THE PLANETARIUM OF ARCHIMEDES

Michael Wright
CHoSTM: Centre for the History of Science, Technology and Medicine,
Imperial College,
London SW7 2AJ
mtw.mechanic@virgin.net

ABSTRACT

Several authors in later antiquity look back on Archimedes as a pioneer of elaborate mechanical sphairopoiïa*, most of them referring to a planetarium that was taken to Rome at the fall of Syracuse in 212 B.C. Of these, the Roman author Cicero presents the earliest and most intelligible account. Recent work in understanding and reconstructing the Antikythera Mechanism, the oldest surviving geared artefact and an instrument in the tradition of* sphairopoiïa*, leads us to take Cicero's description seriously. We consider it in relation both to the early development of toothed gearing and to our understanding of Hellenistic kinematic planetary astronomy, and offer points towards a tentative reconstruction. The question remains, however, whether it is safe to assume that the instrument described by Cicero was indeed designed by Archimedes or was, rather, a later essay in the same genre.*

INTRODUCTION

… Archimedes … would not deign to leave behind him any commentary or writing on such subjects … repudiating as sordid and ignoble the whole trade of engineering …

Plutarch, *Parallel Lives*, Marcellus XVII 3–5.

In spite of Plutarch's view that he disdained the practical applications of mathematics, Archimedes was widely cited in later antiquity as a pioneer of *sphairopoiïa* ("sphere-making": that is, of the design and construction of models and instruments to represent celestial bodies and elucidate their motion). He was said to have written a book on the subject, perhaps already lost by the time of Pappus (4th century A.D.). Otherwise, his reputation in this field seems to have rested largely on two instruments attributed to him that were taken to Rome following the capture of Syracuse in 212 B.C. These instruments, too, were probably lost within a few centuries; and we are left with just brief notices of his activity in this field and of the models themselves. Within the necessarily limited confines of this paper we review only the more telling of these passages. We give English translations of the passages themselves, and offer specific comments on them. We then discuss them, so far as space permits, in the light of what is known of the state of development of both astronomy and the mechanical arts at the time of Archimedes, and in the light of our new awareness of what could be achieved in *sphairopoiïa* which has been brought about by our growing understanding of the one extant example in this genre from the ancient world: the Antikythera Mechanism.

TEXTUAL PASSAGES AND COMMENTARY

1 Cicero (106 – 43 B.C.): *De Re Publica,* Book I, Sections 21-22

. . . he [Gallus] ordered the celestial globe to be brought out which the grandfather of Marcellus had carried off from Syracuse, when that very rich and beautiful city was taken, though he took home with him nothing else out of the great store of booty captured. Though I had heard this globe mentioned quite frequently on account of the fame of Archimedes, when I actually saw it I did not particularly admire it; for that other celestial globe, also constructed by Archimedes, which the same Marcellus placed in the temple of Virtue, is more beautiful as well as more widely known among the people. But when Gallus began to give a very learned explanation of the device, I concluded that the famous Sicilian had been endowed with greater genius than one would imagine it possible for a human being to possess. For Gallus told us that the other kind of celestial globe, which was solid and contained no hollow space, was a very early invention, the first one of that kind having been constructed by Thales of Miletus, and later marked by Eudoxus of Cnidus (a disciple of Plato, it was claimed) with the constellations and stars which are fixed in the sky. He also said that many years later Aratus, borrowing this whole arrangement and plan from Eudoxus, had described it in verse, without any knowledge of astronomy, but with considerable poetic talent. But this newer kind of globe, he said, on which were delineated the motions of the sun and moon and of those five stars which are called wanderers [the five visible planets], or, as we might say, rovers, contained more than could be shown on the solid globe, and the invention of Archimedes deserved special admiration because he had thought out a way to represent accurately by a single device for turning the globe those various and divergent movements with their different rates of speed. And when Gallus moved the globe, it was actually true that the moon was always as many revolutions behind the sun on the bronze contrivance as would agree with the number of days it was behind in the sky. Thus the same eclipse of the sun happened on the globe as would actually happen, and the moon came to the point where the shadow of the earth was at the very time when the sun . . . out of the region . . .

