For NHRF Athens, 6th March 2007.

The Antikythera Mechanism

Introduction

It gives me pleasure to thank many Greek friends, who have encouraged me with their continued interest in my work on the Antikythera Mechanism. Today I thank especially the National Hellenic Research Foundation for honouring me with their invitation to speak to you, and I thank you all for coming.

The secure dating of the Antikythera Wreck to the early first century B.C. implies that, no matter when it was actually made, the Antikythera Mechanism is by far the oldest known geared instrument, and we are all hungry for news about this important artefact. I regret that I have not been a member of the Antikythera Mechanism Research Project Group, and so I can speak only about the findings that they have published to date. I can, however, also speak about my own research into the Mechanism, which has now extended over more than twenty years. My work remains in progress, so that now the Research Group and I are moving forward side by side. However, this should not be seen as a race because to a large extent our approaches are complementary.

The Group's first publication, of November last year, confirms much of the mechanical arrangement of the reconstruction that I had exhibited in Athens a year earlier. Most importantly, however, the Group has had access to the newly-discovered fragment F, which I have not seen. This piece alone shows clearly what function was displayed on the lower back dial, a point on which I remained uncertain. Remarkably, the dial's use remains what I suggested, a display for predicting eclipses; but the actual display and the rate of rotation of its central pointer are changed. The Group has suggested small, but important, changes to my gearing scheme so that the correct rate of rotation is obtained. These changes are compatible with my own observations. Moreover, they resolve a problem concerning two features which, although I could identify their astronomical significance, appeared redundant in my scheme. I therefore accept these changes provisionally, and I have included them in a revised scheme. In mechanical terms, the modification is very slight; I was able to alter my model accordingly in a single afternoon. We now have a secure grasp of the arrangement and function of much of the instrument and, for brevity in describing it, I make no distinction between the Group's findings and my own.

The Group has been doing interesting work in extending the reading of the inscriptions on the Antikythera Mechanism. Dr Bitsakis has been responsible for much of that work, and I look forward to hearing what he has to say to us. I have always concentrated on the artefact as a mechanical problem, and so this evening I limit myself to mechanical matters. I will however give you just a brief sketch of the simple astronomy on which the instrument's design is based.

Astronomy

The surviving gear trains are largely based on well-known astronomical period-relations, which are attested by inscriptions on the instrument itself. I show these on the screen.
The first is the "Metonic" relation,

235 synodic months = 19 years,

which implies the further relation,

254 (= 235 + 19) tropical months = 19 years.

Taking the year as 365¼ days, Kallippos multiplied these numbers by four to give a period containing a whole number of days:

[27759 days =] 940 synodic months = 76 years.

The "Kallippic Period" was used by astronomers as a way of distinguishing the dates of events widely separated in time, and this probably explains why it is included in one of the dial displays.

The second period-relation is the "Saros", which concerns the three parameters that govern eclipse events:

6585⅓ days
= 223 synodic months
= 239 anomalistic months (revolutions in anomaly)
= 242 draconitic months (returns to the same latitude)

For now, all we need to understand is that as a consequence of this coincidence the pattern of eclipses is repeated after 223 months but with each eclipse occurring about eight hours later. Naturally the pattern is broken because some eclipses become unobservable, but after a period three times as long, the Exeligmos, the original pattern is repeated almost exactly. There is a pointer that rotates in this period, but the Exeligmos plays no direct part in the design.

These period-relations, found by analysing records of simple observations, were already ancient. The designer also used more recent, geometrical astronomy: the Sun, Moon and planets are observed to pass through the Zodiac at varying speeds; Greek astronomers attempted to describe these non-uniform motions as combinations of uniform circular motions.

By the time of Hipparchos in the 2nd century B.C., it was known that the motion of either the Sun or the Moon could be described quite well if it were imagined to move with uniform circular motion about a centre that was displaced from the Earth. In this *eccentric hypothesis* the direction and distance of the centre are chosen to give an appearance at the Earth that imitates the observed *anomaly*, or variation in velocity. For the Sun, the model is very simple, but the Moon's motion is more complicated: in this case the centre of the circle had itself a uniform circular motion about the Earth. I will show how this lunar theory is directly modelled in the Mechanism.

