CHAPTER 6

Astronomy

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1. Some Historiographical Issues

The models of the heavens of some Greek thinkers, particularly the earlier ones, can be reconstructed in many ways. We do not have enough evidence to state categorically exactly how these models were put together. If we are generous and allow the best possible reconstruction, it is possible to generate some quite sophisticated models. The limits of what a model can do should, of course, be explored, but with caution and the caveat that this is our best reconstruction. There can also be a tension between astronomy and cosmology in such reconstructions. So, as we will see for Anaximander, attributing a sophisticated astronomy to him compromises his account of the stability of the earth, while attributing a sophisticated astronomy to Plato compromises the idea of perfectly regular circular motion. There is then a choice to be made between attributing sophisticated astronomy or strong cosmological principle. One aspect of that choice is whether the thinker in question should be considered primarily an astronomer or a cosmologist.

An important related issue is whether we should credit that all ancient thinkers believed that the model of the heavens they devised could account for all the phenomena of which they were aware. Simplicius, the sixth-century commentator, tells us:

> The unrolling spheres of Eudoxus' school do not save the phenomena, not only those that were found later, but also those known before and recognized by them. (*On "On the Heavens"* 504.17–20)

It is thus clear that Eudoxus and his followers at least did not have a model that accounted for all of the phenomena of which he was aware. Simplicius then proceeds to give evidence concerning variations in planetary distance and refers to annular eclipses

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(occurring when the moon is at such a distance from the earth that it does not cover the entire sun). He also tells us that it is evident to the naked eye that the moon does not always lie at the same distance from us, as it does not have the same size even when observed under seemingly similar conditions. We cannot then assume that all Greek thinkers thought their models could account for all of the phenomena they were aware of, let alone all of the phenomena we are aware of.

Nor can we suppose a linear progression in terms of sophistication in Greek astronomy. That is, if we have good evidence that one thinker postdates another, we cannot assume that in some way the later model is also more sophisticated.

That the Greeks believed themselves to live in a *cosmos* (plural, *cosmoi*) is significant. The root verb, *cosmeō*, had a sense not only of order but of good order (our words *cosmology* and even *cosmetic* derive from it) and could also have a sense of an aesthetically good or morally good order (see THE CREATION AND DESTRUCTION OF THE WORLD). Depending on the author, these senses can be more or less marked. I will use the word *cosmos* to retain this original sense, rather than the modern term *universe*.

The great majority of Greek and Roman astronomy was geocentric, earth centered. There were good reasons for the Greeks and Romans to believe this, the form of the argument being: if the earth were in motion, or not in the center of the *cosmos*, there would be perceptible consequences. We do not perceive these consequences. Therefore, the earth is not in motion. There is an important consequence of believing the earth to be central and stable. Nowadays, we explain some of what we see in the night sky in terms of the motion of the earth as apparent motion. For geocentrism, though, there are no apparent motions, and all the motions in the night sky are real. There were a wide range of predicted effects, from winds counter to the earth's spin or direction of motion to stellar parallax. This is the source of some of the complexity of Greek astronomy.

A final, yet enormously important, consideration can be put very bluntly: the ancient Greeks and Romans had no conception of gravity. Of course, they knew that heavy objects drop to earth and that the heavenly bodies move in a regular manner. They did not explain these phenomena in terms of gravity, though, and so needed other sorts of explanations for the regular motion of heavenly bodies. Sometimes that was done in a manner we might loosely describe as mechanical (i.e., using vortices), but often the heavenly bodies were seen as intelligent, choosing the correct motions and obeying something closer to civil law than our modern conception of mathematical law. It has not always been evident that the modern approach is correct, and we should allow the ancients some leeway in pursuing what to them were quite rational possibilities. The intelligence/civil law model gave a strong basis for regularities in the heavens.

2. Pre-Greek Astronomy

How much the Greeks knew of pre-Greek astronomy has always been an issue of considerable contention. It is clear that both Plato and Aristotle were at least aware of and praised Babylonian astronomical records. It has now been proved beyond doubt that later astronomers knew of and used these records. Whether the Presocratic Greeks were aware of Babylonian records and methods is still a matter of debate. The Babylonian records, accurate and extensive, were used to make predictions of selected phenomena in the heavens as deemed important for the calendar and for Babylonian astrology (e.g., the gods were thought to send messages to humans via the heavens). The means of prediction was to look for patterns in the data and then to select and refine algorithms. The Babylonians posited a flat earth and a hemispherical heaven across which the celestial bodies passed.

An assortment of contrasts can be drawn between Babylonian and early Greek astronomy. And while none on their own capture the full nature of the contrast, and none are correct in their simplest forms, all contribute something to the discussion. There is sometimes a philosophy of science agenda behind these contrasts, wishing to show that either the Babylonians or the Greeks were the first real scientific astronomers. That debate has generated rather more heat than light. And it may be best to consider science (and disciplines within science such as astronomy) to have multiple rather than singular origins, all making an interesting contribution. First, there is the contrast of arithmetical and geometrical models of the heavens. In relation to the heavens, the Babylonians used numbers, whereas the early Greeks used shapes, in particular, the circle. Although true to a certain extent, this masks other differences, especially in terms of goals and explanations in astronomy. Nor is the contrast absolute. This contrast can also be put in terms of differences between prediction and explanation. The Babylonian emphasis was on prediction, whereas the early Greeks were more interested in generating explanations of celestial motions. Recent work has shown how the Babylonians understood and explained the heavens, albeit in different ways from the early Greeks. Finally, one can rather crudely contrast Babylonian observational methods with the supposed philosophical speculation of the early Greeks. Although the early Greeks were more speculative than the Babylonians, that speculation still at least attempted to produce models which conformed to the motions of the heavens.

