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THE ANTIKYTHERA MECHANISM
2. Is it Posidonius' Orrery?

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ABSTRACT

The structure and functions of the ancient Greek astronomical calculator, known as the Antikythera Mechanism, are still hotly debated. A remarkable quote from Cicero, exactly contemporary with the mechanism, describes an orrery made by Posidonius, which shows the *"...motions of the sun, the moon and the five planets..."*. In Edmunds and Morgan 2000, it is persuasively argued that the device might have been primarily astrological and therefore likely to have included planetary mechanisms - possible designs are also described. Building on this work, a Theory of Planetary Mechanisms is developed which links their gear ratios with the 'period relations' in the Babylonian *Astronomical Diaries*. Several possible designs for these mechanisms are also explored. It is often argued that there is insufficient space for all five planets in the Antikythera Mechanism, but it is shown here that they can fit in the case, using the same basic design and technology - it could in fact be Posidonius' Orrery.

KEY WORDS: Astronomy, Babylon, epicycle, gear, Greek technology, planet

ASTROLOGY

In *Gears from the Greeks* (Price 1974) Derek de Solla Price established that the Antikythera Mechanism is an extraordinary astronomical geared calculator, a thousand years ahead of its time. Yet much of its structure and function is still a mystery. Increasingly there are doubts about Price's classic research and a growing interest in alternative hypotheses (Freeth 2001). It may be an embarrassment for scientists today, but all the great astronomers from antiquity up to the 19th Century were also astrologers. In fact the very origins of astronomy are thought to lie in Babylonian omen telling (Swerdlow 1998).

In a recent article in *Astronomy & Geophysics* (Edmunds and Morgan 2000) there is a fascinating and very persuasive account of the historical and astronomical background in the 1st Century BC, which strongly supports the idea that the primary purpose of the mechanism might have been astrological. Evidence of planetary gearing would greatly strengthen this hypothesis.

The *Antikythera Mechanism* lay at the bottom of the sea for 2,000 years. It is remarkable that Price found a quote from the contemporary orator and statesman Marcus Tullius Cicero, which appears to describe the mechanism itself:

> *"Suppose a traveller to carry into Scythia or Britain the orrery recently constructed by our friend Posidonius, which at each revolution reproduces the same motions of the sun, the moon and the five planets that take place in the heavens every day and night. Would any single native doubt that this orrery was the work of a rational being?"*
>
> De natura deorum, II

Cicero went to the island of Rhodes in 79 BC to study under the leading scientist and Stoic philosopher, Posidonius. Though Cicero himself was very sceptical about astrology, Posidonius was a leading astrologer, who stimulated its widespread introduction to the Roman world. But if Cicero was describing the Antikythera Mechanism, then it must have contained planetary gearing for *"...all five planets..."* - the original Latin phrase *"...quinque stellis erantibus..."* is unambiguous. But what would this gearing look like? And can *all five planets* actually fit inside the mechanism's case (previously thought impossible)? In other words, could the *Antikythera Mechanism really be Posidonius' Orrery?*

A THEORY OF PLANETARY MECHANISMS

The Greeks, like the Babylonians, were fascinated with the wandering movements of the planets and developed a simple geocentric model of how they moved. Their system was modelled on circles. The planet moves on a circle (the epicycle) whose centre in turn moves on another circle (the deferent) – so that the planet follows an epicycle. It was an approximation, and later models complicated it to get more accuracy, but it was a beautifully simple conception. From our heliocentric viewpoint, it corresponds to a *Simplified Solar System*, where all the planets move in circles at a constant rate around the Sun in the same plane - the simplest Greek epicyclic model is a mathematically equivalent description, from a geocentric viewpoint. For the five inner planets known to the Greeks, it is a very good approximation because their orbits are very nearly circular.

In Morgan 2000, Phil Morgan proposes simple and elegant planetary mechanisms (also described in Edmunds and Morgan 2000) for the *Antikythera Mechanism*. He later discovered that Giovanni De Dondi in the 14th Century had included similar (but more complex) mechanisms in his famous *Astrarium* (Baillie 1974). Morgan's *Venus Mechanism* (see Fig. 1) directly mirrors our *Simplified Solar System*. There is a fixed central gear. An epicyclic gear (a gear with a moving axle) meshes with this fixed gear and is forced to turn, as its axle is carried round by an epicyclic table (a disc which carries an epicyclic gear) at the rate of the Sun. A slotted rod follows a peg fixed to the epicyclic gear and this is linked to a pointer, which indicates the longitude of Venus. The centre of the fixed gear corresponds to the Earth, the centre of the epicyclic gear to the Sun and the peg to Venus. The top of Morgan's *Mars Mechanism* is similar to his *Venus Mechanism*, but the rotation of the epicyclic table is now scaled to turn at the rate of Mars round the Sun. There are a number of mistakes in the mechanisms described in Edmunds & Morgan 2000. In particular, the pegs should be outside the faces of the epicyclic gears and the scaling gears in the Mars Mechanism do not work as intended. At first, I could see why the *Venus Mechanism* would track Venus in a *Simplified Solar System* because it mirrors reality, but I couldn't understand the underlying principle of the *Mars Mechanism*. When I started to model them in a 3-D computer programme, I also thought that some of the gear ratios and peg distances must also be wrong. So I decided to work it all out from first principles and this proved to be very productive.

There are just two parameters which define the orbit of a planet in our *Simplified Solar System:* its rotational period in years around the Sun, r, and its distance in Astronomical Units (AU) from the Sun, p. We can therefore determine the geometry of our planetary mechanisms in terms of these two parameters. We shall call a mechanism, like Morgan's *Venus Mechanism, a simple mechanism* (see Fig. 1). The first step for Posidonius in building his famous orrery is to calculate the correct geometry of *simple mechanisms.* How many teeth should the gears have? How far should the peg be from the centre of the epicyclic gear?

