

# A New View of Early Greek Astronomy

By Bernard R. Goldstein\* and Alan C. Bowen\*\*

THE STANDARD HISTORY OF GREEK ASTRONOMY emphasizes the role of planetary theory in its earlier stages, by supposing that the early astronomers aimed primarily to explain planetary phenomena. This view derives from a passage in Simplicius (sixth century A.D.), based on the lost *History of Astronomy* by Eudemus (fourth century B.C.), in which Plato is said to have set astronomers the task of saving planetary phenomena by means of uniform circular motions.<sup>1</sup> Many scholars doubt Simplicius's authority and question Plato's putative role in the development of astronomical theory.<sup>2</sup> But their alternative accounts, while none too clear, likewise assume that the early period of Greek astronomy was concerned mainly with planetary motion. Some assign Plato's role to the Pythagoreans who preceded him, following Geminus (first century A.D.), who reports:

It is presupposed in all astronomy that the sun, the moon, and the five planets move in circular orbits with uniform speed in a direction opposite to that of the universe. For the Pythagoreans, who were the first to apply themselves to investigations of this kind, supposed the motions of the sun, the moon and the five planets to be circular and uniform. . . . For which reason, they put forward the question as to how the phenomena might be explained by means of circular and uniform motions.<sup>3</sup>

In our view, however, planetary theory was not central to early Greek astronomy as Simplicius and Geminus suggest; consequently, interpretations that stress it minimize the true significance of what is universally acknowledged to be a major scientific achievement of the period, Eudoxus' homocentric model for planetary motion.

We contend that Greek astronomy falls into distinct phases, that the earliest

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<sup>1</sup> Simplicius, *In libros Aristotelis de caelo Commentaria* 488.18–24, 492.28–493.5, in J. L. Heiberg, ed., *Commentaria in Aristotelem Graeca*, Vol. VII (Berlin: Academia Litterarum Regia Borussica, 1894). Trans. in M. R. Cohen and I. E. Drabkin, *A Source Book in Greek Science* (Cambridge, Mass.: Harvard Univ. Press, 1948), p. 97.

<sup>2</sup> See, e.g., O. Neugebauer, *The Exact Sciences in Antiquity* (2nd ed., 1957; New York: Dover, 1969), p. 152.

<sup>3</sup> Geminus, *Elementa astronomiae* 10.2–21, ed. C. Manitius, (Leipzig: Teubner, 1898) (our trans.). Geminus is followed by B. L. van der Waerden, "The Earliest Form of the Epicycle Theory," *Journal for the History of Astronomy*, 1974, 5:175–185; cf. van der Waerden, "The Motion of Venus, Mercury and the Sun in Early Greek Astronomy," *Archive for History of Exact Sciences*, 1982, 26:99–113. On Geminus's date, see Otto Neugebauer, *A History of Ancient Mathematical Astronomy* (hereafter *HAMA*) (New York/Heidelberg/Berlin: Springer-Verlag, 1975), pp. 579–581.

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phase extends from the eighth century B.C. to the time of Plato, and that Eudoxus is the starting-point of the second phase. This division is based on philological considerations and on the observation that, in the earlier period, the motives and problems of Greek astronomy proper differed from those of early cosmology and that any scientific concern with planetary motion was characteristic of the later period.

In studying the history of Greek astronomy, one should recognize that the late evidence on which one must rely may be contaminated by later developments. The most important witness to Greek astronomy is Ptolemy's *Almagest*, written in the middle of the second century A.D. Its successful reception occasioned the loss of most of the earlier texts on Greek astronomy, including all those of Hipparchus (second century B.C.) save his commentary on the astronomical poem of Aratus. The earliest surviving works are those of Autolycus and Euclid (both ca. 300 B.C.). For the period prior to Autolycus, and, to a lesser extent, for that between Autolycus and Ptolemy, historians must depend on fragments preserved in diverse ancient and medieval sources. This state of affairs has made writing the history of Greek astronomy extremely difficult and has introduced into it a considerable amount of reconstruction, much of it highly speculative. Moreover, it has encouraged attempts to locate the ideas, models, and parameters of Ptolemy (or, for some, Copernicus) in the theories of his predecessors, as if their goals and those of Ptolemy (or Copernicus) were identical.

