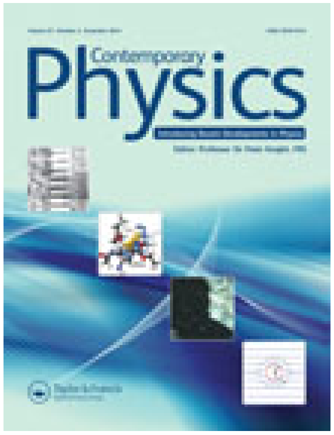

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The Antikythera mechanism and the mechanical universe

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The Antikythera mechanism and the mechanical universe

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How did our view of the Universe develop? By the mid-eighteenth century, a world view had developed of a system constrained by physical laws. These laws, if not entirely understood, showed regularity and could be handled mathematically to provide both explanation and prediction of celestial phenomena. Most of us have at least some hazy idea of the fundamental shift that came through the work of Copernicus, Kepler, Galileo and Newton. The idea of a 'Mechanical Universe' running rather like a clock tends to be associated with these sixteenth- and seventeenth-century pioneers. It remains a useful – and perhaps comforting – analogy. Yet, recent investigations based around the Antikythera Mechanism, an artefact from ancient Greece, reinforce a view that the 'Mechanical' conception has been around for a much longer time – indeed certainly as far back as the third century BC. The extent of mechanical design expertise existing around 100 BC as witnessed by the Antikythera Mechanism comes as a great surprise to most people. It is certainly a very ingenious device, often referred to as 'The World's First Computer' although it is really a sophisticated mechanical astronomical *calculator* with its functions pre-determined rather than programmable. In this review, the structure and functions of the Antikythera Mechanism are described. The astronomy, cosmology and technology inherent in the machine fit surprisingly well into the context of its contemporary Classical world. A strong claim will be made for the influence of such mechanisms on the development of astronomical and philosophical views, based on literary reference. There is evidence that the technology persisted until its spectacular and rather sudden re-appearance in Western Europe around 1300 AD. From then on it is not hard to chart a path through the astronomical clocks of the sixteenth century to Kepler's aim (expressed in a 1605 letter) to 'show that the heavenly machine is not a kind of divine, live being, but a kind of clockwork …', and on to the widespread development of popular visualisation of the heliocentric Solar System in the orreries of the eighteenth century.

Keywords: History of Science; history of technology; history of astronomy; history of cosmology; mechanistic philosophy

> a tiny device pregnant with the world, a portable sky, a compendium of the universe, a mirror of nature which reflects the heavens.
>
> –Cassiodorus, sixth century AD, trans. Barnish [1]

1. Discovery and recognition

The Antikythera Mechanism was found in the first ever major under-water archaeological expedition, mounted from November 1900 until September 1901 by the Greek Navy, Ministry of Education and Archaeological Society. The exploration of the wreck of a Roman-Era trading ship very close to the Mediterranean island of Antikythera had been organised after sponge divers discovered the wreck and its rich cargo of statues and other artefacts in spring 1900. Material from the wreck was transferred to the National Archaeological Museum in Athens, and the Mechanism itself was only recognised a few months later when gear wheels were noticed in a lump of corroded bronze. The reading of Greek text on its surface made it known as an astronomical device. The story of the wreck and recovery of the Mechanism is well covered in de Solla Price [2], Marchant [3], Tsipopoulou et al. [4] and Jones [5], although some minor details vary between the accounts. The wreck is fairly reliably dated to the decade following 60 BC, particularly from recovered coins [6], with earlier conflicting radiocarbon dates for the ship's timbers now resolved by recalibration [7] to 211–40 BC at 84.8% probability. The epigraphy (letter forms) of inscriptions on the Mechanism are consistent with its having been made in the last half of the second century BC [8, supplementary material], with an uncertainty of a few decades either way. The present best estimate of its construction date is around the middle of the range 150–60 BC – although a date as early as 220 BC is not completely ruled out.

The Mechanism first became widely known through a popular article by de Solla Price [9], but it was as a result of radiography of the surviving fragments by Price and Ch. Karakalos in the early 1970s that the true complication of the Mechanism became apparent. It was evident that 30 gear wheels remained, and that originally it contained more. There is no known surviving geared mechanism as complicated as this until the era of the cathedral and town clocks in the fourteenth century AD,

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over a millennium later. The work of de Solla Price [2], Wright [10] and the international Antikythera Mechanism Research Projects (AMRP) [8,11,12] has led to a broad agreement about reconstruction of the structure and function of Mechanism's main calendrical, solar and lunar displays, as described in Section 2 below. There is good evidence from the inscriptions on the device that it would also have displayed planetary positions, a function which we will see is also supported by contemporary literature descriptions of similar devices. The way in which planets were *actually* displayed on the Mechanism remains controversial (Section 2.4). Except where relevant we will concentrate on the mechanics of the Mechanism, rather than the inscriptions. These have yet to be published in full, although many preliminary details may be found in Freeth et al. [8,12], Jones and Freeth [24] and Zapheiropoulou [13]. The recent X-ray tomographic examinations have yielded a great increase (by a factor of about three) in the number of deciphered characters over de Solla Price's [2] work.

Before describing the *functions* of the Mechanism, it must be admitted that there is no real consensus as to its *purpose*. The limitations in the accuracy of some of its positional displays (see Section 3) suggests that it would not be particularly useful for an astronomer or astrologer as calculator – except in so far as it could give reasonable calendrical data and rapid approximate celestial positions, which might impress a client! There is no evidence to suggest its use in a temple, although lunar calendrical information was certainly important in arranging religious ceremony. Despite having been found in a shipwreck, none of the functions of the device would have been useful for navigation. Its most likely application was as a display or teaching device [14], and certainly more than just an 'executive toy' – as we shall see, it is too sophisticated for that, although it would be unwise to underestimate the importance of entertainment activities in the classical world. Perhaps the best notion of the device is as a *statement* of what is known about the Universe – or 'Cosmos' – a sort of hardware publication that would be accessible to non-astronomers, and whose purchase would at least show commendable aspirations. The astronomy in the device certainly represents very well the astronomical knowledge current around 100 BC, and indeed the word 'Cosmos' is found in its inscriptions.

The Antikythera Mechanism could certainly not have been unique, because its complexity and design requires a considerable tradition of development from simpler mechanical devices (explored by Tassios [15] and Keyser [16]). In Section 5, we shall show that literary references to geared mechanical astronomical display, both simple and complex, occur over at least 700 years of the classical era and into the sixth century AD. Although the references do not really help with the identification of the purpose of such devices they do show that the market must have continued, since most individual devices would surely have broken or worn out on something less than a 100-year timescale if the technology was that of the thin (2 mm) bronze gears of the Antikythera Mechanism. The lack of surviving artefacts from before 1000 AD – we only have two certain ones, the Antikythera Mechanism and a much simpler geared sundial from c 520 AD – is not surprising. When broken such devices would have had little value – they are not art objects, decorated with gold or jewels. Metal was valuable and a thriving recycling industry existed through the classical era into the mediaeval, so preservation would be expected only in special circumstances.

2. Basic structure of the mechanism

The modern discovery of the basic structure of the Antikythera Mechanism owes a great deal to the investigations of the historian and sociologist of science, de Solla Price [2,9] and to the 'mechanician and historian of mechanism' Wright [10]. Reasonable agreement on what original structure can reliably be deduced from the surviving fragments came with the application of detailed, high-resolution X-ray tomography and optical surface imaging by the AMRP ([8,12; also discussion by Wright [10]). The AMRP is a collaboration between academics in Greece, the UK and the USA, staff at the National Archaeological Museum of Athens, and two industrial corporations who freely loaned staff effort and equipment – X-Tek (now part of Nikon Metrology, www.nikonmetrology.com) and Hewlett Packard Laboratories (www.hpl.hp.com/research/ptm). A short overall account of the imaging and computing methods used is given in Edmunds and Freeth [17]. There was considerable damage and loss to the device during its shipwreck, and some inevitable separation of parts during a century of cleaning and conservation. There are 82 known surviving fragments, now finely displayed in the National Archaeological Museum in Athens. Most of the information is in the largest fragments (designated A–G, with smaller fragments numbered 1–75). The gears are in fragment A (remains of 28 gears), fragment B (one gear) and fragment D (one gear).