Thales

Although we find no technical astronomy as such in Homer and Hesiod, there is some knowledge of the heavens and some sense of a cosmology, albeit with a heaven above the earth and an underworld below. Thales, the first person in the Greek tradition of natural science/philosophy, is famed for predicting an eclipse (*TEGP* 5), but there are problems with the evidence. We are not sure if he did predict a solar eclipse, nor of the degree of accuracy of the prediction, nor of his methods. Since the Babylonians were able to predict eclipses, it is tempting to suppose that Thales had access to their records and methods, or perhaps even just their results. However, we have no concrete evidence of this. Other than supposing a central and stable earth, supported by water, we know little of Thales' picture of the heavens.

Anaximander

With Anaximander we have more information, and there has been considerable debate about the sophistication of his model of the heavens. Let us begin with the earth (*TEGP* 19–20). In shape, it is likened to a section of a stone column, so it is round with two flat surfaces. We are told that its depth is one third of its width (or three times its width, according to a minority view). It is probable that the surfaces were in fact slightly concave. The earth is in the center and does not move. On the standard view, the earth is unsupported. It does not move as it has no reason to move in any specific direction. That is a remarkable departure in cosmology from any previous conception. Also remarkable are the facts that Anaximander is the first to have the heavenly bodies make full orbits under the earth and to give depth to the heavens (*TEGP* 22–23, 25, 28).

Anaximander divided the heavens into rings around the earth: the stars (closest), the moon, and sun (furthest). The heavenly bodies are, in fact, rings of fire for Anaximander. A ring is surrounded by condensed air that makes the fiery core invisible, except for a small hole. What we see as the heavenly bodies are then not separate entities, such as stars and moons as we understand them, but glimpses of the fiery core observed through a small mouth in the compressed air. One advantage of these rings is that they are continuous such that they do not upset the indifference argument for the earth, as would be the case with planets. The rings are also spaced equally from each other, giving them no preferred direction of movement. The usual reconstruction of the spacing is 9 (stars) 18 (moon) 27 (sun), the numbers here being proportions, probably in relation to the radius of the earth (Figure 6.1).

How were these rings arranged? We do not know for certain. One possibility we can reasonably reject is that the rings are arranged concentrically in the same plane as the faces of the earth. If this were so, the stars, moon, and sun would only be visible near the horizon (Figure 6.2).

The problem with this arrangement is that sun and moon would have the same paths across the sky each day, when in fact there are significant variations. We do have evidence for this arrangement. For Anaximander, the rings are said to lie “aslant” (*TEGP* 25), but we have no values for their slanting.

Some scholars have proposed a more complex scheme, whereby the sun and moon rings move up and down the axis of the *cosmos*. The summer solstice occurs when the sun is

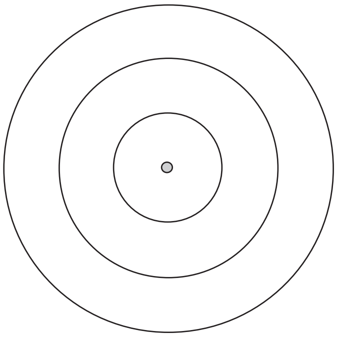


Figure 6.1 Anaximander’s solar system.

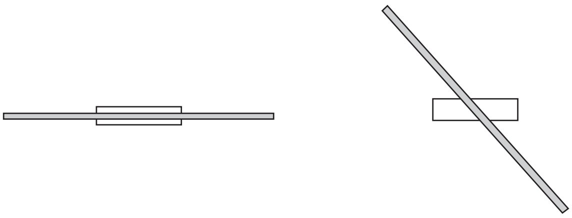


Figure 6.2 Stars viewed from the horizon.

furthest “up” and winter solstice when the sun is furthest “down.” This is highly ingenious, but we have no textual evidence for this motion. It is also problematic in that if the sun and moon did move like this, then the earth would no longer be at the center of their orbits and so would have reason to move, compromising the argument for the stability of the earth.

This brings us to the type of difficulty in reconstructing models outlined earlier. We can give Anaximander a more sophisticated astronomy, allowing him to account for more phenomena, but this comes at the cost of cosmological principle in ruining the argument for the stability of the earth. There is no absolute answer to this issue, though my personal sense is that Anaximander pays a great deal of attention to the symmetry and stability of the *cosmos* and is unlikely to have compromised that.

Philolaus and the Pythagoreans

Aristotle gives us a good description of Philolaus’ system (*TEGP* 24). At the center of the *cosmos* we have the central fire, with the earth, sun, moon, stars, and planets all orbiting around it. Between the earth and the central fire is the counter-earth, presumably in synchronous orbit with the earth such that we are unable to see the central fire. We then have the moon, sun, the five planets, and the sphere of the stars (Figure 6.3).

While the description of Philolaus’ system is reasonably clear, the purpose of this model is not. It is remarkable that the earth is in motion, though it is orbiting round the central fire, not the sun, and the sun is orbiting the central fire as well.

If the model is set up to accord with Pythagorean eschatology, rather than cosmological principle or astronomical observation, it is not clear how the model and any proposed eschatology fit together. It may be that, as Aristotle says, ten bodies were supposed in order to match with the Pythagorean perfect number, ten. That, of course, depends on how one counts the bodies. Some sources attribute the origins of the idea of regular circular motion to the Pythagoreans. That too is possible, though the sources on the Pythagoreans are notoriously corrupt, tending to aggrandize Pythagoras in particular by attributing ideas which were in fact formulated later.

