The Antikythera Mechanism: a New Gearing Scheme

M.T.Wright

Introduction

The Antikythera Mechanism, the oldest geared instrument in the world, became widely known through the work of Professor Derek de Solla Price; and for anyone seriously interested in this seminal artefact his *Gears from the Greeks* is still essential reading.[1] Price was the first to show the remarkable complexity of this unique survivor of what must have been an extensive tradition of instrument making, forcing us to rethink fundamentally our appreciation of the technical achievement of Hellenistic culture in the first century B.C.

Price's monograph stands as a classic for this reason, but his interpretation of the device itself is flawed because his observation of its detail was poor. In giving the Society's Invitation Lecture in November 2003, I spoke about my progress to that date in my attempt to understand the Mechanism and to prepare a more satisfactory reconstruction than Price's, on the basis of a detailed new examination of the original fragments carried out by the late Allan Bromley and myself.[2]

Any such attempt centres around discussion of the gear trains. Figure 1 is Price's diagram of his gearing scheme.[3] This is to be compared with the diagram of my new gearing scheme, Figure 2, which represents more accurately what is found in the original and indicates how I think it should be completed. In further papers I will expand on several novel points that the attentive reader will notice here, supporting my argument by reference to the very considerable wealth of detail that can be seen in the original fragments.

The surviving gearing may be divided into three groups, corresponding closely to the three dials with which the instrument was furnished:

1. The foundation of the instrument is the provision of two concentric mobiles behind the *Front Dial*, a large wheel and a central spindle, connected by a reverted train (loop) of gearing so that one revolution of the wheel represented one year, and one revolution of the spindle represented one tropical month. The large wheel was worked by a gear connected directly to a hand knob, and everything else was worked through it in turn.

2. A second train of gearing leads away from the one-turn-per-tropical-month motion towards the *Lower Back Dial*.

3. A third train leads from the one-turn-per-year motion towards the *Upper Back Dial*.

In a later paper I will discuss a number of features that point to a strong possibility that the instrument may have been radically rebuilt at some time. If so, it was perhaps only at that stage that the present scheme emerged, but it is important to emphasize the tripartite arrangement of the instrument *as it survives* because this validates my approach in developing a new reconstruction by treating the parts in turn: each part should make sense within itself. Ultimately, however, one might expect to see the distinct parts as a coherent whole. Further papers, drawing on the material set out here, will show to what extent this has now been achieved.

I began by developing a reconstruction of the front dial, based on the first section of the gearing: the initial driving arrangement and the reverted train. I accepted Price's numbers for the wheel teeth of that train "provisionally", but I have now confirmed them. My demonstration that the front dial must have been more elaborate than was previously supposed offers, for the first time, an explanation for several features on and around the Mean Sun Wheel. The possibility that the instrument might plausibly have been a complete planetarium is important because it links this one surviving instrument more strongly with the tradition of the making of astronomical models attested by the literature. Besides, the intricacy of what survives seems more in keeping with an elaborate function than with the rather banal display of Price's reconstruction.

The motions of a planetarium call for the introduction of further gearing: I have demonstrated the possibility of including epicyclic trains on the Mean Sun Wheel modelling the anomaly of the Sun and one anomaly each for Mercury and Venus, and further epicyclic arrangements modelling one anomaly each for the Moon, Mars, Jupiter and Saturn. The arrangements that I have built into a working practical reconstruction are described elsewhere.[4] I will however repeat the point that it is the principle that is important, not the detail. Although my arrangement is economical and efficient, embodies very good approximations to the several period relations and is consistent with the evidence of the original fragments and with what we know of the astronomy of the first century B.C., there is simply no way of knowing whether or how closely any such reconstruction represents what has been lost. Therefore no detail of this conjectural restoration is included in the gearing scheme that I present in here, since my present aim is to elucidate what remains within the original fragments.

New Gearing Scheme: General Features

I retain Price's convenient system of nomenclature – alphabetical letter for axis and number for wheel – with some necessary modifications. Firstly, not all the wheels in Price's scheme are actually found in the original. Secondly, in a few cases he was mistaken in interpreting the evidence as to where a wheel lay or with which other wheel it was engaged. Thirdly, in other cases he argued that he had to restore a wheel to fill out his scheme when, in fact, the scheme was incorrect. Consequently I have moved some wheels and removed others. I have also introduced a few new ones. In all cases I have simply abandoned the designations of moved or removed wheels, and I have extended Price's system to give a new designation to each wheel that has been moved or introduced. Reallocating the abandoned designations would have given a tidier appearance, but comparison of my scheme with Price's and others based on it would then be very confusing.

