ARISTARCHUS AND THE MOVING EARTH

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One of the most imaginative and revolutionary ideas that the Greeks bequeathed to the modern world was the concept of a moving earth. The story has been fully told by Sir Thomas Heath in his great book *Aristarchus of Samos* but many historians of science have tended to treat it rather as a sort of deviation from the main highway of Greek astronomy that runs through Eudoxus, Apollonius and Hipparchus to Ptolemy. It is more realistic to identify another branch-route from the Pythagoreans via Aristarchus to Copernicus and Kepler. The aim of this paper is to present the heliocentric theory more as an integral chapter in the history of Greek thought, and I have collected together most of the relevant source material, either quoted in extenso or given in reference.

Aristarchus hailed from Samos, the homeland of Pythagoras. He belongs to the early Hellenistic era, and his floruit may be put c. 270 BC. He is said to have been a pupil of Straton, the physicist, head of the Lyceum after Theophrastus, and he is most commonly referred to as ‘the mathematician’. Only one of his books is extant, a short one on the ‘Sizes and Distances of the Sun and Moon’, and this assumes a geocentric cosmos in the style that had eventually become established during the fourth century.

But for his heliocentric cosmos we have excellent authority in a book by Archimedes, who was only 20-30 years younger and equally skilled in mathematics. In a short work entitled *Psammites* (usually known by its Latin name *Arenarius*) Archimedes develops a method of expressing astronomically large numbers, and demonstrates how to count the number of grains of sand that would fill the entire universe. For this purpose he adopts as his definition of the cosmos the sphere whose radius is the distance from the earth to the sun, which he says is the one in general use by astronomers. The choice of the sun as the limit rather than the fixed stars may perhaps be explained by the fact that contemporary research was beginning to find ways of measuring distances as far as the sun, but had no possible means of attempting to measure the distance of the fixed stars.

At all events, having thus defined his limited cosmos, Archimedes then alludes to a much greater one envisaged by Aristarchus (*Aren.* 1.4):

Aristarchus of Samos published an account of certain hypotheses, in which it follows from his premisses that the cosmos is much bigger than the one now so-called. His hypotheses are (i) that the fixed stars and the sun are stationary, (ii) that the earth revolves round the sun along the circumference of a circle, with the sun situated at the centre of the orbit, (iii) that the sphere of the fixed stars is situated about the same centre as the sun, and (iv) is so vast that the circle round which he supposes the earth to revolve bears

the same kind of ratio to the distance of the fixed stars as the centre of the sphere to its surface.

In other words, compared with the great distance of the fixed stars the radius of the earth's orbit is a negligible quantity. Archimedes goes on to comment:

Of course it is obvious that this is impossible. The centre of the sphere has no magnitude, and it cannot be assumed that it bears any ratio at all to the surface of the sphere. But it must be understood that what Aristarchus means is this: just as we assume that the earth is, as it were, the centre of the cosmos, the ratio that the earth bears to what we call the cosmos is the ratio that the sphere in which the earth's orbit is supposed to be bears to the sphere of the fixed stars. He adapts the evidence of the phenomena to such a hypothesis, and in particular he appears to assume that the size of the sphere in which he makes the earth revolve is equal to what we call the cosmos.

Archimedes, then, has no objection to this fourth hypothesis, and sees it as a reasonable extension of the normal practice of astronomers. In the geocentric system the cosmic centre is strictly speaking the centre of the earth, but in practice the earth as a whole is assumed to be the centre, because the distance from the centre to the surface of the earth is negligible compared with the distance of the sun, and so the observer anywhere on the surface can be counted as the centre of the cosmos. Similarly in the heliocentric system the centre of the system is strictly the centre of the sun, but the distance from the sun to the earth is taken to be negligible compared with the distance of the fixed stars, so the observer on the earth's surface at any point in the earth's orbit can be assumed to be the centre of the sphere of the fixed stars. Hence the very neat and convenient proportion: earth is to earth's orbit as earth's orbit is to sphere of fixed stars. Throughout his book Archimedes keeps coming back to this Aristarchan system and to the equating of the size of the earth's orbit with the size of the conventional cosmos.