First, a cautionary tale, in case it might be thought to be completely obvious! Epicyclic

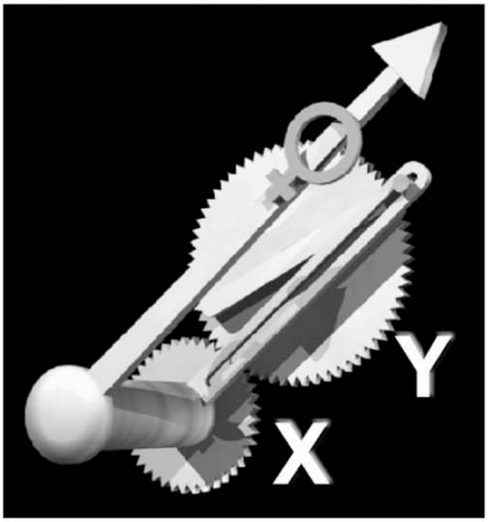

Fig. 1: Simple Venus Mechanism - [40 ~ 64]
X has x teeth and is fixed. Y has y teeth and meshes with X. Y's axis is carried by an epicyclic table (not shown) which rotates at the rate of the Sun. A slotted rod follows a peg attached to a bar that is rigidly fixed to the gear Y. The slotted rod is free to rotate on an axis at the centre of X, and is rigidly linked via an axle to a pointer that shows the longitude of Venus. We use the notation [40 ~ 64] to describe this mechanism, where the underlined gear is the fixed gear with 40 teeth and the other gear is the epicyclic gear with 64 teeth.

gearing really is quite subtle. Martin Gardner (Gardner 2000) recounts that in 1866 the Editor of *Scientific American* set a problem for their readers: if you roll a coin once round an identical fixed coin, how many times does the coin rotate? Simple enough you might think and very like our problem with the *Venus Mechanism.* There was nearly three years of heated debate in the letters column – with *"half a bushel"* of letters. (A bushel, of course, is 4 pecks or 8 gallons.) Finally *Scientific American* had to put a stop to it and in 1868 apparently set up a magazine called *Wheel* dedicated entirely to this sort of question!

Let r be the period of the Planet round the Sun in sidereal years – for Venus r = 0.6151854. We want to chose x, y so that the rotation of Y, Rot(Y) = 1/r revs/year. The easiest technique is to imagine yourself sitting on the epicyclic table, E. Then you can use the basic property of meshing gears because both gears have fixed axes in this frame of reference. We use Rot (Y | E) to mean the rotation of Y relative to E. Then (using '*' for 'multiply'):

$$\mathrm{Rot}(Y \mid E) = -(x/y) * \mathrm{Rot}(X \mid E) \qquad (1)$$

Since X is fixed in the 'real world', relative to E it goes round backwards at the rate of the Sun, in other words at the rate - 1. Therefore:

$$\mathrm{Rot}(X \mid E) = -1 \qquad (2)$$

Putting these together:

$$\mathrm{Rot}(Y \mid E) = x/y \qquad (3)$$

The rotation of Y in the 'real world' is its rotation relative to E plus the rotation of E itself. In other words:

$$\mathrm{Rot}(Y) = \mathrm{Rot}(Y \mid E) + \mathrm{Rot}\ (E) = x/y + 1 \qquad (4)$$

If x = y, then Rot(Y) = 2 and this answers the Scientific American question about the coins!

For the *Venus Mechanism,* we want:

$$x/y = 1/r - 1 = .6255262 \qquad (5)$$

5/8 is a fairly good approximation – here I've used 40/64 because it makes for easy division of the gears when cutting the teeth. This mechanism clearly has a periodicity: if we wind the mechanism forwards 8 years, then the epicyclic gear turns 5 times. In the general case, a *simple mechanism* [$\underline{x}$ ~ y] goes through x cycles in y years.

What is the peg distance for the mechanism? Let p be the distance of the Planet from the Sun in Astronomical Units (AU). Let d be the distance of the peg from the centre of Y. Let i(X, Y) be the interaxial distance between X and Y. Then we want:

$$d = p^* \, i(X, Y) \qquad (6)$$

Let us make the simplifying assumption that the radius of a gear is proportional to its tooth count. Then, using Kepler's Third Law, it is straightforward to show that, for an inferior planet, the peg must be outside the face of the gear.

Posidonius then tried to make a *simple mechanism* for Mars. In Fig. 3 X is the fixed gear with x teeth and Y the epicyclic gear with y teeth. Recall that: $x/y = 1/r - 1$. For Mars: $r = 1.8808148$. We want: $x/y = -0.4683155$. So one of the gears has a negative number of teeth! Initially I thought this was a terminal problem, but then I realised that one of the gears, instead of having a negative number of teeth, might have a positive number of negative teeth! In other words, the teeth might point inwards.

On the left-hand side of Fig. 3, is shown a *simple mechanism* for Mars, which is a surprising consequence of the mathematics. [$\underline{37}$ ~ - 79] gives a good approximation as I shall discuss later. As for the *Venus Mechanism*, the small gear is fixed. The larger gear with 'negative teeth' is moved around the fixed gear at the Sun's rate with a mechanical arrangement that is not shown and is hard to implement. For this reason, I don't think it is a practical proposition for the *Antikythera Mechanism*, but it is theoretically interesting, as we shall see. The slotted peg-follower is free to turn on its axle centred on the fixed gear. In contrast to Venus, and by the same argument, the peg is on the face of the gear. This *simple mechanism* for Mars tracks the planet correctly in our *Simplified Solar System* (within the accuracy of the gear ratio) because, like the *Venus Mechanism*, it is a mirror of reality. So Posidonius needs to look for other mechanisms which are equivalent to this but easier to make mechanically. Lacking a heliocentric model of the Solar System, it is likely that he would have done what Phil Morgan did when designing his *Mars Mechanism* – use a similar mechanism to Venus, scale the epicyclic table to turn at the rate of Mars and work out the gear ratios empirically to match observations. However there is an attractive way of looking at the problem, which not only gives a theoretical answer to the geometry in terms of our parameters r and p, but also shows that the mechanism does in fact track the planet correctly in our *Simplified Solar System*,