Figure 2 shows that the reverted gear train (from axis B through C and D and back to B) now includes axis E. Wheels E6 and E7 are those understood by Price as E1, E2i and E2ii, and their changed designations reflect their altered functions in my scheme, which now accord with actuality. Since they have equal numbers of teeth, their effect on the reverted train is simply as though an idle wheel were introduced, so that wheel B2 (and with it B1, representing the mean motion of the Sun) and B4 (representing the mean motion of the Moon) turn in the same sense. Price's conjectural *Sun Position* wheel is therefore redundant and is discarded.

Price's wheels B3 and E1 are not present, and so the central arbor on axis E, and wheel E5 on it, remain stationary. The epicyclic gear based on E4 as a platform is therefore not a differential gear. The wheels E2ii and K1 within this epicyclic cluster, shown by Price as lying below E4, are moved to accord with the actuality and are now called E8 and K3, but the principle of their action is not changed. I retain Price's conjectural wheel J a little tentatively, because it is not quite clear from the physical evidence that it is called for; but I can make sense of the train of wheels leading to the Lower Back Dial only with such an idle wheel.[5] It remains doubtful whether wheel J should be placed between E8 and K3 or between E5 and K2, but that detail is unimportant.

Price's single wheel N is replaced by the more extended conjectural restoration of wheels N1 and N2 and a further axis P with wheels P1 and P2, affording a rational connection between axes N and O. Wheels O1 and O2 of Price's scheme are rejected in favour of a single wheel O, which is all that I find.

The provision on axis B of a stationary boss with a squared upper end indicates that at least one fixed wheel was planted there. I indicate this by introducing wheel B5, but since nothing survives of the epicyclic gearing under the front dial to which it gave motion no attempt is made to show a restoration.