There remains one other hypothesis in Aristarchus's scheme, and that is the rotation of the earth on its axis. This is not mentioned by Archimedes, because it is not relevant to his subject-matter, but it is recorded by Plutarch, *De Facie in Orbe Lunae* 923a:

Cleanthes thought that Aristarchus of Samos ought to be prosecuted by the Greeks for impiety for moving the hearth of the universe, because he tried to save the phenomena by assuming that the sky is stationary and that the earth revolves in an oblique circle while at the same time rotating on its own axis.
It should be noted that several other late sources confirm one or more of the Aristarchan hypotheses.2

Another passage in Plutarch raises the interesting question of the status of these hypotheses, i.e. do they offer a possible account of the universe, or are they purely imaginary for the sake of the mathematical exercise? Plutarch in his Platonicae Quaestiones 1006c gives us the information that Seleucus of Seleucia, probably about the middle of the second century BC, also adopted the heliocentric theory, but he contrasts Aristarchus as ‘only supposing’ with Seleucus as ‘also demonstrating’ it. Some modern scholars interpret the ‘only’ as implying a purely mathematical hypothesis, as was Eudoxus’ model of concentric spheres, designed to explain the movements of the planets. And as a matter of fact it came to be understood later that the business of astronomers was to work out a scheme that would allow accurate prediction of the celestial movements, whereas it was for the physicists to tell us the real nature of the universe. This is a distinction attributed to Posidonius,3 early in the first century BC. But Aristarchus’s concern with the consequential need to assume a vast distance for the fixed stars indicates that he meant the theory as a possible explanation of the real universe: he need not have bothered about the fixed stars if all he wanted was a mathematical exercise. And apparently the theory was taken seriously by the contemporary Cleanthes and by later writers who refer to it or refute it. So I suggest that the point of the ‘only’ in Plutarch is that Aristarchus merely put forward the hypothesis without any supporting arguments, whereas Seleucus in adopting the hypothesis also backed it with supporting arguments. He had, of course, no evidence available to him whereby he could actually prove it to be true.

There is no record of the arguments that Seleucus or anyone else used to back the heliocentric hypothesis, but it is not difficult to imagine some considerations that might have made the idea attractive. In the first place, the concept of a moving earth had already been mooted much more than is commonly realised, and Aristarchus’s theory could have been seen as a logical next step. As early as the sixth century, and as soon as the earth came to be thought of as freely suspended in space (Anaximander’s ‘meteoros’4), questions were naturally asked about why it should remain stationary, and such questions implied at least the possibility that it might move. Once the spherical sky became established in the fifth century, the Pythagoreans came out with the startling notion that the worthiest element, fire, should occupy the centre of the universe, and the earth and planets should then be thought of as circling round it.5 Our earliest source

2. Aetius 2.24.8; Galen, Placita 66; Schol. ad Aristot. p.495 (Brandis); Sextus Empiricus, Adv. Math. 10.174; Simplicius, in Ar. De Caelo 444-5.
4. Hippolytus, Phil. 6.3; Theon Smyrn. f.26a (Martin p.324).
5. Cic. Acad. Pr. 2.123; Aetius 3.9.2; 3.11.3; Diogenes Laertius 8.85; Hippolytus, Phil. 15.1-2; Plut. Numa 11.1-2; Simplicius, in De Caelo 519.
for this is Aristotle, *De Caelo* 293a:

It remains to speak of the earth, its position, whether it is one of the stationary or moving bodies, and what its shape is. Not all men have the same opinion about its position. The majority say it is in the centre, and they are the ones who say that the universe is finite, but the opposite is said by the Italian school known as the Pythagoreans. They say there is a fire at the centre, and that the earth as one of the planets creates day and night by moving in a circle round the centre.

This system is attributed by Aetius and Galen to Philolaus, a late fifth century Pythagorean, and Aristotle’s account seems to suggest that Pythagoreans were still talking about it in his time. It was a fantastic idea, which had unforeseen consequences for astronomy, and it illustrates the freedom and flexibility with which people were able to think about the universe before the geocentric system became institutionalised and rigorously taught in the schools of later antiquity and the middle ages. Aetius (*Placita* 3.13) has collected a little section on the moving earth, showing different approaches to the question.

One of these envisaged the daily rotation of the earth on its axis as a simple way of explaining the phenomena of day and night. This idea is attributed by various writers to the fourth century Pythagoreans Ephrantus and Hicetas of Syracuse and Heraclides of Pontus. Cicero, *Academica Priora* 2.123, quotes Theophrastus as authority for Hicetas:

Hicetas of Syracuse, as Theophrastus says, thinks that the sky, sun, moon, stars, in fact all celestial bodies, are stationary, and nothing moves in the universe but the earth, and as it turns and rotates about its axis at great speed the same effects are produced as if the earth were stationary and the sky in motion.

At this point Cicero adds a note to the effect that some people attribute a rotating earth to Plato in the *Timaeus*, ‘sed paulo’, as he rightly observes, ‘obscurius’.

