Towards a New Reconstruction of the Antikythera Mechanism
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Introduction

The fragmentary Antikythera Mechanism, recovered from a shipwreck dated to the 1st century B.C., is by far the earliest geared mechanism in the world. It is preserved in the National Archaeological Museum in Athens.[2] The largest part, fragment A, seen in figure 1, contains the remains of some thirty small gear wheels. Using superb radiographic plates prepared by Dr. Karakalos of Democritos, the late Professor Derek J. de Solla Price first showed the extent and the complexity of the Mechanism's internal arrangement, and presented a reconstruction that offered an explanation of many of its features.[3] All subsequent accounts of the Mechanism, except our reports of our own observations, are based more or less securely on that of Price.

According to Price, the instrument was contained in a flat box, having dials on both faces. These were interconnected through trains of toothed gears, so that a single input, probably the turning of a hand winch or knob, caused all the indicators to advance together. The "front" had a dial with two concentric rings: the inner divided into the twelve signs of the Zodiac and subdivided into 360 degrees; the outer divided into the twelve months of the year (named according to the Egyptian calendar) and subdivided into 365 days. Around these rings worked two indicators, showing the positions in the Zodiac of the Sun and the Moon, the former also indicating the date; therefore they rotated in one tropical year and in one tropical month respectively.[4] The "back" bore two dials, one above the other. The lower back dial had a pointer rotating in one synodic month and so perhaps showing the Moon's phases or other events of the month. The pointer on the upper back dial could have rotated once in four years, but the evidence is uncertain. The Mechanism might have been used for demonstrating or predicting celestial or calendrical phenomena.

Wright has worked on another, later and simpler, geared mechanism from the Greek world.[5] This prompted us to a re-examination of Price's monograph, which gave rise to doubts over details of his treatment and led us to work on the Antikythera Mechanism.

We agree, at least provisionally and as far as it goes, with Price's description of the general nature of the Mechanism and the sort of function that it probably performed. We certainly agree with his assessment of its importance as evidence of a previously unexpected level of technical achievement of Greek culture and as a remarkable survival of an early tradition of fine mechanism. The details of Price's work that troubled us are unimportant by comparison. Nevertheless the significance of the Mechanism is so great that further attempts to resolve these problems and to develop a more satisfactory reconstruction seem justified.

We therefore undertook several campaigns of investigation including direct visual examination, measurement, photography and radiography. In order to obtain resolution in depth through radiography, we exploited the technique of linear tomography.[6] Our work yielded a mass of detail that has proved hard to digest. Some of it even casts doubt on crucial elements of Price's reconstruction but, so far, provides no new reconstruction to put in its place. We expected the information to fall into a pattern that would simplify its presentation, but so far no complete and unambiguous scheme has emerged.[7]

A Problem with the Accepted Reconstruction

We begin by recounting the main features of Price's gearing scheme, referring to figure 2 which is taken from his own account.

At the top we must imagine the "front" dial with the Zodiac laid out on it. Price has the instrument driven from the contrate wheel A which engages the "drive wheel" B1. B1 goes round once in a year, and the loop of gearing B2-C1-C2-D1-D2-B4, which embodies a form of the Metonic ratio (here, 19 tropical years = 254 tropical months), causes the central spindle attached to B4 to go round once in a month, but in the opposite sense to B1. Price therefore introduces, as a conjectural restoration, another wheel identical to B1 engaging the upper limb of wheel A, to effect a reversal so that the indicators for Sun and Moon move in the same sense around the Zodiac as they should.

These motions are also fed through to the lower part of the instrument at axis E, through gearing B3-E1 and B4-E2i, where they are combined as inputs to a differential gear assembly.[8] The output, the rate at which the "turntable" E3/E4 rotates, is half the difference of the rates of rotation of the two inputs. It is doubled through gears E3-F1-F2-G2 to give the motion of the Moon relative to the Sun, the synodic month, at the "lower back dial", seen to the right.

We have found major difficulties with this pair of connections. Axes E,B and D actually lie in a triangular pattern. Our tomographic plates do not show wheels E2i, B4 and D2 engaged as Price has them; rather, D2 is engaged directly with a wheel on axis E, and another wheel on axis E engages B4. The two wheels on axis E both seem to have 32 teeth, so the ratios remain unaltered. The effect is to reverse both axes B and E relative to axis D.[9]

The first of these reversals is to the good: it does away with the need for Price's clumsy conjectural reversing mechanism using the duplicate of wheel B1. That arrangement is inadmissible in any case, because there are the remains of a structure carried on wheel B1 which rise above the upper limb of wheel A, making it impossible to bring Price's conjectural wheel into engagement. B1 and the central spindle, to which B4 is attached, turn in the same sense. Sun and Moon indicators, respectively, may be driven directly by them.