(Translation by Keyes)

Commentary**:**

Writing in about 54 B.C., Cicero recounts a discussion supposed to have taken place in 129 B.C. One of the speakers recalls a yet earlier incident from 166 B.C., in which Gaius Sulpicius Gallus, a man known for his learning in astronomy, demonstrated the working of one of two instruments attributed to Archimedes and taken at the fall of Syracuse in 212 B.C. Cicero begins by distinguishing between the two: a *celestial sphere* on which the constellations are depicted, which had been placed on public view and was presumably well known; and the mechanical instrument that he goes on to describe, a *planetarium* which showed the apparent motion of the Moon, Sun and planets with some approach to their correct relative speeds.

Cicero shows an intelligent and well-informed interest in the history of the celestial sphere. His attribution of its invention to Thales, whose name had long been a byword for wisdom, may be false but was presumably traditional. Various inventions were credited to Thales, and stories of his interest in astronomy were widely known. The connection with Eudoxus, a pupil of Plato, is more supportable. Plato shows in *Timaeus* that the armillary sphere (one made up of rings), which we would regard as an abstraction from the celestial sphere with a continuous spherical surface, was already known. *A fortiori*, then, the simple celestial sphere was known. Cicero is correct in saying that a descriptive work of Eudoxus relating to the concept of the celestial sphere was the basis of the immensely popular *Phainomena* of Aratus.

Cicero describes the celestial sphere as “solid”; and if it were of wood or of stone that is what we would expect. Were it of metal, it would almost certainly have been a hollow shell (see passage 5), but probably Cicero had no opportunity to handle it and perhaps it was not generally known whether it was solid or hollow. In describing it as “solid” Cicero tells us that it had an unbroken spherical surface, but the point he is making is that it contained no mechanism; and in this respect he contrasts it to the other instrument.

Cicero describes the planetarium also as a sphere (*sphaera*, here translated as “globe”); but just as *sphairopoiïa* comprised the making of instruments other than globes that illustrated the arrangement of the heavenly spheres, so here “sphere” may have been used as a generic name for any astronomical model. On the strength of this word alone we are not compelled to conclude that the instrument was actually made in the form of a sphere but, as we shall discuss below, there would have been no great difficulty in fitting the sort of mechanism that we envisage within a spherical shell.

Cicero writes: “… when Gallus moved the globe, …”. If the instrument were made in the form of a celestial sphere, one might imagine the input being made by providing the diurnal rotation by hand. This is feasible but it does introduce complications which will be discussed below.

There is just one hint that the instrument might not have been a sphere but might instead have presented a planar dial display. As Gallus illustrates the occurrence of eclipses, Cicero’s wording seems to suggest that both solar and lunar eclipses are demonstrated, and he refers specifically to the shadow of the Earth. He writes of the “cone representing the shadow of the Earth”, but the translator has suppressed the word *meta* (cone). This is unfortunate, because Cicero writes as though it were a visible feature of the instrument; but if it were in the form of a celestial sphere the Earth would be imagined as a small sphere at its centre, and the conical umbra of its shadow reaching back from it would likewise have been mostly within the sphere. The shadow could not be modelled, and conditions for lunar eclipse could be found only by comparing the place of the Sun on one side of the sphere and that of the Moon diametrically opposite to it. On the other hand, Opposition of the Moon and Sun would be far easier to see in a planar display, on which a physical cone representing the Earth’s shadow could be modelled to make the point clearer.

2 Cicero (106 – 43 B.C.), *Tusculan Disputations,* Book I, Section XXV(63)

For when Archimedes fastened on a globe the movements of moon, sun and five wandering stars, he, just like Plato's God who built the world in the *Timaeus,* made one revolution of the sphere control several movements utterly unlike in slowness and speed. Now if in this world of ours phenomena cannot take place without the act of God, neither could Archimedes have reproduced the same movements upon a globe without divine genius.

(Translation by J. E. King)

Commentary:

In this late work (45 B.C.) Cicero refers again to the same planetarium instrument that he had previously described in the *De Re Publica*, and in much the same terms: the instrument is said to be a sphere; there are seven indications, for Moon, Sun and the five planets; the indications are all worked, at their proper speeds (whether with constant mean speeds or with anomalous motion), by a single action which may have been the rotation of the globe itself.

3 Cicero (106 – 43 B.C.), *De Natura Deorum*, II, xxxiv-xxxv (88)

Suppose a traveller to carry into Scythia or Britain the orrery recently constructed by our friend Posidonius, which at each revolution reproduces the same motions of the sun, the moon and the five planets that take place in the heavens every twenty-four hours, would any single native doubt that this orrery was the work of a rational being? These thinkers however raise doubts about the world itself from which all things arise and have their being, and debate whether it is the product of chance or necessity of some sort, or of divine reason and intelligence; they think more highly of the achievement of Archimedes in making a model of the revolutions of the firmament than of that of nature in creating them, although the perfection of the original shows a craftsmanship many times as great as does the counterfeit.