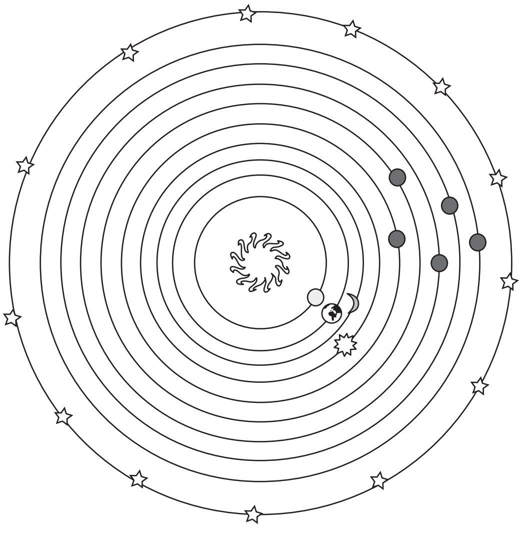


Figure 6.3 Philolaus’ system.

Other Presocratics

The later Presocratic thinkers added little to technical astronomy, but there are some interesting discoveries and new ideas in cosmology. One important idea is that of the vortex, whereby the heavenly bodies are propelled round the earth. In Anaxagoras, the heavenly bodies are specifically heavy entities which need to be held aloft (*TEGP* 31). Parmenides was the first to speak of the moon as shining by reflected light (*TEGP* 35). The idea that the earth was spherical also dates from this period, though it is more difficult to pin down to any one person.

3. Euctemon and Meton

Euctemon and Meton are credited with an important discovery, that of the inequality of the seasons. The year can be divided into four parts by the two solstices and two equinoxes. The equinoxes are days of equal day and night, the solstices the days of maximum and minimum night and day. One might think that there would be equal numbers of days between equinoxes and solstices and between solstices and equinoxes. In fact, there are not, as Euctemon and Meton discovered. The reason for this is that the earth's orbit around the sun is elliptical (Figure 6.4).

Meton is also credited with introducing the Metonic cycle, that nineteen solar years are very nearly equivalent to 223 lunar months, an important discovery in relation to generating a stable calendar (Diodorus Siculus 12.36.2).

4. Plato

Let us here concentrate on the model put forward in Plato's *Timaeus*, with, of course, reference to the *Republic*. The key idea is that the motions of the sun, moon, and planets can be analyzed in terms of combinations of regular circular motions. The *Timaeus* may mark a departure from the views of the *Republic* in two important ways. First, there is the *Republic's* attitude to the regularity of celestial motion:

> Concerning the proportion of night to day, and of these to the month, of month to year, and of the other stars to these and to each other, wouldn't he consider it absurd to think that these things always come to be the same manner and never undergo any deviation, as they are both physical and visible. (530a3–7)

Second, there is the *Republic* VII passage where Plato has Socrates say the following:

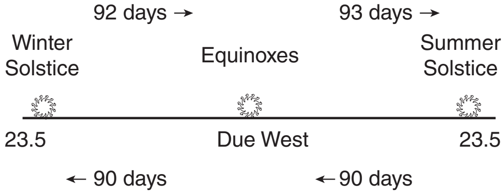


Figure 6.4 Inequality of equinoxes and solstices.

> It is by means of problems, then, that we shall proceed with astronomy as we do geometry, and we shall leave the things in the heavens alone, if by really taking part in astronomy we propose to make useful instead of useless the understanding that is by nature in the soul. (530b6–c1)

Timaeus 47a on the other hand tells us that

> God devised and gave to us vision in order that we might observe the rational revolutions of the heavens and use them against the revolutions of thought that are in us, which are like them, though those are clear and ours confused, and by learning thoroughly and partaking in calculations correct according to nature, by imitation of the entirely unwandering revolutions of God we might stabilize the wandering revolutions in ourselves.

The "unwandering revolutions of God" here are the motions of the heavens, and there is ample evidence elsewhere in the *Timaeus* that the motions of the heavens are regular. *Timaeus* 34a and 40b tell us that the motions of the cosmos as a whole, and those of the fixed stars, are unwandering. There cannot then be a metaphysical problem with the regular motions of the heavens (i.e., that which is visible and bodily *can* move in a regular manner; cf. *Republic* 529d–530d). If the "wanderings" of the planets constitute time (39c), and the planets, sun, and moon are the "guardians of time" (38c), then, unless Plato envisages a non-uniform passage of time, the motions of the heavenly bodies are regular. For there to be a contrast between time and eternity, all that is required is that time moves while eternity does not. This is similar to the position of the *Laws* (822a) and *Epinomis*, but different from the *Republic* and the *Statesman*, where the cosmos is degenerating toward chaos, and so the heavenly motions become chaotic. It is interesting to note that while both the *Republic* (616b) and the *Statesman* (270a9) have the *cosmos* rotating on a pivot, the *Timaeus* (34a; cf. 33d) has the *cosmos* free floating. It is also arguable that Plato moves from a degenerating to a stable cosmos (see Gregory 2001, 101–113).

Some commentators have detected a rejection or denigration of the phenomena or of observational astronomy in the second *Republic* passage (Heath 1913, 135–140; cf. Mittelstraß 1963, 117; Neugebauer 1951, 157). There are alternatives here, based on the conditional nature of the passage (*if* we use astronomy for this purpose, then … other purposes may have other protases), and much depends on what is thought to be the epistemological import of the middle books of the *Republic* (for further details: Gregory 2001, chapter 2). In the *Timaeus* passage, observation of the heavens is encouraged.