A conservative reconstruction of the exterior appearance of the Antikythera Mechanism is shown in Figure 1. Constructed mainly out of bronze sheet, it was housed in a wood or wood-framed box roughly 320–330 mm tall, 170–180 mm wide and at least 80 mm from front to back. It was worked by turning a handle or knob on the side of the box, which was connected to a crown gear (designated a1) of 48 teeth. The AMRP reconstruction of the gear trains is shown in Figure 2. The reconstruction uses 29 of the 30 surviving gears plus 3 conjectural ones – now missing but with assumed tooth counts that would be consistent with their necessary sizes. Gear designations are given by a lower-case letter for the shaft or axis

Figure 1. An impression of the front (left) and back (right) faces of the Antikythera Mechanism. The casing may have been wood framed, rather than solid wood, and was about the size of a shoe-box. Both front and back also had protective doors or plates made of sheet bronze, which carried inscriptions. The front dials certainly showed the position of the Sun and Moon in the Zodiac, and the phase of the moon, but the nature of the planetary pointers is speculative. The spiral dials at the rear showed the Metonic lunar-solar cycle (top) and Saros eclipse cycle (bottom). Details are given in Section 2. The right-hand sub-dial inside the Metonic spiral is a pan-Hellenic games indicator, and a left-hand sub-dial is conjectured to show the lunar-solar Callipic cycle – although no physical evidence for this survives. An Exeligmos dial to cover three Saros eclipse cycles is present inside the Saros spiral.

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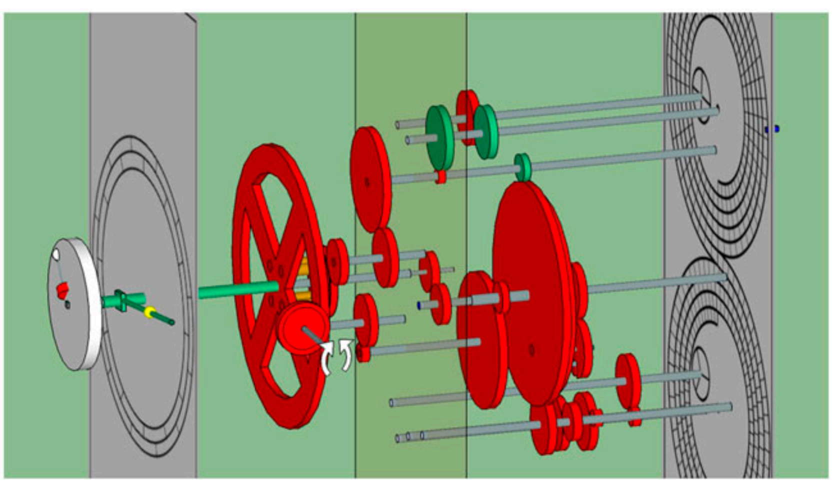

Figure 2a. The established gear trains of the Antikythera Mechanism. The gears and shafts are shown in their correct geometric relationship, except that the front-to back spacing has been arbitrarily expanded. The surviving gears are shown in red, and the three conjectured missing (but almost certainly present in the original) gears in green. The manual input drive is indicated by the white arrows.

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on which they are mounted, together with a number. The designations and data used here are as given in Freeth et al. [8], except for the addition of the conjectural gear *n*3 [12] in a slight re-arrangement of the sub-dial on the upper back dial. The crown gear a1 drove the large main four-spoked gear b1, clearly visible in Figures 3 and 4. One turn of this main wheel represents one year in driving the subsequent gear trains and displays. It is unlikely that the device was used as a daily calendar, advancing the main wheel by one day – 1/365th of a revolution – at a time. Although this might have been possible by careful turning and inspection of the sun's

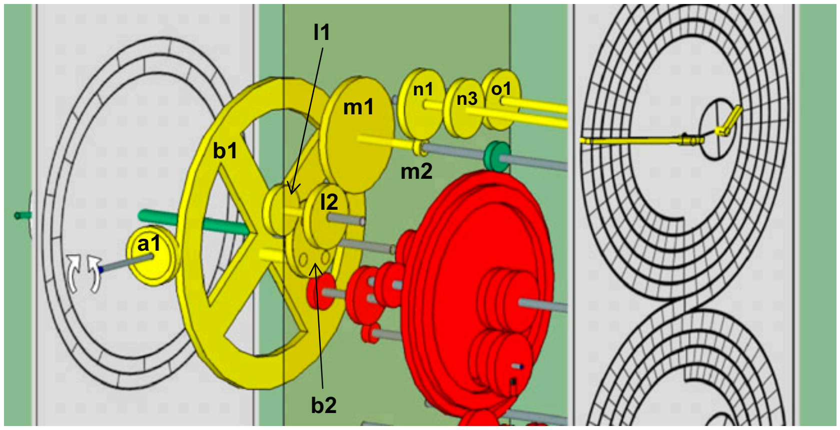

Figure 2b. From a different viewpoint, showing highlighted in yellow the drive train to the 19-year Metonic Cycle dial on the top back, with its subsidiary four-year-games dial. In the following gear train nomenclature a − sign indicates meshing of two gears, a + sign indicates the connection of the two gears on the same shaft or axis, and italic indicates a conjectural gear. The measured or conjectured tooth count is given in brackets after the gear designation. All trains are driven by the 48-tooth crown wheel (a1) turning the 223-tooth 'Sun wheel' (b1). For N turns (years) of b1 which is directly coupled to b2 the corresponding rotations are:
Metonic Dial: b2(64) − l1(38) + l2(53) − m1(96) + m2(15) – n1(53) → N × 64/38 × 53/96 × 15 /53 = N × 5/19
Games Dial: b2(64) − l1(38) + l2(53) − m1(96) + m2(15) − n1(53) + n3(57) − O1(60) → N × 64/38 × 53/96 × 15 /53 × 57/60 = N × 1/4
So 19 turns of b1 gives the five turns of the spiral on the Metonic dial, four turns of b1 gives one turn of the four-year games dial.
Graphic: M.G. Edmunds, Copyright Antikythera Mechanism Research Project.

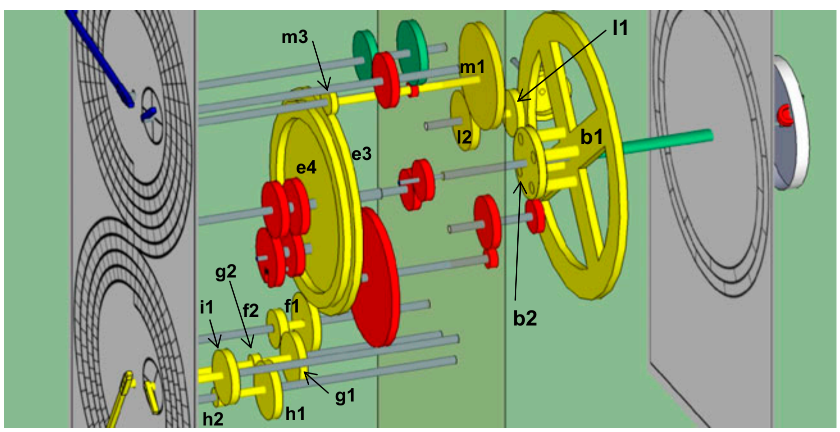

Figure 2c. The Saros and Exeligmos drive, highlighted in yellow, viewed from the other side compared to Figure 2a.
Saros Dial: b2(64) − l1(38) + l2(53) − m1(96) + m3(27) − e3(223) + e4(188) − f1(53) + f2(30) − g1(54) → N × 64/38 × 53/96 × 27/223 × 188/53 × 30/54 = N × (4/19) × (235/223) = N × (4/18.029..)
This gives the four turns of the spiral in just over 18 turns of b1 for the 18 years $11^{1}{}_{3}$ days of the Saros eclipse Cycle.
The gearing from the Saros dial shaft for the Exeligmos dial is: g2(20) − h1(60) + h2(15) − i1(60) → 20/60 × 15/60 = (1/3) × (1/4)
so that it needs 3 cycles of 4 turns on the Saros dial and just over 54 turns (years) of b1 to give one Exeligmos cycle.
Graphic: M.G. Edmunds, Copyright Antikythera Mechanism Research Project.

position pointer on the front dial, there is no evidence of gearing and a dial for easier day-to-day adjustment. It is more likely that the device was moved forward or backwards at a much faster rate to allow prediction or retrodiction of astronomical and calendrical events.