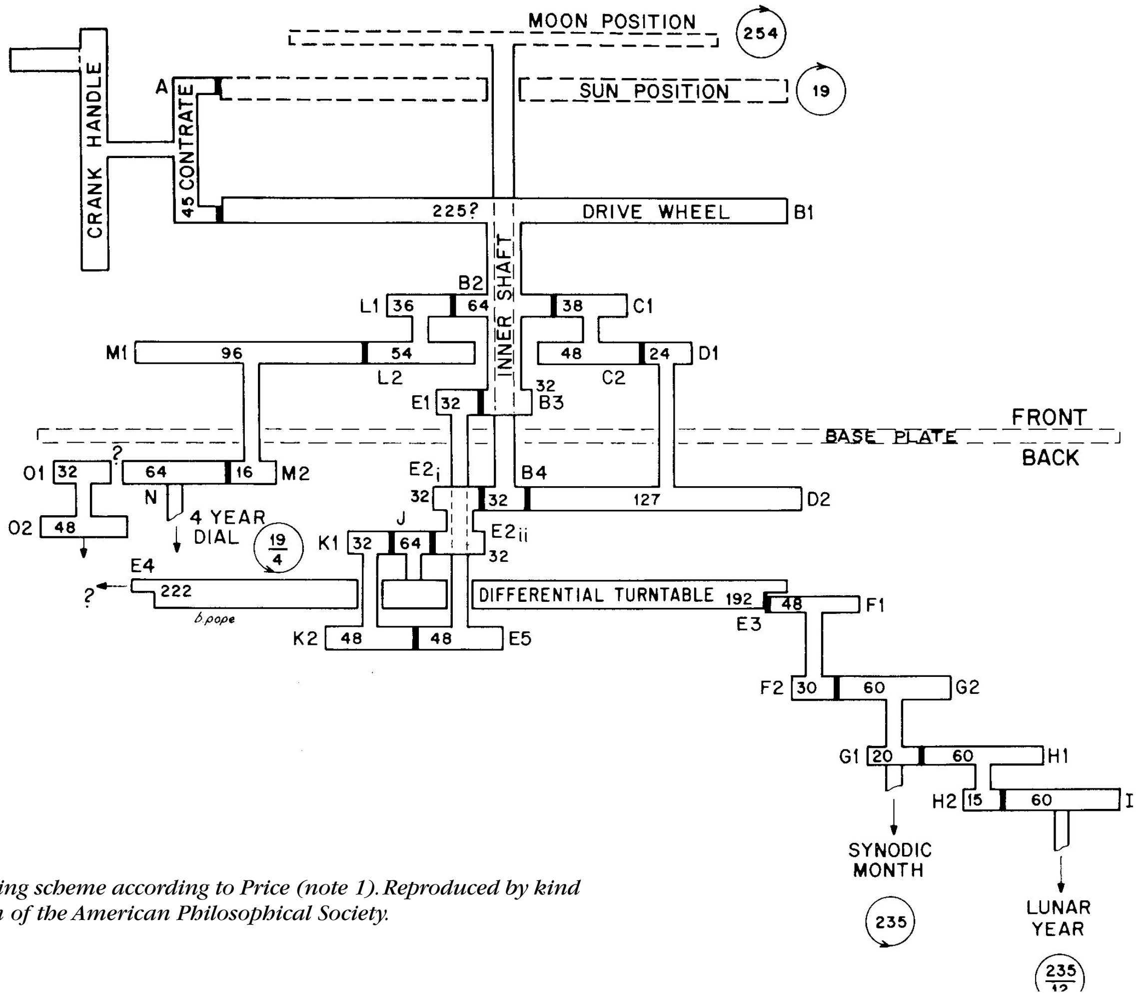

Fig. 1 *Gearing scheme according to Price (note 1). Reproduced by kind permission of the American Philosophical Society.*