(Translation by H. Rackham)

Commentary:

In this further late work (c. 45 B.C.) Cicero again makes an allusion to the planetarium by Archimedes; but he precedes it with mention of another instrument, by his own older contemporary Posidonius. Cicero had studied with Posidonius in Rhodes about thirty years earlier, and the two men had continued to correspond. Posidonius died in 51 B.C., some six years before this work was written, so Cicero cannot mean “recently” (*nuper*) in any strict sense. Possibly the instrument already existed when Cicero was in Rhodes. Cicero may intend to contrast this instrument of his own time with the earlier one which he mentions immediately afterwards.

“Orrery”, meaning an instrument illustrating elements of the Copernican system, is a solecism on the part of the translator; since Cicero mentions motion of the Sun, the system modelled was, as we would expect, geocentric. Cicero’s word is again *sphaera*, and the instrument may actually have been made in the form of a celestial sphere, as discussed above (commentary on passage 1); and again there is a suggestion that the instrument may have been driven by an input representing the diurnal motion, perhaps effected by rotating the globe itself. Both these points are discussed further below.

The description is strikingly similar to that of the Archimedean instrument in passages 1 and 2 above, and there is room to speculate as to whether Cicero has transferred detail from the instrument of Posidonius (of which he had probably received a clear description, even if he had not examined it himself) to the one ascribed to Archimedes which very probably did not survive to his own time.

4 Ovid (43 B.C. – A.D. 17 or 18), *Fasti,* Book VI, Lines 277-279

There [in the Hall of Vesta] stands a globe hung by Syracusan art in closed air, a small image of the vast vault of heaven, and the Earth is equally distant from the top and bottom. That is brought about by its round shape.

(Translation by J. G. Frazer)

Commentary:

Ovid has just described the circular temple of Vesta, and has drawn a parallel with the world view according to which the Earth is spherical and hangs in the middle of space which must, therefore, also be spherical. Now he draws a third parallel by describing the celestial sphere of Archimedes which, he says, is displayed there.

We have the problem that Cicero tells us that Marcellus placed the celestial sphere in another building, the Temple of Virtue. It might have been moved during the intervening period, or there may be some confusion over place or over two comparable instruments. In any case it is unsafe to assume that Ovid describes the same instrument as Cicero. Ovid's wording suggests that a representation of the Earth could be seen at the centre of the sphere, and this does not agree with Cicero's description of the celestial sphere as "solid". Unless Ovid is inviting us to use our imagination in picturing the Earth at the centre of a solid sphere, his description seems to apply either to an armillary sphere or, just conceivably, to a celestial sphere of glass with a small sphere for the Earth at its centre. On the latter, see the commentary on passage 7.

5 Lactantius (c. A.D. 240 – 320), *The Divine Institutes,* Book II, Chapter 5, 18

Could Archimedes the Sicilian have devised from hollow brass a likeness and figure of the world, in which he so arranged the sun and moon that they should effect unequal motions and those like to the celestial changes for each day as it were, and display or exhibit, not only the risings and settings of the sun and the waxing and waning of the moon, but even the unequal courses of revolutions of the heavens, and that sphere, while it revolved, exhibited not only the approaches and the wandering of the stars as that sphere turned, and yet God Himself be unable to fashion and accomplish what the skill of a man could simulate by imitation? Which answers, therefore, would a Stoic give if he had seen the forms of stars painted and reproduced in that sphere? Would he say that they were moved by their own purpose, or would he not rather say by the skill of the designer?

(Translation by McDonald)

Commentary:

Lactantius is the first of our authors to mention risings and settings. To show them, an instrument must both model the diurnal motion and have some way of marking the horizon. The most obvious way of doing this is to mechanize the usual arrangement for a celestial sphere: the sphere is set over, with its pole making an angle with the vertical that corresponds to the observer's co-latitude, in a stand with its horizontal upper surface (corresponding to the horizon) level with the centre of the sphere. Rotation of the sphere about its pole models the diurnal motion. If the same instrument were to show the "unequal courses of revolutions" – the motion of the Moon, Sun and planets around the Ecliptic as considered above – a further complication is added (as discussed below) but the arrangement is feasible. It is however not clear how such an instrument could also show – directly, as Lactantius seems to imply – the phases of the Moon. We are led to suspect that Lactantius is fantasizing about an instrument that would combine all the display elements that he can imagine.