2.1. *Front dials*

On the front of the device (see Figure 1), behind a protective plate or door carrying inscriptions, there was a circular dial, part of which survives (see Figure 5). The inner annulus represents the ecliptic with its division into zodiac

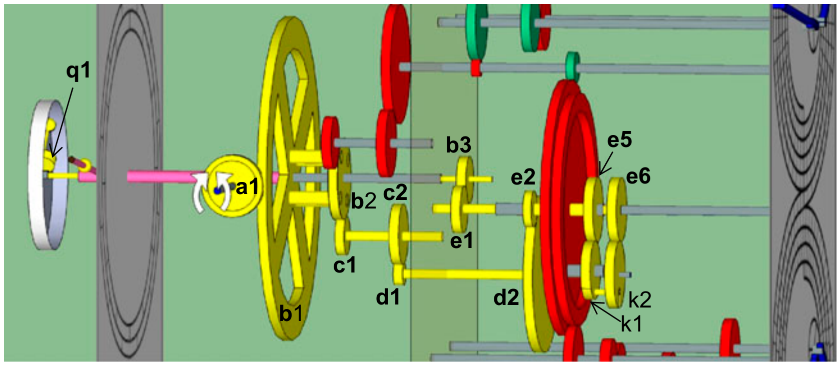

Figure 2d. The Lunar drive, highlighted in yellow.

b2(64) − c1(39) + c2(48) − d1(24) + d2(127) − e2 (32) + e5(50) − k1(50) [+] k2(50) − e6(50) + e1(32) − b3(32)

The symbol [+] is coupling via a pin-and-slot variable-speed device (see Section 3.3 and Figures 7–9) which replicates the first anomaly of the lunar motion. The last gear b3 is attached to the shaft of the lunar pointer, involving a double concentric shaft, and a second double shaft connects e2 with e5 and e6 with e1 . The epicyclic mounting of gears k1 and k2 on the 'turntable' gear allows replication of the first anomaly of the lunar motion at its correct period.

Since the last three pairs of meshing gears in the train have unit ratio, then the rotation relative to b1 can be represented by:

$(64/36) \times (48/24) \times (127/32) = (2/19) \times 127 = 13.368 \ldots$

which is a good representation of the ratio of the lunar sidereal month to the solar year, i.e. giving how many times the moon would go around the zodiac in a year, compare to the single journey of the Sun.

The Sun pointer on the front dial may have been directly driven from b1 as shown in pink in the figure, but the drive is missing and might have incorporated another variable-speed device (analogous to the lunar one) to simulate the slight inequality of the lengths of the seasons between solstices and equinoxes. The details of the drive of the lunar phase ball is also uncertain (Section 10), although one 20-tooth crown gear (q1) survives in it and an addition of a meshing gear of 20 teeth fixed to the sun pointer shaft would fulfil the function.

Graphic: M.G. Edmunds, Copyright Antikythera Mechanism Research Project.

signs through which the Sun passes during the year, and the outer annulus gives the corresponding Egyptian calendar months. The relatively stable Egyptian calendar was preferred for astronomical purposes over the much more variable local civil calendars. The outer dial could be rotated manually and has 365 small holes around it to allow registration and occasional manual adjustment for the effect of the quarter of a day by which the year exceeds 365 days. On the surviving part of the front dial, there is a radial mark just outside the Egyptian calendar scale. Although this is probably a damage crack, it has been interpreted by some researchers ([2], Evans and Carman [46]) as a fiducial reference mark for setting the calendar ring. Price suggested a reference date of 87 BC, although he was unsure, since he felt that there were conflicts in the dating evidence using the mark. Evans and Carman suggest that a very early reference date around 222–198 BC would be implied, but they allow that the mark – if real – might simply have been copied from an earlier version of the Mechanism.

To show the motion of the Sun and Moon there would have been pointers – that for the Sun being identified according to the inscriptions by 'a little golden sphere', and that for the Moon incorporating a half-silvered ball driven by simple gearing to indicate its phase [18]. It is very probable, based on the inscriptions that the changing positions of the planets around the ecliptic were also shown by pointers on the dial.

Around the zodiac annulus there are index letters which refer to a 'Parapegma' inscription which was displayed near the front dial and partially survives. A parapegma is a calendar of 'heliacal risings' during the year, when stars or constellations first become visible in the night sky just before dawn. The index letters link the risings to the solar calendar of the zodiac. Parapegma were widespread around the Mediterranean, and this one on the Mechanism is quite similar to one given by Geminos in the first century BC [19,20]. An analysis by Anastasiou et al. [21] suggests that it was designed for use close to a geographical latitude of 33–37° North, consistent with Rhodes or Syracuse but not particularly favouring the more northerly Greek provinces which might be implied (see next section) by the month names on the upper back dial.

2.2. Back dials

Three numbers – 76, 19 and 223 – are clearly visible in the inscriptions of fragment 19, part of the plate or door protecting the back of the Mechanism. These numbers are fundamental to the luni-solar cycles displayed on the two large dials on the rear of the Mechanism. Both were spiral in form, with the upper dial having five turns and 235 divisions and the lower having four turns and 223 divisions. The division into 235 is mentioned in the inscription 'the spiral divided into 235 sectors' on fragment E, again from the back door. The spirals are defined by a slot

Figure 3. Fragment A, which contains 28 of the Mechanism's gears. The large four-spoke 'chariot' or 'Sun' wheel (nomenclature: b1) has 223 or 224 teeth around its rim, and is 130 mm is diameter. In use, one turn of this wheel represented one year of time. National Archaeological Museum, Athens, Greece. — Ο Μηχανισμός των Αντικυθήρων. Εθνικό Αρχαιολογικό Μουσείο. Αθήνα. © User: Marcus Cyron/Wikimedia Commons/CC-BY-SA-2.0.

cut through the bronze sheet of the dial, as can be seen in Figure 6. The pointers – pieces survive – were designed with one end carrying a pin which fitted into the slot while the other end could pull at right angles out of the rotating shaft at the centre of the dial. This allowed the pin end of the pointer to indicate the relevant turn and division on the spiral. Once the pointer had traversed the whole dial, rather like a needle on a vinyl gramophone disc, it could be manually reset to the beginning.

The upper dial showed the Metonic calendar, 235 lunar synodic months (i.e. full moon to full moon, 29.53 days) which is equivalent to almost exactly 19 years. This luni-solar cycle was known to the Babylonians from recording of observational data over several centuries. Many clay cuneiform tablets of systematic observation and interpretation survive from around 750 to 50 BC, and knowledge of the cycle is believed to have passed to the Greeks in the late fifth century BC, possibly through the astronomers Euktemon and the eponymous Meton. The cycle's virtue is in keeping track of lunar months and the phase of the moon relative to the solar year, and is necessary because of course there are not an integer number of lunar months in a year. The cycle is still used today as the basis of setting the date of the Christian Easter festival as the first Sunday after the new moon following the spring equinox.

The names of the months varied greatly around the classical world [22], but those on the Metonic dial are characteristic of the Corinthian colonies of north-east Greece or Syracuse ([12], although [23] pp. 60–62 has doubts), prompting Freeth et al.'s [12] suggestion of a Corinthian manufacture and possible association with Archimedes. It may be safer to suggest that an identification of month names would imply manufacture for *use* in a particular region or to suit a particular client's taste – indeed the device was in transit when shipwrecked on a trade route past Antikythera. The dial divisions are laid out on the five-turn spiral in a way that takes account of the pattern of 'full' 30-day and 'hollow' 29-day months characteristic of a calendar described in the astronomy textbook by Geminus written sometime between 90 and 35 BC [19, 20]. The gear train driving the Metonic dial is highlighted in Figure 2(*b*).