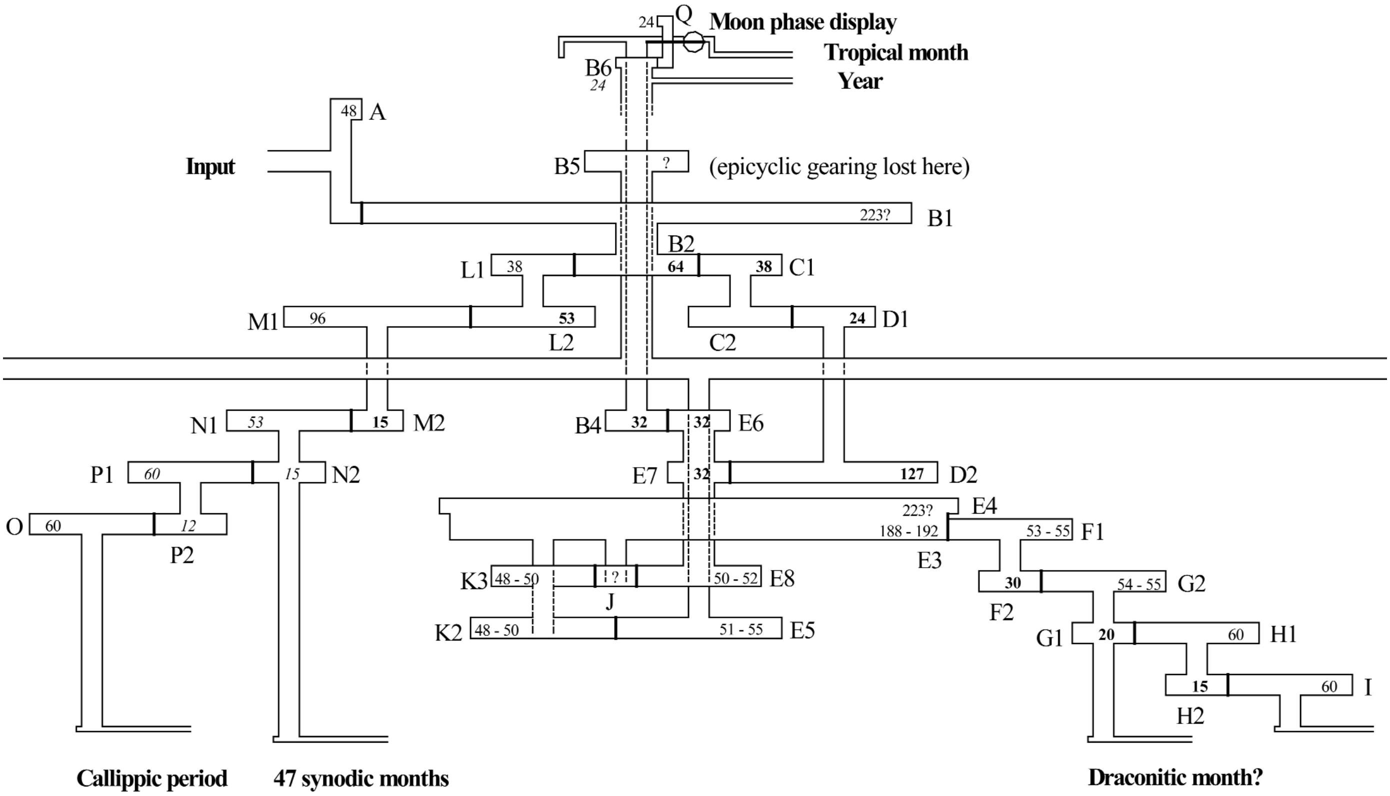

Fig. 2 *Gearing Scheme according to M.T.Wright.*

At the top of the diagram I indicate the conjectural placement a small "drumlike component" (Price's description) found in fragment C (Γ). The arrangement provides a rotating Moon ball display, using just two wheels: the contrate wheel Q actually exists in this fragment, but the spur wheel B6 fixed to the Sun indicator is a restoration.

Gearwheel Analysis

The tooth counts for the wheels shown in Figure 2, and listed in the Table, are the outcome of my reappraisal of each individual wheel, working from digitized versions of both plain radiographs and images taken from tomographic sequences.[6] Three different type faces are used. Tooth-counts printed in bold type are certain. Those printed in ordinary type – whether given as single figures or as ranges – are not; further information on their interpretation is given below. Those that are printed in italic type are suggested numbers for wheels that are conjectural restorations. In the Table my counts are compared with those made by Karakalos (as reported by Price) and with the numbers subsequently adopted by Price. To the Table I have added a wheel Q, as explained above; wheel Δ1 from fragment D (Δ), which Price restored conjecturally as wheel N but which is too large to be placed there; and a further wheel Δ2 which I believe I see within this fragment. I have no clear suggestions as to where the latter two wheels might have been placed, but since at the very least there must have been an epicyclic train on wheel B1, there is scope for excluding them from the scheme illustrated in Figure 2 without embarrassment.

The following notes refer briefly to the derivation of the tooth-counts given in Figure 2 and the Table. From them the reader may form an impression of the degree of confidence with which the counts are given. The assessment is not wholly objective, and I doubt whether, in the more difficult cases, it can ever be so. It depends on judgment as to how far the pitch of the lost parts of each wheel might have varied, either by design or by accident, and how great a variation in pitch is likely to have been tolerable in the immediate circumstances under which that wheel worked.

A

The limb of this contrate wheel is so encrusted and so damaged that no direct tooth-count is possible. It may be estimated only roughly, by taking the ratio of its diameter to that of B1 which it engaged together with a tooth-count for the latter which (as noted below) is insecure. This procedure suggests about 48 teeth. In my reconstruction the gear-pair A : B1 serves only as the means of giving motion to the mechanism, and the number of teeth is unimportant.

B1

The teeth of B1 are rather poorly preserved. In many places no trace of them is found, while in others we see "ghosts", distinct images of the outline of teeth at several radii, an appearance that may be an artefact of the corrosion process. Besides all this, the limb does not appear very truly round. It is therefore difficult to give a close tooth-count. I find 223 as a "preferred" value, with probable low and high limits of 216 and 231. Presumably the closer limits given by Karakalos reflect his assumption that the division is more uniform than it really is. However, in my reconstruction the number of teeth in this wheel is unimportant.

B2

Most of the teeth of B2 can be seen. Some seem rather unevenly cut: one single space measures 1.26 time the mean, but since the adjacent space is small this may be partly a result of damage. There are two lacunae. The smaller must have contained three tooth-spaces. The larger measures 8.2 times the mean pitch of the surviving teeth and I suppose that it must have contained 8 spaces. Therefore I offer a confident count of 64 teeth.

B4

The tomographic sequences show that there is no wheel B3 in front of the frame plate, and only this one wheel behind. I see 30 teeth with well-constrained geometry. The count of 32 is certain.

B5

B5 appears in the gearing diagram simply because we know that there must have been such a wheel; but since we have none of the wheelwork that was driven through it I cannot offer any meaningful conjecture as to its number of teeth.

B6

If it is correct to place the assembly containing wheel Q at the centre of the Moon indicator, then there must have been a wheel of the same number of teeth fixed to the Sun pointer. Q appears to have had 24 teeth. If so, B6 also had 24 teeth.

C1

Most of the teeth of C1 can be found, and their division is fairly uniform, so that I am confident in taking the two lacunae as 2 and 7 spaces and in giving a count of 38 teeth.