In the *Timaeus'* model of the heavens, there is a sphere of fixed stars which rotates once a day. The sun, moon, and planets share in this motion, but they also have a second circular motion, with the axis offset to that of the stars. The sun, moon, and planets will then be seen in successively slightly different positions relative to the fixed stars owing to this second motion. We are not given any specific angle here. Plato merely says this is like the Greek letter θ, with the model working best if we use the angle of the ecliptic, around 23.5 degrees (Figure 6.5).

Plato says that the moon completes its second motion in a month, the sun in a year, and Mercury and Venus in about a year. But he omits values for the other planets. There

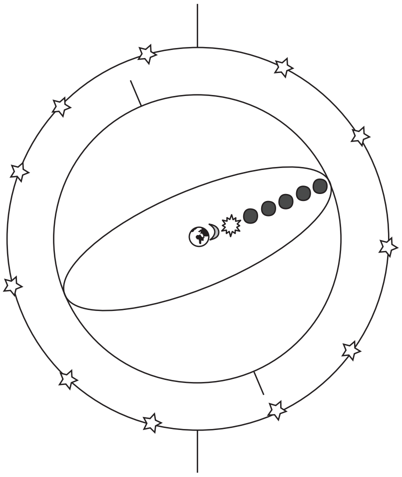


Figure 6.5 Plato’s two-sphere model.

are several advantages of this model, which gives reasonable approximations for the motions of the sun, moon, and planets using only two regular circular motions. There are also significant problems. The sun, moon, and earth are all permanently in the same plane so there will be full solar and lunar eclipses roughly every month, and there will be no variation in the type of eclipse. The planets are also in the same plane and so will occlude each other every time they pass (which is rare) rather than passing each other in the zodiac. Plato is also aware that Mercury, Venus, and the sun “overtake and are overtaken by each other” (38d), which occurs because Mercury and Venus are inferior planets; that is, their orbit around the sun is smaller than that of the earth. Plato then says that Mercury and Venus have a contrary power (38d4) to the sun. We do not know the nature of this “contrary power.”

Plato is another example where we have a conflict between a simple and strong cosmological principle and astronomical sophistication. There can be no doubt that Plato is aware of more phenomena than any model using two regular circular motions for sun, moon, and planets can reproduce. The most interesting passage in this respect is 40c:

> (1) The dances of these stars and their juxtapositions with one another, (2) the circling backs and advances of their own cycles, (3) which of the gods come into contact with each other and which into opposition, (4) which cover each other relative to us, and (5) for what periods they each disappear and again re-appear.

When planets pass each other in the zodiac, they can be close to one another (1), be so close that they appear to merge into one large object (3), or occlude one another (4). Planets can undergo retrograde motion (2), and Mercury and Venus disappear as they come close to the sun and then reappear on the other side of the sun, a phenomenon much studied by the Babylonians. None of these phenomena can be accounted for by the *Timaeus* model. As Vlastos (1975, 50) has commented, “Plato’s language here is saturated with the terms of observational astronomy” (Figure 6.6).

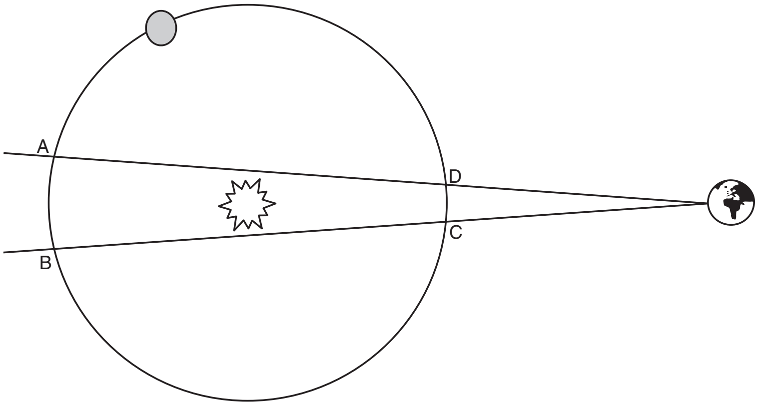


Figure 6.6 Venus, Mercury, and the Sun.

It has been argued that the contrary power can apply more widely than just to the overtaking/overtaken phenomenon of Mercury, Venus, and the sun. The text does not justify this, and there is a question of which phenomena we apply it to, if we do not apply it to all the phenomena of which Plato was aware. It should be evident that the more we allow the application of some form of contrary power, the more regular circular motion will be compromised.

The alternative here is to treat the *Timaeus* model as a prototype, strong on cosmological principle (regular circular motion only) but weaker on astronomical detail. The "contrary power" merely notes there is a difficulty with Mercury, Venus, and the sun without giving an answer, and it does not apply to other phenomena. If we take this view, then the evidence of Simplicius makes good sense:

> Plato assigned circular, regular and ordered motions to the heavens, and offered this problem to the mathematicians: which hypotheses of regular, circular and ordered motion are capable of saving the phenomena of the planets, and first Eudoxus of Knidos produced the hypothesis of the so-called unrolling spheres. (*On "On the Heavens"* 492.31–493.5; cf. 488.18–24)

Plato was not able to do this himself with combinations of two circular notions, but keeping to the program of analyzing the motions of the heavens in terms of regular circular motions, he challenges others to provide solutions within that framework.

5. Eudoxus

Eudoxus, noted also for producing a star catalog, put forward a view which was more complex than that of Plato's *Timaeus*, and that could also account for a good deal more of the phenomena. Instead of proposing two motions for the sun, moon, and planets, Eudoxus proposed three for the sun and the moon and four for the planets. These were all regular circular motions with a common center (homocentric/concentric sphere model). Two of the motions were the same as those proposed by Plato in the *Timaeus*, one taking the body round in a full circle in one day, the other generating motion along the ecliptic (Figure 6.7).