The other reversal would cause a very serious problem, if the other connection to the differential gear, B3-E1, were as Price suggests; reversing just one of the inputs to the differential gear, its output would become not the difference but the sum of the two rotational velocities, in this case a quantity that is astronomically meaningless. However, referring again to our tomographic plates, we can find no clear trace of wheels B3 and E1 at all, but because the gears are thin and are arranged in closely-packed layers, and with the deterioration and distortion that the fragments have suffered, it is surprisingly hard to be sure.

Driven by this problem, we have spent much time questioning Price's system, trying to devise other ways in which the parts of the instrument, especially the "front" and "back", could have been connected. On the basis of our present information, however, we can find no alternative scheme that makes any sense. Provisionally we accept Price's arrangement for the wheelwork serving the "front dial", but without the need for the reversal through the contrate gear. The problems of the connections to the differential gear, and the functions driven from it, seem best left until we can take advantage of the developments described in the next section.

Data Manipulation and Image-Enhancement

It is an irony of our work that the gathering of new information should have brought us greater doubt, not certainty, as to the basic mechanical arrangement of the Mechanism. It is also a puzzle: the conventional resolution of our radiographs, in the plane of the plate, seems excellent, and the resolution in depth afforded by our tomographic technique seems more than adequate. It may be that the details of the fragments that we wish to study are simply not sufficiently well preserved to bear the scrutiny to which we are attempting to subject them.

The images of some parts are, however, hard to read. This is especially true of those of the volume containing the connections between axes B and E, embedded in a thick and dense part of the object so that the contrast achieved is low. In recent years the techniques for addressing just such problems have made great advances. Modern techniques offer both superior possibilities for straightforward image-enhancement and other ways of making good use of our material. Since our plates themselves are good, they can be scanned, using appropriate equipment, to capture a great body of digitised information.

Besides providing the basis for the enhanced images that we need, this data may be used in other ways. It can, for example, be reconstituted to yield a virtual solid image which may be inspected at will from any angle. In principle, it is possible to combine data taken from both radiographic and photographic images, together with that obtained by direct measurement. It is also possible to manipulate the data so as to remove from the three-dimensional images at least some of the distortion that the original fragments have suffered, making it possible to bring the images of the separate fragments, freed of distortion, together in their correct spatial relationships.

Whereas our original radiographic material is difficult to publish, digitised data, and images derived from it, can be replicated, and may be made available to others for research and for display purposes.

We are currently in discussion with leading experts in the field of Information Engineering, with a view to exploring just how far these goals can be achieved. So far it appears that the results of the procedures outlined may yield results at least as good as those which would be obtained from the use of more modern scanning equipment; the advantage of the latter, in ease of image capture, is offset by the compromised resolution of the image. We expect to report on our progress at an early date.

With these developments in prospect it makes sense to stand back for the present from problems that depend on clearer visualisation of obscure detail. Image-enhancement may afford certainty or compel us to change our view, but provisionally we accept the arrangement of Price's model, with the reservations that we have already mentioned, as the basis for further work that can be done meanwhile. In the next section we suggest how studying features that can already be seen in good detail, and considering questions of context, may illuminate the use of the Mechanism.

Upper Back Dial

One abiding problem of all attempts at reconstruction of the Antikythera Mechanism concerns the upper back dial. A satisfactory reconstruction would account for the evidence of the dial itself and would entail a plausible reconstruction of the wheelwork behind it. In addition, we would expect it to have a function which, with the functions of the other dials, would provide a unified purpose for the whole instrument. No such reconstruction has been devised. In fact we understand little enough about the Mechanism that this proposition may be inverted: a purpose for the upper back dial, which was in agreement with the physical evidence of the fragments and which formed a coherent whole with the functions of the other two dials, might lead us to a better understanding of what the Antikythera Mechanism was and how it was intended to be used.

The divisions and lettering on the exposed portion of the upper back dial, preserved in fragment B, cannot be made out sufficiently clearly to offer much guidance.[10] Price reported radial lines suggesting division into 47 or 48 equal parts, but we think the number may be higher: 48 to 50 parts. There is uncertainty due to the difficulty in finding the centre of the dial, besides which we should not take it for granted that the divisions were uniform.

The train of gearing leading to this dial is incomplete, spanning as it does the break between fragments A and B. Referring back to Price's gearing scheme in figure 2, the wheel shown on axis N is not actually there; this represents a conjectural placing of the wheel preserved separately within fragment D. The wheel shown as O1 is reported only tentatively by Price, and we find no clear evidence for its existence. Ironically, we do have for this dial, and not for any of the others, the remains of a radial pointer, embedded in the concreted mass above the plane of the dial.

Price's scheme incorporates the suggestion that the pointer should turn once in four years. Alternatively, he suggested that it might turn five times in the 19 year Metonic cycle, with synodic months indicated by division of the dial into 47. He preferred the former suggestion as fitting the evidence of the gearing better, while recognising that the latter offered a more coherent set of functions for the whole instrument.