6 Pappus (c. A.D. 290 – 350), *Mathematical Collection,* Book 8: 2,3

Also included in mechanics are those spheres that are constructed to resemble the heavens, which are made to move in a regular and circular motion as would be their motion in water. According to some, the man who knew the causes of all these things and the rules governing them was Archimedes the Syracusan. For he alone of those in this world of ours had so diverse a nature as to apply himself to all things, and he was prolific in ideas as was mentioned by Geminus the mathematician in the book which he wrote "On the arrangement of mathematics". Carpos of Antioch has claimed somewhere in his writings that Archimedes the Syracusan only wrote one book on mechanics this being his work on the construction of spheres, and he did not think that he need write anything on any branch other than this. However the ancients honoured him with respect to the science of mechanics, and they held his nature to be so remarkable that he continues to have great fame and praise among all people.

(Translation by D. Jackson)

Commentary:

Pappus lived and worked in Alexandria, where we may presume he had access to as wide a range of texts as anywhere at that time; but he writes as though he himself had not come across the book by Archimedes on *sphairopoiïa*, so we perhaps by his time it had been lost. His scholarly opinion of the standing of Archimedes must, however, carry weight.

7 Claudian (A.D. 370? - 404?), *Shorter Poems,* "Archimedes' sphere"

When Jove looked down and saw the heavens figured in a sphere of glass he laughed and said to the other gods: "Has the power of mortal effort gone so far? Is my handiwork now mimicked in a fragile globe? An old man of Syracuse has imitated on earth the laws of the heavens, the order of nature, and the ordinances of the gods. Some hidden influence within the sphere directs the various courses of the stars and actuates the lifelike mass with definite motions. A false zodiac runs through a year of its own, and a toy moon waxes and wanes month by month. Now bold invention rejoices to make its own heaven revolve and sets the stars in motion by human wit. Why should I take umbrage at harmless Salmoneus and his mock thunder? Here the feeble hand of man has proved Nature's rival".

(Translation by M. Platnauer)

Commentary:

The technique of glass-blowing, developed around the first century A.D., made the manufacture of glass goods more rapid, and economized material, as compared to the earlier technique of casting. Consequently glass had become a widespread commodity throughout the Roman Empire well before Claudian's time. Clear glass was also developed early in the Imperial period, and different methods of decorating glass articles such as painting, engraving and cameo-cutting (of glasses of different colours fused together) were already well established. Many remarkable specimens in museums show that glass-workers of the time were capable of most exquisite work.

Claudian's wording (sphere of glass … fragile globe) leads us to imagine a celestial sphere based on a blown glass globe, with the Equator, Zodiac and other circles marked out together with the constellations, and perhaps accorded some decorative treatment. If such an instrument had a small sphere at the centre to represent the Earth, it would also fit Ovid's description; but while there is no reason to doubt that a celestial sphere of transparent glass might have been made by Claudian's time, it is doubtful whether it might have been done as early as Ovid's. In any case, quite apart from the disagreement with the descriptions of Cicero and Lactantius, such an artefact could not possibly have existed so early as to have been taken from Syracuse in 212 B.C.

Passing on from his reference to Archimedes, Claudian goes on to refer to a mechanized instrument, although he is a little unclear as to just what it shows. As in the passage from Lactantius, the mention of representation of the lunar phases on what may be supposed to have been a spherical instrument is a small difficulty. We have however a much greater difficulty if we suppose that Claudian means to suggest that the glass instrument contains hidden mechanism. Either there would have to be a central globe of considerable size to enclose the wheel-work, leading to the suggestion that the glass globe must, in its turn, have been very large; or the wheelwork must have been put elsewhere, such as in the pedestal supporting the globe. We are left in doubt as to whether Claudian means to describe a single instrument, or conflates features of several.

The most significant points in this passage are that the beautiful idea of making a celestial sphere of glass had been conceived, whether or not it had actually been executed; and that Claudian places Archimedes at the head of the tradition of making mechanized instruments.