The proper way, however, to recover the history of Greek astronomy is to treat the subject in each period on its own terms. Greek astronomy, as the very name implies, began as the organization of the fixed stars into constellations. The purpose was to construct a calendar by correlating dates and weather phenomena with the risings and settings of the fixed stars or constellations.<sup>4</sup> This tradition, which is the framework of Hesiod's *Works and Days*, persists throughout Greek history and is well represented in Ptolemy's *Phaseis*. The astronomical calendar of risings and settings, weather phenomena, and seasons took the form of a *parapêgma*, quite possibly invented by Meton.<sup>5</sup> Ptolemy cites twelve *parapegmata*, beginning with Meton, Euctemon, and Democritus in the fifth century and Eudoxus, Callippus, and Philippus in the fourth.<sup>6</sup> In some of these calendars the dates are simply listed in zodiacal months. (The sun stays in each of the twelve zodiacal signs for one month: these months should not be confused with lunar months, which are defined with respect to the first visibility of the new moon.) The stars, moreover, are not assigned coordinates, and there is no allusion to a celestial sphere: no precise measurement was involved in

<sup>4</sup> See P. Tannery, *Recherches sur l'histoire de l'astronomie ancienne* (Paris: Gauthier-Villars, 1893; New York: Arno Press, 1976), pp. 1–25; and H. Diels and W. Kranz, *Die Fragmente der Vorsokratiker* (hereafter DK) (6th ed., Berlin/Zurich: Weidmann, 1951), Ch. 4 (Hesiod), Ch. 6 (Cleostratus of Tenedos).

<sup>5</sup> See Neugebauer, *HAMA*, p. 622; T. L. Heath, *Aristarchus of Samos: The Ancient Copernicus* (Oxford: Clarendon Press, 1913), p. 295, n. 1. On the tradition, see Hesiod, *Opera et dies*, e.g., lines 383–387, 614–623; Plato, *Respublica* 527d1–4, *Symposium* 188a1–b6, *Gorgias* 451c5–9; Hippocrates, *De aeribus aquis locis* 2.14–26; Ptolemy, *Phaseis*, in *Claudii Ptolemaei Opera quae exstant omnia*, ed. J. L. Heiberg (Leipzig: Teubner, 1897–1898), Vol. II: *Opera astronomica minora*; see also Neugebauer, *HAMA*, pp. 926 ff.

<sup>6</sup> In the *Phaseis*: see Neugebauer, *HAMA*, pp. 588, 929.

determining their risings and settings. Finally, there is no mention of planetary motion or eclipses in the *parapêgmata*.

Since the accounts of celestial motions found in the tradition of cosmological speculation, a tradition which was independent of Greek astronomy in its earliest phase, are, as we shall explain, tangential to the strictly scientific treatment of the same phenomena, it appears that all aspects of astronomy prior to Eudoxus concern the calendar and calendaric cycles.<sup>7</sup> For periods less than a day, although it is difficult to ascertain the methods used, a few passages suggest that the water clock, or *klepsydra*, served to measure relatively brief spans of time. Anaxagoras and Empedocles (both fifth century) are credited with a physical explanation of how this device works.<sup>8</sup> There is also in Herodotus (late fifth century) a report that the Greeks learned of the *polos*, the gnomon, and the twelve-fold division of the day from the Babylonians. Since the word *polos* certainly signifies a hemispherical bowl, it follows that the Greeks had a sundial in the fifth century. Whether these items were indeed borrowed from the Babylonians is a question that need not concern us here.<sup>9</sup>

The person largely responsible for turning astronomy into a mathematical science, that is, a deductive mathematical explanation of physical phenomena, was Eudoxus of Cnidus (ca. 390–337 B.C.).<sup>10</sup> His inspiration was drawn from two sources. The first was the science of music, a theory that analyzed an aesthetic phenomenon, melodious sound, by means of whole-number ratios. The invention of this science is usually associated with Pythagoras but given the state of our sources, this is unverifiable. Nevertheless, a Pythagorean science of music was well established in the fifth century, for Archytas of Tarentum, a Pythagorean contemporary of Plato, presents his own harmonic theory in terms of an older and authoritative tradition.<sup>11</sup> As for Eudoxus' knowledge of this science, there are fragments attesting his familiarity with Archytas's work in this domain.<sup>12</sup>

Second, we propose that Eudoxus was influenced by cosmological speculation, particularly that of the Pythagoreans and Plato. For, in their view, the circular motions of the heavenly bodies manifested a *moral* order that was ul-

<sup>7</sup> See Neugebauer, *HAMA*, pp. 588, 619–624; Heath, *Aristarchus*, pp. 130–133.

<sup>8</sup> On Anaxagoras, see Aristotle, *De caelo* 309a19–21; *Physica* 213a22–27 (= DK 68 A68): [Aristotle], *Problemata* 2.16, 914b9–915a25 (= DK 68 A69). On Empedocles, see Aristotle, *De respiratione* 473a15–474a6 (= DK 31 B100).

<sup>9</sup> Herodotus, *Historiae* 2.109; see also Neugebauer, *Exact Sciences*, pp. 81–91. On the *polos*, see W. W. How and J. Wells, *A Commentary on Herodotus* (Oxford: Clarendon Press, 1928), Vol. I, pp. 221–222; and Ernst Maass, *Aratea*, Vol. XII of *Philologische Untersuchungen*, ed. A. Kiessling and U. v. Wilamowitz-Moellendorf (Berlin: Weidmann, 1892), pp. 123–140. On the question of Babylonian origins, see, e.g., B. L. van der Waerden, *Science Awakening, II: The Birth of Astronomy* (New York: Oxford Univ. Press, 1974), pp. 70–71, 285; together with B. R. Goldstein's review in the *Journal of Near Eastern Studies*, 1978, 37:275–277.