Later, I will discuss the restoration to the instrument of further elements, modelling the Sun's anomaly and representing the motion of the planets, and then I will speak of a different way of combining circular motions. According to this *epicyclic hypothesis*, we imagine the body rotating on one circle, the centre of which is itself carried on another circle around the Earth. The diagram illustrates the two versions of the solar theory: eccentric to the left and epicyclic to the right. They achieve identical effects, and it was understood that the hypotheses were formally equivalent; but each leads the designer to a different mechanical solution and, of the two, the epicyclic form lends itself more easily to the description of planetary motion with its retrograde episodes.

Surviving Mechanical Arrangement

We now turn to the instrument itself, beginning with those features of which enough can be traced directly for us to be certain of them. Many details are however difficult to show in photographs or radiographs, and I illustrate what I have to say with photographs of my model. The model includes further, conjectural features and I shall discuss those later. I also illustrate the gearing using a diagram which shows the wheels in a wholly artificial way. They are seen edge-on, and as though they could all be seen side-by side in one view.

Most of this gearing is attached to the flat frame plate that we saw in fragment A. It is set in motion by inserting a driving knob into a socket in the side of the wooden case to turn a contrate wheel that lies inside. The contrate wheel engages the largest wheel, seen on the surface of the original fragment, which lay centrally under the front dial – a piece of which survives in fragment C – with its Zodiac and annual calendar scales, and it made one turn in a year. (I mean that each turn of the wheel represents the passage of one year, but for brevity I speak as though the instrument were worked in “real time”.) A pointer connected directly to the wheel could have indicated both the place of the Mean Sun and the day of the year on the dial. It is convenient to give this important wheel a name. I call it the *Mean Sun Wheel*.

A smaller wheel, fixed under the Mean Sun Wheel, drove two trains of gears. One, based on the period-relation 254 tropical months = 19 years, shown here in blue, led through axes C and D to axis E, where it turned wheel E2, making one turn in a mean tropical month; if this motion had been transmitted to the central arbor on axis B, and thence up to the dial, shown in pale blue, it would have driven a pointer indicating the place of the Mean Moon.

This is the conceptual heart of the instrument: a geocentric display, on the large front dial, with concentric mobiles for the apparent solar and lunar motions. But the mean lunar motion on axis E was not brought up to the front dial. Instead it passed to an epicyclic arrangement at the back where it was modified, and only then was it passed to the central arbor on axis B and to the Moon pointer on the front dial. We will see the point of this arrangement shortly.

The second train, shown in green, led from the mean solar motion on axis B, through axis L to axis M. Here it branched, leading – in yellow – to the centre of the upper back dial on axis N; and – in red – through axes E and F, to the centre of the lower back dial on axis G. Each back dial included a subsidiary display, in which the pointer rotates much more slowly. The gearing behind the lower dial can be traced from its centre, axis G, through axis H to the subsidiary pointer on axis I. The corresponding train for the upper dial, from axis N to axis O, is lost, but the gear ratio is certain and the intermediate axis P is restored with confidence.

Both back dials had spiral scales. These enabled the designer to include long sequences of divisions without each division being inconveniently narrow. Sliders, working in the slots beside the spiral scales, controlled the positions of riders on the hands which showed the user which turn of the scale he should look at.

In each case the divisions represent synodic months. On the upper dial there were five turns of 47 divisions each, a total of 235 divisions. This dial was, therefore, a display of the Metonic period-relation. The subsidiary pointer rotated once in the Kallippic period of 76 years, its dial divided into four to indicate individual Metonic periods. This display probably had a purely calendrical use, either indicating the intervals between settings of the instrument that were widely separated in time or allowing the user to convert between the date in the Egyptian calendar shown on the front and one or other of the lunar or luni-solar calendars otherwise used in the Hellenistic world. A more secure reading of the inscriptions on the scale may make the intended use of this display clearer. In any case, it cannot possibly have been read to the nearest day, but in my model I show how the user might have read the days of the synodic month, as well as those of the calendar month, on the front dial.

