicates how far Aristarchus's ideas had spread in the Hellenistic world. According to the Greek philosopher Plutarch (46–c. 120 CE), "Seleucus the Mathematician" not only affirmed Aristarchus's model of the Earth rotating around the Sun, Seleucus added that the Moon, rotating around the Earth, helped account for the presence of the tides, which the Mediterranean people knew well. Seneca the Younger (c. 4 BCE—65 CE), writing around 60 CE, shows that over 200 years after Aristarchus's death, his ideas were still in circu-



During a period of retrograde motion, the planet Mars appears to change course and go backwards for a few weeks, relative to the stars in the background.

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lation. In providing a review of Greek ideas about cosmology, Seneca wrote:

> It will be proper to discuss this, in order that we may know whether the universe revolves and the earth stands still, or the universe stands still and the earth rotates. For there have been those who asserted that it is we whom the order of nature causes to move without our being aware of it, and that risings and settings do not occur by virtue of the motion of the heaven, but that we ourselves rise and set. The subject is worthy of consideration, in order that we may know in what conditions we live, whether the abode allotted to us is the most slowly or the most quickly moving, whether God moves everything around us, or ourselves instead.

Writing around 100 CE, Plutarch also mentioned Aristarchus in discussing the pushback Aristarchus received. Plutarch cites the Stoic philosopher Cleanthes (c. 331–231 BCE), who was a contemporary of Aristarchus. Cleanthes thought Aristarchus's hypothesis was blasphemous, because it went against the long-held idea that Earth was the "hearth of the gods" and could not be put in motion. Plato had mentioned this idea, and others had interpreted his comment in a dogmatic way. One said, "we must suppose the earth,

This scaphe, found at the site of Ai Khanoum in the Hindu Kush of Afghanistan, is an improved hemispherical sundial of a type invented by Aristarchus.

MUSÉE GUIMET

the Hearth of the House of the Gods according to Plato, to remain fixed, and the planets with the whole embracing heaven to move, and reject with abhorrence the view of those who have brought to rest the things which move and set in motion the things which by their nature and position are unmoved . . ." Cleanthes published a tract, or paper, titled, "Against Aristarchus," which was published in Aristarchus's lifetime. Plutarch cited this in repeating Cleanthes's ideas:

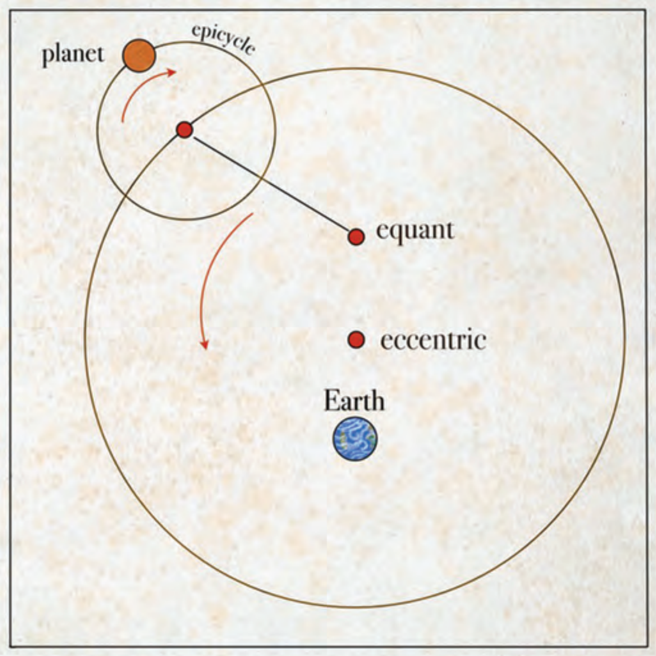
> [Cleanthes . . .] thought it was the duty of Greeks to indict Aristarchus of Samos on the charge of impiety for putting in motion the Hearth of the Universe, this being the effect of his attempt to [explain] the phenomena by supposing the heaven to remain at rest and the earth to revolve in an oblique circle, while it rotates, at the same time, about its axis."

By the time of Aristarchus's death, his idea about a heliocentric model of the cosmos was increasing in influence and acceptance, but because of the issues raised earlier, and through the work of a few influential scholars, his model was discarded in favor of a stationary Earth becoming, once again, the center of everything.