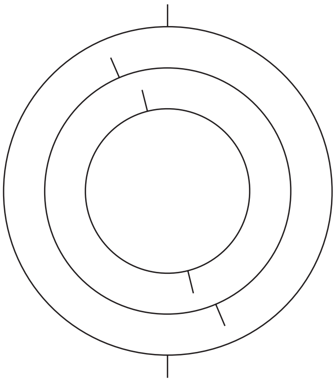


Figure 6.7 Third sphere for the sun and the moon.

Eudoxus, though, proposed a third motion for the sun and moon. This works reasonably well for the moon if we suppose that the third motion is offset for the motion that drives the moon along the ecliptic by about five degrees. This will give the moon a deviation from the ecliptic of five degrees on each side, which is correct. It is interesting that Eudoxus proposes a third motion for the sun. We think of the ecliptic as the path followed by the sun. The ancient Greeks thought in terms of the line through the middle of the zodiac, with the possibility that the sun might deviate from that. While we think of the sun as something special in astronomical terms, it is clear that the Greeks did not, not privileging it in any way and generating similar models for the sun as for other heavenly objects. It may be that, given the difficulty of measuring the precise point of the solstices, Eudoxus had a small third motion for the sun to account for data which appeared to give a variable point for the solstices. It is also possible that Eudoxus gave the sun a small motion in order to improve his model for eclipses (Figure 6.8).

Eudoxus proposed a four motion model for the planets. Again, two of the motions take care of the daily motion and motion along the ecliptic, respectively. The other two motions were used to give a representation of retrograde motion. If we take these two motions on their own, they make a shape known as a hippopede (Figure 6.9).

If we combine them with the first two motions, then we get something like retrograde motion (Figure 6.10).

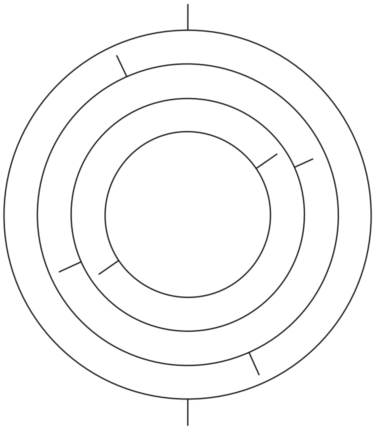


Figure 6.8 Eudoxus' four spheres.

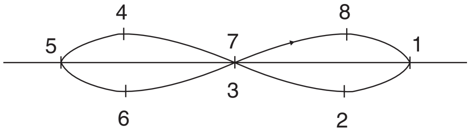


Figure 6.9 A hippopede.

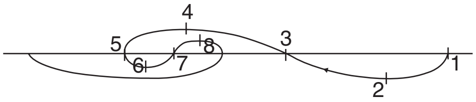


Figure 6.10 Motion resulting from daily motion and motion along the ecliptic.

With the benefit of modern mathematics and computer modeling, we have a better appreciation of what Eudoxus' model could and could not do. One of the problems is that we have little in terms of figures to apply to the spheres. We do not know much about the angles they were set at relative to each other, nor about their speeds.

6. Callippus

Callippus further developed Eudoxus' work and moved to a five motion concentric sphere model for most celestial bodies. Where Eudoxus used a total of 27 spheres, Callippus used 34. This is likely to have produced greater accuracy in modeling the celestial motions, but we have no quantitative assessment of by how much. Callippus produced a system of 5 spheres for the sun and the moon. The standard explanation is that the extra spheres for the sun give an approximation of the inequality of the seasons, and those for the moon give a similar approximation of differences in the moon's orbital velocity, neither effect being explicable on Eudoxus' model. Callippus also produced 5 sphere models for Mercury, Venus, and Mars, staying with 4 sphere models for Jupiter and Saturn. While tolerable approximations of the retrograde motion of Jupiter and Saturn are possible on Eudoxus' model, they are not for Mercury, Venus, and Mars (see Yavetz 1998; Mendell 1998).

There are inherent problems with the concentric sphere model. The first is intrinsic to the nature of the model: all the entities must of necessity be at a constant distance from the middle. But there are some quite noticeable variations in the apparent size/brightness of the moon and the planets, well known to the ancients and indeed mentioned by Simplicius. While Eudoxus' solution to retrograde motion was ingenious, its application was difficult. While concentric sphere astronomy could, just about, produce retrograde motion, it could not produce the actual shapes of retrograde motion seen in the night sky. Finally, although Callippus' work produced some improvement, concentric sphere astronomy, it had difficulty in modeling the changes in angular motion actually made by the celestial bodies.

There has been some debate about the nature of the motions proposed by Eudoxus and Callippus. Were they simply means of calculating and predicting the celestial motions? Or were the circles conceived as actual circles, in some way mechanically driving the heavenly bodies? Concentric sphere astronomy has been characterized in this manner by those seeing it as an early example of instrumentalism or of realism. It is important to note here that Plato thought that heavenly bodies were intelligent and selected their best path—consistently choosing the best path being the mark of intelligence, thus giving a strong underpinning to the regularity of the heavens. If Eudoxus and Callippus worked in this tradition, then neither instrumentalism or full realism seems appropriate. This illustrates the futility of imposing modern debates in the philosophy of science on ancient thinkers.