There is scope for other suggestions. Bromley suggested a function connected with eclipse-prediction.[11] The most attractive of the possibilities that he considered is a display of the so-called Saros cycle of 223 lunations, for which there seems to be some evidence in the fragmentary inscription found on this face of the Mechanism. We are now diffident about the interpretation because it does not seem compatible with the observed divisions on the dial. It does however fit the evidence of the fragmentary wheel train as well as any other suggestion to date, and should not yet be rejected altogether.

Kramer has proposed a different scheme for eclipse-prediction, in which the main indication of the upper dial is driven from wheel E4, the teeth of which are not accounted for in Price's scheme, whereas the subsidiary dial is driven from M2.[12] We hope that he will develop his idea into a form in which its merits may better be judged.

A quite different interpretation is offered by Albert.[13] He suggests that the pointer of the upper back dial should have rotated four times in a year, and that the dial indication would have been used for weather-prediction. The fragmentary inscription on the dial plate itself offers some basis for the possibility of a meteorological function, which should be borne in mind; but there are difficulties with Albert's reconstruction. There is in reality far less scope for adjusting the relative positions of fragments A and B, and so for making a free choice in making a conjectural restoration of the gearing, than Albert supposes. A discussion of his argument based on units of measurement must be reserved for another occasion.

Yet another use of the upper back dial is proposed by Edmunds and Morgan, in exploring the possibility that the Mechanism might have displayed the motions of planets according to a simplified epicyclic model.[14] Adjusting the gearing reported by Price behind the upper back dial to yield an approximation to the mean motion in longitude of Mars, they suggest a display of the planet's motion on this dial. Unfortunately Price's evidence for this gearing is most insecure, but if that were its function, then it would be necessary for the further mechanism suggested to be carried above the existing dial plate. Far from fitting in with the divisions and inscriptions on the dial, this clumsy arrangement would obscure them. It makes no sense of the detail of the dial plate that we report below, and is hard to reconcile with the evidence of a radial pointer above the dial. Moreover, there seems no obvious reason why Mars should be singled out for this treatment when comparable arrangements cannot be contrived for the other planets.[15] The question of modelling planetary motions is discussed below.

Efforts at the interpretation of both upper and lower back dials have been hampered by faulty observation on the part of Price. Noting that each dial was made up of several distinct rings, with clear annular spaces in between, he supposed that the rings might have been capable of being rotated independently. On the contrary, these rings were certainly fixed, supported from behind in such a way as to allow moveable pieces, fitted to the slots between them by pins with heads behind, to be slid around. These moving pieces might have been small markers, like the beads of an abacus, or rings or segments each attached by several pins. Rather than sets of concentric rings, these dials should be described as provided with sets of concentric slots.

In the central disc of the upper dial there is a curved slot, uniform with the others but with a closed end. Just possibly, the system may not have been a set of concentric slots but a single spiral. In either case the maker took pains to construct the systems of slots with great care; no reconstruction of either dial can be satisfactory if it does not offer a reason for their presence.[16]

Modelling Planetary Theory

Price associates the Antikythera Mechanism with a contemporary literary tradition that attests to the making of planetaria and similar devices. Others have speculated as to how the motions of planets may be added to Price's reconstruction.[17] We too have explored the possibilities for further astronomical functions, in an attempt to explain enigmatic features of the original fragments.

Any such exercise is largely an essay in speculation, having a value only if it enhances our understanding of what remains. Regarding planetary motions in particular, there is a special difficulty in determining what model is appropriate to the Antikythera Mechanism, because very little is known of the planetary theory of the time in which it was made. The triumphant success of the mathematical astronomy of Ptolemy's *Almagest* (*ca.* A.D. 150) was such that the work of his predecessors was neglected and has been preserved only in fragments.

Ptolemy's description of the noticeably non-uniform apparent motions of the planets depends on compounding circular motions, using a system of epicycles. In the simplest epicyclic model, a celestial body is imagined as rotating with constant angular velocity in a circle, the *epicycle*, the centre of which is carried at constant angular velocity around a second circle, the *deferent*, at the centre of which is the Earth.

This model had already been shown to be kinematically equivalent to the eccentric model, adopted with success by Hipparchus (*fl. ca.* 150-125 B.C.) in describing the apparent motions of the Sun and the Moon, as we know because Ptolemy incorporates this work with acknowledgement. Ptolemy also preserves a theorem of Apollonius of Perga (*ca.* 200 B.C.) concerning the determination of stationary points in such an epicyclic system, from which we conclude that Apollonius was aware that it held possibilities for the description of planetary motion. There is, however, no evidence that any predecessor of Ptolemy regarded this as anything other than an abstract problem.[18]

Ptolemy's schemes for the planets are highly sophisticated, and much more elaborate than the crude sketch given above indicates. Although it is tempting to suggest that his work must represent the culmination of a long incremental tradition, there is no clear evidence of any such tradition. No astronomer prior to Ptolemy is known to have employed any form of epicyclic system as a descriptive or predictive model for planetary motion, and it is equally possible that the whole development of the epicyclic planetary system was due to Ptolemy alone. Ptolemy himself appears to claim as much.