C2

Nearly half the teeth of C2 are lost. Those that remain show some variation in pitch, so that in the middle of a continuous run of 23 spaces the data points are displaced by nearly 0.4 of a space from points dividing the arc equally into the same number. There is one large lacuna which, with the preferred count of 48, contains 18 narrow spaces, but we must admit the possibility that it contained only 17 wide ones. So, on the basis of this analysis, a count of 48 is not quite secure; but in reviewing the velocity ratio of the whole reverted train of which this wheel is a member, we see that it is the only number that makes sense.

D1

Price's "direct count" of 24 teeth is puzzling, because the wheel cannot be seen clearly by direct inspection, and in radiographs I find only 19 teeth. The geometry is however well constrained and the two small gaps must have contained 2 and 3 teeth respectively. Therefore the count of 24 teeth is certain.

D2

Many teeth can be seen, and because they are rather well divided I have some confidence in filling the lacunae (with 23, 13, 10, 4 and 3 spaces) to give a count of 127.

E3

The epicyclic assembly is broken almost exactly in half, leading to considerable uncertainty in the tooth count of each wheel within it. For the platform itself (E4) and the gear ring E3, however, a small fragment of the edge from the lost half remains cemented to the frame plate, which reduces the uncertainty so long as we can be confident that it has not shifted relative to the remaining half during the destruction of the assembly. For E3, the counts for lacunae of up to about 9 spaces seem safe, but there are two lacunae of about 23 and about 70 spaces. Taking into account the variations in pitch of the remaining teeth generally, and the pitch of the teeth immediately to each side of these lacunae, I arrive at a preferred count of 191 within a range of possible values 188 to 192.

E4

The problem of E4 is similar to that of E3, except that I find a more alarming variation in pitch of the surviving teeth, amounting to over ±4%. The two lacunae giving rise to uncertainty should contain about 25 and about 67 spaces. The preferred count is 223, but the range of possible values may be as wide as 218 to 228. It happens that the result makes no difference to my reconstruction, because this wheel does not engage any other and appears redundant. Its existence is, in fact, one of the planks in my argument that the instrument has been altered.

E5

This wheel, and E8 lying directly under it, are really difficult. We have only fragmentary remains of each. By direct observation E5 is the larger of the two, and analysis based on radiographs shows that it appears to have had the greater number of teeth; and so it is listed here. I have however found rational results for the velocity ratio of the train only if the number of teeth of E8 equals or exceeds that of E5. The breadth of the uncertainty in the counts of all four wheels within the epicyclic assembly, E5, E8, K2 and K3, provides just enough latitude to allow us to reconcile the evidence with rational function. Otherwise the suspicion arises that the arrangement could have been garbled by an unsuccessful attempt at repair or alteration. The data points span only 17 spaces, and although they seem well-divided and offer a good match for a count of 53, there must be considerable doubt about the number of lost teeth. I offer the range 51 to 55 as a conservative estimate.

E6

This wheel, lying close to the frame plate, is relatively well preserved. I see 31 teeth with well-constrained geometry and one obvious gap, so that a count of 32 is certain.

E7

This wheel lies directly against E6 and is a little smaller. There can be no doubt about its engagement with D2, and the fact that E6 runs under D2, when inspecting a good radiograph under magnification; Price may be thought to have been unfortunate to have mistaken these details. I find a lacuna of 8 spaces, but the geometry is well constrained and a count of 32 teeth is secure.

E8

See the note under E5. For the smaller wheel of these two I find data points spanning 26 spaces, which offer a good match for a count of 51; but, as with E5, there must be great doubt about the true count. A range of 50 to 52 is a conservative estimate.

F1

Wheel F1 is exposed at the broken edge of fragment A, and more than half its periphery is lost. I find a run of 21 teeth showing good circularity. From these I might extrapolate to a reasonably confident count of 54, except that I see just two points on a projecting tongue of metal on the opposite side of the wheel which do not fit in with an equally divided wheel of 54. If we accept them as they are, a count of 53 is a better compromise. However, if we suppose that this tongue may have been bent aside, 54 is a better fit and 55 also becomes possible. I favour a count of 54, but I set limits 53 – 55. Price's adopted count of 48 is impossible.

F2

I can see all the teeth; there are 30.

G1

19 teeth can be found and the geometry is well constrained. A count of 20 is certain.