<sup>10</sup> See George de Santillana, "Eudoxus and Plato: A Study in Chronology," *Isis*, 1940, 32:248–262.

<sup>11</sup> See Heath, *Aristarchus*, pp. 319–320; for correction and discussion of the text Heath translates, see A. C. Bowen, "The Foundations of Early Pythagorean Harmonic Science: Archytas, Fragment 1," *Ancient Philosophy*, 1982, 2:79–104.

<sup>12</sup> See fragments D63, D64 (= DK 47 A19a) in F. Lasserre, *Die Fragmente des Eudoxos von Knidos* (Berlin: De Gruyter, 1966) (hereafter cited as *Eudoxus* followed by a fragment number); compare Porphyry, *In Ptolemaei harmonica Commentaria* 93.5–17 (= DK 47 B2). Diogenes Laertius, *Vitae philosophorum* 8.8.86, states that Eudoxus learned geometry from Archytas (= *Eudoxus* T7).

timately analyzable by means of the same whole-number ratios as melodious sound. As Aristotle claims:

Contemporaneously with these thinkers and before them [i.e., the atomists], those called Pythagoreans, who were the first to engage in the sciences, advanced them; and, having been trained in the sciences, they thought that scientific principles were the principles of all things. Since, of these principles, numbers are by nature first, and since they expected to see in numbers many likenesses to things which are and which come to be, more than in fire, earth and water—because such a property of numbers as this is justice and such a property as that is soul and intelligence, and another is opportunity and likewise so to speak for each of the others; and further, since they saw the properties and ratios of *harmonia* in numbers—since, then, all other things appear in their whole nature to resemble numbers and numbers are first in the whole of nature, they supposed the elements of numbers to be the elements of all things and the entire heaven to be a *harmonia* and number.<sup>13</sup>

The Pythagoreans regarded the explanation of the heavenly motions in terms of these ratios as knowledge of the speeds, risings, and settings of the celestial bodies; and Plato called it astronomy. But, though such speculation did relate celestial movement and number, it would be wrong to see in this any attempt at precise measurement of what is observed. The *explanandum* in these theories is not so much a physical phenomenon as the ethical and aesthetic order it supposedly exhibits. Thus, for the Pythagoreans, the numerical analysis belongs to the reduction of all things to number and of number to the *tetraktys* of the decad; whereas, for Plato, it is part of his theory of the virtuous soul and its *harmonia*.<sup>14</sup>

Eudoxus' innovations in astronomy include the use of homocentric spheres to explain planetary motion (for which he is best known today) and an improved sundial, both of which are discussed below. But we maintain that his fundamental contribution was the two-sphere model: an arrangement of two concentric spheres in which the inner sphere represents the earth, and the outer, the orb of the fixed stars. (By "model," we mean the mathematical analogy of the celestial and terrestrial spheres, an analogy which was exploited on the principle that the properties of one must correspond to the properties of the other. We are not here concerned with the ontological and epistemological status of this model.)<sup>15</sup> It is unlikely that any one of the components of this model was novel: the curvature of the celestial vault or its depiction as a concave hemispherical bowl, the sphericity of the cosmos as well as of the earth, and the belief that the fixed stars rotate about the earth in circular orbits are all attested prior to Eudoxus. Moreover, the myth of Er in Book X of Plato's *Republic* and the construction of the world-soul in his *Timaeus* suggest a multisphere model of

<sup>13</sup> Aristotle, *Metaphysica* 985b23–986a3; our trans. from W. D. Ross, *Aristotle's Metaphysics* (rev. ed., Oxford: Clarendon Press, 1953), Vol. II. On Aristotle's reconstruction of Pythagorean thought, see A. C. Bowen, *The Preface to Plato's Dialectic: The Science of Music*, Ch. 5 (forthcoming).

<sup>14</sup> For defense of this account of Pythagorean astronomy and explanation of Plato's assessment of it in the *Republic*, see Bowen, "Archytas"; A. C. Bowen, "Plato on Science and the Sciences," *Ancient Philosophy*, 1983, 3(2), forthcoming; and Bowen, *Plato's Dialectic*, Ch. 6.