8 Proclus (A.D. 410? - 485?), *A Commentary on the First Book of Euclid's Elements,* Book I, Chapter XIII

Under mechanics also falls the science of equilibrium in general and the study of the so-called centre of gravity, as well as the art of making spheres imitating the revolutions of the heavens, such as was cultivated by Archimedes, and in general every art concerned with the moving of material things.

(Translation by G. R. Morrow)

Commentary:

Proclus turned from the practice of law in Constantinople to philosophy. After studying in Alexandria he moved to Athens where he lived for the rest of his life. The value of the short statement quoted here is that Proclus, working in an academic tradition and distanced from the literary tradition of Rome, agrees with the other authors considered here in naming Archimedes as a man who studied *sphairopoiïa*, and in terms that suggest that he saw Archimedes at the head of this field.

DISCUSSION

Cicero, our earliest author, makes a clear distinction between two instruments from Syracuse, both attributed to Archimedes: a simple celestial sphere and a mechanical planetarium that was perhaps made in the form of a celestial sphere. He is evidently well-informed about the nature and history of the celestial sphere, and this may lend some authority to what he writes about the other instrument. However, it seems possible, even probable, that the celestial sphere still existed in his time and remained visible to anyone who visited the temple where it was displayed; on the other hand, there is no suggestion that Cicero had himself seen the mechanical instrument which, due to its nature and due to the fact that it was kept in a private house, was far more likely to have been ruined and then cast aside. There is room to suppose that Cicero's description of it was fictional, drawing on features of the later instrument by Cicero's teacher Posidonius about which Cicero would certainly have been well informed and which he might well have seen.

Add about the cone of shadow: was Cicero conflating several instruments?

The descriptions by Ovid, Lactantius and Claudian are still less to be relied on. If these authors write about real instruments at all, they may refer to later productions. Otherwise, they may rely on hearsay. In any case, the detail may be garbled. There is a further suspicion that they may fantasize both about the appearance and about what functions might be included in a single instrument.

Pappus and Proclus are clear in their opinions that Archimedes had worked in the field of *sphairopoiïa*: Pappus, in particular, states that he had written on the subject. All the authors except Ovid concur in stating that Archimedes had made a mechanical planetarium (and Ovid does not disagree). The question then arises: just what mechanism might it have contained, and just what motions might it have shown?

Any device with several rotating outputs running at different speeds must make use of some sort of gearing. The spool-and-string arrangements widely used in Heronic devices would not serve, and we have no evidence for the use of a continuous band running over pulleys before the mediaeval period. Toothed gearing remains as the only practicable option. The artefactual evidence of the Antikythera Mechanism shows that its use was highly developed by the first half of the first century B.C. at the latest, and arguments (albeit rather insecure ones) have been brought forward for dating that instrument to the second century. The subtlety and accomplishment of the gearing in the Antikythera Mechanism suggests a prior history reaching back at least some decades, even if for less elaborate geared mechanism. A passage in the *Mechanica* attributed to "Pseudo-Aristotle" has been interpreted as suggesting that spur gearing was known early in the third century, and the water-clock that Vitruvius attributes to Ctesibius, who lived at about the same time, includes the use of wheel-and-rack gear. Archimedes himself is credited with the endless screw or worm-and-wheel gear, and so we must suppose that he was aware of other configurations of toothed gearing also. Therefore we have no difficulty in accepting that the planetarium instrument, which tradition in late antiquity so insistently ascribed to him, depended on the use of toothed gearing.

At a cautious estimate, we might suppose that only the mean motion of each planet was modelled. However, Cicero (our earliest and most trustworthy witness) writes that the indicators for the planets exhibit "… various and divergent movements with their different rates of speed". If the inferior planets moved merely with their mean motion, they would simply have moved round with the Sun. This would have been a very dull display, hardly living up to Cicero's description. We are therefore led to speculate on how the anomalous motion of the planets might have been modelled, and according to what theory.

The first kinematic planetary theory of which we are aware is the system of homocentric spheres suggested by Eudoxus and elaborated by Calippus. In this system a multiplicity of spherical shells all move with uniform motions about a common centre but about different axes, each having the pivots of its polar axis planted in the shell next outside it and at some distance from the outer shell's polar axis. It is hard to imagine that this system of shells could ever have been realized as an automated mechanical model: the transmission of motion to each shell would be highly complicated, and it is difficult to imagine how the indications of the planets' positions could have been brought to the outside to be seen. For these reasons, and quite apart from the fact that this model gives – at best – only qualitative agreement with the planets' motion in longitude and yields quite unrealistic motion in latitude, we do not think it can ever have formed the basis of a workable planetarium instrument.

