The Front Dial of the Antikythera Mechanism

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Abstract. The Antikythera Mechanism, found in a shipwreck dating from the first century B.C., is the oldest geared mechanism known. Its general function was astronomical or calendrical, but the exact nature of the display on its front dial remains uncertain. We know that the places in the Zodiac of the Sun and Moon were shown, and the date. The author has previously argued that the places of the five planets known in antiquity must also have been shown. He devised mechanism to drive these indications, and demonstrated the viability of his reconstruction by building a working model. Reviewing his earlier publications, he clarifies obscure points and shows how recent study by others supports his arrangement of the display. Others, again, have proposed an interesting alternative to some parts of his restored mechanism for the planetary indications. It bears a close relationship to the device found in the original instrument for modelling the lunar anomaly, and may offer certain practical advantages. The author welcomes the new proposal, and suggests its further development. He concludes, however, that as yet there is no compelling reason to abandon any significant part of the reconstruction that he previously proposed.

1 Introduction

The Antikythera Mechanism [1], found in a shipwreck datable to the second quarter of the first century B.C. [2], is the earliest known geared instrument. Price gave the first correct account of its general arrangement, with front and back dial displays on two opposite faces of a wooden case, interconnected by internal mechanism worked by the rotation of an arbor projecting from one side [3]. Inscriptions on several surfaces had already indicated an astronomical context. Subsequently, making use of radiography, Price studied the instrument's internal mechanism with a view to identifying its precise function. In his reconstruction, the front dial showed the places of Sun and Moon in the Zodiac and the date, while the back showed the age of the Moon and other, less confidently identified, calendrical information. This instrument had no clear purpose, but he called it a "calendar computer" [4]. Price's reconstruction has now been superseded: partly by my own findings, described in a series of papers which are listed in two recent publications [5, 6]; and partly by those of the *Antikythera Mechanism Research Group* [7], who have published two papers [8, 9]. There is now general agreement over many features of the Antikythera Mechanism although, due to its poor state, minor points of uncertainty can probably never be resolved; but here I consider a major source of continuing debate, the reconstruction of its front dial.

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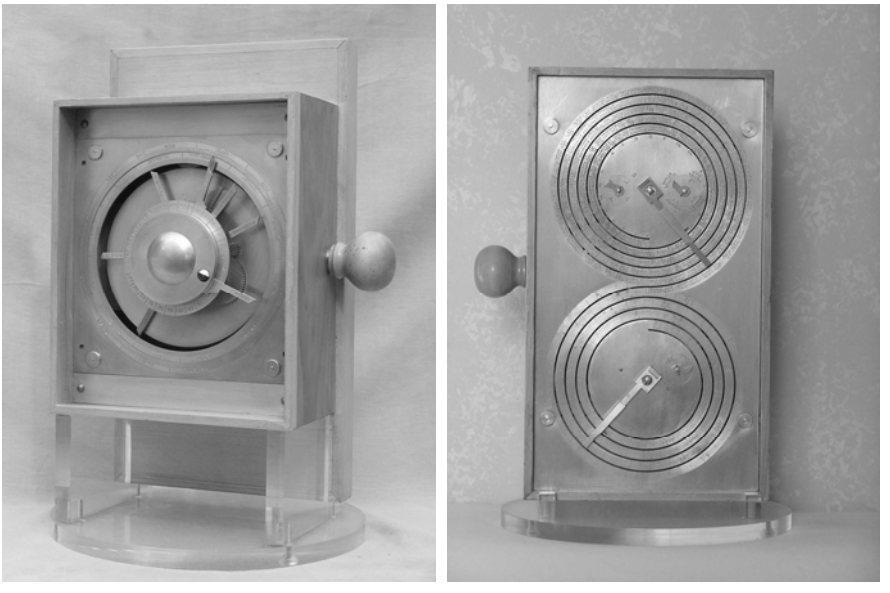


The Antikythera Mechanism, Reconstruction by M.T. Wright: left, front dial; right, back dial.

The two dials differ markedly in character. The back dial, which we now understand fairly fully, presents straightforward periodic information in two separate displays: principally a cycle of 235 months or 19 years (the calendrical cycle associated with Meton) above; and a cycle of 223 months (the cycle now called the Saros, indicating eclipse-possibilities) below. The arrangement is ingenious, elegant and efficient, particularly in its use of spiral scales to spread out these two long sequences of months over five and four turns respectively, making them easily legible and allowing the displays to yield further information; but the effect is simply that of sets of tables with moving pointers. The mechanical arrangements for driving these displays are essentially also simple. The user turns an input – a hand-knob in my reconstruction – which rotates a contrate wheel; this wheel engages a large spur wheel, one rotation of which represents one year, and the pointers on the back dial all derive motion from this wheel through straightforward compound trains of spur gearing embodying velocity-ratios reflecting the well-established period-relations noted above. I shall have occasion to refer to the large wheel again, and I follow Price in referring to it as wheel B1, the first wheel on axis B.