<sup>15</sup> For a different assessment of Eudoxus' contribution to astronomy, see E. Maclaughlin, "The Constants of Nature," *Philosophia* (Athens), 1974, 4:211–246; and Maclaughlin, "The Spider in the Sphere: Eudoxus' Arachne," *Philosophia* (Athens), 1975/76, 5/6:225–257. For an instance of the theoretical revision of the celestial sphere as a consequence of change in the conception of the terrestrial sphere, see B. R. Goldstein, "The Obliquity of the Ecliptic in Ancient Greek Astronomy," *Archives Internationales d'Histoire des Sciences* (forthcoming).

the heavenly motions. But these passages, like those in which the other elements of Eudoxus' scheme are found, are not texts in astronomy: they belong to a tradition of cosmological-moral theory. Eudoxus' originality lay in using the two-sphere model, with its fixed spherical earth and its rotating sky, to account for the risings and settings of stars, to provide a framework for geographical studies, and to justify a more mathematically sophisticated sundial. At the same time, he laid the foundations for the application of geometrical argument to the study of celestial phenomena, an application manifested a generation later in the extant texts of Autolycus and Euclid.

The fullest definition of the two-sphere model (see Figs. 1 and 2) appears in Strabo's *Geography* (first century B.C.):

Thus we must take as an hypothesis that the heavens have five zones, and that the earth also has five zones, and that the terrestrial zones have the same names as the celestial zones. . . . The limits of the zones can be defined by circles drawn on both sides of the equator [equinoctial circle] and parallel to it, namely, by two circles which enclose the torrid zone, and by two others, following upon these, which form the two temperate zones next to the torrid zone and the two frigid zones next to the temperate zones. Beneath each of the celestial circles falls the corresponding terrestrial circle which bears the same name: and, in like manner, beneath the celestial zone, the terrestrial zone.

The same idea is found in Aristotle's *Meteorology*:

There are two inhabitable sections of the earth: one near our upper, or northern pole, the other near the other or southern pole; and their shape is like that of a tambourine. If you draw lines from the center of the earth they cut out a drum-shaped figure. The lines form two cones; the base of one is the tropic, of the other the ever-visible circle, their vertex is at the center of the earth. Two other cones towards the south pole give corresponding segments of the earth.<sup>16</sup>

The following passage makes it possible to date the invention of this two-sphere model within rather narrow limits. In the *Meteorology* one reads:

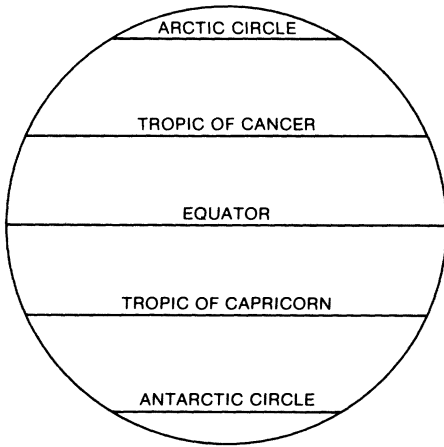
Again in the archonship of Nicomachus a comet appeared for a few days about the equinoctial circle (this one had not risen in the west), and simultaneously with it there happened the storm in Corinth. That there are few comets and that they appear rarely and outside the tropic circles more than within them is due to the motion of the sun and the stars. For this motion does not only cause the hot principle to be secreted but also dissolves it when it is gathering.<sup>17</sup>

The passage mentions an event in the year 341 B.C.; the equinoctial circle referred to here is the celestial equator. Aristotle speaks of two other comets, but both are prior to this date (427/426 and 373/372 B.C.) and neither is defined with respect to circles in the heavens;<sup>18</sup> we doubt, therefore, that the two-sphere model

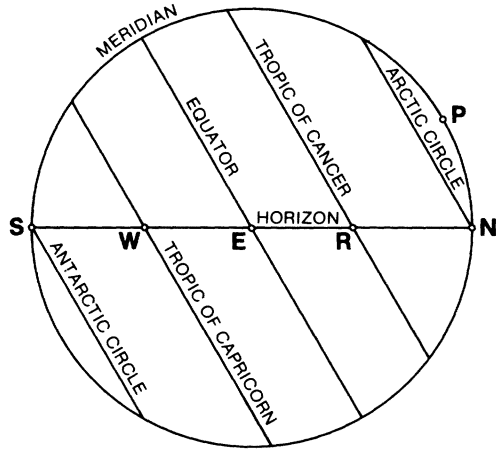
<sup>16</sup> Strabo, *Geographica* 2.5.3, from H. L. Jones, ed. and trans., *The Geography of Strabo* (Loeb Classical Library) (Cambridge, Mass.: Harvard Univ. Press, 1917), Vol. I, pp. 425-427 (see Germaine Aujac, "L'image du globe terrestre dans la Grèce ancienne," *Revue d'Histoire des Sciences*, 1974, 27:193-210); Aristotle, *Meteorologica* 362a32-b5, trans. from E. W. Webster, *Aristotle: Meteorologica*, in W. D. Ross, ed., *The Works of Aristotle*, Vol. III (Oxford: Clarendon Press, 1931).

<sup>17</sup> *Ibid.*, 345a1-8.

<sup>18</sup> *Ibid.*, 343b1-7.