G2

I see runs of 18 and 13 tooth spaces, with a small lacuna between them that certainly contained 4 spaces. The remaining large lacuna could have contained 19 large spaces or 20 small ones, and the latter represents a slightly more even division. Therefore I prefer a count of 55, but 54 is possible. Price's 60 is impossible.

H1

Very little of wheel H1 survives, at the bro-

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Table

	Karakalos	Price	Wright	
A		45 (or 48)	48	44 – 52
B1	223 to 226	225	223	216 – 231
B2	64 to 66	64	**64**	
B3	32	32		
B4	32	32	**32**	
B5				
B6			*24*	
C1	38	38	**38**	
C2	48	48	48	47 - 48
D1	[24]	24	**24**	
D2	128	127	**127**	
E1	32?	32		
E2i	32?	32		
E2ii	32?	32		
E3	192	192	191	188 – 192
E4	222	222	223	218 – 228
E5	50 – 52	48	53	51 – 55
E6			**32**	
E7			**32**	
E8	(50 to 52)		51	50 – 52
F1	54	48	54	53 – 55
F2	30	30	**30**	
G1	20	20	**20**	
G2	54/55	60	55	54 – 55
H1	60 to 62	60	60	57 – 64
H2	16	15	**15**	
I	60	60	60	59 – 60
J				
K1		32		
K2	48 or 51	48	49	48 – 50
K3	48 or 51		49	48 – 50
L1	36+	36	38	37 – 38
L2	52	54	**53**	
M1	96+	96	96	95 – 98
M2	14	16	**15**	
N	63	64		
N1			*53*	
N2			*15*	
O1		32?		
O2		48		
O			60	57 – 62
P1			*60*	
P2			*12*	
Q			24	
Δ1			**63**	
Δ2			65	

ken edge of fragment A. I trace runs of 10, 4 and 2 data points only. The mean of these 13 spaces leads to a count of 60 with gaps of 31, 11 and 5 spaces, but the run of 4 points is noticeably misaligned for an equally divided wheel. Perhaps this part of the wheel has been distorted. (Elsewhere I see that small fragments have dropped out and have been cemented back slightly out of alignment, although I do not actually see clear evidence of that here.) If we take the four points as reliable, then the pitch varies enough that there could have been 5 small teeth in the gap of 4.6 mean spaces and there must be considerable uncertainty in deciding on the number of teeth in the largest lacuna. The analysis favours a count of 60 (with 61 as a strong second-best) but it is uncertain, with wide limits of 57 to 64. However, I agree with Price's argument that the number must be 60 so that the velocity ratio between axes G and I may be exactly 12 : 1, because I cannot find any use for the subsidiary dial if the two periods are not simply commensurate.

H2

It is common for wheels of few teeth to be poorly divided. This one is, which may have led Karakalos astray into counting 16; but I find 13 data points and the geometry is sufficiently well constrained that there is no room to doubt that the true count is 15.

I

According to the argument offered above (under H1), wheel I should have 60 teeth, the number found by Karakalos. However, this case demonstrates the difficulty of obtaining counts from irregularly divided teeth on fragmentary wheels, because my analysis leads to a seemingly confident result of 59 with lacunae of 13, 8 and 2 spaces. Within the range of pitch variation that I find in some other wheels, however, the largest of these gaps does afford the possibility of having a run of 14 undersized teeth, thus permitting the count of 60 which is the only number that can make sense.

J

No count can be offered for the conjecturally-restored idle wheel on axis J, seeing that we do not even have a position for its axis. As I have discussed elsewhere, I have misgivings about whether the interposition of an idle wheel, either between E5 and K2 or between E8 and K3, is justified by the direct evidence at all, but I find it necessary to fit one because only in this way can the output period at the Lower Back Dial make any sense.

K2

As with wheels E5 and E8, it is particularly difficult to offer secure counts of wheels K2 and K3. The analyses are very sensitive to choice of the centre, and neither periphery is very truly circular. In one analysis of K2, taking data points at the roots of the teeth, I find 25 data points for K2, a continuous run of 24 spaces, which looks like part of a well-divided wheel of 49. Repeating the analysis taking data points from the tips, I get an equivocal result of 49 or 50. We have to allow the possibility that the division of the lost half of the wheel might have been less uniform. Counts of 48 or 50 could certainly be achieved without gross variation in pitch, and still wider limits might be set. Price reports that Karakalos saw a "double wheel" here and counted 48 and 51. Karakalos was acute to see both sets of teeth but his numbers carry little weight because he was probably misled by supposing that the wheels were concentric.