The lower dial had a spiral of four turns, containing altogether 223 divisions for the 223 months of the Saros eclipse period. Expected eclipses were marked in the appropriate places (on the original, not on my model), each with information about the type of eclipse and its time. Since the whole pattern shifts by about ⅓ of a day – 8 hours – for each successive cycle, the subsidiary pointer indicated whether a correction of 8 or 16 hours should be added to the times given on the main display.

Here is the gearing behind the dial. Both back dial outputs, driven from the annual motion, are functions of the synodic month, and the 19 : 235 period-relation is used in both cases. On the screen I show how the factors are distributed in the trains of gears and – in the case of the upper display – on the dial itself. It is not immediately obvious just how economical this design actually is. For the lower display it was necessary to include a wheel of 223 teeth because this number is prime, but the designer took advantage of this large gear for a further purpose: as the platform for an epicyclic assembly with which he modelled the lunar theory.

According to the eccentric version of lunar theory that I showed earlier, the Moon Σ moves with constant velocity in the circle AB, with centre at Δ; but its apparent speed, seen from the Earth at Γ, varies. It is slowest as the Moon passes the Apogee A, on the line ΓΔ; but as Δ moves slowly round the Earth Γ, so the Apogee also moves round.

The large wheel carries a little assembly that models the effect of this eccentric hypothesis exactly. As I showed earlier, the lower wheel at the centre makes one rotation in one mean tropical month. Its uniform motion is transferred to the lower offset wheel. This is the motion of the Moon in its eccentric circle. The upper offset wheel turns about a different centre, and is coupled to the lower one by the pin and slot, so that its speed varies just as the Moon's speed – as seen from the Earth – seems to vary; the wheel goes slowest when the pin is towards the edge of the platform, which corresponds to the Moon at Apogee, point A. This motion is transferred to the upper wheel at the centre, and from there through to an arbor at the centre of the front dial which carries the pointer for the Moon's position. Because the slot-and-pin ensemble is mounted on a rotating platform, the point at which the motion is slowest moves round the Zodiac, just as the theory requires.

Here we see the same sequence on the gearing diagram. The mean motion, in dark blue, becomes pale blue when it is modified to agree with theory, and is then fed to the front dial.

It is not necessary to show that the behaviour of the arrangement is equivalent to that of the epicyclic hypothesis which, it seems, Hipparchos preferred to the eccentric hypothesis when treating lunar motion. It is more to the point to appreciate that the design of this mechanical arrangement is based directly on the eccentric hypothesis.

The platform, shown in red, is driven through the green train so as to rotate at the same rate as the motion of the Apogee in the Zodiac. It is easier to understand the design by considering periods of rotation than by discussing angular velocity, as I show here, and in doing so we probably trace the original designer's thought process closely. My point here is that this is as complicated as the design process for this instrument gets, and it is actually quite simple.

Some commentators have expressed surprise about the freedom with which the designer chose whatever numbers of wheel teeth he needed. I will therefore repeat a point that I published many years ago. The workman who makes gears like this, without the help of any mechanical device for division of the circle, does not find any number of divisions either significantly easier or harder to generate than another. Whatever the number, whether it can in principle be found wholly by exact geometrical construction or not, in practice he completes the division by trial. Since the teeth are to be cut by hand and eye, it is in any case pointless to worry too much about the precision of the preceding division.

There is just one further part of the Mechanism that we are sure of. The pointer on the front dial, driven as I have just described, includes an arrangement for showing the phase of the Moon. A small rotating ball, half light and half dark, is mounted in an opening in the boss of the Moon pointer to show the appearance of the Moon. It is rotated by the differential motion between the Moon and Sun pointers.

Extending the Partial Reconstruction: Front Dial Display

The arrangement and function of everything that I have described so far is supported by artefactual evidence, as will become plain when either the Research Group's observations or mine are published in full. Here, however, the account of what is certain comes to an end. We have seen the whole of the back of the instrument, and we have glimpsed parts of the front, but still we do not have a fair impression of the whole thing. The front face of the largest fragment bears clear evidence that further mechanism has been lost from below the front dial. Most obviously, there is the question of the large Mean Sun Wheel; the cutting, by hand, of a wheel of over 200 teeth is tedious, and thus far our reconstruction offers no reason for making it so large. Moreover, it is certain that the wheel carried elaborate structure. Some upstanding pieces and the "footprints" of others that were once fixed there are visible to the naked eye. Further traces are seen clearly by radiography. To be satisfactory, our reconstruction must explain why this big wheel is there and must make sense of all the other evidence. We are forced to conclude that the front, principal display was considerably more elaborate than I have suggested so far.