The question of what Plato really meant in *Timaeus* 40b is still hotly debated. The critical word is ‘ιλλομένην’ (or its variant ‘εϊλομένην’) in the passage:

He devised the earth, our foster-mother, ‘ιλλομένην’ round the axis that extends through the universe, as guardian and creator of night and day, first and eldest of the gods that have been created within the cosmos.

Unfortunately ‘ιλλεοθα’ is an ambiguous word, which can describe either movement, as of men swarming round (*Iliad* 5.203), or rest, as of sails tightly
furled (A.R. 1.329). In the *Timaeus* context it has been taken to mean either ‘rotating round’ or ‘tightly packed round’. Now as Plato elsewhere consistently presents a cosmos with the earth at rest in the centre, the latter sense is clearly the appropriate one for Plato, and it suits the basic sense of the verb, and it is also the only one that makes astronomical sense, because only a stationary earth can be guardian of night and day if it has the sun circling round it. Such is the interpretation implied by Cicero, *Timaeus* 37: ‘quae trajecto axe sustinetur’. And it is specifically confirmed by Plato’s late commentators Proclus and Chalcidius. But according to Aristotle, there were some who tried to interpret Plato’s verb as implying motion, and he twice quotes the passage with the words ‘καὶ κυλεύσθαι’ added to Plato’s ‘ιλλεσθαι’.

Some modern scholars (e.g. A.E. Taylor and F.M. Cornford) have been at pains to save Aristotle from the charge of misrepresenting Plato, and they have forced a sense of rotation on the controversial verb, which even when implying motion never means that. But Aristotle does not in fact attribute this sense to Plato, but only to ‘some’ who have interpreted the words in this sense. These would be contemporary Pythagoreans, anxious to enlist the authority of Plato on their side; and the interesting point in Aristotle’s comments is that they reveal a considerable controversy going on in the second half of the fourth century as to whether the earth is in motion or not. Thus when Aristarchus propounded his theory a few decades later, he was to a large extent combining the older Philolaic notion of the earth in orbit with the later Pythagorean belief in a rotating earth. The main novelty was that he put the earth in orbit round the sun instead of round an imaginary central fire.

A second argument in support of Aristarchus would have been the specifically astronomical one that his theory offered a single explanation of the several planetary movements as they had become apparent to investigators during the fourth century. This came to be known as ‘saving the phenomena’, a phrase attributed by Simplicius to Plato, and used, for example, by Plutarch in the passage already quoted from the *De Facie* (923a). It assumes that the movements we observe are more apparent than real and that the real movements are in perfect circles and at uniform speeds. This was a momentous assumption, which dominated astronomical research until Kepler discovered that the planets orbit in ellipses after all. The chief irregularities of the planets are: (1) a slow eastward progress through the zodiac, (2) a periodical stopping of this movement followed by a retrogradation westwards and then a resumption of the eastward progress, (3) movement in latitude north and south of the ecliptic, (4) variations

6. *In Timaeum* 281d-e.
11. *In De Caelo* 488.18.
in speed apart from the retrograding loop, and (5) variations in brightness, which imply varying distance from the earth. By putting the earth into orbit Aristarchus offered a means of explaining all these irregularities at once, and even Ptolemy had to concede that ‘as far as the stellar phenomena are concerned, there is perhaps nothing to prevent the theory being true, in view of the greater simplicity of the concept’. The only weakness of the theory was the assumption of circular orbits and uniform speeds, so that the mathematical data obtained from it would not in fact have agreed with the observed phenomena.

A third argument that ought to have favoured Aristarchus’s theory was the appropriateness of having a system with the sun as centre. It is often said that the Greeks were never sun-worshippers, and on the whole this is true. But something of this Middle East cult did filter through, and it is relevant to recall the story Plato tells in the Symposium (220d) about Socrates after his night-long trance offering a prayer to the sun before going about the business of the day, or to remember that the Rhodian colossus was a sun-god statue, or to think of the many invocations of Apollo as sun-god that occur throughout Greek poetry.

So with the philosophers. Plato in Rep. 508-9 takes the sun in the visible world as a symbol of the Good in the intelligible world, and even in the Timaeus creation-myth we find the sun being given a special role to measure time and to illuminate the whole cosmos. We have seen too how the Pythagoreans regarded fire as a worthier element than earth, and so more appropriate as a cosmic centre. Even Aristarchus’s critic Cleanthes is recorded by more than one authority as believing the sun to be the ruling principle of the cosmos, because it is the largest of the planets and contributes most to the economy of the whole. Cicero in his Somnium Scipionis (17) similarly describes the sun as chief luminary, ‘dux et princeps et moderator luminum reliquorum, mens mundi et temperatio etc.’