MARTIAN ANTIKYTHERA MECHANISM

The key idea is to consider what a *Martian Antikythera Mechanism* would be like. In this device the Sun pointer would go round the Front Dial at the rate that Mars rotates round the Sun – once every Mars year. From the point of view of Mars, the Earth is an inferior planet, so the Martian *Earth Mechanism* can be made just like the simple Venus Mechanism. Could the Martian *Earth Mechanism* be used as a *Mars Mechanism* back on Earth? The answer is yes because: if the Earth, viewed from Mars, is at a particular point in the Zodiac, then Mars, viewed from the Earth, will appear 180° round from this point. The Martian *Earth Mechanism* tracks the Earth from Mars, so it would track Mars from the Earth if is rotated through 180° and we arrange for the axis of its epicyclic gear to rotate at the Mars rate.

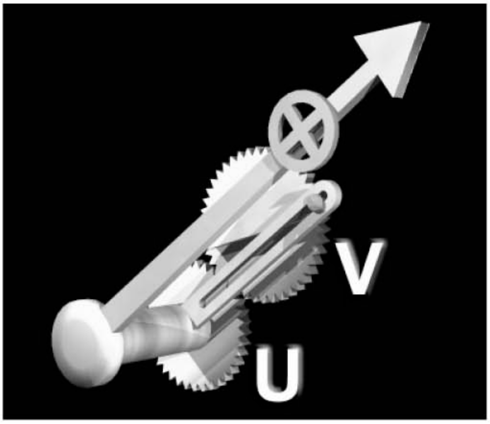

Fig. 2: Martian Earth Mechanism - [37 ~ 42].

What is the geometry of the Martian *Earth Mechanism?* Suppose its fixed gear is U with u teeth and its epicyclic gear is V with v teeth. It's very similar to the simple *Venus Mechanism* and we can easily work out the gear ratio in the same way. Let r be the rotation time of Mars in Earth years (r = 1.8808148). On Mars they work in Mars units, where 1 Mars year is r Earth years. So the Earth's rotation period is 1/r Mars years. Of course the mathematics stays the same on Mars. So just as for Venus:

$$u/v = (1/(1/r)) - 1 = r - 1 \qquad (7)$$

For Mars, this means u/v= 0.8808. Now let's compare the *Martian Earth Mechanism* with Posidonius' original *Mars Mechanism* with gears X and Y, where y < 0. Recall that:

$$x/y = 1/r - 1 \qquad (8)$$

Eliminating r from these two equations, we get the symmetrical relationship:

$$(u/v + 1)\ (x/y + 1) = 1 \qquad (9)$$

Or in other words:

$$u/v = x/ - (x + y) \qquad (10)$$

Remember that y is negative and larger in absolute value than x – so this is a positive number. If [37 ~ - 79] is a good approximation for Posidonius' original *Mars Mechanism*, then [37 ~ 42] should be good for the Martian *Earth Mechanism*.

What is the peg distance for the Martian Earth Mechanism? Let p be the distance of Mars in AU (p = 1.5236910). Then 1 AU = 1/p MU. So the peg distance is given by:

$$d = (1/p) * i(U, V) \qquad (11)$$

To adapt the Martian *Earth Mechanism* as an Earth-based *Mars Mechanism,* we must now scale the rotation of the epicycle so that it rotates at the Mars rate – Fig. 3. We shall call this a *scaled mechanism.* The gear S turns at the Sun's rate and this turns T at the Mars rate. Attached to T is a plate (not easily see in this picture) and this carries the epicyclic gear V which meshes with the fixed gear U. Now we want to find s, t, u, and v in terms of the x, y that defined Posidonius' original *Mars Mechanism*. Recall that:

$$x/y = 1/r - 1 \qquad (12)$$
$$1/r = x/y + 1 = - (x + y)/ - y$$

We want T to turn at the Mars rate. In other words we want:

$$s/t = 1/r = - (x + y)/ - y \qquad (13)$$

Also recall that:

$$u/v = x/ - (x + y) \qquad (14)$$

Let us use the notation: s ~ t [u ~ v] to describe the *scaled mechanism* on the right in Fig. 3:. Then Posidonius' new *Mars Mechanism* is:

$$- (x + y) \sim - y[x \sim - (x + y)] \qquad (15)$$

So Posidonius now had two different mechanisms and they are equivalent.