Ptolemy's fully-developed theory was represented by wheelwork in the famous Planetarium (or Astrarium) of Giovanni de'Dondi, completed in 1364.[19] From earlier times there survive only *equatoria*, instruments in which the epicycle disc is set by hand, but subsequent mechanical models of the Ptolemaic System, more or less simplified, are well known.[20]

In any model of the Ptolemaic system, the observer, on the Earth, is imagined at the centre of the dial, and the fixed stars are imagined around the outside where a divided ring represents the Zodiac. In a simplified arrangement commonly found in mechanised instruments, the planet on its epicycle is represented by a pin, fixed eccentrically to a toothed wheel which rolls around a stationary toothed wheel fixed in the centre of the dial. The numbers of teeth of the two wheels are chosen to make the epicycle turn the appropriate number of times as it runs around the central wheel, and the radius at which the pin is set on the epicyclic wheel is chosen in proportion to the radius of the deferent, which is the circle that the centre of the rolling wheel traces out. The observer's line of sight may be represented by an arm, pivoted at the centre, having a slot riding on the pin, the outer end of which reaches the Zodiac ring to indicate the observed position of the planet.[21]

The "line of sight" arm, reminiscent of the alidade of an observing instrument, displays the underlying principle rather well. But if several motions are to be displayed together on one dial, the arms would, in general, project at different levels. The inconvenience, of having so to arrange the mechanism above each as to allow its free rotation, may be avoided by fixing the slotted arms to concentric pipes which pass up through the overlying layers, carrying indicators at their upper ends, much like the conventional arrangement of the hands of a clock.

The mechanical elements are related to the astronomy as follows. For the inferior planets, Mercury and Venus, the centre of the epicycle is carried around the dial once in a year, since this motion corresponds to the Earth's rotation around the Sun. The rotation of the epicycle itself corresponds to the orbit of the planet about the Sun. For the superior planets, Mars, Jupiter and Saturn, it is the rotation of the epicycle that corresponds to the rotation of the Earth about the Sun, so that in each case it turns once in a year relative to the dial, while the motion of the epicycle around the deferent is slower, corresponding to the orbit of the planet around the Sun.[22]

We will show in outline how mechanism of this type may be fitted, as a conjectural addition to the surviving fragments of the Antikythera Mechanism, to achieve a display of the motions of all the planets together in the most natural place, on the front dial with its Zodiac ring, together with motions of the Sun and Moon modified according to the theory of Hipparchus. The starting point for this reconstruction is a twofold observation concerning the large wheel B1 seen in figure 1 and shown diagrammatically in section in figure 2.

As figure 2 shows, wheel B1 it is part of an assembly with a hollow centre. In figure 1 a projecting boss is seen, at the centre of the wheel, the upper end of which is formed as a square. The square suggests strongly that this component did not rotate with the wheel, because the probable purpose of the square would have been to carry one or more wheels, and if there were.to be wheels at this level rotating with wheel B1 then there are much easier ways in which they might have been fixed there (for which parallels can be found elsewhere in the surviving fragments). We suggest that the pipe was fixed to the base plate, and that the rotating assembly turned on it, with the central arbor to which wheel B4 is fixed passing up its middle. This is a satisfyingly workmanlike arrangement.
The evidence that there were probably central wheels, together with the clear evidence that there was further structure, now lost, mounted on wheel B1,

suggests very strongly that epicyclic wheelwork was fitted here. The fact that wheel B1 rotated once in a year suggests further that the wheelwork on it could have been intended to model either the motion of the Sun or that of the inferior planets, or both.

Modelling Solar and Lunar Theory after Hipparchus

All reconstructions of the Antikythera Mechanism to date have followed Price in showing, on the front dial, the mean motions of the Sun and Moon. Since it is accepted that the loss of the Mechanism, and probably also its manufacture, postdate Hipparchus by a good margin, we may reasonably investigate how the Mechanism might have incorporated models of his solar and lunar theory.

Hipparchus's solar theory may be regarded as an epicyclic system. The centre of the epicycle for the Sun, the Mean Sun, moves at a constant speed around a deferent circle with the Earth at its centre, while the radius joining the Mean Sun to the True Sun remains fixed in direction in space. It is easy to model this system exactly, and to fit such a model to the fragments of the Antikythera Mechanism.

Wheel B1 moves at the rate of the Mean Sun. In other words, it is appropriate to mount the epicycle for the Sun on it. The epicycle is made as a toothed wheel, with an eccentric pin representing the True Sun. A fixed wheel of the same number of teeth is planted on the central square, and the two equal wheels are connected by an intermediate, idle, wheel. This configuration ensures that the radius from the centre of the epicycle to the eccentric pin remains fixed in direction relative to the dial as the epicycle is carried around. The actual numbers of teeth are immaterial. The motion of the True Sun is relayed from the eccentric pin to the dial display using the slotted arm and pipe described above.