The Callipic cycle of 76 years (slightly more accurate that four metonic cycles, involving subtraction of one day) is implied by the number 76 in the fragment 19

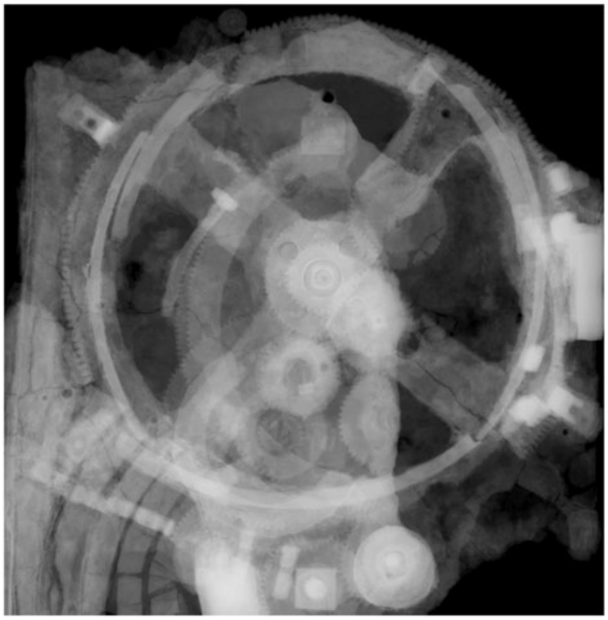

Figure 4. X-ray image (150 kV) of Fragment A. The teeth of the main wheel (b1), and its double central shaft are visible. The double row of teeth of the surviving half of the 'turntable' gear (e3/e4) can be seen behind b1.

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inscriptions. The cycle might have been displayed by a subsidiary dial, but no evidence remains of such a dial or its gearing. However there is a subsidiary dial on the face of the Metonic dial which is divided into quarters and shows the four-year cycle of the pan-Hellenic athletic games [12]. It includes the biennial Isthmian and Nemean games, and the four-yearly Olympic Games. This might imply a social function in an otherwise astronomical display, but it may have acted as a 'reality check' in anchoring the year by the games cycle (of which people would be aware) in a world where many different calendars existed. There are remnants of a 60-tooth gear (o1) on the axle of its pointer, the stump of which survives [24], and the drive could easily have been made by engagement with a (lost) gear of 57 teeth (*n*3) on the axis n of the Metonic dial pointer, as included in Figure 2(*b*).

The lower dial on the back shows a Saros cycle of eclipses [8,12]. A 'glyph' of some six characters occurs in one of the 223-lunar month divisions whenever there is the possibility of a solar (character H for Helios) or lunar (character Σ for Selene) eclipse during that month. The eclipse must, of course, occur at the new or full moon, respectively. The cycle was again known to the Babylonians, but known by other names until the term Saros was coined by Edmund Halley. Simply stated, if an eclipse occurs then a very similar eclipse is likely 223 synodic lunar months later, but shifted later by about eight hours in time. Such behaviour can persist over hundreds of years. Equipped with a list of historic eclipses it is thus possible to predict into the future the months in which eclipses are likely to occur. At a given location a particular solar eclipse may not be seen, or be only partial, since the total solar eclipse path on the surface of the Earth is quite narrow (nearly always less than 270 km), but lunar eclipses are more generally observable. The glyphs on the Saros dial give some additional information about the expected time of the eclipse, although the basis for these extra predictions (or indeed the extent of their reliability) is not yet fully understood. The one-third of a day shift from cycle to cycle is indicated by a subsidiary dial divided into three equal segments. The first segment is blank, the second has the number 8, and the third the number 16, showing the number of hours to be added to predicted eclipse time in each successive Saros to make up an Exeligmos (in Greek – 'turn of the wheel') cycle after which the predicted times would return to the glyph values. The gear chains for the Saros and Exeligmos dials are highlighted in Figure 2(*c*). At first sight double gear e3/e4 is un-necessarily large and the chain could have been designed more economically in a way similar to the Metonic train. In fact the design is ingenious, as we shall see in Section 2.3.

Although remnants of pointers for the Metonic and Saros dials survive, only the Metonic pointer points to a month on the dial, but is not of help in providing an overall dating. The eclipses specified by the 'glyphs' at various month positions on the Saros dial repeat over many cycles. The glyph positions are consistent with modern calculations of eclipses during the three centuries from 300 BC, and with methods of prediction that would have been available at the time. It has not proved possible to establish a unique 'in use' date (or indeed a tighter constraint on an interval) within the 300–60 BC period that it is bracketed by a fairly definite earliest possible manufacturing date and the latest date for the shipwreck.

2.3. *The lunar motion*

The motion of the moon in the sky is remarkably complicated, and indeed made even Newton claim that 'his head never ached but with his study on the moon' [25, p. 544]. In a mean 'sidereal' month of 27.32 days the Moon would return to the same point in the sky relative to the background stars as viewed from Earth. The 'moon phase' synodic month mentioned in the last section is longer due the Earth and Moon's joint motion around the Sun. But the lunar orbit around the Earth is elliptical, not circular, and the moon moves more slowly and is further away at apogee – both effects leading to slower apparent motion. At perigee, the apparent motion is faster. The resulting variation has an amplitude of about 6° compared to the mean position on the sky expected if the orbital motion were circular. The Babylonians knew of the anomaly – later

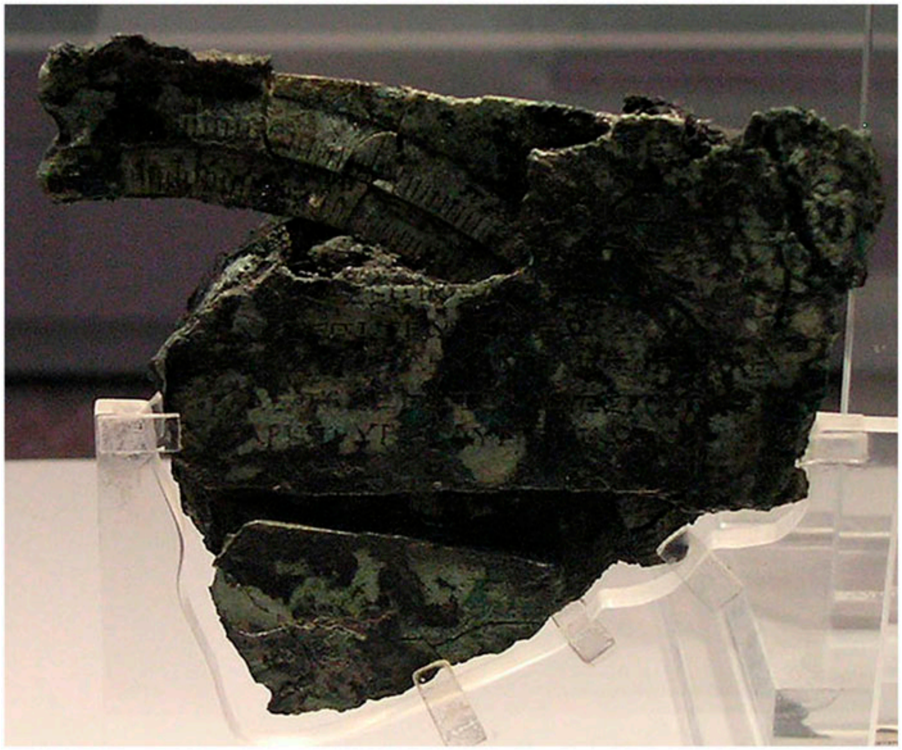

Figure 5. Fragment C, which shows the remnant of the front dials of the Mechanism. The inner annulus showed the twelve signs of the Zodiac at 30° intervals, while the outer annulus showed Egyptian month names, a calendar convenient for astronomy. The division between the two annuli is 144 ± 3 mm in diameter. National Archaeological Museum, Athens, Greece. © User: Marsyas/Wikimedia Commons/CC-BY-SA-3.0.

known as 'first anomaly of the lunar motion' – and Hipparchos (active around 160–128 BC) developed a geometric theory to explain it. Nowadays, we know that it is the gravitational effect of the Sun that causes the Moon's elliptical orbit to precess, so that the period of the variation is the *anomalistic* month of 27.55 days – slightly different from the sidereal month. Viewed from above, and exaggerated in ellipticity, the lunar orbit would trace out a 'flower petal' pattern in just less than nine years. Many smaller anomalies were later identified which also arise from the gravitational influence of the Sun. The largest are the second anomaly or evection of about 1.3° amplitude, the existence of which Ptolemy (c.90–168 AD) was aware, and a 0.66° 'variation' noted by the Tycho Brahe at the end of the sixteenth century AD, which vanishes at full or new moon.