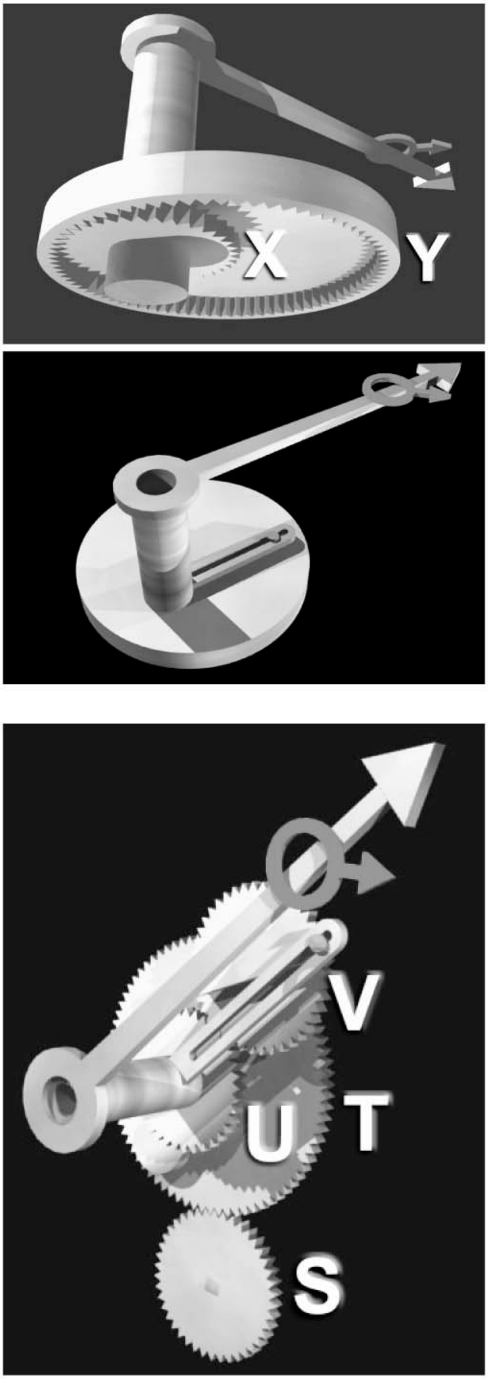

Fig. 3: Simple Mars Mechanism [37 ~ - 79] (upper). Scaled Mars Mechanism 42 ~ 79 [$\underline{37}$ ~ 42] (lower).

EQUIVALENCE THEOREM

1. [$\underline{x}$ ~ y] is equivalent to - (x + y) ~ - y [$\underline{x}$ ~ - (x + y)]

For the first mechanism the peg distance is p times the interaxial distance and for the second one, it is 1/p times the interaxial distance.

2. A *scaled mechanism:* s ~ t [$\underline{u}$ ~ v] is equivalent to a *simple mechanism* if and only if: t/s - u/v = 1, and this is equivalent to Rot(V) = - Rot(S)

A purely geometric proof can be devised for Part 1. Part 2 answers the important question: when is a *scaled mechanism* equivalent to some *simple mechanism* - in other words: when does a *scaled mechanism* actually track a planet in our *Simplified Solar System?* In our machine, S will have the Sun's rotation, so this means that the epicyclic gear also moves with the Sun's rotation (in the opposite direction). This doesn't mean that Mars goes through it's retrogrades and stationary points on an annual cycle – the periodicity of its phenomena is determined by the rotation of the epicyclic gear relative *to its epicyclic table*, not its *absolute* rotation.

Part 2 probably shouldn't surprise us. In our *Simplified Solar System*, from a geocentric point of view, the motion of Mars is the sum of two vectors: a vector rotating at the Sun's rate plus a vector rotating at the Mars rate. If we reverse the order of this vector addition, we get a vector rotating at the Mars rate plus a vector rotating at the Sun's rate. This is what our *scaled mechanism* does. However it's not as simple as vector addition for the mechanisms since gears complicate the issue. In fact the scaled *Mars Mechanism* produces a 'scalar multiple' of the simple *Mars Mechanism* as you'll see if you do the geometric proof of the *Equivalence Theorem*.

GOOD PLANETARY MECHANISMS

Now we have a strategy for finding good planetary mechanisms. For an inferior planet with rotation period r sidereal years, use a spreadsheet to find simple mechanisms [$\underline{x}$ ~ y], which give good approximations to x/y = 1/r -

1 or r = y/(x + y). We also want the tooth counts to be within the range 14 to 225 teeth - as in the *Antikythera Mechanism*. We only chose larger gears if they give more accurate results. For a superior planet, we will want to find the equivalent *scaled mechanism*. This yields the *Good Gear Guide* in Fig. 4. For simplicity we haven't included all the results – for example, there are another ten possible ratios for Venus between (92, 47) and (147, 235). Most of the ratios in the *Good Gear Guide* were already known to the Babylonians as can be seen from the columns Π, Y in the table, which are extracted from Swerdlow 1998. The remarkable decipherment of the Babylonian cuneiform tablets, called the *Astronomical Diaries*, is told in fascinating detail in Neugebauer 1969, 1983, Britton & Walker 1996 and Swerdlow 1998 – it is perhaps the greatest discovery in the History of Science. The tablets included ephimerides of the Sun, Moon and Planets – regular observations of their positions and characteristic phenomena, such as retrograde motion. From the third century BC the tablets included the *Goal Year Texts*, which were concerned with 'exact' repeating cycles of the Moon and Planets in the form *"Π phenomena in Y years"*. Also arithmetical procedures for computing these cycles. The *Goal Year* was the desired year 'Y' when the phenomenon repeated. These results (Neugebauer 1969) are thought to have been transmitted to the Greeks via the astrologer Berossos and the Greek astronomer Hipparchus (c. 190 - 120 BC) – the greatest astronomer just before the era of the *Antikythera Mechanism* and resident on Rhodes, where Cicero saw Posidonius' Orrery

The coincidences of the cycles in Fig. 4 simply reflect the rotational periods of the

		SPREADHSEET		BABYLONIAN			
Planet	Period r	x	y	Π	Y	Calc. Per. r'	Error
	Years	*No.*	*No.*	*No.*	*No.*	*Years*	*°/year*
MERCURY	0.2408404	**63**	**20**	**63**	**20**	0.2409639	0.766
	0.2408404	**104**	**33**	**104**	**33**	0.2408759	0.221
	0.2408404	**145**	**46**	**145**	**46**	0.2408377	0.017
VENUS	0.6151854	**40**	**64**	**40**	**64**	0.6153846	0.189
	0.6151854	**92**	**147**			0.6150628	0.117
	0.6151854	**147**	**235**			0.6151832	0.002
MARS	1.8808148	**15**	**-32**	**15**	**-32**	1.8823529	0.156
	1.8808148	**22**	**- 47**	**22**	**- 47**	1.8800000	0.083
	1.8808148	**37**	**- 79**	**37**	**- 79**	1.8809524	0.014
	1.8808148	**96**	**- 205**			1.8807339	0.008
JUPITER	11.8617555	**54**	**- 59**	**54**	**- 59**	11.8000000	0.159
	11.8617555	**65**	**- 71**	**65**	**- 71**	11.8333333	0.073
	11.8617555	**76**	**- 83**	**76**	**- 83**	11.8571429	0.012
SATURN	29.4565217	**28**	**- 29**	**28**	**- 29**	29.0000000	0.192
	29.4565217	**57**	**- 59**	**57**	**- 59**	29.5000000	0.018
	29.4565217	**199**	**- 206**			29.4285714	0.012