By contrast, although it is more poorly preserved, the front dial display was clearly more visually appealing. There were two large concentric graduated rings. The inner was divided into twelve parts bearing the names of the signs of the Zodiac, subdivided into degrees of longitude. The outer bore the names of the months of the year according to the Egyptian calendar, subdivided into days. Price suggested that two pointers showed the mean motions of the Moon and Sun, and that the Sun pointer also showed the date on the outer ring; or (for a reason that need not detain us) he envisaged the possibility of a third, separate date pointer.

I argue that the front dial originally carried further pointers, for the five planets known in antiquity. Price also thought of this possibility; or, more precisely, he suggested that an empty space behind the dial in his reconstruction might have contained gearing to drive such planetary indications [4]. It was characteristic of Price that he would drop into a paper any idea that he thought might possibly be relevant [10], but he appears not to have taken this one very seriously because he did not pursue it in any way. He passed over his seemingly prescient remark quickly and lightly, so that by the time I began developing my own reconstruction of the front dial display I had forgotten it; when I came to examine the Mechanism for myself I found Price's account so much at variance with what I saw that I chose to ignore the written word altogether and to look at the artefact with an "innocent eye".

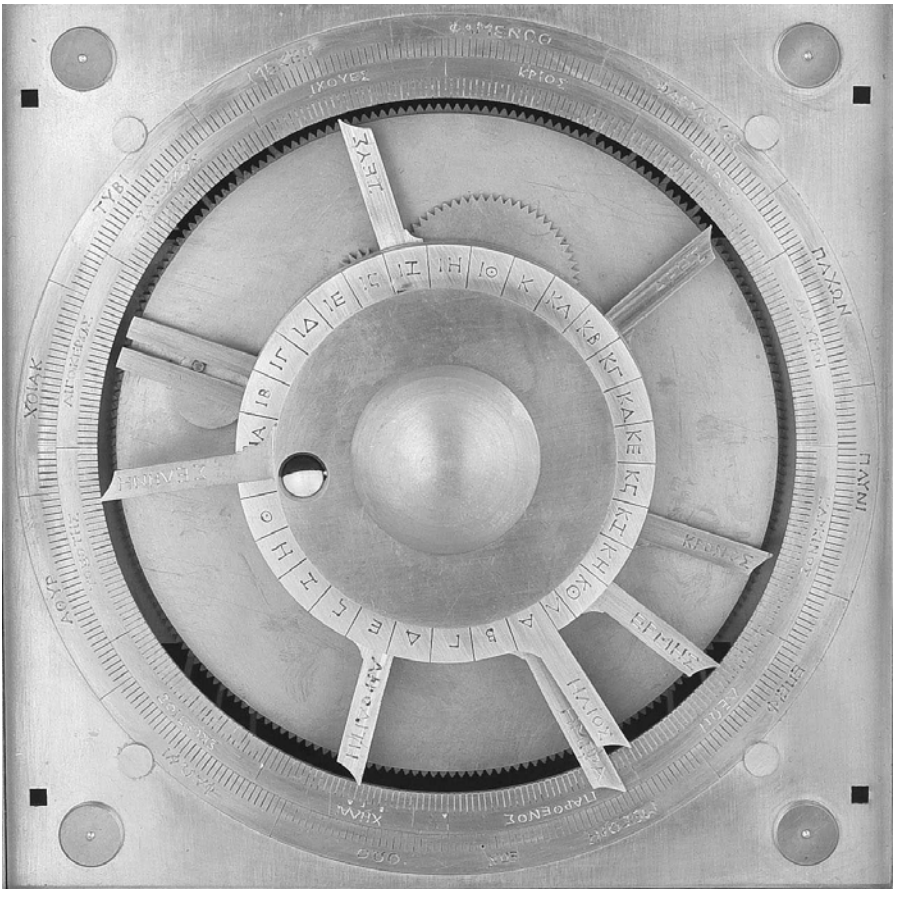
As Price had conjectured and I later confirmed [11], wheel B1 and a central arbor on axis B passing coaxially through it were geared together so that if one rotation of B1 were to represent one year, one revolution of the central spindle would represent one sidereal or tropical month. ("Sidereal month" was Price's term. However, the dial includes a formal representation of the Zodiac and not a star-map; and the tropical year, not the sidereal year, had come to be regarded as a constant in Hellenistic astronomy [12]. Therefore the term "tropical month" is correct.) Significantly, it also emerged that Price had made a mistake in tracing this gear train. He believed that the two mobiles turned in opposite senses, and so he introduced a conjectural reversing arrangement. In reality, the two turn in the same sense, and pointers for the mean motions of the Moon and Sun could have been connected directly to the central arbor and to the wheel respectively [13].