K3

Here I find 26 data points, a run of 26 spaces with one point missed. Again the pattern is close to that of a well-divided wheel of 49, but the limits must be set at least as wide as 48 to 50, perhaps wider.

L1

I find a continuous run of 27 data points, 26 spaces. The lacuna equals 11.6 times the mean of these single spaces, which might contain 12 small spaces or 11 large ones. The former represents a better approach to uniformity, leading to a preferred count of 38. Although 37 remains a possibility on the basis of the analysis, a rational explanation for the use of the Upper Back Dial reinforces my preference for 38.

L2

I find a continuous run of 48 points, 47 spaces. These show rather uneven division but even so the remaining lacuna can only have contained 6 spaces, leading to a secure count of 53.

M1

This wheel lies near the edge of fragment A so that about one third of its periphery has been destroyed, and therefore the count is sensitive to the placement of the centre, which is in turn made difficult by lack of roundness. Analysis leads to a preferred count of 96 with 97 as second best, but the uncertainty due to the poor division of the remaining teeth is expressed by suggesting a range of 95 – 98. Again, a rational explanation for the use of the Upper Back Dial suggests that the count of 96 is correct.

M2

Only about half the wheel is preserved, showing 8 teeth in a continuous run. The result is therefore sensitive to centre placement, which probably explains the divergence in results between Karakalos (who counted 14), Price (who seems to have explored how far he could manipulate the evidence in adopting 16) and me. With so small a number of teeth it seems a valid approach to inspect the effect of taking in the tooth analysis program centre-positions which give integral results for the number of tooth-spaces in the lost half. In this way I obtain 15 as by far the best fit for roundness and equality of division together, and the centre position so found appears satisfactory when checked back on the image. Therefore I give a count of 15 with confidence.

N1

Axis N lies at the break between fragments A and B. The stub of the arbor survives in the latter, but there is no wheel on it. The size, and therefore the approximate wheel-count, of the wheel to be led by pinion M2, in fragment A, can be found only roughly, by estimating the centre-separation of axes M and N. This depends on fitting the two fragments together correctly, which can be done when we notice that traces of axis O can be found in both, and that the line NO is at right angles to the centre-line of the instrument through G, B and M, which also contained N. It is clear that the wheel that Price placed here (which I call Δ1) is far too large, but when (as here) the pinion leads the wheel the actual size and number of teeth in the large wheel are not well defined. A rough calculation suggests 53, and this number suits my reconstruction.

N2

Wheels N2, P1 and P2 are conjectural restorations. With wheel O (see below), they form a train connecting axes N and O and, as with the wheels connecting axes G and I of the lower dial, I argue that the periods of revolution of the main and subsidiary pointers of the upper dial must have been in some simple ratio. In a later paper I shall show that in this case it should be 20 : 1, and since wheel O probably had 60 teeth we require that (N2 x P2) ÷ P1 = 3. The choice of N2, P1 and P2 having 15, 60 and 12 teeth respectively would suit. Wheels of these numbers of teeth, and of a pitch within the range found among the other wheels, would fit. The pinion of 12 is smaller than any found among the surviving wheels, but there is no reason why the maker should have avoided it where, as here, it leads the wheel. Axis P would have been planted beyond the broken edges both of the frame plate and of the back dial plate, and so no further constraints are imposed.

O

I find only a single continuous run of teeth over about one third of a circle, 21 points or 20 spaces. The tooth count is highly sensitive to the choice of centre, and on the basis of the analysis alone it is hard to choose between preferred values of 59 and 60. The very large size of the sector to be restored introduces a further uncertainty, widening the limits perhaps as far as 57 and 62. However, as with the wheels connecting axes G and I in the lower dial, I argue that the periods of revolution of the main and subsidiary pointers must have been in some simple ratio. Later I shall show that in this case it should be 20 : 1, which argues strongly for this wheel having 60 teeth.

P1, P2

See under N2.

Q

This small, mutilated contrate wheel was found within fragment C by Bromley and me.[7] It is seen edge on when one views the fragment full-face, and so a direct count of its teeth is impossible. By comparing its diameter with the size of teeth as seen in a full-face radiograph from a tomographic sequence, I obtain a rough estimate of 24 teeth. In my reconstruction the actual number is unimportant, but B6 must have the same number of teeth.

Δ1

Price placed this wheel, found within fragment D (Δ), on axis N and called it wheel N, but it is too large to be fitted there. I see a complete circle of teeth with just one missed, and the count is certainly 63.