Fig. 4: Good Gear Guide

The Period r is the period of the planet in years; the Calculated Period r' is the approximate period calculated from the gear ratio y/(x + y); the Error is the error in degrees per year in this approximation to the planet's rotation (= 360 *|1/r – 1/r'|).

planets. However I found it a strange feeling first to calculate the ratios in the *Good Gears Guide* and then to find later that the Babylonians had already discovered them more than 2,000 years earlier. The Babylonians found some shorter cycles and some much longer, which yield gears, which are too small or too large. For example, a cycle of (720, 1151) for Venus, which turns our to be much less accurate than our (147, 235); and (391, 427) for Jupiter which is remarkably accurate and an extraordinary achievement for a culture with no telescopes or scientific instruments.

To build his Orrery, Posidonius needs to choose accurate planetary mechanisms. There is clearly a trade-off between accuracy and the work needed cutting teeth. Fig. 5 is not comprehensive, but suggests possible candidates. The Metonic ratio, with an average error of about 0.1° per year, gives us a yardstick for accuracy. All these mechanisms have errors less than 0.25° per year.

The inferior planets are straightforward, the superior planets less so. For Mars we choose the best *simple mechanisms* and then use the *Equivalence Theorem* to find the equivalent *scaled mechanisms*. For Jupiter 1 there is an immediate problem because the equivalent *scaled mechanism* has gears with 6 teeth – so we need to multiply the whole mechanism by 3 to get reasonable gears. Similarly for Jupiter 2. For Saturn the situation is even worse and means we must use 'two-stage' gearing – both to drive the epicycle and on the epicycle itself (with an idler gear to get the final epicyclic gear to turn in the right direction). There will certainly be mechanical problems with these cumbersome *Saturn Mechanisms*. Though the input gear turns at the same rate as the final epicyclic gear, it does this via a geartrain with a very high step-down ratio followed by a very high step-up ratio and all this stress bears on those soft and bendy teeth (95% copper according to Price 1974). Later I shall look at some alternatives.

Mercury 1	**[104 ~ 33]**
Mercury 2	**[145 ~ 46]**
Venus	**[40 ~ 64]**
Mars 1	[22 ~ - 47]
	25 ~ 47 [22 ~ 25]
Mars 2	[37 ~ - 79]
	42 ~ 79 [37 ~ 42]
Jupiter 1	[65 ~ - 71]
	18 ~ 213 [195 ~ 18]
Jupiter 2	[76 ~ - 83]
	14 ~ 166 [152 ~ 14]
Saturn 1	[57 ~ - 59]
	16~64 + 16~118 [114~16 + 64~16~16]
Saturn 2	[199 ~ - 206]
	16~48 + 21 ~ 206 [199 ~ 16 + 48 ~ 16 ~ 21

Fig. 5: Planetary Mechanisms.

IS PRICE'S 'DIFFERENTIAL' A PLANETARY MECHANISM?

In Freeth 2002 I question whether Price's *Differential* really is a differential – there is much which doesn't really make sense about Price's model and Price found no function for one of the largest gears in his Differential, E4.

It is remarkable how similar Jupiter 1 and Saturn 2 look to the large gears, E3 and E4, in Price's Differential. The crucial tooth counts of E3 and E4 are uncertain. In An Ancient Greek Computer (Price 1959) he estimates 196 and 205 for these gears. In Gears from the Greeks (Price 1974) he writes: "The sizes of the gears would indicate tooth counts of 201 and 210 respectively, but Karakalos counts from the much more extensive radiographic evidence 192 and 222…" . In the light of the fact that Jupiter 1 incorporates ratios consistently used by astronomers from Babylonian times to Ptolemy and Copernicus, I favour the idea that Price's Differential might just possibly be a Jupiter Mechanism. It's certainly not a Saturn *Mechanism* of this sort because it wouldn't turn given ancient Geek technology. Also the ratios in Saturn 2 were apparently unknown to Babylonian astronomy (though of course the historical record may just be missing).

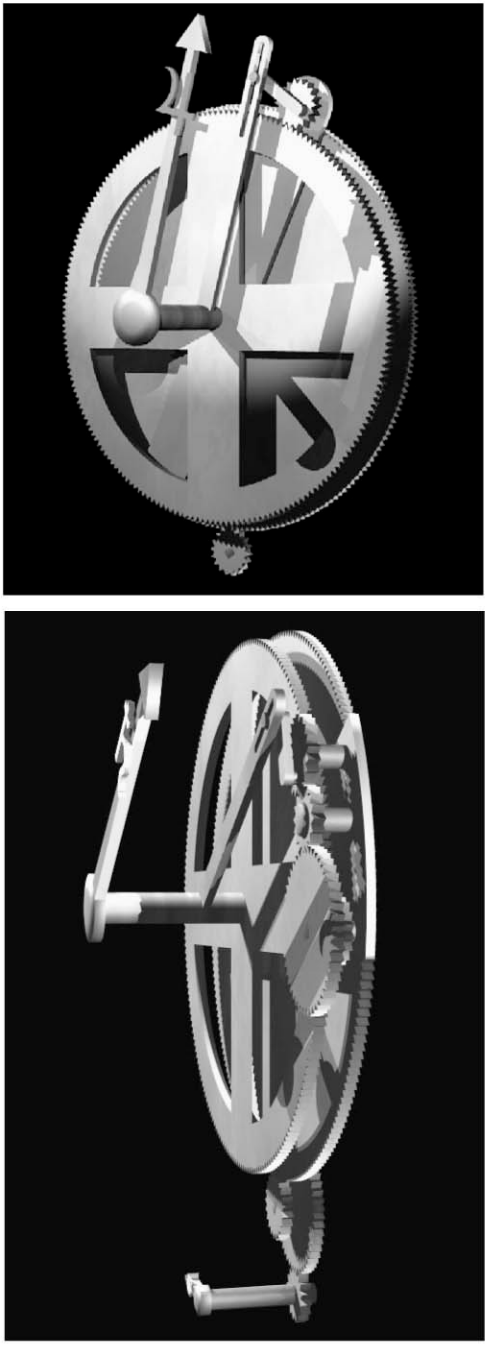

Fig. 6 Jupiter 1: 18 ~ 213 [195 ~18] (upper)
Saturn 2: 16 ~ 48 + 21 ~ 206
[199 ~ 16 + 48 ~ 16 ~ 21] (lower).