The mechanical representation of the first anomaly of the lunar motion in the Antikythera Mechanism was first identified by Freeth et al. [8] following recognition by Wright of the components of a pin-and-slot variable-speed device. As shown in Figure 7, four gears in the lunar drive train provide the modulation. Gear e5 is turned by the outer part of a double shaft which passes (unattached) through the centre of the large 'turntable gear' e3/e4. Gear e5 drives gear k1. This gear has a pin perpendicular to its surface which pushes on the side of a radial slot in gear k2. The gear k2 is mounted above and almost co-axially with gear k1. Because the axes of the two gears are not exactly aligned, the pin is pushing sometimes closer, sometimes further away, from the axis of gear k2 and rotating it faster for half its cycle, and slower for the other half. Gear e6 picks up the modulated drive from k2 and passes it back through the centre of the turntable gear e3/e4 via the inner part of the double coaxial shaft to the lunar display on the front dial. A simple mathematical demonstration can be given by following Evans and Carman [45]. Using the notation shown in Figure 8, sine rule on triangle C_1C_2D gives $\frac{\sin\beta}{C_1C_2} = \frac{\sin[180-(\theta+\beta)]}{C_1D} = \frac{\sin(\theta+\beta)}{C_1D}$. Setting $e = C_1C_2/C_1D$, using $\cos\beta = \sqrt{1-\sin^2\beta}$ and re-arranging to solve for $\sin\beta$ gives $\sin\beta = e\sin\theta/\sqrt{1-2e\cos\theta+e^2}$. With gear k_1 rotating uniformly θ will increase linearly with time. In the Antikythera Mechanism, the measured $C_1C_2 = 1.1$ mm and $C_1D = 9.6$ mm give $e = 0.11$ and an angular variation amplitude of 6.5°, corresponding reasonably well (within the CT measurement errors) to modern values and to what historically was estimated by Hipparchos from eclipse data. Figure 9

Figure 6. Fragment B showing part of the five-turn spiral slot of the Metonic Cycle dial from the upper back face of the Mechanism. Each turn is formed from two semi-circles of different radii. The outer radius of the slot would have been about 150 mm. National Archaeological Museum, Athens, Greece. — Ο Μηχανισμός των Αντικυθήρων. Εθνικό Αρχαιολογικό Μουσείο. Αθήνα. © User: Marcus Cyron/Wikimedia Commons/CC-BY-SA-2.0.

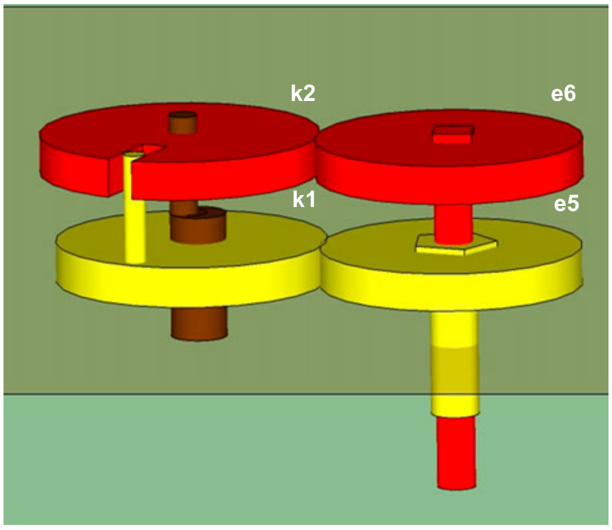

Figure 7. The Pin-and-Slot Variable-Speed Device: All four of these gears have 50 teeth. The lunar drive (here initially shown in yellow) enters by the outer tube of the co-axial shaft on the right, which passes through (but is not connected to) the centre of the large 'turntable' gear (e3/e4) of the Saros dial drive. The shaft turns gear e5 which engages with and turns gear k1. The pin in gear k1 pushes on the slot in gear k2, but as this gear is mounted 'off centre' its rotation rate varies slightly faster and slower over one rotation. The modulated drive (now shown in red) is transmitted to gear e6, back through the centre of the double shaft and on to the lunar position indicator on the front dial.

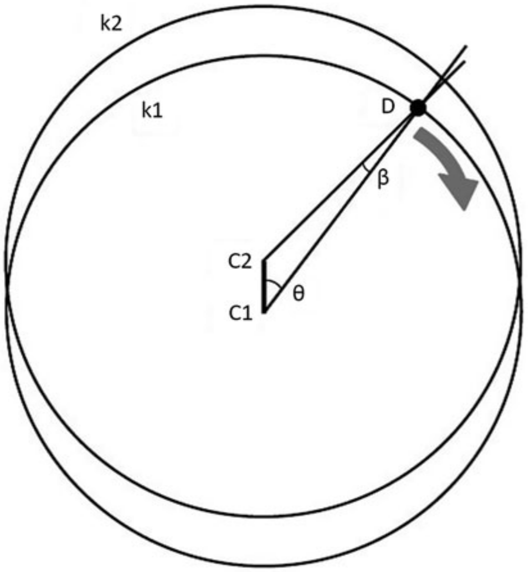

Figure 8. The geometry of the pin-and-slot variable-speed device of Figure 7. Gear k1 turns on centre C1, with pin at radius D pushing on slot in gear k2, centre C2. For details see text.

gives a plot of β through a 360-degree rotation of both k1 and k2 for $e = 0.11$, demonstrating clearly the quasi-sinusoidal behaviour as the rotation of k2 first leads and then falls behind k1.

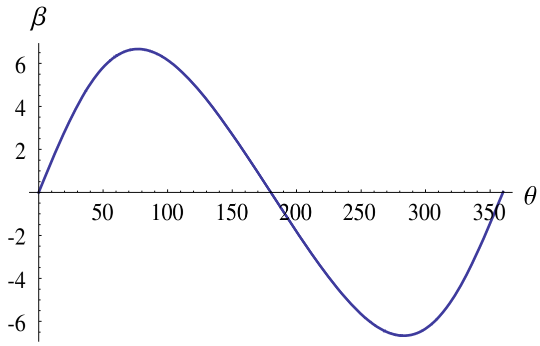

Figure 9. The operation of the pin-and-slot variable-speed device. The plot shows angle β of Figure 8 as a function of θ, where 360° represents a complete rotation of gear k1. The rotation of k2 first leads and then falls behind k1 in a quasi-sinusoidal fashion. The equation for β is given in the text.

To find a variable-speed device may seem surprising in itself, but the true sophistication of the Antikythera Mechanism's design is realised in the mounting of these gears (i.e. the shafts of k1 and k2) on the turntable gear e3/e4, which itself is driven in the Saros train of gears (Figure 2(*c*)) to rotate the equivalent of once every 8.88 years – a reasonable representation of the 8.85 year period of rotation of the Moon's perigee about the Earth (known as the period of the precession of the line of apsides). The remarkable result is that the modulation in the lunar rate not only has about the correct amplitude but also the correct period, the anomalistic month. The lunar and solar gear trains are illustrated in Figure 2(*d*).