7. Aristotle

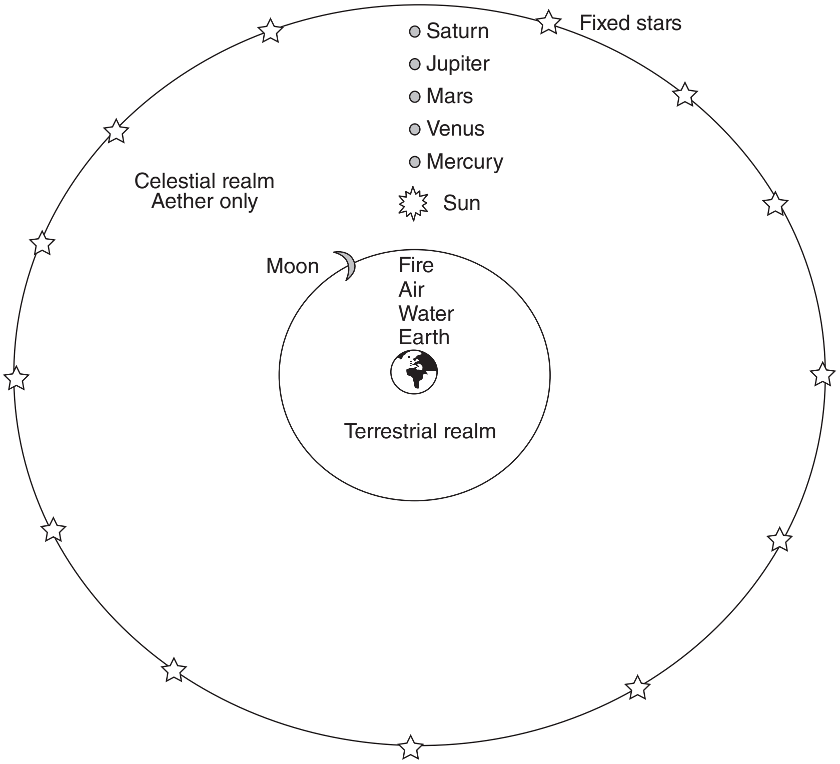
There is a sense that Aristotle adds little to Greek astronomy. His system of concentric spheres is essentially Callippus', and the predictive power of Aristotle's system is certainly no greater than Callippus'. What Aristotle did was to make the spheres in some sense concrete, as being composed out of aether, Aristotle's fifth element whose natural motion was circular (*On the Cosmos* 392a6–10). So the motion of each of the spheres was entirely natural and eternal, as that motion was circular. Aristotle believed that the *cosmos* had always existed in its current form and always would, and that there was never any change in the heavens. The aether is neither heavy nor light, so in Aristotle's scheme it has no natural motion either toward or away from the earth. Any change that might appear to occur in the heavens, in fact, happened in the terrestrial realm. For Aristotle, the terrestrial realm—consisting of earth, water, air, and fire, in roughly that order going outward—encompassed everything from the center of the earth, which was also the center of the *cosmos*, out to the moon. Fire in the heavens was transparent unless inflamed by something.

The arrangement of the spheres for Aristotle was complex. The sphere of the fixed stars, the outermost sphere, was simple enough. However, for each of the other celestial bodies, there were a set of spheres whose combined motion drove the heavenly body. As the spheres are arranged like a huge onion, or Russian doll, with no empty space between the spheres, each sphere drives the next one in. So Saturn, the outermost planet for Aristotle, has a set of driving spheres, but to prevent Saturn's motion from influencing Jupiter's motion, the next planet in, there are also a set of retroactive spheres that cancel the transfer of Saturn's motion before Jupiter's driving spheres can engage. This process proceeds inward, ultimately until we come to the moon, where there are no retroactive spheres since the moon is the nearest body to the earth. There is debate on exactly how many spheres this system requires and whether Aristotle counts them properly!

Celestial motions had to have an effect on what happens in the terrestrial realm, according to Aristotle. Aristotle's theory of motion had earth and water moving naturally toward the center of the *cosmos* (the earth). Earth was heavier than water, and hence water is placed around the earth. Air and fire, on the other hand, were positively light, moving away from the center with the orbit of the moon that formed a barrier to how far they could move. Fire was lighter than air, so it constituted the outermost layer of the terrestrial realm. As Aristotle believed, the *cosmos* had always been in existence, and there had been sufficient time for the natural motions of each element to sort the elements into perfect concentric shells with no mixing of the elements unless some other influence opposed this. The motions of the heavens provided this, their motions affecting the terrestrial realm and preventing the full separation of the elements.

Aristotle's account of what we see when we look at the heavens is interesting. We do not see the celestial bodies directly. Rather, the motion of each of the celestial bodies inflames a patch of the fiery area of the terrestrial realm directly below it. And this is what we see. One implication of this view is that each of the celestial bodies shines by its own light, rather than by any reflected light, which is problematic for the phases of the moon. Nor is it clear what happens at eclipses, especially lunar eclipses, when the moon should continue shining. In other places, Aristotle quite clearly knows the explanation of eclipses, but he does not seem to have thought through the implications of how we see celestial bodies.

There are also some well-known problems with the interface of the terrestrial and celestial realms. Aristotle's account of the motion of celestial objects affecting the fiery part of the terrestrial realm is a possibility for the moon, where the moon is the nearest body to earth, and there are no retroactive spheres. However, the sun has retroactive spheres, so it is by no means clear how the sun's motion could influence what is going on in the fiery part of the terrestrial realm, or indeed any of the celestial bodies farther out than the sun (Figure 6.11).