The eccentric and epicyclic theories that succeeded the homocentric system give much more satisfactory results for motion in longitude. These more successful theories led ultimately to the highly-developed models of Ptolemy, but we do not know when, or by whom, they were first devised. The epicyclic model, at least, was discussed by Apollonius of Perga, a younger contemporary of Archimedes who was born about forty years before Archimedes died. Whatever he wrote on the subject is lost, but in book XII of *The Almagest* Ptolemy includes his theorem investigating stationary points in this model. We are not told that Apollonius was the originator of this theory, but even if he were his work might have been communicated to Archimedes.

If they are restricted to describing motion in longitude – which is by far more significant than motion in latitude – these theories are both planar, and consequently either may conveniently be realized in mechanism. The epicyclic theory lends itself particularly well to being modelled; the reconstruction of a planetary display on the front dial of the Antikythera Mechanism shows just how easily, according to this theory, a display of the motion of Moon, Sun and all five planets can be achieved. That reconstruction includes the modelling of single-anomaly lunar and solar theory, and we have no evidence for these prior to the work of Hipparchus in the century following the death of Archimedes. Therefore it is probable that Archimedes made no such provision, limiting himself to the mean motions of the Sun and Moon. It seems to us, however, probable that Archimedes employed epicyclic mechanism to model planetary motion with a single anomaly. If we take literally what Cicero wrote about the planetarium of Archimedes, only some such model fits his description.

Many of the passages suggest that the planetarium of Archimedes was contained in a celestial sphere. In the Antikythera Mechanism the wheel-work is fitted into a flat-faced rectangular case bearing dials on its faces, which is perhaps the easiest way to house such mechanism and display its output. It is however not the only way, and the shape the case makes relatively little difference to the mechanic. It is certainly a little less straightforward to display the movements of the Moon, Sun and planets around the Ecliptic on a celestial sphere than on a plane dial, but we will outline two ways in which it may be done.

In either case the mechanism would be fixed inside the globe with its axes parallel to the Ecliptic Pole and with all its output motions coaxial with that Pole. These outputs might emerge through the spherical shell as a set of concentric pipes, exactly analogous to the concentric arbors at the centre of a clock dial or of the front dial of the Antikythera Mechanism. Here, though, instead of straight pointers, each would carry an arm curved to a quarter-circle that reached down to the Ecliptic, with a marker representing the relevant celestial body at its end. The mechanical arrangement inside might be very similar to that reconstructed for the Antikythera Mechanism, but without the provisions for lunar and solar theory and for the outputs to the Mechanism's back dial. The way in which it might be driven is discussed below.

Another way of working the markers for the planets would involve dividing the spherical shell in two around the Ecliptic, so that the arms carrying the markers might emerge from a circular slot between the hemispheres. This arrangement would call for some modifications to the mechanism. Firstly, unless there were external framing, there would have to be a central fixed post joining the two hemispherical shells, and all mobiles on that polar axis would have to be pipes running concentrically on it. Secondly, whereas in the reconstructed planetary mechanism for the Antikythera Mechanism the input to each planetary assembly (the mean solar motion) is brought in from a side-arbor, that could not be done here because a continuous side arbor would obstruct the free rotation of the output arms projecting radially from each assembly. The mean solar motion would therefore have to be carried through to all the planetary assemblies as a pipe running on the central post; but this would be made much easier by the absence of the concentric output pipes all passing through to one end of the axis in the arrangement outlined in the previous paragraph; overall, the latter scheme would actually be the less complicated of the two. No doubt other ways of arranging similar mechanism might be found.

Several of the authors imply that the instrument modelled the diurnal rotation, and some appear to suggest that the sphere was rotated by hand. Inclusion of the diurnal motion would have provided a pleasing completeness to the model, and it would then have made good sense to use manual rotation of the globe as the input motion to the whole mechanism. The diurnal motion is far faster than all the other motions, and it is much easier to build satisfactory gear trains for reduction in speed, rather than for its increase, especially when using gears of the crude triangular form found in the Antikythera Mechanism and all other early instruments. On the other hand, with the diurnal motion as the input, most of the output motions might be found frustratingly slow; in the extreme case, for the marker for Saturn to make one full circuit of the Ecliptic the globe would have to be rotated about 10,800 times. Whether or not such a slow output would have been seen as a difficulty depends wholly on how the instrument was to be used. In the hands of Gallus, demonstrating how eclipses may occur, the typical change in setting from one eclipse-possibility to the next, a shift of five synodic months, would require the sphere to be rotated some 148 times. In the Antikythera Mechanism, one turn of the input knob represents the passage of nearly 79 days, making the output motions significantly faster.