The problem with the front is quite different from that of the back, because here the evidence shows that something is missing, but does not offer us any certainty about just what it was. In order to solve it, we must exercise an educated imagination. We begin by thinking about what else the designer might have wished to include. We know that lunar theory was modelled. That provides a strong argument for supposing that a corresponding solar theory was also modelled. The solar anomaly is smaller than the lunar anomaly, but its omission would at times lead to an error of over two days in the predicted date of New or Full Moon: a significant defect in an instrument intended, at least in part, for the prediction of eclipses with some degree of precision. Besides, solar theory precedes lunar theory heuristically, so that without it the original instrument would have presented a curiously unbalanced representation of contemporary astronomy. So, let us consider the ways in which solar theory might have been modelled.

On the screen are the diagrams of lunar and solar theory that I showed before. H, the Sun, and Σ, the Moon, both move with constant velocity in their circles AB with centres Δ. For the Sun, however, the centre Δ does not move. Solar theory could therefore have been modelled in the same way as lunar theory, but even more simply. While the lunar assembly had to rotate on a platform to mimic the rotation of the line ΓΔA, a corresponding solar assembly would have been fixed to the frame plate. If the designer did not intended to include any further complication, he would surely have modelled solar theory in this way; and it would have been easier to do if the large Mean Sun Wheel were not present. It follows that the solar theory was probably not modelled in the way that I have just outlined, and that the large wheel must have been included to achieve some further purpose.

Besides the traces of structure on the Mean Sun Wheel itself, there is also a boss at the centre, separate from the wheel and therefore fixed to the frame plate, which has a squared upper end. Taking these features together, it seems certain that there was epicyclic mechanism mounted on the wheel. The structure would have carried a wheel or wheels which rotated in engagement with a central wheel fixed on the square seat of the boss. The purpose of this epicyclic mechanism is limited by its mechanical and astronomical context.

I introduced both lunar and solar theory by describing the eccentric hypothesis which forms the basis for the lunar mechanism, but I mentioned in passing that it was understood that an epicyclic hypothesis was formally equivalent. For the Sun, the epicyclic model is particularly simple, as this diagram shows. The centre E of a small epicycle moves with uniform circular motion around the Earth Γ. The Sun is at H on the epicycle, and the radius EH remains always parallel to the line ΓΔ. We see that H traces out uniform circular motion around the eccentric circle centred at Δ. This epicyclic hypothesis is very easy to mechanize, using just three wheels; the gear attached to the epicycle and the one at the centre have equal numbers of teeth, and the wheel between may have any convenient number. The Sun's position on the epicycle is represented by a pin, the angular motion of which is followed by a lever with a slot. A precedent for this arrangement is found in the pin-and-slot device within the assembly that models the lunar theory. The lever, in turn, works the pointer on the dial.

So the large Mean Sun Wheel makes it difficult to model the eccentric solar theory, but easy to model the epicyclic alternative; and since I argue that the solar theory must have been included, I conclude that it was done in the latter way. But the small epicycle and three wheels take up very little room. A further reason is needed for the presence of the large Mean Sun Wheel, and the extensive structure, suggesting epicyclic mechanism, that it carried.

The epicyclic hypothesis that I have just described was also used to describe planetary motion, with its puzzling episodes of retrograde motion. The planet Π moves uniformly round an epicycle, while the centre of the epicycle E is carried uniformly round a circle centred at the Earth Γ. Apollonios discussed this hypothesis. He found the conditions for the two stationary points at which the planet would appear from Earth to stand still, and between which it would appear in retrograde motion.