One of the most influential and strongest opponents of Aristarchus's was Hipparchus (c. 190–c. 126 BCE), born in the Greek city of Nicaea near the Black Sea in Turkey. Often referred to as the "father of astronomy," as well as the "father of trigonometry," Hipparchus took Aristarchus's work on measuring the relative size of the Earth, Sun, and Moon, and greatly refined them, transforming the mathematics of using triangles to measure sizes and distances. Both Aristarchus and Hipparchus used solar eclipses as a way to measure the distance from Earth to the Moon, which they worked out, as an accurate estimate, to be about sixty of Earth's radii. Hipparchus's observational methods and mathematics were more precise than Aristarchus's, due in part to working a century later and having more measurements available.

Hipparchus's refined methods, however, led him away from the breakthrough insights of Aristarchus. His measurements convinced him that the orbit of the Sun around the Earth (or vice versa, depending on one's perspective) was not completely regular. This flew in the face of one of his most basic assumptions that the movement of celestial objects had to be in a perfect circle. For Hipparchus, it was an unacceptable conclusion that the orbits could be oval, or elliptical, or that objects could be moving faster at some times than at others. If the heavenly bodies were not where they were supposed to be, he felt the problem had to be in his mathematics.

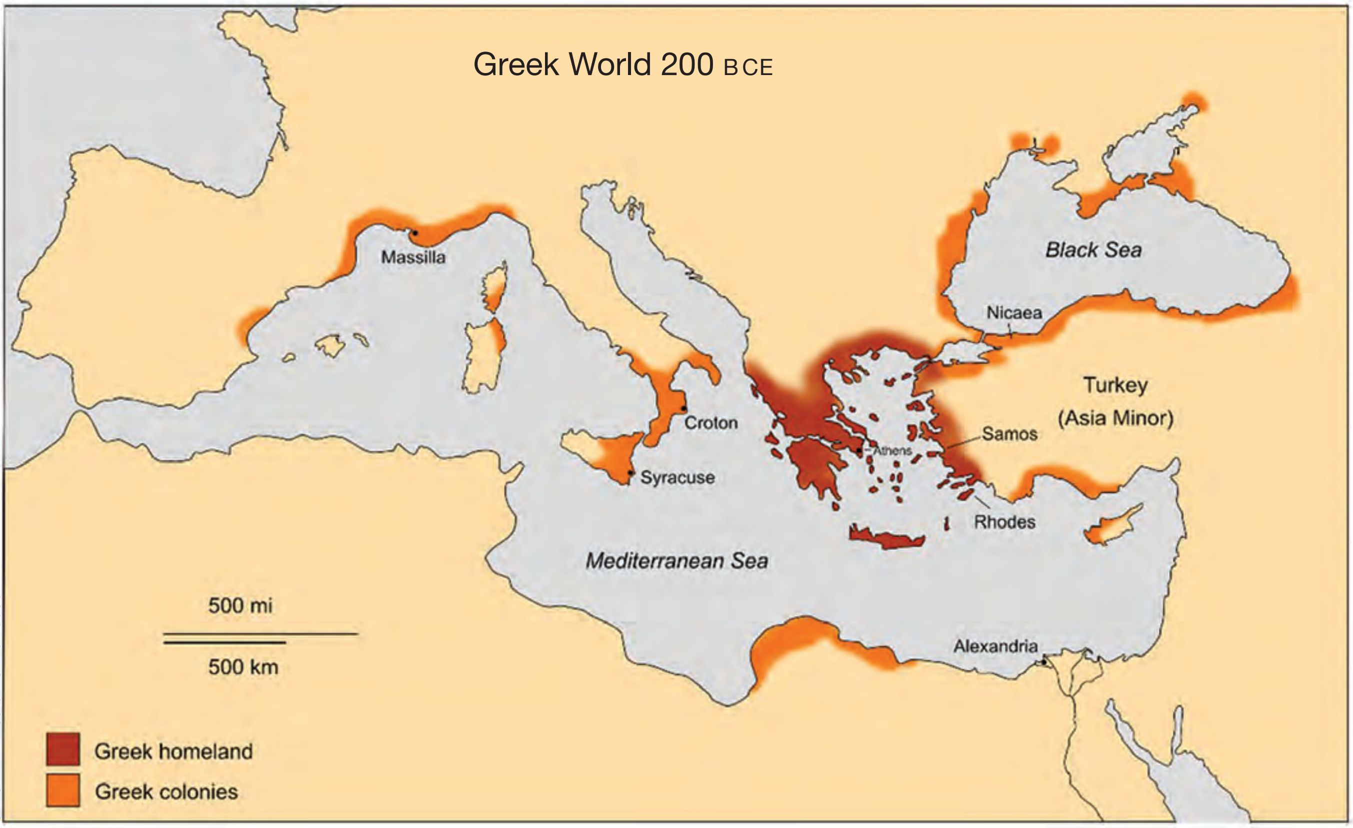
To account for the irregularity of the seasons and the back-and-forth motions of the planets, Hipparchus came up with a brilliant mathematical solution, which—unfortunately for the advancement of understanding the Solar System—was wrong. His model had two correction factors. The center of the Sun's orbit was not the center of the Earth, but rather a point in space near Earth, which allowed Sun's orbit to still be circular, even though it did not appear that way from Earth. Hipparchus called this imaginary point, the geometric center of the orbit, the "eccentric."