Hipparchus's lunar theory is similar but a little more complicated: the True Moon is on an epicycle that moves slowly in the sense opposite to that in which the Mean Moon is carried around the deferent.

The motion of the Mean Moon is given by the rotation of the central spindle to which wheel B4 is fixed. This may carry a platform, bearing the epicycle wheel for the True Moon, just above the central square. The gearing to rotate this epicycle is comparable to that used to keep the Sun's epicycle stationary; the wheel for the epicycle is driven from a central fixed wheel through an intermediate arbor. In this case, however, the central and epicyclic wheels do not have equal numbers of teeth. Having 118 teeth on the central wheel and 117 on the epicycle, connected by an idle wheel, would give a fair approximation, but a compound train can be more accurate and may be more convenient. The slotted arm embracing the pin for the True Moon is attached to a central arbor that passes up to the dial.

The whole assembly for the motion of the True Moon must be small enough for the arbor, carrying the epicycle disc for the True Sun (and, anticipating the next section, those for Mercury and Venus), to rise past it. Otherwise, the epicycle(s) mounted on wheel B1 would be below it. The corresponding slotted arm(s) would then have to be crooked, passing outward, turning down at a sufficient radius to leave clearance for the rotation of the lunar assembly, and then turning to form the slotted portion engaging the pin. The former arrangement seems preferable.

The mechanism to display the True Sun, together with the mechanism for the inferior planets to be outlined next, may be fitted to the wheel B1, where it offers a rationale for the size of this wheel as well as a possible account of what has been torn away from it. The mechanism for the True Moon, on the other hand, is conceived as being mounted on a platform that is now lost. It is offered merely because it balances that for the True Sun, and because the arrangement can be fitted without conflicting with the observed details of the original fragments. It merely calls for the presence on the central square of a second fixed wheel.

An Epicyclic Model for the Inferior Planets

There is some historical justification for applying epicyclic movements for the motions of the Sun and Moon to a new reconstruction of the Antikythera Mechanism, because this follows Hipparchus. On the other hand, as described above, we have no evidence that any form of epicyclic planetary theory had been developed by the time that the Mechanism was made; the Antikythera Ship was, after all, lost some two hundred years before Ptolemy wrote. Therefore to extend the use of epicyclic gearing in any form as a basis for planetary motions in the Antikythera Mechanism is to risk committing a gross anachronism. It is, however, interesting to see that epicyclic planetary models for the inferior planets may be devised to fit, offering a further rationale for the evidence that extensive additional mechanism has been lost from wheel B1.

The centres of the epicycles for the inferior planets are identical with the

Mean Sun. That is, the epicyclic wheels for Mercury and Venus may appropriately, like that for the True Sun, be planted on the large wheel B1. In these cases the epicycles turn in the same sense as that of their motion around the deferent, so that, if appropriate numbers of teeth could be found for the gears, the epicycle wheel and the central fixed wheel could be directly engaged with one another. Better approximations to the astronomical ratios can be obtained using compound trains, which must have an even number of intermediate arbors (in practice, two) to obtain rotation of the epicycles in the correct sense.[23] Moreover, compounding offers the possibility of using a common fixed central wheel for the two trains and even a common idle wheel or first pair engaging it. Also, since in the mechanism for the Sun described above the numbers of teeth are not material, the same central wheel and even the same idle wheel may be used for this ensemble too. As with the mechanism for the Sun, the slotted arms for Mercury and Venus must reach around the mechanism for the Moon.

Although in the mathematical model the centres of all three epicycles, for the Sun, Mercury and Venus, coincide (in the "Mean Sun"), there is no reason why the mechanical epicycles should not be distributed around the wheel. It is physically possible to fit such wheelwork for the inferior planets on wheel B1 in this way, together with that for the motion of the True Sun. The traces of lost components that were once mounted on wheel B1 are very plain to see, but they do not lead us immediately to an unique solution. The question of matching such a reconstruction to the evidence will be discussed in a later paper.

The most straightforward explanation of the presence of the central pipe with its squared end is that it carried a wheel or wheels for epicyclic gearing. Such mechanism also offers a satisfactory reason for the presence of the large wheel B1, as a platform to carry the epicyclic train or trains. The fact that this wheel was to turn once in a year offers us a strong argument for suggesting that, if such epicyclic gearing was present, it was either a model of Hipparchus's solar theory or a model of some form of epicyclic theory for the inferior planets, or both. Were it to carry only wheelwork for the solar theory, there would still be no need for it to be nearly as large as it is; it is the addition of wheelwork for the inferior planets that makes the adoption of so large a wheel rational, and which also offers a plausible explanation for the evidence of extensive work now lost from the wheel.