From our modern heliocentric point of view, we see how the two circular motions combined by the theory represent the motion of the planet round the Sun and that of the Earth round the Sun. For Mercury and Venus, with orbits inside that of Earth, the epicycle represents the orbit of the planet and the carrying circle reflects the orbit of Earth. For Mars, Jupiter and Saturn, which have orbits outside that of Earth, the model is inverted; the epicycle and the carrying circle reflect, respectively, Earth's orbit and the planet's orbit. The relative sizes of the epicycle and of the carrying circle reflect those of the two orbits; for example, the epicycle for Venus must be large because the orbit of Venus is close to that of Earth.

This simple epicyclic theory effectively assumes that the orbits are concentric circles, and so it cannot offer good quantitative agreement with observation. Close agreement was later achieved by the elaborate planetary theories described by Klaudios Ptolemaios, but it seems probable that little progress had been made in improving the simple theory by the time that the Antikythera Mechanism was designed. The simple form of epicyclic planetary theory is therefore historically appropriate, and it is easily translated into mechanism.

Returning to the instrument, we now see that epicyclic mechanism mounted on the Mean Sun Wheel could model the epicyclic theory for either Mercury or Venus, and it is the need to accommodate the large epicycle for Venus that finally offers a rationale for the size of the wheel. Firstly, the arrangement must be made on a scale large enough that the epicycle disc may clear any central obstruction. Secondly, there is a high angular acceleration of the planet relative to the Sun during the retrograde episode, and high loads are developed in the linkage driving its pointer. The designer would therefore avoid making the assembly on too small a scale. The Mean Sun Wheel is large enough to model the epicyclic theory of Venus on a scale that is both mechanically satisfactory and commensurate with that of other parts of the instrument.

Unless an equally satisfactory alternative explanation for the evidence can be found, Venus must be restored to the display. But in Hellenistic astronomy no planet was any more important than the others. The designer who knew how to model the motion of one planet would surely include others if he could. The Mean Sun Wheel affords ample room for an epicycle for Mercury in addition to that for Venus, and the gears to drive them both, as well as the small epicycle for the Sun for which I argued earlier. All three epicycles and their gearing can easily be fitted on the wheel, and only such a combination seems likely to account for the extensive traces of structure on the Mean Sun Wheel. My arrangement is conjectural, but the scheme is wholly compatible with what survives of the original. It must be said, however, that I devised its details at quite an early stage in the development of this reconstruction, intending only that it should illustrate the principle that I meant to convey. There is a considerable number of holes and other cut-outs in the Mean Sun Wheel, and beyond those already mentioned that bear witness to a fixed symmetrical structure on the wheel. So far, I have not recognized in them any pattern that leads to an unambiguous reconstruction. I mean to revise this work.

Taking the same argument further, we should explore the possibility that the other planets – Mars, Jupiter and Saturn – should also have been included. For these planets, having orbits outside that of Earth, it is the rotation of the platform that models the planet's individual Zodiacal motion. Each must therefore have its own epicyclic platform. The extra mechanism could only have been placed between the Mean Sun Wheel and the dial, being driven from the Mean Sun Wheel. I see evidence in support of this conjecture. There are two small bars fixed to the frame plate, which I interpret as fastenings for the lower bearing of an arbor. Physically slight as it is, this evidence is significant, and no other explanation for it has been offered.

I have therefore restored mechanism for these further planets, as you see in my model. Naturally, this part of the work can only be almost wholly conjectural. My main intention is to illustrate the principle, bur my additions are entirely consistent with what remains, and I devised them using only machine elements and combinations for which there are precedents in the original fragments.

Conclusion

I conclude, therefore, that the Antikythera Mechanism was a planetarium, with eclipse-prediction as a supplementary function. My model illustrates this interpretation and demonstrates that it is workable. Of course there can be no certainty about any such reconstruction, unless new evidence should be found. However, my reconstruction accounts for all the evidence that we now have, and makes sense of the degree of complication that we find in the original. It also builds a bridge between the artefact and the evidence of literature contemporary with it, in which planetaria are the only mechanical astronomical instruments to be described.

Finally, the Antikythera Mechanism has a wider significance. It shows, plainly and dramatically, just how high was level of attainment, both in the design and in the construction of intricate mechanical devices, in the Hellenistic world.

I look forward to your questions, and I will be happy to show you how my model works.