**Figure 1.** The zones of the earth in cross section.



**Figure 2.** The zones of the sky for a latitude in the northern hemisphere in cross section, where P is the pole of the equator, S the south point and N the north point on the horizon.

was developed until shortly before 341 B.C. It is highly implausible that the reference to the equinoctial circle was added to the observational report at a later date. Moreover, the model can reasonably be dated after 372 B.C., and probably after the composition of Plato's *Timaeus*, which was written sometime between 367 and 347 B.C.<sup>19</sup>

That Eudoxus used the two-sphere model is clear from passages in which he locates on the celestial sphere the tropics, the equator or equinoctial circle, the arctic and antarctic circles—or, as he terms them, the circles of the ever-visible and the ever-invisible stars—according to the fixed stars that lie on them, and defines locations on earth by reference to the tropical circles. Moreover, in three different sources, including Galen's *History of Philosophy* (second century A.D.), we are told: "Eudoxus says that the [Egyptian] priests claim that the flood-waters [of the Nile] occur according to the change of the seasons. When we who live beneath the summer tropical circle have summer, those who live on the opposite side [of the equator] beneath the winter tropical circle then have winter, from which regions the flood-waters break forth."<sup>20</sup>

That Eudoxus actually invented the two-sphere model is supported by Vitruvius's discussion of sundials. According to Vitruvius, Eudoxus or Apollonius

<sup>19</sup> See F. M. Cornford, *Plato's Cosmology: The "Timaeus" of Plato* (London: Routledge & Kegan Paul, 1937), p. 1; H. F. Cherniss, "The Relation of the *Timaeus* to Plato's Later Dialogues," *American Journal of Philology*, 1957, 78:225–266 (rpt. in *Harold Cherniss: Selected Papers*, ed. L. Tarán [Leiden: Brill, 1977], pp. 298–339).

<sup>20</sup> Galen, *De philosophia historia* 23, in C. G. Kühn, ed., *Claudii Galeni Opera omnia*, Vol. XIX (Leipzig: Teubner, 1830; rpt. Hildesheim: Olms Verlag, 1965) (= H. Diels, *Doxographi Graeci* [henceforth, *DG*], 4th. ed. [Berlin: De Gruyter, 1965], p. 386) (= *Eudoxus* F288). See *Eudoxus* F1–2 (celestial sphere: cf. T14, F3b), F11 and 76 (north pole), F64a–b (ever-visible or arctic circle), F64–65 (summer tropic or Tropic of Cancer), F69 and 71 (equinoctial circle or equator), F72–73 (winter tropic or Tropic of Capricorn), F74 (ever invisible or antarctic circle), F76–78 (solstitial and equinoctial colures). Eudoxus also used this two-sphere system to define geographical latitude (*clima*): see *Eudoxus* F350, F67–68.

invented the *arachnê*, a device which Vitruvius seems to think is a sundial. But we take the *arachnê* (literally, the spider web) to be a network of intersecting lines or curves and, for sundials, this is the projection on the dial surface of the celestial equator and tropics, which are intersected by the lines for the twelve seasonal hours (of which six lie to the east of the meridian and six to the west).<sup>21</sup> Since such lines are found on extant dials of the third century B.C., Vitruvius's alternative suggestion that Apollonius (second century B.C.) may have devised the *arachnê* is not to be given serious consideration.<sup>22</sup> Such a network of lines allows one to tell time with moderate accuracy. But it should not be confused with a coordinate system; indeed, there is no evidence of such a system in early Greek astronomy.

On what sort of sundial did Eudoxus put his *arachnê*? We think a hemispherical bowl most likely. It is "natural" to transfer the equator and the tropics from the celestial vault to a bowl-shaped sundial, which is simply the vault of the sky turned upside down. The day arc of the sun in the sky thus becomes an arc of a circle in the bowl, and the hour lines for sunrise and sunset are well defined.<sup>23</sup> The horizontal plane-dial is, in fact, much more complicated and requires considerable knowledge of conic sections before the appropriate curves can be drawn on it.

According to Vitruvius, Aristarchus (third century B.C.) invented the hemispherical bowl-dial, and there is independent evidence that Eratosthenes (third century B.C.) used one whose rim lay in the horizontal plane.<sup>24</sup> In his list of inventors of sundials, Vitruvius assigns the first sundial, a hemispherical bowl-dial cut for the latitude of its location, to Berosus the Chaldean who, he tells us elsewhere, transmitted Babylonian astrology to the Greeks.<sup>25</sup> Berosus (ca. 300 B.C.) wrote a history of Babylonia in Greek, preserved only in fragments, that concerns the period from creation to Alexander the Great; he is also supposed to have founded a school of astrology on the island of Cos. His scientific activity is reported by Pliny, Seneca, and Vitruvius; and none of their remarks suggests that he had the mathematical ability required to design a cut hemispherical dial. For this reason, we agree with Albert Rehm in mistrusting Vitruvius's claim that Berosus invented this sundial. Moreover, since the *polos* referred to in the passage from Herodotus cited above was a hemispherical bowl and not a plane-dial, we also doubt that the former was invented by Aristarchus

<sup>21</sup> Vitruvius, *De architectura* 9.8.1 (= *Eudoxus* D17), trans. in F. Granger, *Vitruvius: On Architecture* (Loeb Classical Library) (Cambridge, Mass.: Harvard Univ. Press, 1931–1934), Vol. II, p. 255; *arachnê* may mean either spider or spider web; Granger wrongly prefers the former. A seasonal hour is 1/12 of the period of daylight or night (i.e., from sunrise to sunset or from sunset to sunrise); it varies in length from day to day throughout the year (on seasonal hours, see Neugebauer, *Exact Sciences*, pp. 81–91).