Price referred to the large wheel B1 as the "drive wheel" and supposed that it was made large because the torque that activated the whole mechanism was transmitted through it. That argument is not sound. According to his reconstruction, the torque applied to B1 is immediately transmitted to much smaller wheels. As Zeeman has stated, the designer would have done better to drive the Mechanism from another point, because it appears inept to apply the input at the slow end.[24] Bromley's model, in which the input is made to the gear E4, is in fact the only one that we have handled which runs at all sweetly, although this may be partly because it is better made than the others.[25]

However, with the abolition of Price's reversal through the contrate wheel A, on the basis of our present understanding we are left with no function for wheel A than that of being the input through which torque is applied to wheel B1. Not only does the conjectural restoration of epicyclic wheel work to wheel B1 provide a reason for that wheel to have been made so large. It also suggests why the designer might have chosen to drive the whole instrument at this point, since the extra mechanism is both a load to be carried and a resistance, demanding the transmission of extra torque through wheel B1.

The introduction of the motion of the True Moon actually adds a load at the other end of the train, but it is slight because the correction is small and changes only slowly. Similarly, the effort required to drive the motion of the True Sun is also only small. The addition of the motions of Mercury and Venus is however more significant, since these are greater in magnitude and faster-moving. The extension of the reconstruction to include models of the superior planets, as described below, would increase considerably the load to be driven. Since this further wheelwork would run at the same rate as B1 or slower it would most probably have been connected closely to this end of the train. The additional demand for torque at the slow end of the train would offer a further reason for the designer to have chosen to drive the instrument by turning B1.

The Superior Planets

The arrangements just described are conjectural, and those for the inferior planets can be justified historically only in the most qualified way, but the idea that they might have been present springs from actual features of the original fragment A. Our further speculations call on no such physical evidence, but are guided by the following argument: if the designer of the Antikythera Mechanism incorporated the motions of the inferior planets, he would surely have wished to include the motions of the superior planets also. Our objective here is simply to indicate how this could have been done.

We imagine three sets of mechanism, one for each of the three superior planets, fixed one above another on top of the system just described. Broadly, the arrangement of each would be similar to the mechanism for the inferior planets; that is, for each planet there would be a slotted arm connected to a central pipe rising to the dial (and enclosing the central arbor and other pipes rising from below), controlled by an eccentric pin in an epicyclic wheel that would ride on a rotating platform. The proportions of each set would of course be different, and in each case the platform would rotate at a different speed.

Such sets of mechanism could be built as independent units, each arranged on a fixed plate by which its weight is transferred to the case. They might have been supported by wooden battens, similar to those of which traces are found in the original fragments.

One might envisage each of these assemblies as similar to those for the inferior planets, having gearing to connect the epicycle wheel to a fixed central wheel and being set in motion by driving the platform. This would, however, probably not be a good arrangement for Jupiter and Saturn. In these cases the epicyclic wheel turns much faster than the platform, and the epicyclic trains would have to work as step-up ratios of about 10.6 and 28.4 respectively; the latter, particularly, would be a challenge to the mechanic.

The step-up ratios may be avoided by driving the epicycle wheels directly. Since, for the superior planets, the epicycles all turn once in a year, motion may be transmitted to them from wheel B1, where this rate of rotation is already established. Each epicycle can be driven, through an idle wheel planted on the platform, from an equal central wheel turning also once in a year. This arrangement is entirely analogous to that described above to keep the orientation of the epicycle for the Sun fixed. The central wheels could be driven, stage by stage, through the central cluster of rotating pipes, but it would simpler to drive them through plain spur gearing from a countershaft to one side.

With trains of wheels planted on the platforms to connect the epicycle wheels to central fixed wheels, driving the epicycle wheels would cause the platforms to turn. In working the ensemble by driving the platform, the epicyclic train would function as a step-up ratio, but in this case it would be working as a reduction and would therefore run much more freely. Alternatively, one might dispense with the epicyclic trains altogether, and drive the platforms separately, by trains outside the rotating assembly.

In whatever way rotation of the platforms is achieved, this system has a certain conceptual elegance. A consistent value for the rate of rotation of the Mean Sun is used throughout the display. In other words, the rotation of the epicycles for all the superior planets, relative to the dial, remains exactly in step with the indication for the Sun. When the accumulated error in the display of any superior planet called for resetting, it would be necessary only to shift the platform, not the epicycle. Moreover, the common once-a-year rotation, the most rapid and therefore the main source of resistance in this part of the mechanism, would be derived through wheelwork connected closely to wheel B1 and so, according to Price's model, to the input to the whole instrument. The arrangement provides a further argument for the input at B1 as a rational choice.

We emphasise that we have found no physical evidence for wheelwork for the superior planets. We may point out, however, that if such additional mechanism was ever present, it is easy to see that it might have been arranged so that, once torn away, it would have left little or no trace on the surviving fragments.