By simplifying the arrangement behind the front dial, the removal of Price's reversing system made it easier to develop a new reconstruction based on hitherto unexplained features on and around wheel B1 which suggested strongly that epicyclic mechanism had been mounted on it. This in turn brought to mind the epicyclic theory of Hellenistic astronomy, a kinematic device for the compounding of two circular motions. The earliest trace of this idea is the interest shown in it by Apollonios of Perga (*fl. c.* 200 B.C.), reported by Ptolemy. In *The Almagest* [14], Ptolemy includes a theorem of Apollonios in which he explores the applicability of epicyclic theory to the apparent motion of the planets. Ptolemy follows Hipparchos (*fl. c.* 140 B.C.) when he discusses this same "Apollonian" epicyclic theory in connection with his treatment of the anomalous motion of the Sun and Moon. The construction of the Mechanism almost certainly postdates the work of Hipparchos, so the inclusion in it of a mechanised version of epicyclic theory to portray the motion of the Sun, Moon and planets is chronologically acceptable. This is the theoretical basis of my reconstruction of the front dial, as a concentric planetarium display of Moon, Sun and the five planets known in antiquity.

I first presented this scheme, illustrated by sketches and a crude cardboard model, in a conference paper read in 2001 (but publication of the proceedings was delayed) [15]. Early the next year I announced the completion of a working model [16], and later the same year I described both the model and some of the reasoning behind it more fully [17]. For reasons beyond my control all three papers were severely limited in length. Further papers were planned, but events took on a momentum of their own, with other aspects of the Antikythera Mechanism occupying what little time I could devote to the subject.

I felt no urgency. It seemed likely that this material would be of concern to only a small community composed mainly of those studying the history of instruments, of mechanism, and of astronomy. I supposed that anyone sufficiently interested to wish to discuss my work would apply to me for information and for the opportunity to inspect my model, which I regarded as a form of publication in itself. The main message, after all, had already been broadcast by Price: the Hellenistic world was capable of this degree of mechanical achievement; the detail was less important and, for those who worked in these fields, I thought much of it would be obvious.

That perception may have been mistaken. A relentless publicity machine has now brought the Antikythera Mechanism to the attention of a very much wider public, increasing the scope for misunderstanding and misrepresentation. The priority and value of my work has been contested. In revisiting the subject some ten years after having first presented my reconstruction, I show here that my contribution is still relevant and I welcome some newer developments.



Front dial of the Antikythera Mechanism, Reconstruction by M.T. Wright, second model, 2009.

2 The Planetarium Dial

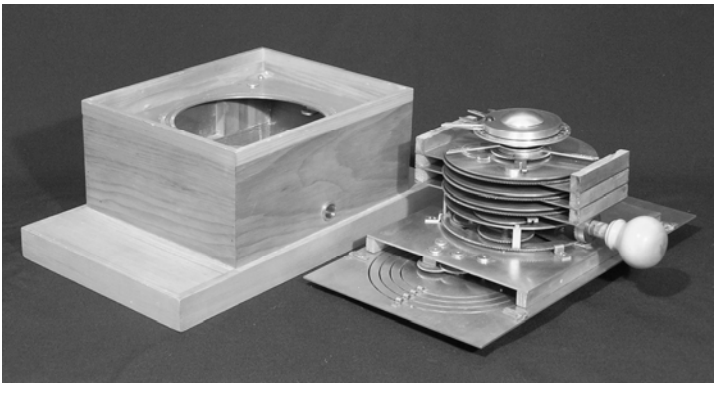
I have explained my methodology, in using model-making both as an aid to developing my reconstruction and as a medium for subsequent communication [6]. The resort to model-making has however had an unintended consequence. As the model became well known, uncertainty grew both about it and about the reconstruction that it illustrates. Some suppose that I claim the model as a faithful representation of the original in every respect; others suppose that I do not intend my reconstruction to be taken as a serious essay in any way. Neither extreme view does justice to my work. I wrote about the design choices involved some ten years ago when the model was new [15, 16, 17], but it will be helpful to reiterate and emphasise some points before carrying the argument further forward.