In the same passage Cicero also writes of Venus and Mercury as the sun’s attendants in its progress round the zodiac. It had been known at least since the fourth century in Greece that these two planets traverse the zodiac in the same period as the sun, and that they are never seen at a greater angular distance than about 45° from it. It is therefore not surprising that some time in the Hellenistic era the idea emerged of Venus and Mercury moving in orbits round the sun. This theory used to be ascribed to Heraclides on the strength of a passage in Chalcidius (110), but it has recently been shown that the words may not mean this. Vitruvius however describes the system clearly, as if it were an accepted belief, so it must have originated in the Hellenistic period and found

12. Syntaxis 1.6 (Halma I p.19).
14. Arios Didymus, Epit. fr. phys. 29.7; Aetius 2.4.16; Cic. Acad. Pr. 2.126.
considerable support. It may well have appeared after Aristarchus, as a modification of the full heliocentric theory, just as it was later revived by Tycho Brahe, because he could not accept all the implications of the Copernican solar system. Some five centuries after Vitruvius it appears again in Martianus Capella, through whom it was transmitted to the Renaissance. Some medieval scholars also thought it was to be found in Macrobius, but mistakenly: the passage in question, as W.H. Stahl rightly explains, is all about whether Venus and Mercury are nearer the earth than the sun or beyond it.

So much for the arguments that might have been used in support of the heliocentric hypothesis. The arguments against it were the following. The chief astronomical argument would have been the absence of stellar parallax. That is, if the earth really did travel round such a wide orbit in space, you would expect some changes in the relative positions of fixed stars when observed from different points in that orbit. Yet no such change had ever been detected. This seems to have been the objection that Aristotle was making to the Pythagorean system in *Cael.* 296a-b: there would have to be ‘passings and turnings’ of the fixed stars. These terms are not too clear, but ‘passings’ may refer to the displacement known as parallax, and ‘turnings’ may then mean the return of displaced stars to their previous relative positions.

Aristarchus however has anticipated this objection, and has overcome it by putting the fixed stars at such a great distance that no parallax is detectable. This is why he describes the earth’s orbit as a mere point at the centre of the sphere of the fixed stars. Archimedes seems to accept this part of the hypothesis as quite reasonable, and it probably did not worry the ancient astronomers as much as some moderns think it did. The Greeks were already used to the idea of the earth being very small, since they did not have to travel very far south to bring new stars into view, as Aristotle notes in *Cael.* 297b. Similarly the distance of the sun was not thought to be so very great either. From the evidence of Aristarchus’s own treatise and from the figures given by Archimedes it seems likely that the distance of the sun was estimated at c. 2.5 million miles (actually c. 93 million miles), and the distance of the fixed stars in Aristarchus’s hypothesis somewhere between 20 and 50 thousand million miles. His earth’s orbit was therefore a mere fraction of what we know it to be today, and so the absence of stellar parallax was probably not too serious an objection to the theory.

A more weighty objection was the physical law laid down by Aristotle that
the natural movement of heavy bodies is towards the centre of the cosmos, i.e. towards the centre of the earth. He had already made this point against the Pythagorean system (*Cael. 296b*):

Further the natural movement of the earth as a whole, like that of its parts, is towards the centre of the universe. In fact this is the reason why it is situated in the centre of the universe now. But since both the earth and the universe have the same centre, the question might be asked, which of the two centres do heavy bodies and parts of the earth naturally move towards? Is it the centre as centre of the universe or the centre as centre of the earth? It must inevitably be the centre of the universe.

Later Ptolemy repeats it as a self-evident proposition that the earth occupies the centre of the cosmos and all heavy bodies move towards it (*Syntaxis* 1.6, Halma I p.17):

For the same reasons as before it will be shown that the earth cannot make any movement whatever in the sideways direction aforesaid or ever dislodge itself from its central position. This would have the same consequences as if it had had a position anywhere else than at the centre. So it is my view that it is superfluous to inquire into the reasons why it moves towards the centre, once the fact that this earth occupies the centre of the cosmos and that heavy bodies all move towards it is so clearly seen from the actual phenomena.

There was no easy argument against this seemingly self-evident doctrine.