Since all the required outputs are of motion in celestial longitude around the Ecliptic the mechanism driving them would be aligned on the Ecliptic Pole as its central axis. It would therefore stand oblique to the Equatorial Pole about which the sphere itself rotates, providing the input motion. The input gearing would therefore have to incorporate a pair of gears working in planes at an angle to one another equal to the value chosen for the obliquity of the Ecliptic: say 24º. This need not alarm us; in the Antikythera Mechanism we have two examples of the most extreme case, contrate gearing, in which the two wheels work in planes mutually at right-angles, and in which the contrate wheels have rather few teeth. Experience shows that, when correctly sized, these gears work smoothly and wholly reliably; and the less the angle between the planes, and the larger the numbers of teeth in the wheels, the less difficulty the engagement presents. With two wheels engaging at 24º, having fairly large numbers of teeth and a triangular tooth form, and the smaller wheel leading the larger, one could obtain a satisfactory engagement between two plain spur gears.

Basing the mechanism on the Calippic period-relation, the ratio to be accommodated in driving the Moon pointer (the fastest-moving output) is 1016 : 27835. This can be realized exactly if wheels of 127 and 293 are accepted (along with smaller ones). The Antikythera Mechanism contains a wheel of 127 teeth, about 63mm. in diameter. To the same scale, a wheel of 293 teeth would have a diameter of about

145mm. With the other wheel-work envisaged, the gear train including these wheels might easily be fitted within a globe about 400mm. in diameter. If a less good approximation to the input were acceptable, much smaller wheels might be used. Motion might be transmitted from the Moon to the Sun pointer (and thence to the planets) by a further train based on the Calippic period-relation (or on the Metonic one, which comes to the same thing), realizing the ratio 19 : 254 found in the Antikythera Mechanism; or the same result might be obtained by driving the Sun directly from the input using a train employing a second wheel of 293 teeth to realize the desired ratio 4 : 1465 (1 : 366¼).

CONCLUSION

Our understanding that Archimedes designed instruments in the genre of *sphairopoiïa* depends on two strands. Firstly, there is the literary tradition which, as we have it, begins with the Roman author Cicero; and secondly, there are the scholarly comments by Pappus and Proclus, the first referring to a work on “sphere-making”, and the second referring more generally to Archimedes’s “cultivation” of the art. The evidence is slender but is sufficient, and sufficiently self-consistent, for us to accept that it has some basis in fact.

We consider that any instrument showing the motions of the Moon, Sun, and planets, however crudely, must have employed trains of toothed gears. There is other evidence to suggest that, at the latest, toothed gears had been introduced in the Hellenistic world when Archimedes was a youth. One form of toothed gearing, the endless screw or worm-and-wheel, is attributed to Archimedes himself. We therefore suggest that the planetarium of Archimedes represents an early essay in the elaborate use of toothed gearing.

Cicero’s description, emphasizing the individual motions of the several indicators, leads us to believe that not merely were the mean motions of the planets modelled, but that some form of planetary theory was adopted which, at the least, showed the inferior planets travelling sometimes ahead of, and sometimes behind, the Sun. Of the planetary theories known to Hellenistic astronomy, the epicyclic theory is the one most readily adapted in such a model, and a plausible case may be made for it having been known to Archimedes. We have therefore explored the possibility that the planetarium of Archimedes made use of such a device.

We have indicated that, if spur gearing and epicyclic planetary theory were available to Archimedes, no great difficulty would have stood in his way in building a planetarium just such as Cicero and later authors describe. We have however pointed out that the instrument attributed to Archimedes might well not have survived to Cicero’s time, and that the description that he gives may well rest on detail transferred from a similar but later instrument known to Cicero. He himself tells us that his older contemporary Posidonius had built one, and of this Cicero almost certainly had either a clear description (perhaps from Posidonius himself) or even first-hand knowledge.

Finally, therefore, we must admit that we cannot with confidence attribute our reconstructed planetarium to Archimedes; but in the minds of the men on whose evidence it is based, Archimedes stood at the head of the tradition of *sphairopoiïa* in which it was created.