<sup>22</sup> See Sharon L. Gibbs, *Greek and Roman Sundials* (New York/London: Yale Univ. Press, 1976), pp. 5, 10: for examples of spherical sundials dating from the third century B.C., see pp. 123, 158.

<sup>23</sup> *Ibid.*, pp. 12–14.

<sup>24</sup> Vitruvius, *De architectura* 9.8.1. On Eratosthenes, see Cleomedes, *De motu corporum caelestium* 94.23–100.23, trans. in I. Thomas, *Greek Mathematical Works* (Loeb Classical Library) (Cambridge, Mass.: Harvard Univ. Press, 1941), Vol. II, pp. 267–273. On the design of this sundial, see Gibbs, *Sundials*, pp. 14–18, 66–71, 122–123.

<sup>25</sup> Vitruvius, *De architectura* 9.6.2 (Granger, *Vitruvius*, Vol. II, p. 247). Here Vitruvius uses the term "astrology" unambiguously to signify a system of divination. The modern discovery of Babylonian texts has led to skepticism concerning the reliability of Greek and Latin reports on the relationship of Hellenistic astrology to its Babylonian predecessors: see Neugebauer, *Exact Sciences*, pp. 187–189; Neugebauer, *HAMA*, pp. 474, 609–610.

and that the cut hemispherical sundial was invented first, and follow Rehm in saying that by "inventor" Vitruvius simply meant the earliest person known by him to have described or used a certain kind of dial.<sup>26</sup>

As to whether some other astronomer who was a contemporary or predecessor of Eudoxus could have devised the two-sphere model and used it in this way, the available evidence suggests not. Both Meton and Democritus might be thought to have the requisite credentials, but there are fatal difficulties in either case. Meton is the earliest authority cited in the *parapêgma* tradition; and he is credited with an observation made on 27 June 432 B.C. of the summer solstice, which served as the starting point for the Greek astronomical calendar. Furthermore, he is considered the discoverer of the nineteen-year calendaric cycle, known as the Metonic cycle, in which nineteen years correspond to 235 synodic months.<sup>27</sup> But, in none of this is there any hint of a model. Even if it is suspected that Meton was influenced by the Babylonians in setting up the nineteen-year cycle and in deciding the date of the summer solstice, a suspicion that has arisen since the recovery of Babylonian astronomical texts in this century, it still remains true that no model is presupposed. Indeed, the Babylonians used an arithmetical scheme to determine the summer solstices in a nineteen-year cycle. This scheme was based, apparently, on the date in their calendar for the heliacal rising of the star Sirius: summer solstice was thought to occur 21 days before this rising.<sup>28</sup> Meton was also understood to be concerned with the division of the year into seasons. In the *Ars Eudoxi*, a papyrus of the second century B.C. that exhibits the state of astronomy in the third century, it is reported that Euctemon, whose accomplishments are not well distinguished from those of Meton in our sources, divided the year into four unequal seasons of 90, 90, 92 and 93 days, beginning with summer.<sup>29</sup> In Simplicius's commentary on Aristotle's *De caelo*, the inequality of the seasons is ascribed to both Meton and Euctemon. (Rehm is probably correct in arguing that Meton and Euctemon simply posited 7 consecutive zodiacal months of 30 days each, and 5 consecutive zodiacal months of 31 days each; that is, that he had no intention of describing the length of the seasons.)<sup>30</sup> The *Ars Eudoxi* also states that Eudoxus and Democritus pre-

<sup>26</sup> See A. Rehm, "Horologium," col. 2419, in A. Pauly, G. Wissowa, W. Kroll, eds., *Real-Encyclopädie der klassischen Altertumswissenschaft* (Stuttgart: Metzler, 1913), Vol. VIII. On Berossus' date, see Neugebauer, *HAMA*, p. 607. For his work, some of which seems more pertinent to astrology than astronomy, see F. Jacoby, *Die Fragmente der Griechischen Historiker* (hereafter *FGH*) (Leiden: Brill, 1959), Part III.C, Vol. 1, pp. 367–393, No. 680, esp. frags. T5b, T5c, T6, F22a, F16b, F21, F18, F19, F17. The fragments of Berossus' writings are also collected in P. Schnabel, *Berossus und die babylonisch-hellenistische Literatur* (Leipzig: Teubner, 1923).