Δ2

Within fragment D (Δ) I see a ghostly trace of teeth outside the periphery of wheel Δ1, rather similar to the appearance noted above in some places around wheel B1. I see two long continuous arcs of teeth, which I believe to be independent of Δ1 because they lie on a well-defined circle eccentric to Δ1. Analysis offers an insecure count of 65 teeth.

Conclusion

This dry but necessary paper provides the basis for some interesting conclusions and further developments.

Firstly, the velocity ratio of the reverted gear train, from axis B through axes C, D, E and back to B, connecting the two concentric mobiles under the front dial, is confirmed as 19 : 254. In Price's treatment this appeared to be a leap of faith.

Secondly, the tooth-counts for the train to the lower back dial, axes E to K, including the epicyclic cluster on axis E, provide the data for an analysis of the intended function of this train, and of the Lower Back Dial that it served, which is published elsewhere (note 5).

Thirdly, the counts of the wheels on axes L, M and O contribute to my identification of the intended velocity ratio for the train to the Upper Back Dial and so to the function of the dial itself, which is reflected in the conjectural restoration of axis P and the numbers of the wheels on it and on axis N.[8] Finally, the discovery of wheel Q within the "drumlike component" in fragment C leads to the restoration of this assembly as a rotating Moon display of a type not otherwise attested before the late Middle Ages. Besides this, the feature provides evidence that the instrument was in a slightly disordered state when it was lost. These points will be discussed fully at another time.

Notes and References

1. D.J. de S. Price: 'Gears from the Greeks', *Transactions of the American Philosophical Society*, **64** No.7 (1974). Reprinted as an independent monograph, *Science History Publications* (New York, 1975).

2. M.T. Wright, 'The Scholar, the Mechanic and the Antikythera Mechanism', *Bulletin of the Scientific Instrument Society*, no. 80 (March 2004), pp. 4 – 11.

3. Price (note 1) fig.33, p. 43, reproduced by kind permission of The American Philosophical Society.

4. M.T. Wright, 'A Planetarium Display for the Antikythera Mechanism', *Horological Journal*, **144** No. 5 (May 2002), pp. 169 – 173, and **144** No.6 (June 2002), p. 193; M.T. Wright & A.G. Bromley, 'Towards a New Reconstruction of the Antikythera Mechanism', S.A. Paipetis, editor, *Extraordinary Machines and Structures in Antiquity* (Patrs: Peri Technon, 2003), pp. 81 – 94; M.T. Wright, 'In the Steps of the Master Mechanic', *Η Αρχαία Ελλάδα και ο Σύγχρονος Κόσμος (Ancient Greece and the Modern World)* (University of Patras, 2003), pp. 86 – 97.

5. The point is discussed in detail elsewhere: M.T. Wright, 'Epicyclic Gearing and the Antikythera Mechanism', *Antiquarian Horology*. Part 1 appears in **27** No. 3 (March 2003), pp. 270-279; parts 2 and 3 are forthcoming.

6. The procedure is outlined in Wright (note 2), and is treated in more detail in a further paper: M.T. Wright & G.J.T. Wright, *Computer-Aided Analysis of Radiographic Images, applied to the Antikythera Mechanism*, in preparation.

7. Initially we misread the evidence as showing a small rack. We took the feature as a case study in: M.T. Wright, A.G. Bromley & H. Magou, 'Simple X-ray Tomography and the Antikythera Mechanism', *PACT*, **45** (1995), pp.531 – 543.

8. M.T. Wright, 'Counting the Months and Years: The Upper Back Dial of the Antikythera Mechanism', *Bulletin of the Scientific Instrument Society*, forthcoming in the September issue.

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The Millennium Measure

To mark the Millennium, the Worshipful Company of Scientific Instrument Makers (see page 24), gave the City a specially commissioned, stainless steel and glass obelisk: the Millennium Measure

The Measure takes the form of a "length standard" divided into 2000 mm symbolising 2000 years of history and bearing at appropriately marked intervals the dates of significance, from the birth of Christ to the year 2000, in the fields of science and instrumentation, the City and the Nation, and religious happenings. There are a number of happy coincidences, for example, the letters "mm" signify millimetres whilst "MM" is the Roman numeral equivalent of 2000 as well as the initials of the words "Millennium Measure".

The designer was WCSIM Liveryman Joanna A. Migdal. The Measure stands below the Millennium Bridge at the St Paul's side of the river.