*In a diagram of Ptolemy's Earth-centered universe, a planet's orbit is centered on the eccentric, a point that is offset from Earth. The planet follows an epicycle or small orbit pinned to its larger orbit. The equant is a spot from which the angular momentum of the planet—how many degrees of arc it travels in a set period of time—always remains the same.*

Hipparchus's second correction applied to the planets. A planet followed a large circular path, but it did not stay on track. It went around an additional little orbit—an "epicycle"—which was pinned to the larger orbit. Once this factor was added, his numbers worked better. He had not deviated entirely from Aristotle's heavenly spheres, as Aristarchus had, but he had added tweaks to make the math work—in effect, the eccentrics and epicycles were coming close to describing elliptical or elongated orbits.

These correction factors came close to answering the two vexing questions. The seasons were not the same length because at one end of the Sun's orbit it was at the distant edge of its offset orbit, and at the other end it was close to Earth. For the baffling retrograde motion of the planets, they were exhibiting two kinds of motion: their circular orbits around an eccentric point near Earth and their epicycle orbits. With epicycles, Hipparchus was able to predict where the planets were going to be fairly accurately. They were close enough to be rough-



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ly correct, given the naked-eye observations of the time.

In just a few generations, between Aristotle and Hipparchus, Greek philosophers had come nearly full circle, so to speak, in their theories about the workings of the cosmos—from the semi-mythical idea of nested spheres with the Earth at the center, to a heliocentric model with a rotating Earth orbiting the Sun, back to nested spheres with a few modifications. The powerful assumption that orbits had to be circular drove this reversal. Nearly everyone from the ancient Mesopotamian and Indian astronomers onward had made the same assumption—including Nikolaus Copernicus (1473–1543) in his writing in 1543. Finally, Johannes Kepler (1571–1630) realized that the orbit of Mars was an ellipse. In 1609, in *Astronomia Nova*, he wrote, "I was almost driven to madness in considering and calculating this matter. I could not find out why the planets would want to go in an elliptical orbit . . ."

Two-hundred years after Hipparchus died, Claudius Ptolemaeus (c. 100-c. 170 CE)—a Greek-descended Roman citizen who lived in the Roman city Alexandria—took the astronomical ideas of Hipparchus and others, elaborated on them, and published them in a book, called the *Almagest* (from the Arabic "*al-magesti*," or "The Greatest"). The Greek text was lost to European scholars for a long time but existed in an Arabic translation and was used by generations of Islamic scholars during Islam's "Golden Age"—roughly the eighth to the thirteenth centuries CE. In the 1100s, a Latin translation, the *Almagestum*, was made from the Arabic and was studied by European scientists of the time and for some time thereafter. Ptolemaeus, anglicized as Ptolemy, was to become the most influential voice in Roman, Islamic, and European astronomy until Europe's scientific revolution in the 1500–1700s.