Celestial Realm (moon and beyond)	**Terrestrial Realm** (up to the moon)
Made of the fifth element, aether	Four elements of earth, water, air, and fire
Not subject to change	Always changing
Natural motion is circular	Natural motion is linear
Aether is neither heavy nor light	Earth and water are heavy, air, and fire are light
Mathematics applies precisely	Mathematics applies imprecisely

Figure 6.11 The celestial and terrestrial realms.

It is important to note here that all the stars are equidistant, so there is no depth to the star field, and that the distance from Jupiter to Saturn is on the same order of magnitude as the distance from Saturn to the fixed stars.

8. Aristarchus

Aristarchus needs to be mentioned in any history of Greek astronomy, if only to dispel some of the misconceptions which have surrounded him. In older historiographies, Aristarchus was given a prominent place in histories of Greek astronomy for his proposal of heliocentricism (Heath's 1913 history of Greek astronomy is simply called *Aristarchus of Samos: The Ancient Copernicus*). Aristarchus was seen to have had the correct idea and to have anticipated Copernicus. The question, then, was why the Greeks had not adopted this correct idea. This was put down to religious reasons, with the following passage from Plutarch often cited:

> Cleanthes thought that the Greeks ought to indict Aristarchus of Samos on a charge of impiety for putting in motion the hearth of the universe (that is the earth). (*On the Face in the Disc of the Moon* 922f–23a)

Some older histories of science, pursuing a strong agenda in terms of a perceived conflict between religion and science, saw this as prima facie evidence of the religious suppression of Aristarchus' theory. Often overlooked, however, is that there were good astronomical and physical reasons to reject heliocentricism. If the earth were in motion, then a good deal of Greek physics would have had to be wrong, but we have no trace of any replacement physics from Aristarchus. The observable effects for a mobile earth predicted by Greek physics were not seen. If the earth were in motion, that should have been detectable against the background of the stars in a small *cosmos* (an effect known as parallax), but it was not. The alternative, of a massive expansion of the *cosmos*, was not seen as necessary. This was an issue for Copernicus, Kepler, and Galileo, as well. If the earth were in regular circular motion around the sun, then there would be a perfect equality of the seasons and no precession of the equinoxes. The inequality of the seasons was known, and the precession of the equinoxes was soon discovered, a slow change in the orientation of the earth due to a small wobble in its axis of rotation which results in a small change in how the stars are observed. Both effects were explained within the geocentric system without recourse to a mobile earth. In contrast, the geocentric programmed had no physical or conceptual problems, parallax was not an issue, and geocentrism could account for the inequality of the seasons and the precession of the equinoxes.

9. Hipparchus

Hipparchus was possibly the greatest observational astronomer in antiquity. Although Ptolemy achieved more in terms of a fundamental theoretical synthesis for the heavens, Hipparchus possibly made the greatest advances in generating reliable astronomical data.

Of particular importance is Hipparchus' star catalog, detailing the positions of the stars with considerable accuracy, by far the best star catalog to this point in antiquity.

Hipparchus also introduced distinctions between the apparent brightness of the stars, introducing a six-point scale which is the basis for the scale used today. An important part of Hipparchus' work was comparing his star catalog with previous work, and attempting to improve on accuracy. Hipparchus found small but systematic differences, due not to error but to a small change in the apparent positions of the stars relative to the earth. This was the discovery of the precession of the equinoxes, caused by a systematic change in the inclination of the earth's axis of spin. This was a remarkable discovery: the change is quite subtle and requires a great deal of accurate and diligent observation to be detected. It is also clear from Hipparchus' work that he knew a good deal about the Babylonian data and their methods in astronomy. Much of Hipparchus' work involved small but important improvements on technical issues. He worked on producing better values for many of the cycles of the heavens, attempting to produce models for phenomena such as the inequality of the seasons.

10. Ptolemy

The work of Claudius Ptolemy is generally recognized as the pinnacle of ancient work on astronomy. His model of the heavens was comprehensive, systematic, and highly accurate by the standards of the time. In many ways it was a typical Hellenistic synthesis, bringing together existing knowledge of astronomy with Ptolemy's own research and innovations and forging a comprehensive system that would last at least until the Renaissance, parallel to Galen with anatomy and physiology and Euclid with geometry. Ptolemy's great text in astronomy was the *Syntaxis*, the "gathering together," commonly known by its Arabic name, the *Almagest*, the "greatest." Also of significance is Ptolemy's *Planetary Hypotheses.* Often ignored or marginalized is the *Tetrabiblos*, a work on astrology. It should be noted that Ptolemy considered his work on astrology to be a valid part of his work on the heavens more generally—ancient astrology was concerned with the broader effects of the heaven on the earth, and Ptolemy considered these influence to be entirely natural (see also ASTROLOGY). Ptolemy also wrote works on music, geography, and optics.

Ptolemaic astronomy produced accurate representations of the motions of the heavens even if the models could be quite complex. There are three basic devices within Ptolemaic astronomy: epicycle, eccentric, and equant. Here we have the basic epicycle device (Figure 6.12).

The planet rotates in a circle, the epicyclic circle, which has its center on the larger circle, the deferent circle. The center of the epicyclic circle also moves with regular

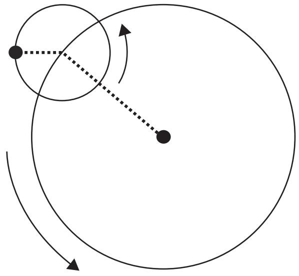


Figure 6.12 The basic epicycle.

circular motion around the deferent circle. These motions can be made to produce loops like retrograde motion with appropriate choice of the sizes and speeds of the circles. It is possible to use circles of radically different sizes and to compound further circles in order to generate the motions of the heavens. The second device is the eccentric (Figure 6.13).