IMPROVED JUPITER AND SATURN MECHANISMS

How do we overcome the mechanical problems of these *Saturn Mechanisms?* The essence of a *Saturn Mechanism* is that it has an epicyclic gear turning at the rate of the Sun on an epicyclic table turning at the rate of Saturn. What if the 'fixed' gear is allowed to turn? For a *scaled mechanism* for a superior planet, let E be the epicyclic table, which is turned at a rate j that approximates to the rate of sidereal rotation of the planet, 1/r. Let B be the central gear with b teeth (which was formerly fixed) and let C be the epicyclic gear with c teeth, which carries the peg. If we assume that B is turned anticlockwise at the rate of the Sun, how many teeth should B and C have to make C turn at the rate of the Sun? Using the techniques of this paper, it is easy to show that $b/c = (1 - j)/(1 + j)$. For example, if we use the approximation $j = 2/59$, then $b = 57$, $c = 61$. Let us call this (Fig. 7) an *enhanced mechanism.* It would certainly turn much more easily than our previous *Saturn Mechanisms.*

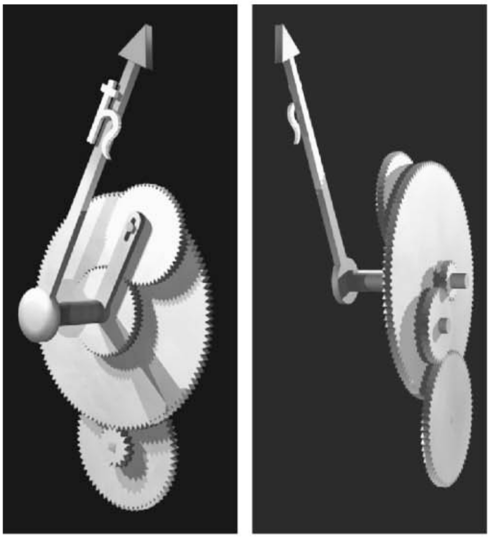

Fig. 7: Enhanced Saturn Mechanism (2/59)
The large gear has 118 teeth, the central gear at the front has 57 teeth, and the epicyclic gear 61 teeth and all the others have 16, 32 or 64 teeth.

The Enhanced Mechanism in Fig. 7 is driven from below via any of the fixed axles. It's relatively compact - with only seven gears – has much fewer teeth and is much easier to turn than our previous Saturn Mechanisms. We can make a similar mechanism for Jupiter for the approximation 7/83. If, however, we want to use the better approximation 7/206 for Saturn, this process leads to gears that are too large. To solve this, there is an idea, which I found through a misunderstanding of one of the most famous astronomical clocks of all time.

GIOVANNI DE DONDI'S PLANETARIUM

In the mid-14th Century, Giovanni de Dondi made an extraordinary planetarium (Baillie 1974), with seven faces, which showed the Sun, Moon and five planets. The original is lost, but a number of reconstructions have been made (for example, in the London Science Museum). The *Venus Mechanism* is familiar and uses the Babylonian ratio 5 : 8. One difference though is that de Dondi implemented Ptolemy's corrections to the simplest epicycle model and so all his peg-followers rotate on eccentric axes. Mars, Jupiter and Saturn are very complex. Mercury uses elliptical gears; the Moon incorporates the Metonic ratio and has gears shaped like squashed pears! It is a truly wondrous machine. Originally I thought that de Dondi's Jupiter and Saturn were similar to our *enhanced mechanisms* with the addition of an 'idler' gear between the central gear, B, and the epicyclic gear, C. What for? I wondered how fast we should turn B, with this additional idler gear, if B and C have the same number of teeth? The answer turns out to be 1. This result stunned me. Suddenly de Dondi's design made absolute sense. Or so I thought until I discovered that the blurred pictures of the *Astrarium* that I had seen on the Internet had misled me – his planetarium