From the outset this was a serious attempt to develop a reconstruction that would fit the extant fragments; was of the same character and class of work as the original; could account for hitherto unexplained features; and could endow the instrument – for which no-one had yet offered any satisfactory rationale – with a plausible function. These points, together with the further one that reconstruction as a planetarium connects the artefact to the literary evidence for planetaria in Graeco-Roman antiquity, have already been made [15, 16, 17]. Perhaps, however, I have not recorded in print how the evidence of an inscription on the instrument supports my reconstruction. Among the lettering that has long been legible to the naked eye, on a part that Price named the "Back Door", he records ΤΗΣ ΑΦΡΟΔΙΤΗ[Σ] (*tēs Aphroditēs*: of Venus); two lines further on is ΓΝΩΜΩ[Ν] (*gnōmōn*: pointer); and on the next line ΗΛΙ[Ο]Υ ΑΚΤΙΝ[?] … ΗΛΙΟΝ (*hēliou aktin[?] … hēlion*: Sun's ray … Sun) [4]. The implication is that something was stated about Venus, and that Venus might be associated both with a pointer and with the Sun. There was a pointer for the Sun on the front dial, and it followed, as a strong possibility, that Venus was also displayed there. Price had earlier reported "terms … that refer to stations or retrogradations of planets" [3]. These readings, implying strongly that the instrument was concerned with planetary phenomena, which (as we now know) can only have been displayed on the front dial, are now being gradually confirmed and extended, as we shall see.

Epicyclic theory was almost certainly widely known and discussed at the time that the Antikythera Mechanism was made, but it is proper to be cautious in considering just how freely the instrument's creator might have translated it into practical mechanism. Therefore I adopted a strict design criterion, introducing no subtlety into the process: as in the treatment attributed to Apollonios himself, the larger circular motion of the platform would always represent the Zodiacal motion of the body.

The general arrangement of the reconstruction followed directly from this point of principle. The epicyclic mechanism to be restored to wheel B1 – a platform rotating at the rate of the Mean Sun – was thereby limited to modelling the motion of the inferior planets, Mercury and Venus, and the anomalous motion of the Sun. Unfortunately, the ideal of devising a reconstruction accounting for all traces of structure on the wheel was – and remains – elusive. In my first model I was content to show that mechanism serving the three functions described could be fitted to the space, knowing that there were many ways in which an appropriate supporting structure could be devised that

would make use of at least some of the fixings for which we have evidence. In a second model, I took more trouble to match my structure to the evidence, but still it is not all accounted for. A survey of this evidence is being prepared for publication. Identical sets of wheels, described and illustrated elsewhere, are fitted to each model [16, 17].



Reconstruction of the Antikythera Mechanism by M.T. Wright. The internal mechanism is shown removed from its case.

According to my design principle, mechanism for modelling the motion of the superior planets, Mars, Jupiter and Saturn, with their individual Zodiacal periods, called for three further epicyclic platforms. These could be interposed between the assembly on wheel B1 and the front dial, because the separation between those parts of the original instrument is indeterminate.

The wheel-work for the superior planets used in the first model has also been described and illustrated [16, 17]. In the second model, the same velocity-ratios and the same arrangements are used throughout, but the numbers of teeth are multiplied to make the wheels larger without making much change to the pitch, so that alterations to the design (whereby the central pipes and bosses are of larger diameter) are accommodated. I note in passing that the arrangements chosen have intrinsic advantages of interest to the designer of mechanism; but since this part of the scheme is conjectural I shall not discuss them here. It is however appropriate to say that the rather high number of wheels used represents no real objection; the trains run freely, and it is clear that the designer of the original mechanism was not afraid to use many wheels, some with high numbers of teeth.

The wheel-count was increased significantly by my decision to substitute compound gear trains for simple wheel-pairs in all the planetary models, in order to show that good approximations to the planetary periods could successfully be modelled. It is widely recognised that Babylonian planetary period-relations were available to the Hellenistic astronomer, and that these might have recommended themselves to the instrument-maker because they can be modelled using simple gear-pairs; but I thought it important to show that the designer might easily have attained a much higher accuracy

in modelling the planets, comparable with that of the Metonic period-relation (determining the length of the month) which is already attested within the Mechanism. If compound trains realising good approximations would run, there could be no doubt that simple gear-pairs, having about the same velocity-ratio but representing coarser approximations (such as those derived from Babylonian period-relations), would run even more freely. The accuracies achieved have been described [17], but the justification for making this demonstration has not been fully argued. A discussion of the sort of refined periods that the Hellenistic designer might plausibly have aimed to approximate, and of the way in which he might have cast up approximations in designing compound gear trains, is the topic of a further paper now in preparation.