This is the eccentric in its simplest form. The planet revolves around a center, with regular circular motion, but the earth is no longer at the rotational center, but is slightly offset. Here the earth is significantly offset to make the effect evident. The eccentric helps to model variations in distance from the earth. It is evident that the planet will be nearer the earth when it is at the bottom of its circle than when it is at the top. One can also add an epicyclic circle to the eccentric.

One consequence of the eccentric is that the earth is not at the center of the deferent circle. Technically then, Ptolemy's theory was geostatic but not geocentric. As Copernicus adopted this device but with the places of the earth and sun reversed, his system was technically heliostatic rather than heliocentric. It was not until 1609 and Kepler's recognition that the planetary orbits were ellipses that a truly heliocentric system emerged (Figure 6.14).

When observed from the earth, the planets do not move with uniform angular motion across the sky even when they are not undergoing retrograde motion. This is no great surprise, as the planetary orbits are not in fact centered on the earth. The equant helps to model variations in the motions of the planets as seen from earth. And it builds in the eccentric idea, so once again there is a center to the deferent circle with the earth offset from this. There is a further important point though, the equant point, marked x. The planet has regular angular motion around x, but not around the center or around

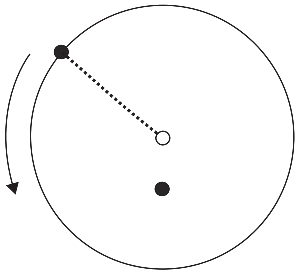


Figure 6.13 Eccentric circle.

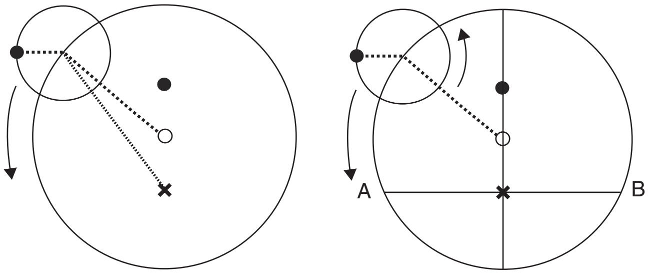


Figure 6.14 The equant.

the earth. Consider the second diagram here (Figure 6.14). Ignoring the effect of the epicycle, the planet will move from A to B in the same time as it moves from B to A, as there is regular angular motion around the equant point. Now consider this phenomenon as seen from the earth. A to B is around 90 degrees, B to A is around 270 degrees, and both are completed in the same time. Again, the offset of the earth and the equant point is greatly exaggerated in the diagram to make their effect evident. The equant has an interesting subsequent history, as Copernicus commented that

> The planetary theories of Ptolemy and most other astronomers, although consistent with the numerical data, seemed likewise to present no small difficulty. For these theories were not adequate unless certain equants were also conceived; it then appeared that a planet moved with uniform velocity neither on its deferent nor about the center of its epicycle. Hence a system of this sort seemed neither sufficiently absolute nor sufficiently pleasing to the mind. (*Commentariolus*)

In terms of cosmology, the earth was central, even if it was no longer the center of rotation. Then followed the moon, Mercury and Venus, the sun, Mars, Jupiter, and Saturn, and then the sphere of the fixed stars. The orbits were spaced on the principle that, while they could not overlap, there could be no empty space between the orbits either. One issue with Ptolemaic astronomy was that it was difficult to interpret in a realistic manner, especially as the earth was no longer the center of rotation. Another was that the system of circles used for the motion of each heavenly body was arbitrary. They were put together simply to generate the motion rather than in accord with any schematic plan. Both criticisms, incidentally, apply to Copernicus as well. When Copernicus introduced heliocentrism in 1543, his "Revolutions of the Celestial Orbs" swaps the places of the earth/moon with the sun and then recalculates the orbits using Ptolemaic devices in a Ptolemaic style. Tycho Brahe's system, the earth in the center with the planets orbiting the sun, while significantly different from Ptolemy's, still borrows many devices and explanations from Ptolemy. It was not until the work of Kepler, when each orbit was considered to be an ellipse around the sun, with the sun at the focus of the ellipse, that there was a coherent, unitary scheme for each planet, and there could be a conception of a force emanating from the central body controlling the motions of the planets. Kepler wrongly guessed magnetism, but others soon supposed it to be gravity.

11. Conclusion

Ptolemy's *Syntaxis* undoubtedly is the greatest work in astronomy in the ancient world. It forms the basis for all astronomy, both in Western Europe and in the Arabic/Islamic culture through to the sixteenth century. There was a tension between the relatively simple Aristotelian cosmology based on concentric spheres and the more sophisticated Ptolemaic astronomy based on the epicycle, and there were also questions about how, physically, the mathematical constructions of epicycle, eccentric, and equant were to be interpreted. These questions were more prominent within the Islamic tradition. Ptolemaic astronomy is sometimes seen as something of a dead end, and a rather moribund research program. At the time of Ptolemy, and immediately succeeding him, this is certainly not so. The Ptolemaic system improved considerably on the system of homocentric spheres, and it could model quite subtle and recently detected phenomena in the heavens such as the precession of the equinoxes. In a sense, its own success became its problem. Sufficiently accurate for all practical purposes, fitting reasonably well with the dominant Aristotelian philosophy and cosmology, there was little pressure for radical change. The Ptolemaic system was remarkably long lasting. Even when challenged it continued to have a significant effect, influencing both Copernicus and Tycho Brahe by its methods well into the sixteenth century.

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