2.4. Planetary display in the Antikythera mechanism

de Solla Price [9] mentions that he had seen inscriptions on the back of the Mechanism 'which refer to stations and retrogradations of the planets', although he does not give further details in his later *magnum opus* [2]. The AMRP X-ray tomography [8, supplementary material] confirmed the reference to Venus and stationary points. Jones and Freeth [24] give good evidence that *all* the known 'planets' of the time were listed in the inscriptions the order of the contemporary visible 'cosmos' above the Earth – i.e. Moon, Mercury, Venus, Sun, Mars, Jupiter and Saturn. So it seems very likely, supported by literature descriptions of similar devices (Section 5), that planetary positions were displayed. That 'stationary points' are mentioned in the inscriptions does imply that the Mechanism's geocentric representation was more realistic than simply uniform mean-speed circular motion of the planets around the zodiac. Unfortunately, almost all the planetary part of the Mechanism has been lost – presumably detached during the shipwreck. All that remains is that (i) on the main fragment (A) and its large main wheel b1 there are tantalising small details of structure which might be associated with the bearings of additional gearing; and (ii) there is one extant gear (r1) of 63 teeth on its own in fragment D which is not required for the accepted reconstruction of the solar, lunar and calendrical functions, and might therefore be part of a planetary drive.

There have been several possible theoretical reconstructions of planetary displays, involving sub-mechanisms of epicyclic gears (i.e. gears mounted on gears), compound gear trains, sliding arms, pins-in-slots, etc. to reproduce the retrogrades [24,26–33]. Suggested displays involve pointers on the main front dial, or individual dials for each planet. The proposed arrangements tend to echo either the pin-in-slot-in-gearwheel technology of the Mechanism's lunar motion, or pivoted slotted arms driven by rotating pins – as used in much later astronomical clocks. It is not currently possible to make any firm statement about which reconstruction is closest to the original, and none accounts completely for all known aspects of the surviving fragments. Nevertheless, what is significant is that viable reconstructions *can* be made, and it is clear that the makers of the Mechanism would have been able to build planetary displays using the level of technology and techniques that they had already achieved, as witnessed by the clever design and construction of the rest of the Mechanism.

3. The performance of the mechanism

How well would the Mechanism have worked? The gear teeth are triangular, with perhaps a slight tip rounding by wear or filing, and it is believed that the gears were cut by hand. The triangles appear roughly equilateral, but the tip angles are probably closer to 75° [34] than 60°. Five of the 30 extant gears have complete teeth. Although the other gears are damaged and incomplete, seven of them have contiguous runs of half or more teeth. For the incomplete gears, it has proved possible to estimate tooth counts and uncertainties by fitting model gears to the X-ray tomographic images using mean-square error minimisation [8, Supplementary Notes 3]. A total of 14 gears have definite counts and 14 have counts estimated to be within two teeth of the original. Noteworthy definite values are the 127 teeth for gear d2 and 53 teeth for gear l2, both primes of importance in the functioning of the Mechanism. Unlike more subtle teeth profiles (see Appendix 1), triangular teeth will not give smooth transmission of motion, but when physical replicas of the Mechanism have been made (e.g. by John Gleave and by Michael Wright) they do in fact turn reasonably well. Imperfect spacing of the gear teeth would, however, have had an effect on the accuracy of the functions of the original, and a first analysis [35] has been based on the statistical characteristics of the measured tooth spacings. Using these characteristics in computer simulations of the gear trains suggests that the Metonic month indicator would be on average two days away, and the Saros indicator on average five days away, from what the designer would have intended. This is probably a satisfactory performance – since, for example, an eclipse must occur at either the full or new moon and all that need be known is whether such an eclipse is likely in that particular month. These are average values, and larger deviations would occur during the complete cycles and it is possible that an eclipse might be predicted in the wrong month. The lunar pointer is geared up from the main drive, rather than down as for the other dials, and hence the angular errors are larger. The result could easily be as far as 20° away from its intended position at some time during the year, an error greater than the first lunar anomaly that it was designed to incorporate. If prediction of the date of new or full moon were done by aligning moon and sun pointers – then typically about half the predictions would be one day out, and once a year two days out. These are effects due to unintended random and systematic errors in manufacture. Backlash in the gear trains must have been considerable, resulting in some inconvenience in use. But there is another source of inaccuracy, which is particularly significant in considering possible planetary mechanisms, which is *representational* error. By this, we mean a situation in which the particular design of the gear trains (including sliding arms, pins-in-slots, etc.) does not allow particularly good representation of the celestial motion because the underlying theory is not sufficiently accurate or is difficult to put into mechanical form. Simple sub-mechanisms can be designed that follow the major mean periodicities of the planets reasonably well, but which may often have a positional error of 30° in the short term.

The overall implication may be that the Antikythera Mechanism would have been used for *display* purposes, rather than for 'accurate' calculation. But the attitude of the classical era astronomers and their audiences to the notion of accuracy was probably very different from modern ideas, and deserves closer study.

4. Design elements

Very little has been recognised by way of 'decoration' on the surviving fragments of the Antikythera Mechanism. There may, however, be a few 'design elements' that hint at a tradition. The most striking visual element is the large gear wheel b1 of 223 or 224 teeth on the main fragment. In the functioning of the mechanism, one turn of this wheel represents one year, and it has sometimes been referred to as the 'Sun' wheel. It is the only wheel in the Mechanism that has spokes, and its four-spoke construction is reminiscent of a chariot wheel. As it was inside the case, the wheel might not have been immediately visible, but it may be no coincidence that the idea of a sun-chariot with four-spoke wheels was widespread in the ancient world – for example in the Bronze-Age Trundholm sun-chariot sculpture and Scandinavian rock carvings that may have been influenced by Mycenaean Greece ([36,37]. Image at http://natmus.dk/en/historical-knowledge/denmark/prehistoric-period-until-1050-ad/the-bronze-age/the-sun-chariot/). The symbol ⊕ of the Sun and the cycle of the seasons appears in prehistoric art worldwide [38], and in Greek pendants and votive offerings. If the correct number of teeth on the gear is 223, the symbolic link with the Saros eclipse cycle could be coincidence rather than intentional, but a more easily laid-out gear of 240 teeth would easily fit in the box. No reason for the 223 teeth on this gear has been suggested – other than that the 223-tooth e3 turntable gear might have been a convenient pattern for its angular tooth spacing. The b1 gear meshes with the 48-tooth crown gear (a1) which would have been attached to the driving handle or knob on the side of the box. This implies 4.6458 … (for 223 teeth) or 4.666 … (for 224 teeth) turns of the handle to represent one year. An integer number of turns might seem more logical – for example, a 240/48 combination would give exactly five turns – surely preferable unless the 223 is significant for representational reasons. We hasten emphasise that we are not suggesting some kind of 'ritual' significance, merely that there might have been a design tradition. Seiradakis [39] has reported that the ⊕ design is found on the top of the remains of the sliding pointer of the Metonic solar/lunar cycle dial. The 'double spiral' of the back dials is certainly distinctive. It is probably pushing the analogy too far, but images of double spirals have been associated with calendars and are present on the Trundholm sun-chariot [40], and on some megalithic monuments. Persistence over long periods of design elements can easily be shown by dentils – the architectural detailing consisting of lines square or rectangular blocks in relief around a roof line. This was particularly popular in architecture of the eighteenth and nineteenth centuries AD, and is still occasionally used today. It is a two-thousand year survival of the appearance of roof-beam ends on Greek temples.

The cross-section of the shaft carrying gear e5 shows up in the X-ray tomography as an exquisite pentagon with sides of length 2.5 mm [8], but the temptation to interpret in terms of Pythagorean shapes should be quickly tempered with realisation that a pentagonal shaft/gear-centre combination is an excellent engineering solution to prevent slipping.

Further engineering details that are seen such as retaining pins, horseshoe-shaped spacers on gear shafts and shaft/arbour design all await detailed consideration.

5. Evidence of geared astronomical displays from classical literature

When people today hear about the Antikythera Mechanism for the first time, its complexity and ingenious design seem to come as considerable surprise. Indeed, there have been claims that it is so anachronistic that it must be a fake from a much later era, or even part of an alien navigation system for interplanetary travel. Its uniqueness as an artefact inevitably provokes suspicion. Fortunately, there is ample evidence in classical literature, discussed below, to provide contemporary collateral evidence for the existence of geared mechanisms, and in particular of mechanisms representing the cosmos. Compared to present-day amazement, it is interesting that the compiler of an encyclopaedia in 1819 AD had no difficulty is assuming – guided by literary sources – that Archimedes could have constructed such a device [41], although this was some 80 years before the Antikythera Mechanism was found. Perhaps it reflects benefits of rather more classical education than would be usual today, allowing appreciation of the capabilities of the ancient Greeks. Even the briefest look at the jewellery of the era shows their superb metal-working skills. What does surprise is the sophistication of the engineering design, with its spiral displays, interleaved gear trains and variable-speed device. Table 1 is a list, no doubt incomplete, of references in classical literature to mechanisms which represented motions of or in the heavens. It traces a long-lived tradition c250 BC–600 AD.