It was only some time after developing the basic reconstruction that I identified the boss of the Moon hand for the front dial, with its indication of the Moon's phase [18]. The addition of this central feature, together with a corresponding conjectural alteration to the Sun hand to provide a display of the day of the month, brought the front dial to its present state.

As well as having been described in print [6, 16, 17], a version of my model may be viewed as a computer-animation generated by Vicentini which may be accessed either directly from his own website [19] or through mine [20]; but note that the program "VCL Media Player" must be selected to play the animation. Currently it may also be seen, without the need to change default software, on the website of the Museo Galileo of Florence [21]; but there it is not seen in a full-screen view. This animation actually illustrates a second model, differing slightly from the first one; the few points of difference relevant to this paper are described here.

I devised my reconstruction before it was understood how the pin-and-slot modelled the lunar anomaly. So, intent on demonstrating just how complete a planetarium display the Hellenistic mechanic might easily have developed using only the epicyclic theory, I added to the first model a further small epicyclic system for the Moon. The discovery of the purpose of the pin-and-slot system made this conjectural addition redundant, whereupon I removed it. The certainty that lunar theory was included did, however, increase the probability that solar theory, for which I fitted conjectural epicyclic mechanism to both models, would have formed a part of the original scheme.

The identification of the pin-and-slot device and its purpose revealed greater subtlety of mechanical design than had been appreciated, and indicated that my adherence to a literal, direct realisation of epicyclic theory may have been unduly strict. Below I shall discuss the interesting suggestion of Carman *et al.*, that this device presents us with an alternative way of modelling the motion of the superior planets.

3 Other Conjectural Schemes

My restoration of planetary mechanism originated in the need to explain evidence seen in the original fragments, which is surely a *sine qua non* for any satisfactory reconstruction. However, two papers published by other authors at about the same time, exploring the idea of planetary displays from more abstract standpoints, should be mentioned.

Edmunds and Morgan [22] argued, plausibly, that hints found in the fragmentary inscriptions encouraged one to speculate about possible planetary indications. Basing their conjectural mechanisms on the epicylic theory, they outlined simple arrangements; but, having no first-hand knowledge of the instrument and apparently relying mainly on their reading of Price, they envisaged assemblies that simply could not be fitted to the original. Despite information and comments from myself, the authors thought it impossible to fit more than one epicyclic display on any one dial, and concluded that it would be "difficult" to incorporate more than two planets at once in the whole instrument.

Taking the ideas of Edmunds and Morgan as his starting point, Freeth [23] followed them in adopting directly epicyclic theory for the inferior planets. Unlike them, he thought both inferior planets might be fitted to the front dial, but only with "some difficulty". For the superior planets, Freeth developed several options. In the first, the epicyclic platform rotates – as in the case of an inferior planet – at the rate of the Mean Sun, but the epicycle is envisaged as a large internally-toothed gear-ring which runs around a smaller fixed central wheel. Freeth wisely expressed doubt as to whether the Hellenistic mechanic could have made this arrangement work, but he seemed unaware that it was, in fact, a realisation of the *eccentric* theory, understood by Hellenistic astronomers to yield the same effect as the epicyclic theory [14]. He then developed what was in effect the Apollonian epicyclic model, but again seemed unaware how close was the parallel between his scheme and conventional Hellenistic astronomy. In a first version he followed Edmunds and Morgan, applying torque to the platform, and driving the epicycle wheel by running it round a fixed central wheel. Freeth was right in suggesting that this system could work for Mars; but in advocating its use for Jupiter his judgement was more questionable because a significant step-up ratio was involved in driving the epicycle. For Saturn, with a much higher step-up ratio still, Freeth devised two further mechanisms, finally preferring one in which the epicycle was to be driven independently of the platform, using the same device that I had previously adopted.

Freeth's reasoning seemed to be mathematical, not directly related to Hellenistic astronomical theory, and arguably somewhat anachronistic; he acknowledged that his analysis "depend[ed] on a heliocentric knowledge of the Solar System". We are left unsure as to how readily the designer of the Mechanism might have arrived at some of these schemes.

It was however in the suggested placement of his mechanisms in the instrument that Freeth lost touch with reality altogether. Like Edmunds and Morgan, he indulged in a pure flight of fancy, envisaging modifications to the reconstruction of Price so that he might fit displays of the three superior planets (and one for the age of the Moon) to the back of the instrument.

In neither case had the authors actually examined the Mechanism, and their suggestions bore no very close relation to the surviving parts of the original. Neither paper need detain us further, except to remark that Freeth's first proposal for the superior planets – a platform rotating at the rate of the Mean Sun with an anomaly-generating device mounted on it – may be said to contain the germ of the idea more recently developed by Carman *et al*. [24] which I will discuss below.