In his book, Ptolemy worked out the mathematics of the Earth-centered universe in great detail, building on the ideas of the eccentrics, equants, and epicycles. He had studied the observations of solstices, equinoxes, and eclipses that had been recorded by Aristarchus, Archimedes, Hipparchus, and Babylonian astronomers, and produced refined tables for the movement of the planets, including future eclipses. His observations were more methodical (although still limited by human eyesight in these pre-telescope times), and his mathematics were more precise than those of Hipparchus or others. His models for the motion of things were far from perfect, however. The planets would not behave as his calculations predicted, even with eccentrics and epicycles, so in the case of Mercury he added an additional epicycle to try to fine tune planetary positions. Mercury, in other words, was not just orbiting Earth, it was following a small circular epicycle that was connected to a larger epicycle that was pinned to its main orbit.

For around 1,300 years, astronomers fought the battle to either perfect Ptolemy's model or replace it. Part of the difficulty in getting rid of Ptolemy's view of the heavens was that it took so long to master his mathematics. Following the ancient Sumerian and Babylonian astronomers, Ptolemy made his calculations in the base 60, sexagesimal system. In this system, the circle of horizon was divided into 360 degrees and the same scale was used for the arc of the heavens above and below Earth. It took so long to master Ptolemy's system that by the time students were adept with it, they were also steeped in the model's logic and assumptions. Scientists in the Islamic world studied Ptolemy's *Almagest* and tried to solve the mathematical problems of the motions of the planets. They steadily improved observations of the sky, with better and better observatories, and they developed mathematics that included algebra, trigonometry, and the precursors of calculus. Copernicus cites five of these Islamic scholars as part of the basis of his work on heliocentrism. In a handwritten manuscript of *De Revolutionibus Orbium Coelestium,* Copernicus mentions Aristarchus as an early proponent of his theory, but this reference was not included in the published book.


REVOLVTIONVM LIB. I. 27

30 anno ſuum complet circuitum. Poſt hunc Iupiter duodecennali revolutione mobilis. Deinde Mars, qui biennio circuit. Quartum in ordine annua revolutio locum obtinet, in quo terram cum orbe

*Copernicus solar system from* De Revolutionibus Orbium Coelestium *(1543)*

Ptolemy's *Almagest* stood as the most important astronomical reference point for 1,400 years, until Copernicus published his work in 1543. This is a remarkably long time for one set of ideas to be accepted. It is especially notable when contrasted with the three centuries before Ptolemy, when so much scientific progress had been made. The decline in interest and support for science coincides with the rise of Rome's power over the Greek world and reflects Rome's diminished interest in and support for science and philosophy. Science continued in the Roman world, as Ptolemy's publications attest, but Rome's overarching project was to integrate and rule an empire comprised of dozens of separate languages and cultures and build the infrastructure to hold it all together. Although the Romans did not greatly advance fields such as astronomy, they surpassed anything the Greeks had done in the fields of applied technology, architecture, and engineering.

The growing power of the Catholic Church also inhibited research in science and astronomy until the European scientific revolution of the 1500s. The revival of the heliocentric model of the cosmos was championed by Copernicus, Galileo (1564–1642), and Kepler, and all had their works viewed with suspicion or overtly suppressed by the Church. Even the physical treatises of Aristotle were placed on the "Condemnations" (list of prohibited books and ideas) of the 1200s, showing the Church's great uneasiness with the ideas of Greek and Islamic philosophers. But, eventually, the old geocentric model of Aristotle, Ptolemy, and Hipparchus gave way, mostly because of the weight of more and more observational evidence that the model simply could not be correct.

How could scientists have gotten wrong for so long a model of the Solar System? The answer is the force of gravity, which was not included in their calculations. Not until 144 years after Copernicus died in 1543 did Isaac Newton (1643–1727) come to understand that what kept the Moon from sailing off into space was the pull of Earth's mass. In his 1687 book, *Philosophiae Naturalis*, he postulated that there was a force, which he called gravity, that was defined by the masses of the Earth and Moon, and proportional to the physical distance between them. This gravitational attraction held the Moon in Earth's orbit. And by the same principle, it held the planets on their elliptical orbits around the Sun.

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