An objection of a different kind is noted by Plutarch in the passage already cited from the *De Facie* (923a), when he recalls that Cleanthes charged Aristarchus with impiety for putting into motion the hearth of the universe. This is a curious tradition on several counts. In the first place Cleanthes, as we have seen, thought of the sun as the ruling force in the cosmos, and so might have been expected to welcome its promotion to the central place. Secondly, the term 'hearth of the universe' was one of the names the Pythagoreans applied to their central fire, and it would have suited the sun much better than the earth, though Hestia is in fact used by Plato in the *Phaedrus* (246d) with reference to the earth, and it is this myth that Cleanthes is thought to have had in mind. But in general there was no religious dogma that Aristarchus's theory could have offended in Greek society, as there was in the centuries after Copernicus. The story seems to echo the tradition about Anaxagoras being prosecuted for impiety by the Athenians, but even that may have been largely a political move by enemies of Pericles. Cleanthes was perhaps an unusually bigoted Stoic, and not typical of that sect. Other Stoics were more open-minded, e.g. Seneca (*N.Q.* 23. Aetius 2.7.7.)
7.2.3):

It will also be relevant to discuss this, so that we can know whether the sky revolves and the earth is stationary or the sky is stationary and the earth rotates. There have been men who said that it is we who are unwittingly moved by nature, and it is not the movement of the sky that causes risings and settings, but we ourselves who rise and set. The question merits consideration for the sake of knowing what conditions we live in, whether we have been allotted an inert dwelling or a fast-moving one, and whether God moves everything round us or just us.

In short, I have found no evidence for thinking that the religious objection was at all significant in the Greco-Roman world.

The fourth argument against Aristarchus is what I have called the common-sense one, and I have the impression that it was the most cogent of all. It is very difficult to believe that the great mass of the earth could be moving at such speeds, both whirling round its axis and hurtling through space round the sun, without betraying the least sign of it. Even when we know it to be true, it is still incredible, and must have been more unbelievable when the notion was only a hypothesis, however plausible on other grounds. A similar reaction greeted the Copernican revival in many quarters. For example, a French philosopher, Jean Bodin, wrote in 1597 (a full half-century after the publication of Copernicus’s book):

No one in his senses or imbued with the slightest knowledge of physics will ever think that the earth, heavy and unwieldy from its own weight and mass, staggers up and down around its own centre and that of the sun; for at the slightest jar of the earth we would see cities and fortresses, towns and mountains thrown down.24

As for antiquity, it is only in the astronomer Ptolemy that this kind of argument is extant. In Syntaxis 1.6 (Halma I pp.19-20), after contrasting the great mass of the earth with the slightness of the various objects that fall on it, he goes on to say:

But of course if the earth had a common motion, one and the same with the other heavy bodies, it would obviously have got ahead of everything else in its downward fall because of its enormous superiority in size, and all living creatures and detached heavy bodies would have been left behind floating on air, while the earth itself would speedily have fallen right out of the universe.

Well, ideas like this have only to be thought of to be seen to be utterly ridiculous.

And similarly against the earth's rotation on its axis:

At all events they would have to admit that the rotation of the earth would be the most violent of all the movements in its vicinity, considering that it takes so short a time to complete so great a revolution, with the result that everything not actually standing on the earth would be observed always moving in the same direction contrary to the earth's movement, and no cloud would ever be noticed travelling eastward, or anything flying or thrown, for that matter, because the earth would always be getting ahead of them and forestalling any eastward movement of theirs, so that everything else would be seen disappearing westwards in the direction the earth would be leaving behind it.

Well, as we all know, the arguments against the moving earth prevailed. But the theory was never lost sight of, and even within the limited range of writings now extant, no century to the end of the ancient world is without its testimony to some aspect of it. We have seen how Seleucus upheld it in the second century BC, and how Cicero and Vitruvius referred to different parts of it in the first century. In the first century AD we have one reference in Seneca and several in Plutarch and Aetius; in the second Theon of Smyrna, Ptolemy, Galen and Sextus Empiricus; in the third Hippolytus and Diogenes Laertius; in the fourth century there is the lone voice of Chalcidius, in the fifth Proclus and Martianus Capella, and in the sixth Simplicius.

After Simplicius a whole millennium passed before Copernicus, dissatisfied with the Ptolemaic system, began to explore the ancient authors in search of a viable alternative, and found in some of these surviving sources the answer to what he was looking for. In his introduction to the De Revolutionibus (1543) he pays due tribute to some of these, Cicero and Plutarch, and the Pythagoreans Heraclides, Ecphantus, Nicetas (sic) and Philolaus; and a page of his MS\textsuperscript{25} which never got into the printed edition, enshrines the observation: 'quod etiam nonnulli Aristarchum Samium ferunt in eadem fuisse sententia'.\textsuperscript{26}

\textsuperscript{25} Fol. 11v.

\textsuperscript{26} This paper was delivered at a Conference of New Zealand Universities' Classics Departments at Auckland in May 1975. I acknowledge the help of comments made in the course of the discussion.