4 The Antikythera Mechanism Research Group

The mechanical ensemble now known as the "pin-and-slot" lies within the extant parts of the Mechanism. It comprises two wheels lying face to face, running on a stationary stud that is stepped so that they turn about separate axes. One wheel has a pin planted in its face which projects to enter a radial slot in the other, so that if one of them were to rotate at a steady rate the angular velocity of the other would be modified by a cyclical variation. It was clear that the ensemble might be used to model an astronomical anomaly [25]. In their first publication the Antikythera Mechanism Research Group showed that the device was so arranged as to modify the motion of the Moon pointer on the front dial in accordance with a lunar theory like that of Hipparchos [8]. The conjectural epicyclic mechanism for the same purpose was therefore redundant, but it was the work of a single afternoon to remove it from the model and to effect other small alterations that made my provisional reconstruction conform to the Group's findings. None of this occasioned any outward change to the front dial display.

In the supplementary information appended to the same paper the Group presented provisional readings of the fragmentary inscriptions, extending those previously published. The "Back Door" inscription, mentioned above as including the words "of Venus … pointer … Sun's ray … Sun", now seems even more telling. The words are now seen to lie within a text in which the word ΣΦΑΙΡΙΟΝ (*sphairion*: little sphere, globule) is repeated several times. The line immediately above the one naming the Sun has been expanded to read: ΓΝΩΜΩ … ΚΕΙΤΑΙ ΧΡΥΣΟΥΝ ΣΦΑΙΡΙΟΝ. I translate this as: "… pointer … there lies [or: "is placed"] a golden globule". In a later instrumental tradition a golden marker often denotes the Sun [26], and the mention of a golden globule, possibly in association with a pointer, just before the naming of the Sun, seems very significant. The repetition of the word "globule", before and after this short passage, suggests that "of Venus … pointer … there is a golden globule … Sun's ray … Sun" may be embedded within a longer descriptive list of markers for other celestial bodies besides Venus and the Sun. Such markers would have been useless unless individually distinguishable, and in the later tradition this was commonly achieved by making them of different materials or by painting or enamelling them in different colours. Thus the new reading seems to strengthen the evidence for planetary indications on the front dial along with those of the Sun and Moon, and even to give us a hint as to the appearance of the pointers: distinguished by raised globules or "buttons" of appropriate colours instead of, or in addition to, engraved names. The reading of the inscriptions is in the hands of epigraphic experts with direct access to the Group's images, whose work is still in progress, and I have hesitated to alter the pointers of my model until we know whether further details may emerge.

The Group's further publication in 2008 [9] led to some further small alterations, but only to the back dials.

5 Carman, Thorndike and Evans

Evans *et al*. [27] make the interesting observation that the surviving fragment of the Zodiac scale from the front dial appears to be divided unequally, in a way that is consistent with a deliberate intention that a single pointer should show both the date on the calendar scale (which is taken to be uniform) and the true position of the Sun on the Zodiac scale. They then suggest offsetting the axis of the Sun pointer and the dial so that the Moon pointer shows the Moon's longitude correctly (or more nearly so) on the unequally-divided ring. The scheme is practicable but appears untidy and unnecessarily complicated. Moreover, it seems possible to attribute the observed inequality to error in manufacture.

In the same paper, the authors outline an alternative to my concentric kinematic planetary display, suggesting that a set of five subsidiary dials might have been provided for the planets, each with a pointer indicating the phases of the planet's synodic cycle. The arrangement would certainly side-step problems that might be associated with the proposed increased complexity at the centre of the main dial, but the authors base their argument on the reported number of teeth on wheel B1, from which they derive the motion for working these indications. They also suggest an alternative explanation for the size of wheel B1 and the features on it, as a display of essentially decorative elements.

These ideas merit greater attention on another occasion; but I will now discuss the substance of a further paper by the same authors in which they offer alternative mechanism to drive pointers for the superior planets in a concentric display [24].

Freeth *et al.* [8] went to some lengths to show that the pin-and-slot ensemble can generate an output with a varying angular velocity identical to that of epicyclic theory. Carman *et al.* demonstrate the same point, but more clearly and more economically, as a prelude to showing how this ensemble might have been used to work planetary indications.

It is generally assumed that any kinematic planetary displays in the Antikythera Mechanism would have been based on a single-anomaly theory. That is, only Ptolemy's "second anomaly" – the anomaly with respect to the Sun which accounts for the spectacular episodes of retrogradation – would have been modelled. Carman *et al.* show that the arrangement for the lunar anomaly actually found in the Mechanism can be adapted to become just such a single-anomaly model for the superior planets, and they show in outline how it might have been fitted to the extant fragments.