A particular link is the use of the word sphairai (Greek) or spearae (Latin). The word can be interpreted in at least three ways: (i) as a primer on elementary astronomy by classical authors, sometimes in verse, two of the best-known being Phenomena by Aratus [43] from c.276 BC and the previously mentioned Geminos [20], (ii) as an armillary sphere, a spherical structure with rings to represent the main circles on the sky associated with astronomical phenomena (e.g. the equator, the ecliptic – the path on the sky of the Sun as the Earth moves around its yearly orbit, the tropics) or (iii) as a mechanical representation of the motion of heavenly bodies, particularly of the Sun, Moon and planets. Such devices could be three- or two-dimensional, but there is little doubt that 2-d devices *were* referred to as 'sphaerea'. It is this third meaning of the word that concerns us.

Some commentators ([44, p. 14], quoting Brumbaugh; [45, p. 398]) have suggested that the record of mechanical models of the Universe might date back as far as Plato c 360 BC (reference 21 in Table 1), but the model implied might not be a geared one. We will restrict our consideration of 'mechanical universe models' to those that did use gearing. Our selection is chosen because there are other devices which may have helped the visualisation of astronomical phenomena, and even heavenly motions, and which may have provided metaphors to prompt physical explanations of such motion, but do not have the *transmitted causal element* which geared technology suggests. Use of pulleys and belts would also imply causality, but there does not seem to be any reference to belt-driven astronomical mechanisms. An example of an excluded device without 'causal transmission' would be the armillary sphere. Because of its simplicity we also exclude references to the anaphoric clock, a water- or weight-driven disc, typically engraved with zodiac constellations, arranged so as to replicate the apparent daily rotation of the sky. But we note in passing that the anaphoric clock could be regarded as an excellent conceptual mechanical model of a geocentric Universe.

6. The significance of geared sphaerea

A geared sphaera has certain characteristics which will illustrate general properties of the 'Cosmos'. Even in its simplest form – just showing the mean passage of the Sun and Moon through the sky – it displays regular motion and is 'deterministic' in the sense that future and past behaviour can be predicted. The gearing itself shows that a physical 'mechanism' (a word of obvious derivation!) can exists to account for, or at least approximately represent, the behaviour of the heavens. Recently, Evans and Carman [46] have proposed that the conceptual development may have been two-way, and that the development of the epicyclic theory of the planets by Apollonius and others within a few decades of 200 BC might itself have been stimulated by, and have stimulated, mechanical modelling. With all models – mechanical, mathematical or heuristic – there is always (to quote Samburski [47])

> the question … [as to] whether these models are only convenient means of illustration, devices adapted to our needs for an ordered description, or whether they represent to a greater or lesser degree some faithful image of a physical reality corresponding to them.

Whether there was ever actually a belief that a geared mechanism has any connection with how the motions of heavenly bodies are 'actually' achieved is interesting, but ultimately not important. What *is* significant is the possibility that there could be a physical or 'mechanistic' explanation, whatever its nature and even if it might need substantial future refinement. A rather poor analogy might be drawn from the existence theorems for the solutions to equations – where it is known that there is a solution, even if finding it may be rather difficult.

A recent book by Berryman [48] has looked in detail at mechanical ideas in ancient Greek philosophy, but in a much wider context than just the mechanical models of the heavens considered here. She does not push our view

Table 1. References to sphaerae in classical literature.

Ref	Author	Work	Date	Content	Comment
1	Archimedes	‘De Sphaerae Constructione’	ca 260? −212 BC	Lost book on ‘spheremaking’	Referred to by Pappus Coll. 8.3. citing Karpos of Antioch as source
2	Cicero	De Re Publica 1,14	54–51 BC	Archimedes Sphaerae	Motions of Sun, Moon and five planets. Eclipses
3A	Cicero	De natura deorum II, 88	45 BC	‘Posidonius’ sphaera See: Note (i) to Table, below.	Mechanism must have been made by a rational being
3B	Cicero	De natura deorum II, 97	45 BC	Sphaera, horae and many other things in motion ‘cum machinatione quandam’	
4	Cicero	Tusculan disputations 1, 36	ca. 45 BC	Archimedes sphaerae	
5	Vitruvius	De Architectura 10.1.4	ca 20 BC	Machines as inspired by heavens	Implies sphaerae
6	Theon of Smyrna	Expositio rerum	ca. 70 -ca. 135 AD	Spheremaking, gearwheels	Gears allowing opposite rotations
7	Ptolemy	Almagest XIII, 2	120–150 AD	‘models constructed on earth … difficult to achieve in such a way that the motions do not hinder each other’	
8	Ptolemy	Planetary Hypotheses 1.70.11–23	Mid 2nd C AD	‘motions … sphaera-making …’	
9	Galen	De Usu Partium 14.5	169–176 AD	Models of planetary motion	Used as analogy for the biological body to function as succession of transmitted actions
10	Sextus Empiricus	Adversus mathematicos, IX, 115	3rd C AD	Archimedean sphere …	.. amazed by … the devices and causes of the movements.
11	Pappus	Works VIII, 2	3rd C AD	Spheres..motions..Archimedes..	
12	Agrestius Chromatius	quoted by St Sebastian and St Polycarp	3rd C AD	Cubiculum holovitrium with moon phase and planets ‘in which the whole learning and science of the stars is constructed mechanically’	Implications of impiety – ‘monstrous demons displayed an art hostile to the deity’
13	Lactantius	Institutiones divinae II, 5, 18	4th C AD	Archimedes sphaera	
14	Claudian	Carmina minora Li (LXVIII)	ca. 400 AD	Archimedes sphaera	
15	Proclus	On Providence	? 432 (age 20) – ? 485 AD	Universe as mechanical device with wheels interlocking in proportion	
16	Martianus Capella	De nuptiis 6.583-5	Early 5th C AD	Archimedes sphaera	‘Sicily was amazed by this copy of the cosmos..’
17	Nonnus	Dionysiaca	5th C AD	Sphaera with planets, kept in a box	Used for astrology
18	John Philoponus	De Anima 106, 25	6th C AD	‘… in the case of the bronze sphere the axis moves … but the parts driven by it move … partly in the same sense as the axis, partly in the opposite one’	Discussing Aristotle and soul and body moving in same direction

(*Continued*)

Table 1. (*Continued*).

Ref	Author	Work	Date	Content	Comment
19	Cassiodorus	Variae I. 45.	c.506 AD	'shown how the moon recovers from waning, and set turning by an invisible mechanism a tiny device … a portable sky, a compendium of the universe, a mirror of nature which reflects the heavens' (Trans.: Barnish)	Letter to philosopher Boëthius, implying he knows about sphaerae
The following are less direct or doubtful references					
20	Plato	Timaeus 40c-d	c. 360 BC	'To describe … the counter-revolution of their circles relatively to one another … to tell which … come into line with one another at their conjunction, and which in opposition … to describe all this without visible models of these same would be labour spent in vain.'	Models not necessarily geared
21	Aristotle	On Generation and Corruption Book II, Chapter 11, 338a18-b6	350 BC	'For if that which moves in a circle is always moving something else, the motion of the latter too must be circular – for example, since the upper movement is circular, the sun moves in this way'	Suggestive of gear train, but not certain. Does imply an early mechanical interpretation of Eudoxus' model.
22	Ovid	Fasti VI	8 AD	'There's a globe suspended, enclosed by Syracusan art, That's a small replica of the vast heavens'	Direct reference to Archimedes, but might not be moving model
23	Manilius	Astronomica Book 2, line 127	1st C AD	'Who could deny the sacrilege of grasping an unwilling heaven, enslaving it, as it were, in his own domain, and fetching it to earth'	Might not refer to sphaerae, but demonstrates opposition to mechanical models
24	Manilius	Astronomica Book 4, lines 262 and 267/8	1st C AD	'… to transform the flow of water so as to spray the very stars … water will even set in motion the face of the heaven and the starry habitations, and will cause the skies to move in a novel rotation.'	In passage about water driven devices. May refer to anaphoric clock rather than water-driven sphaerae
25	Mesomedes of Crete		Early 2nd C AD	'a circle the course of the stars - a brass likeness of the cosmos … symbols of the golden constellations wheeling round …'	Probably anaphoric clock

Notes: We quote here more fully the well-known reference (3A) by Cicero, since it is probably represents a device existing within a few years of the Antikythera wreck. 'Our friend Posidonius [c. 135–51 BC, Stoic philosopher and astronomer] has recently fashioned an orrery ["sphaera(m)"]; each time it revolves it makes the sun, the moon and (five) planets reproduce the movements which they make over a day and a night in the heavens' (trans. Walsh, [42]). Cicero had seen the device on a visit to Rhodes sometime during 78–44 BC.