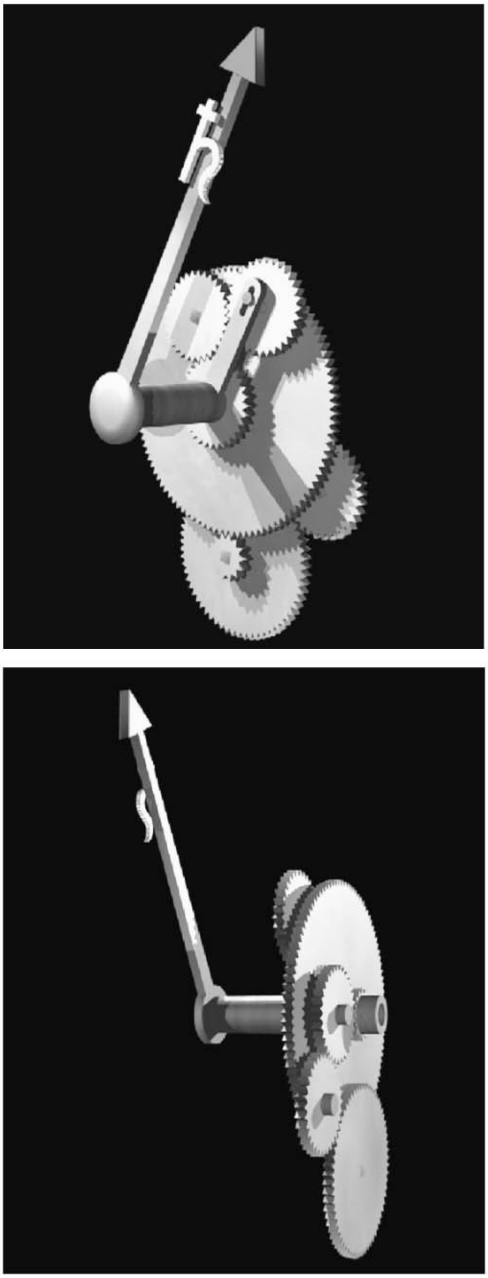

Fig. 8: Improved Saturn Mechanism (7/206)
The large gear has 103 teeth and the small gear that drives it has 14 teeth. All the other gears have 16, 32 or 64 teeth. A similar mechanism can be made for Jupiter (7/83) with only seven gears.

works very differently! Despite this, the idea was surely good. If two gears turn at the same rate (on parallel axes) in some frame of reference, then they must turn at the same rate in all frames of reference. With the idler gear included, if B and C have the same number of teeth, then they turn at the same rate relative to the epicyclic table, so they must also turn at the same rate in the 'real world'. Surprisingly, the rotation of C is completely independent of the rotation of the epicyclic table. It's interesting that this is exactly the arrangement of gears on the front of Price's *Differential*, whereas the *enhanced mechanism* includes the arrangement on the back of his *Differential.* (It would surely be stretching the evidence to suggest that Price's *Differential* is a *Jupiter* and a *Saturn Mechanism* stacked together!) Now we can make a *Saturn Mechanism,* Fig. 8, for the approximation 7/206 with much simpler and smaller gears – let us call this an *improved mechanism.*

We now have four different types of mechanism for each superior planet. A *simple mechanism,* with 'negative' gears, which is virtually impossible to make and won't turn. A *scaled mechanism* – fine for Mars, but very hard to turn for Saturn. An *enhanced mechanism,* which works well for some approximations but not others. And an *improved mechanism*, with easily divided gears and small tooth counts, but which generally needs nine gears. Using all these ideas we can make at least three plausible mechanisms for Mars, nine for Jupiter and five for Saturn.

Though our analysis depends on a heliocentric knowledge of the Solar System, I think it would be possible to discover these mechanisms without this. It would be very interesting to know if there are any other examples of early planetary mechanisms – perhaps in the Islamic tradition, which continued so much of Greek thought. It seems to me to be overwhelmingly likely that the Greeks would have thought of at least some of these planetary mechanisms. They had epicyclic models of planetary motion. They knew of the Babylonian period relations. The Antikythera Mechanism proves that they had precision gearing. There was a huge and growing interest in horoscopic astrology and such a mechanism would be an ideal tool for astrologers. So where are they all? Why do we have to wait for another 1,400 years to find concrete examples in Giovanni de Dondi's Astrarium? The following private communication to Mike Edmunds from Ruth Westgate of the School of History & Archaeology in Cardiff, is helpful: "The proportion of bronze objects that have been preserved from antiquity is minuscule. There were reportedly 3,000 bronze statues on Rhodes by the 1st century AD… Of these all we have left are 240 stone bases _ and, as far as I remember, not even a single bronze toe! Metal was too valuable to throw away, and the chances of even one example of a rare type of object like the Antikythera Mechanism surviving must be infinitesimal."

BUILDING POSIDONIUS' ORRERY

I have built a computer simulation of a machine, which I call the *Maxikythera Mechanism,* which is just one of many versions of what *Posidonius' Orrery* might have looked like. I should emphasize that I am making no claims that it is a good fit with the x-ray evidence of the *Antikythera Mechanism.* The point is to show that it was possible to build *Posidonius' Orrery* with similar design and technology and put it all in the same size case.

In *Gears from the Greeks* (Price 1974) Price writes: "…alternatively there is a possibility that this space between the large wheels may have held a gearing system, now totally vanished, which served to exhibit the rotations of all of the planets other than the Sun and Moon. If such gearing was to be part of the device it would be most appropriate at this place where annual and monthly rotations

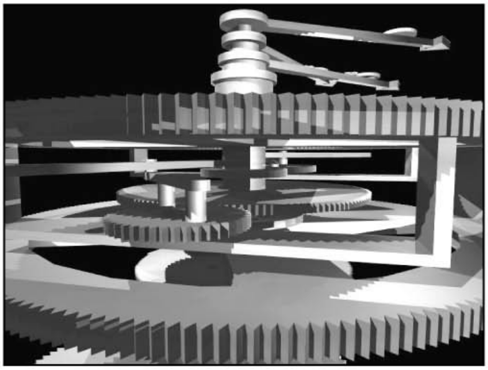

Fig. 9: Mercury & Venus Mechanisms.

were available just under the front dial plate."

My own view is that it is impossible to put five planetary mechanisms in this space. They simply need too many gears. Surely also anything here must output to the Front Dial, which would mean seven co-axial pointers. It just isn't possible. What also is the relevance is of the *"monthly rotation"* to the planets? Phil Morgan (Edmunds & Morgan 2000) suggests that one inferior planet could fit in this space. I think that two are possible and that it is very plausible that both Mercury and Venus were included here - though with some difficulty.