According to the lunar theory associated with Hipparchos, the Moon's motion is described by a single anomaly with respect to a slowly-rotating line of apsides; so the anomalous motion must be compounded with the slow, uniform motion of the line of apsides itself. In the Mechanism this is done by planting the pin-and-slot ensemble, driven at the mean rate of rotation of the Moon and generating the anomaly, on a platform rotating at the rate of the line of apsides. The output motion – comprising two rotations superimposed one on the other – is taken out through the centre of the platform, and transmitted through to the dial pointer.

In the single-anomaly model of a superior planet, the anomaly is symmetrical about the moment of opposition with the Mean Sun; that is, it is symmetrical about

the line through the Mean Sun and the Earth. So the motion of a superior planet may be generated in the same way as is that of the Moon, by superimposing the anomaly on the rotation of the Mean Sun. Wheel B1 rotates at this rate, and Carman *et al.* suggest that three pin-and-slot devices, one for each of the three superior planets, could have been mounted either on wheel B1 itself or on further structure carried on it. There would have been a fixed central wheel for each planet, around which the appropriate pin-wheel would run. The three pin-wheels would, therefore, have been set at different heights on wheel B1. The numbers of teeth in the fixed wheel and in the pin-wheel would have been chosen in each case so that the pin-wheel, and with it the slot-wheel, rotated relative to the Mean Sun Wheel with a frequency approximating the planet's synodic period. The slot-wheels would also have been set at different heights so that each could deliver its output – comprising the anomaly superimposed on the motion of the Mean Sun – to the appropriate pointer through a central wheel with the same number of teeth as itself.

Without having tried it out, one cannot be quite confident that this system is really practicable, especially as applied to Mars. Modelling the very large anomaly for Mars calls for a large offset between the axis of the pin-wheel and that of the slot-wheel. The pin must therefore approach close to the centre of the slot-wheel once every revolution, when the pressure between the pin and the side of the slot, and the reactions at the pivots, will be high. Carman *et al*. appreciate this potential difficulty and claim to have satisfied themselves that it can be overcome. They report having modelled the system for Mars and having tried it in practice, apparently as an independent device. However, they give no details of their trial – scale, materials, parameters &c. – and there is room to doubt how well the device would work, and how long it would remain workable, as part of a complete planetarium instrument. For example, friction between the concentric pipes carrying the hands would place a load on the pin-and-slot mechanism which might, if not carefully managed, lead to its rapid wear; and a quite minor accident could cause pointers to foul one another and give rise to sudden heavy loads.

Carman *et al*. restrict themselves to designs based on approximate period-relations drawn from Babylonian astronomy which can be realised by the use of simple gear-pairs. Better approximations to the planetary periods for the superior planets, such as those used in my models, could be obtained by driving the pin-and-slot ensembles through compound trains. The pin-and-slot device produces a symmetrical effect, so it may run in either direction on wheel B1, and the number of axes in the train driving it may be odd or even; but obviously the final output must run the right way, and so the overall number of epicyclic axes for each planet must be odd. Such compound trains would be less economical in the number of wheels used, and the arrangement would almost certainly be less compact, than the simple gear-pairs envisaged by Carman *et al*.; but the idea is interesting because pin-and-slot devices worked by compound trains could achieve results as good as those of my models while taking less space and using fewer wheels than the gearing that I have suggested. Correspondingly, the epicyclic systems that Carman *et al*. envisage for the inferior planets could also be driven using compound trains, just as they are in my models.

Carman *et al*. appear to urge, as a point in favour of their scheme, the consistency that it offers in using for each superior planet a mechanical ensemble closely comparable with that found modelling the lunar anomaly in the Mechanism itself; but they introduce inconsistency by falling back on the use of the Apollonian epicyclic system for the inferior planets. It is however quite straightforward, in principle, to adopt the pin-and-slot ensemble for each of the inferior planets too. (The same device could also be used for the solar anomaly, but Carman *et al*. adhere to the main idea of their earlier paper in suggesting that the solar anomaly was accommodated by having an unequally-divided Zodiac scale.) Here the stepped stud of the pin-and-slot ensemble might remain stationary, fixed to the frame. Motion from wheel B1, or from any other mobile turning at the rate of rotation of the Sun, would be transmitted to the pin-wheel through gearing with the correct velocity ratio to ensure that the anomaly was generated with the right periodicity. Gearing with the inverse velocity ratio would then return the output to the central axis, so that the resultant motion would have the required mean Zodiacal period of one year. Whoever was sufficiently acute to have devised the known mechanism for the lunar anomaly, and perhaps the similar mechanism that Carman *et al*. propose for the superior planets, should surely have had no difficulty in imagining this application to the inferior planets also.