In any case, the addition of such extra wheelwork above wheel B1 would dictate that the dial must be set higher above the base plate than in previous reconstructions. One of the features of the original fragments, visible even in the earliest photographs, is that there is no clear join between fragment C, containing the dial fragment, and any of the others.[26] We have previously pointed this out, drawing attention to the fact that we cannot, therefore, be certain that this fragment was ever a part of the same instrument. We continue, however, to assume provisionally that it was, and that it must be incorporated into our reconstruction. In this context it is comforting to notice that the lack of such a join makes us free to set the dial (contained in fragment C) as far above the base plate (contained in fragment A) as is needed to accommodate the extra mechanism.

We repeat that these sections on the motions of the Sun, Moon and planets are largely based on speculation. We will probably never know certainly whether the Antikythera Mechanism actually included such a display, still less what would have been the exact nature of the mechanism driving it. In offering these ideas, however, we show that there is no difficulty in devising such a conjectural reconstruction, that it can be made to fit the evidence of the fragments, and even that it can offer an explanation of several features for which no other reason has been forthcoming.

Conclusion

We have referred at several points to our own direct observations of the original fragments. We are now preparing our notes on these observations for publication. These, with the outcome that we expect from the work on our radiographic and other material, as described above, will yield better information on the physical remains than has until now been available.

Most particularly, we hope that the preparation of more easily read images will enable us to clarify those elements of the gearing that we do not currently understand.

Many other features of the Mechanism remain unexplained, such as the component in fragment C that we have described previously, which turns out to be a small contrate wheel for which we have no function.[27] In this paper we have discussed the need for a satisfactory solution to the problem of the upper back dial, in good agreement with the details of the dial itself and with the traces of the wheelwork serving it, and offering a coherent rationale for all those parts of the mechanism that are directly attested to by the surviving fragments.

Beyond that, the evidence of the original fragments bears clear witness to the loss of much else, so that the Mechanism must have been more extensive than previous reconstructions indicate. An exploration of the possibilities for further conjectural reconstruction may aid our understanding, provided that its provisional nature is always borne in mind.

In this connection we draw particular attention to the possibilities of a refinement of the motions of the Sun and the Moon, following Hipparchus, and a display of the motions of the other planets of antiquity. We have indicated that such conjectural additions can be matched to the original fragments, and can actually offer explanations for features that are otherwise enigmatic. A working model will convey these ideas more succinctly than any words; the construction of such a model is now in hand and should be completed next year. An illustrated description, together with a more detailed discussion of the underlying principles, will be prepared for publication when the model itself is complete.

Finally, in recognising that more of the original instrument has been lost than was supposed, we are obliged to accept a corollary: unless further evidence can be found, any new attempt to offer a complete reconstruction of the Antikythera Mechanism will be made with less certainty than earlier writers believed possible.

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It is a great privilege to have been allowed to study this most precious artefact. We record our gratitude to the Greek authorities who granted us access to it, and to the staff of the National Archaeological Museum in Athens, especially Dr. P. Calligas and Dr. R. Proskynitopoulou, former and present Curators of Bronzes (respectively) and Dr. H. Magou, Head of the Laboratory in which we have done much of our work, and their assistants. All have made us welcome and have done everything in their power to help us.

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Notes

1. Probably no paper that is published under joint authorship is written equally by those named, and in this case it was written wholly by Wright. It is, however, proper that Bromley should be named as author, in that the work described depends on observations made by us both in collaboration, and has largely progressed through discussion between us. Moreover, Bromley has made valuable contributions in commenting on earlier drafts. On the other hand, it is only fair to both to state that the conjectural reconstruction of astronomical functions, described in the latter half of this paper, is the work of Wright alone.

2. Inventory number: X.15087.

3. D.J. de S. Price, "Gears from the Greeks", *Transactions of the American Philosophical Society*, new series, volume 64, part 7 (1974).

4. Such expressions are of course but a convenient shorthand; there is no suggestion that the Mechanism was self-moving. More strictly we would have to write some such expression as: "the rotation of the indicators represented the

passage of a year and a sidereal month". The convention is continued throughout this paper.

5. J.V. Field & M.T. Wright, "Gears from the Byzantines: a Portable Sundial with Calendrical Gearing", *Annals of Science*, 42 (1985), pp.87-138. Reprinted in J.V. Field, D.R. Hill & M.T. Wright, *Byzantine and Arabic Mathematical Gearing*, London, The Science Museum, 1985.

Also: M.T. Wright, "Rational and Irrational Reconstruction: the London Sundial-Calendar and the Early History of Geared Mechanisms", *History of Technology*, 12 (1990), pp.65-102.