<sup>27</sup> See Heath, *Aristarchus*, pp. 293–295; Neugebauer, *HAMA*, p. 622; B. R. Goldstein, "A Note on the Metonic Cycle," *Isis*, 1966, 57:115–116. Theophrastus, in *De signis pluvium, ventorum, tempestatis et serenitas* 4 (= DK 6 A1), states that Meton, an Athenian, learned of this cycle from Phaeinos, a resident alien in Athens who observed the solstices from Mount Lycabettus. Nothing else is known of Phaeinos, but could Babylonian data have been transmitted to Meton through him? As for the observation itself, Meton is supposed to have used a *heliotropium* near the wall of the Nyx: see Maass, *Aratea*, pp. 13–14; Heath, *Aristarchus*, p. 294, n. 3.

<sup>28</sup> See Neugebauer, *HAMA*, pp. 357–365 (esp. p. 363).

<sup>29</sup> The *Ars Eudoxi* or *Didascalia caelestis* by Leptines is translated into French in Tannery, *Recherches*, pp. 283–294: see p. 294; cf. Neugebauer, *HAMA*, pp. 627–628, 686–687. The same source also reports that Callippus, a successor of Eudoxus, divided the year unequally into seasons. But this division does not conform to that of Euctemon and was presumably based on different considerations.

<sup>30</sup> Simplicius, *In de caelo* 497.17–24 (trans. in Heath, *Aristarchus*, p. 213); Rehm's argument is summarized in Neugebauer, *HAMA*, pp. 628, 1352 and Fig. 3.

ferred to keep the seasons equal, so Meton's proposal for the length of the zodiacal months did not find acceptance among his immediate successors. But, once again, there is no reason here to connect Meton with the two-sphere model.

Democritus flourished at the close of the fifth century and is often associated with Eudoxus in the extant sources. His mathematical achievement, his work in the *parapêgma* tradition, his speculation about the nature and causes of celestial as well as meteorological phenomena, are all preserved in fragmentary form by later writers. But however remarkable his credentials in mathematics, astronomy, and even geography, he did not conceive of the two-sphere model: he believed that the earth was dislike, basically flat but hollowed out slightly in the center.<sup>31</sup>

Eudoxus is, therefore, the most likely figure to have conceived of using a two-sphere model to account for the stellar risings and settings associated with the calendar. It is also possible to reconstruct how Eudoxus might have based his well-known analysis of planetary motion using homocentric spheres on the two-sphere model. His interest in planetary motion was unusual: Plato states that the periods of the planets had been understood by only a very few; and these few, we suggest, were not those astronomers concerned with *parapêgmata* but Pythagorean cosmologists or philosophers.<sup>32</sup>

To extend the two-sphere model so as to account for the sun's motion seen as the set of circular paths of its shadow on the hemispherical sundial, it suffices to observe that this path shifts from day to day and that it is limited by the circles representing the tropics on the dial. Two spheres for the sun can account for this motion: one sphere which rotates once each day, and another whose axis is inclined to it, which completes one revolution in the opposite direction each year. Both spheres rotate uniformly but at different speeds and in contrary directions. This discovery could occasion a general investigation of the behavior of two such pairs of spheres rotating uniformly with axes inclined to one another, where the speeds are either equal or unequal, and the directions, either the same or opposite. Inclined spheres rotating at the same speed but in opposed directions about different poles lead to the hippopede, a path shaped roughly like the figure 8. Eudoxus' next step would be to realize that an additional rotation would allow the hippopede to account for the retrograde arcs that are characteristic of planetary motion.<sup>33</sup>

According to Aristotle, Eudoxus used three spheres for the sun and moon, and four for each of the five planets. In all seven cases, the first sphere was that of the fixed stars, its function being to supply the daily rotation, and the second sphere accounted for motion along the ecliptic. The third sphere for the sun and moon was to take care of their motion in latitude: as Aristotle says,

<sup>31</sup> See Aristotle, *De caelo* 294b13–21; Simplicius, *In de caelo* 511.22–25; Diels, *DG*, p. 377. Democritus is said to have written a geographical survey: see Agathernus, *Hypotyposes geographiae* 1.1 (= Eudoxus F273a). Compare Democritus's account of the seasonal flooding of the Nile in Galen, *De philosophia historia* 23 (= Diels, *DG*, p. 385) with Eudoxus' explanation cited above: Democritus makes no reference to a two-sphere model.

<sup>32</sup> Plato, *Timaeus* 39c5–d2; see A. E. Taylor, *A Commentary on Plato's "Timaeus"* (Oxford: Clarendon Press, 1928), ad loc. Plato surely cannot mean the parapegmatists (see *Respublica* 527d1–528a5, 528e6–529c6), and there is no evidence that the Pythagoreans as such ever involved themselves in the construction of *parapêgmata*: see notes 6, 11, and 14 above.