Therefore, if it is thought to be a point in favour of any reconstruction that the several anomalies are modelled by similar mechanisms, then the pin-and-slot scheme that I have just outlined for the inferior planets (and perhaps for the solar anomaly) must be examined in connection with that of Carman *et al*. for the superior planets. The most obvious way to mount the non-rotating mechanism would be to plant it on the frame plate, or on a bridge or similar structure spanning the other wheels planted directly on the plate. Either way, this conjectural mechanism for the inferior planets would most naturally have lain behind wheel B1 (now carrying only the mechanism for the superior planets), but there is no room for anything of that sort there.

Perhaps there were such non-rotating pin-and-slot ensembles for Mercury and Venus, arranged in some less obvious way. If, on the other hand, we must accept the use of epicyclic mechanism for these planets, the case for using any different mechanism for the superior planets is weakened. The use of the pin-and-slot in modelling the lunar anomaly would then become the "odd one out": a point that might fit with an idea – first conceived to account for different oddities, some of which still remain unexplained – that the back part of the Antikythera Mechanism may have been partly or wholly rebuilt at some time during its working life [28].

6 Conclusion

In my reconstruction of the front dial of the Antikythera Mechanism, a satisfactory (and satisfying) planetarium display, with concentric pointers for date, Sun, Moon and the five known planets, is plausibly fitted to the instrument. This central focal feature provides the instrument with a rational purpose, and it is in accord with the evidence for an interest in planetary phenomena indicated by the inscriptions on the instrument. The back-dial displays, very different in character, make more sense as supplementaries to a

main, planetarium display than as principal functions in their own right; they are like the smaller tools on the back of a pocket-knife. Fitted with a planetary display, the instrument accords with literary evidence that attests the existence of planetaria; whereas other reconstructions present us with rather complicated devices of very little real purpose, which find no mention in the literary tradition.

The mechanical arrangement that I devised for driving the planetary display accounts for more of the artefactual evidence than does any other reconstruction to date. It is made up of elements which are all based on precedents found within the original fragments, and all are made in the same style, using the same techniques, as the original parts. I have shown that this arrangement works well.

It is important to distinguish between the general principle of the reconstruction and those parts of the particular designs described and modelled that are no more than conjectural. The latter may be changed without vitiating the reconstruction as a whole. In particular, where choice presented itself I elaborated the reconstruction as far as I thought the designer of the original could possibly have desired. In this way I erred – if anything – on the safe side in making my demonstration that the scheme was practicable. I was cautious in another respect, in choosing to implement only the simple epicyclic theory associated with Apollonios, and only in the most straightforward way. This led inevitably to the addition of a significant number of wheels in order to add the superior planets to my concentric display. I went further in showing how, using compound gear trains, all the planetary periods could be approximated very closely. This was intended to demonstrate that the accuracy attainable by the Hellenistic mechanic knew no practical bounds, and that cruder periods, such as those derived from Babylonian period-relations and capable of being realised using simple gear-pairs, could certainly be modelled with ease. In the atmosphere that obtained when I devised my reconstruction, of considerable doubt as to what the Hellenistic mechanician might have been able to achieve, this demonstration was important.

Our subsequent understanding of the working of the pin-and-slot mechanism, as modelling the lunar anomaly in place of my conjectural epicyclic mechanism designed for the same purpose, has led to thoughts about its wider application. Carman *et al.* have shown how it could have been used to drive concentric pointers for the superior planets in a particularly economical way. I point out here that it could also have been applied to modelling the motion of the inferior planets and the solar anomaly. Such changes to the planetary mechanism might allow us to economise the number of gear-wheels used, or to make the wooden case of the Mechanism a little slimmer, but they would not necessarily make any difference to either the appearance or the function of my front dial display.

The extended reading of inscriptions on the instrument suggests a small cosmetic enhancement, with the addition of "globules" of differing materials or colours to distinguish the several pointers on the front dial instead of – or as well as – engraved names; but at the same time it seems to srengthen the evidence supporting my conjectural restoration of a full planetarium display with pointers for Moon, Sun, five planets and the date. So far I see no reason to make any significant changes to this reconstruction. As for the mechanism driving the planetary pointers, the arrangements that I have put forward represent just one set of possibilities among many. It is interesting to consider

other suggestions, but there is as yet no compelling reason to reject my arrangement in favour of another.

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