You can't just stack two mechanisms, one below the other, because it's hard to secure the fixed gear to the case since the mechanism below it 'cuts through' any obvious fixing. However the problem can be solved with some ingenuity by 'interleaving' the two mechanisms The Sun Wheel (the large gear at the top) is used as the epicyclic table. The epicyclic gears in the *Mercury and Venus Mechanisms* are supported by brackets fixed to the Sun Wheel and oriented at 180° to each other. The *Venus Mechanism* is in the background and the *Mercury Mechanism* is in the foreground (with small 'stilts' on the epicyclic gear to hold the peg-bar above the level of Venus' fixed gear). They output, together with the Sun and sidereal Moon, to four coaxial pointers on the Front Dial – perhaps not plausible for ancient Greek technology, but if we can be surprised so dramatically by the *Antikythera Mechanism* itself. It's interesting that Price finds evidence of fixings on B1 – just what you might need for planetary mechanisms. But they are on the wrong wheel, since B1 moves anticlockwise and the pointers must surely go clockwise round the Zodiac and Calendar scales. So it's another mystery, unless there were also reverse scales on the Front Dial.

Alternatively the 'fixed' gears could be attached to the large gear, B1, at the bottom of Fig. 9. In this case they turn anticlockwise at the rate of the Sun and need to be halved in size to make the epicyclic gears turn at the correct rate. This is possible for our *Venus Mechanism*, but for Mercury (145, 46) we would need to go to the worse approximation (104, 33). However this arrangement is much neater than securing the fixed gears to the case as in the previous design and it would also give an elegant justification for the two large gears at the front of the mechanism.

There are many options for the superior planets. It might just be possible to add them to Price's model (without the *4-Year Dial*) though I haven't yet built a computer model and I think a physical model would seize up. So the basis of our new machine is the Minikythera Mechanism, proposed in Freeth 2002. In this we dispense with Price's *Differential* and substitute Price's 4-Year Dial gearing to produce an *Age of the Moon* output. In addition to the *Age of the Moon*, we want to accommodate three superior planets – four outputs in all – on the two Back Dials. So its seems natural to have two on each.

The superior planets are driven (in a fairly ad hoc way) from Price's Axis E. The *Mars* and *Jupiter Mechanisms* are *scaled mechanisms*. The latter looks like Price's *Differential*, though its axis needs to be shifted from the apparent position of the *Differential* given by Price's evidence. The *Saturn Mechanism* is an *enhanced mechanism*.

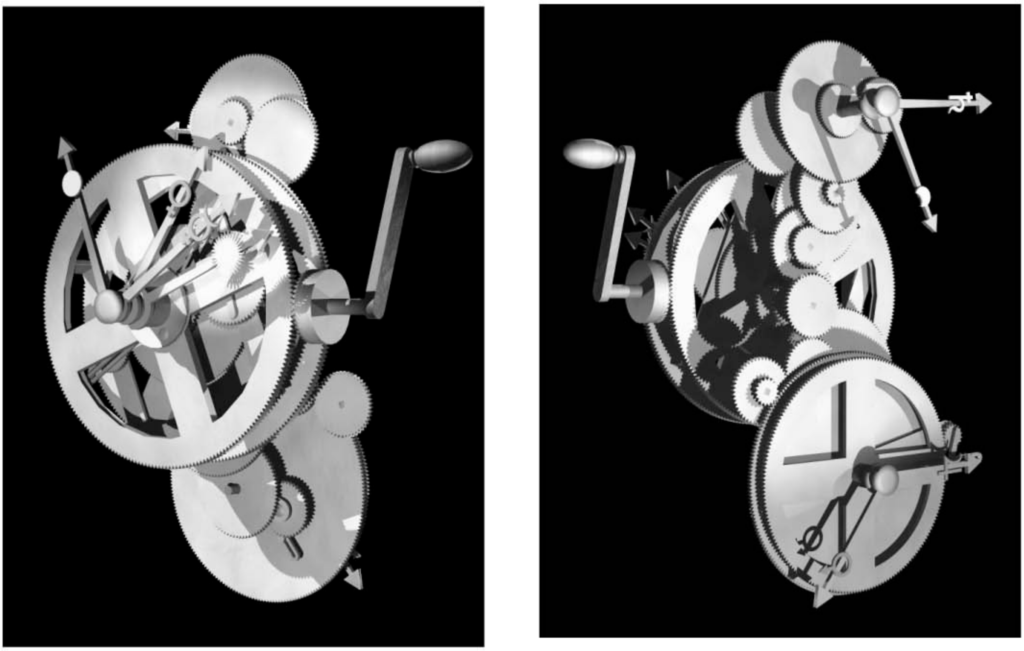

Fig. 10: Maxikythera Mechanism.
The front of the machine shows the Sun, sidereal Moon, Mercury and Venus. The back shows the Age of the Moon and Saturn on the Upper Back Dial and Mars and Jupiter on the Lower Back Dial.

This version of the *Maxikythera Mechanism* uses just 41 gears as opposed to 32 gears in Price's model and most of the tooth counts are consistent with those proposed by Price and Karakalos (Price 1974). If Cicero really was describing the *Antikythera Mechanism*, then it might well look something like this. However computer simulations need no support structure and have no friction and it would certainly be a nightmare to construct and hard to turn. There is also an enormous problem in calibrating the planetary mechanisms (as de Dondi found with his *Astrarium*, Baillie et al (1974)).

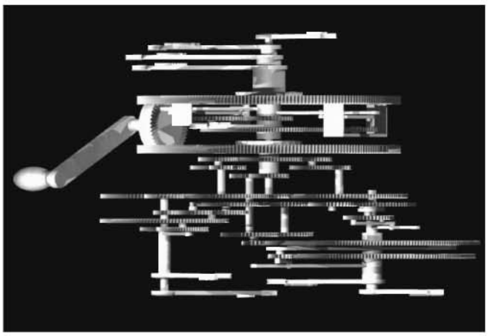

Fig. 11: The Maxikythera Mechanism - Sectional Diagram.

There have been persistent claims that the *Antikythera Mechanism* might have contained planetary mechanisms and there is persuasive historical and circumstantial evidence. However there is as yet no clear evidence from the fragments themselves. So is the *Antikythera Mechanism* really *Posidonius' Orrery?* The *Maxikythera Mechanism* does suggest that it's just possible and gives us a fascinating model to test against new investigations.

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