<sup>33</sup> See A. Aaboe, "Scientific Astronomy in Antiquity," *Philosophical Transactions of the Royal Society of London*, 1974, A.276:21–42; Neugebauer, *HAMA*, pp. 677–685, 1357–1358.

“the circle in which the moon moves is inclined to the zodiac at a greater angle than that in which the sun moves.” That Eudoxus allowed the sun a small variation in latitude is confirmed by Hipparchus: “And that this occurs even Eudoxus admits. Indeed, in his *Enoptron* he declares that the sun appears to vary in its positions at the solstices as well, a variation which is rather obscure and extremely slight.”<sup>34</sup> One may suppose that Eudoxus has here accepted a traditional claim about solar motion, and that it did not affect his basic analysis of the apparent motion of the shadow cast by the gnomon on the surface of a hemispherical sundial. Four spheres for the planets were needed to account for their phenomena, including stationary points and retrogradations.

In the period after Eudoxus, the following astronomers and mathematicians studied Eudoxus’ model for planetary motions: Menaechmus, who is better known for his work on conic sections; Callippus, who altered Eudoxus’ model by adding more spheres; Autolycus, who criticized it for failing to account for the apparent variation in the sizes (i.e., brightnesses) of Mars and Venus, a physical consideration that Eudoxus may have been prepared to ignore; and Polemarchus, a student of Eudoxus.<sup>35</sup> Aristotle had a theory of nested homocentric spheres as well. But of these, Autolycus seems to have been the most influential: there is no evidence of any adherence to homocentric models by ancient astronomers after him. Yet the two-sphere model was never abandoned in antiquity. During the third century, astronomers shifted attention from planetary models to the study of the sizes and distances from the earth of the moon and the sun, of the phases of the moon, and of topics that relate to the general investigation of eclipse phenomena.<sup>36</sup> Interest in stellar risings and settings continued, but it no longer defined the activity of astronomers as before.

By the time of Hipparchus (second century B.C.), Babylonian astronomical data reached the Greek world, although the mode of transmission is unknown. Babylonian astronomy was centuries old and, when it reached the Greeks, it was highly successful at predicting planetary phenomena and lunar eclipses: though they lacked geometrical models, the Babylonians had achieved precise knowledge of planetary and eclipse cycles, and their science was supported with copious quantitative data. The result was a radical transformation of Greek astronomy: Hipparchus not only had access to this data, but also acquired from the Babylonians the notion of quantitative prediction. For he took the Greek models of planetary motion, models whose explanatory function had hitherto been qualitative, and, by using Babylonian data, specified their parameters so as to adapt them for quantitative prediction.<sup>37</sup> This influx of Babylonian data

<sup>34</sup> Aristotle, *Metaphysica* 1073b17–32. Eudoxus F63b: cf. F62, F63a. See Neugebauer, *HAMA*, pp. 629–631.

<sup>35</sup> Simplicius, *In de caelo* 504.17–506.3 (trans. except for 505.11–17 in Heath, *Aristarchus*, pp. 221–223). See also G. Aujac et al., *Autolycus de Pitane: La sphère en mouvement, levers et couchers héliques, testimonia* (Paris: Société Guillaume Budé, 1979), pp. 178–182.

<sup>36</sup> For references to the two-sphere model, in addition to the passages cited above, see those from Posidonius (ca. 100 B.C.) and Ptolemy in Cohen and Drabkin, *Source Book*, pp. 156–181. For later work, see, e.g., Aristarchus’s treatise on the sizes and distances of the sun and moon in Heath, *Aristarchus*, pp. 351–414; Alan E. Shapiro, “Archimedes’s Measurement of the Sun’s Apparent Diameter,” *J. Hist. Astron.*, 1975, 6:75–83; the report on the accounts of lunar phases given by Berossus and Aristarchus in Vitruvius, *De architectura* 9.2.1–4; and, on the treatment of eclipses in the *Ars Eudoxi*, Neugebauer, *HAMA*, p. 688.

<sup>37</sup> See, e.g., Asger Aaboe, “On the Babylonian Origin of Some Hipparchian Parameters,” *Centaurus*, 1955, 4:122–125.

and the resultant transformation of Greek astronomical science effectively obscured the earlier history of this science from later writers. As a consequence, the historian must now exercise care in relying on late testimony in his effort to understand the development of Greek astronomy from the time of Hesiod and Homer to the time when Babylonian science intruded.

The preceding account of the development of early Greek astronomy shows that it may be divided into two phases. The first is defined by the construction of calendars in the form of *parapêgmata*. It is contemporaneous with a tradition of cosmological theorizing in which were treated questions about the nature of the heavenly bodies and their motions. The second begins with Eudoxus' synthesis of these two sorts of activity, and his introduction of homocentric spheres as models to explain the motions of the celestial bodies. Not long thereafter, such models for planetary motion were rejected, and astronomers turned their attention to the study of eclipses, the determination of the sizes and distances of the sun and moon, and the explanation of lunar phases.