6. M.T. Wright, A.G. Bromley & H. Magou, "Simple X-ray Tomography and the Antikythera Mechanism", *PACT* 45 (1995) (Proceedings of the Conference "Archaeometry in South-Eastern Europe" held in Delphi 19th. - 21st. April 1991, pp.531-543.

7. An early report will be found in: A.G. Bromley, "Observations of the Antikythera Mechanism", *Antiquarian Horology*, 18, 6 (Summer 1990), pp.641-652,together with a gearing diagram that may be compared to that of Price reproduced here as figure 2, showing discrepancies noted on direct visual examination.

8. Price explains the oddity of his notation E2i, E2ii thus: at first he imagined that a single wheel E2 might be used, until it was drawn to his attention that, to allow the rotation of turntable E4, wheels K1 and J could not lie in the same plane as D2.

9. We have drawn attention to this problem previously, most notably in M.T. Wright & A.G. Bromley, "Current Work on the Antikythera Mechanism", Proceedings of the conference *Ancient Greek Technology*, Thessaloniki 1997. Limitations on space have, however, previously prevented us from describing it as fully in print as we do here.

10. Price suggests that further cleaning of detritus overlying the surface should make these details more legible. Our opinion, however, is that the surface is already lost.

11. A.G. Bromley, "Notes on the Antikythera Mechanism", *Centaurus*, 29 (1986), pp.5-27.

12. S. Kramer to Bromley and Wright, 1991, private communication.

13. C.-P. Albert, "Das Maßsystem des Mechanismus von Antikythera", D. Ahrens, R.C.A. Rottländer (eds.), *Ordo et Mensura IV/V*, Scripta Mercaturae Verlag, St. Katharinen, 1998.

14. M. Edmunds and P. Morgan, "The Antikythera Mechanism: still a mystery of Greek Astronomy?", *Astronomy & Geophysics*, 41 (2000), pp.6.10-6.17.

15. Edmunds & Morgan (note 14) suggest the possibility of mounting a second planetary motion on the "front" dial, but they themselves draw attention to the difficulty of a reconstruction that incorporates displays of some but not all of the planets. One might also ask why the two planets chosen should have been displayed on dials that are different in character. The use of the front dial, with its Zodiac ring, as a place to display planetary motions, does indeed make better sense.

16. The details of this system will be more fully explained in the account of our visual inspection now in preparation.

17. Most recently Edmunds & Morgan, note 14.

18. A succinct account of the history of planetary theory in this period may be found in: G.J. Toomer, "Ptolemy and his Greek Predecessors", in C. Walker (ed.) *Astronomy before the Telescope*, London, British Museum Press, 1996, pp.68-91. Enough of Ptolemy's treatment for our purpose is presented in a digestible form in: O. Neugebauer, *The Exact Sciences in Antiquity*, second edition, Providence, Rhode Island, Brown University Press, 1957, Appendix I, pp.191-207. For further detail the reader may consult O. Pedersen, *A Survey of the Almagest*, Odense University Press, 1974, or the full text in G.J. Toomer (trans. & ed.), *Ptolemy's Almagest*, London (Duckworth & Co.) 1984, or (with addenda & corrigenda) Princeton University Press, 1998.

19. The original instrument does not survive, but de'Dondi wrote a full description. A modern edition of an English translation is available: G.H. Baillie, H. A. Lloyd and F.A.B. Ward, *The Planetarium of Giovanni de Dondi, Citizen of Padua*, London, The Antiquarian Horological Society, 1974. From this several modern reconstructions have been built.

20. See, for example, H.C. King, *Geared to the Stars*, Bristol, Adam Hilger Ltd. (Toronto, University of Toronto Press), 1978.

21. Edmunds and Morgan, (note 14) illustrate the arrangement described up to this point, and tabulate some tooth-counts for such wheelwork for all the planets. (The numbers for the central and epicyclic wheels in their Table 1 and Figure 6 are transposed.) It is however doubtful whether their simple ratios are all well chosen. Besides this, more accurate approaches to the astronomical ratios may be obtained by the substitution of compound trains for simple pairs.

22. We appreciate that so simple a model can give only a poor representation. This is especially so of the motion of Mercury, to which Ptolemy found it necessary to accord a particularly elaborate treatment.

23. De'Dondi (note 19), however, obtains rotation in the correct sense by using an internally-toothed wheel.

24. E.C. Zeeman, "Gears from the Greeks", *Proceedings of The Royal Institution of Great Britain*, 58 (1986), pp. 139-156.

25. A.G. Bromley, "The Antikythera Mechanism", *Horological Journal*, 132,12 (June 1990), pp.412-415, and 133,1 (July 1990), pp.28-31.

26. I. N. Σβορώνος, *Τό εν Αθήναις Έθνικον Μουσείον*, Athens, 1903. Also published in German: J. N. Svoronos, *Das Athener Nationalmuseum*, Athens, 1908.

27. We took this feature as a case study at Delphi (note 6), but offered a revised opinion of it at Thessaloniki (note 9).