Many of the references refer to the 'Sphere of Archimedes'. This does not imply that Archimedes was himself involved in the design or manufacture, for the term had simply become generic for the type of device, much the same as in the modern usage of 'hoover' or 'biro' for vacuum cleaner or ball-point pen.

It is evident that 'Sphaerae', specifically those that involved gears in representing the motions, or the changing positions, of celestial objects were known about (at least to the literati) during a period of some 750 years from c 250 BC to 500 AD.

of the fundamental importance of 'sphaerae' in the development of philosophy and cosmology, perhaps because of her uncertainty as to whether putting planetary pointers on dials really is an attempt to represent the topography of the heavens (op. cit. p. 152). Support for our more extreme view does seem to come from the likelihood the front dial of the Antikythera Mechanism was indeed a 'cosmos' in miniature (Jones and Freeth [24]) and from the quotation (see below) from Cassiodorus of such mechanisms as 'a mirror of nature which reflects the heavens'. de Solla Price [44] suggests that 'some strong innate urge towards mechanistic explanation led to the making of automata'. We prefer the inverse interpretation – or perhaps a synergy – that actual mechanical models encouraged the development of mechanistic philosophy.

We focus briefly on a few of the references in Table 1. Number 9 is from Galen, the foremost medic of Antiquity. Note that he is not an astronomer but is certainly familiar with sphaerae:

> For just as there are those who imitate the revolutions of the wandering stars [planets] with models … they endow with the principle of motion and who go away themselves while the instruments [continue to] act as if their creator were present and always controlling them, so in the same way, I suppose, each of the bodily parts by a certain consecution and succession of motion always from the very beginning acts without needing a supervisor. [trans. 49]

This is one of the few references that imply some sphaerae were driven by an external force, possibly water power. He is applying the 'mechanical' analogy to animals, with the idea of eternal mechanical motion and that a 'prime mover' is necessary. The sphaerae is relevant since either the user through a knob or handle (as in the case of the Antikythera Mechanism), or the water power, is seen to be able to drive all the different functions of the machine. The notion of the Universe as a 'clockwork' machine re-emerges several times in history – although of course regulated mechanical clocks were not invented until the thirteenth century AD. But we should perhaps be careful to distinguish two themes here: (i) the Universe as a machine which is causally connected by physical mechanism – i.e. a 'gearwork' rather than 'clockwork' Cosmos and (ii) the Universe which is causally connected by physical mechanism and whose prime mover eventually runs down like a clock spring, or is rewound by a deity, or simply continues for eternity without intervention. The second theme would be a cause of considerable debate for Newtonian physics as the 'Clockwork Universe', while the first theme at least eliminates the need for individual gods to push round the planets.

To the properties of regularity, causality and a prime mover can be added to the mechanical generation of 'regular irregularity' such as retrograde motions of the planets. The evidence is in both the pin-and-slot device and the inscriptions of the Antikythera Mechanism. Ptolemy (Table 1 references 7 and 8) seems to have been rather unimpressed by mechanical models, but even his rejection is good evidence for the stimulus that such models gave to discussion of the physical nature of motions in the heavens. We would suggest that the widespread knowledge of such devices (as implied by Galen's casual reference) shows that they also formed an important debating point in the general development of philosophy.

A particularly noteworthy reference is number 19 of Table 1 to Cassiodorus, Roman statesman and sometime secretary to Theodoric, king of the Ostrogoths. Cassiodorus is writing, probably in 506 AD [1], to Boëthius – author of 'Consolation of Philosophy' and a very major figure in late classical and mediaeval philosophy. Cassiodorus implies that Boëthius already knows about complicated astronomical mechanisms – indeed the wording is that Boëthius is 'adorned with acquaintance with such matters' – and Cassiodorus is asking him to procure one:

> I shall say a little about the skill that represents the heavens without sin. This has set a second sun to revolve in the sphere of Archimedes: by human ingenuity, this has constructed another circle of the Zodiac; by the light of art, this has shown how the moon recovers from waning, and set turning by an invisible mechanism a tiny device pregnant with the world, a portable sky, a compendium of the universe, a mirror of nature which reflects the heavens. (trans. [1])

The mention of 'represents the heavens without sin' may be interesting in view of at least one other reference from around the 3rd C AD (Number 12 in Table 1) which hints at impiety in constructing models of the Heavens. Theological criticism might be invoked as an explanation of the apparent disappearance of such devices in the West in early mediaeval times. The use of Archimedes' name is, as mentioned in the notes to Table 1, probably generic. Apart from the obvious implication that important intellectuals still knew about such devices in the early sixth century, the marvellous and rather poetic last line of this extract – 'A portable sky, a compendium of the universe, a mirror of nature which reflects the universe' – supports the view that mechanisms like the Antikythera Mechanism were indeed influential in the development of astronomical thought and philosophy. The passage that follows this in Cassiodorus also shows how a mechanical device could be regarded as giving insight into physical phenomena [our annotation in brackets]:

> Although we know the course of the stars, our eyes cheat us, and we cannot see them moving in this way;

> indeed their transit is static [i.e. things move too slowly for us to see directly their motion]; and you cannot see in motion what you know by true reason is passing swiftly. What it is for man actually to create this device! – even to understand it may be a remarkable achievement. (trans. [1])

7. A continuing mechanical tradition 500–1250 AD

Cassiodorus' description at the end of last section was written at about the same time as the construction of the only other well-established surviving metal-geared artefact from before 1000 AD, parts of a Byzantine sundial [50,51]. The place names in its inscriptions, and the stylistic details of its dials, strongly suggest a Byzantine origin in the late fifth or early sixth century AD. Two shafts (or 'arbours') of the gearing survive, one with a seven-lobed ratchet and two gears of 7 and 10 teeth, the other carrying two gears of 19 and 59 teeth. The gears are made from a low-grade brass, and resemble the gears of the Antikythera Mechanism in that they have triangular teeth and a thickness of about 2 mm (although the ratchet is double this). Field and Wright give a very plausible reconstruction of the original device, guided by a later (996 AD) manuscript source (see below). A total of eight gears and the ratchet would allow a display of the age and phase of the Moon, and the position of the Sun and Moon in the zodiac. The likely gear ratios imply the device would be out by one day in its new moon prediction after about 32 months, and would need re-setting. This is a useful practical and portable device, much simpler than the Antikythera Mechanism but showing that the technology still existed – and we deduce from the contemporary Cassiodorus that this technology was still being used for complicated displays.

Our view of subsequent developments will not fundamentally differ from that of de Solla Price [52], in that we show a clear trail of geared technology to be followed up to the fourteenth century AD, when there is a sudden explosion of complexity and development in the era of the mediaeval cathedral and city clocks. We suggest that a lesson from the Antikythera Mechanism – that literature sources may underestimate the complexity or sophistication of contemporary technology – might be applied to allow that memory, record or devices as complicated as the Antikythera did indeed persist during the intervening period. From the time of Cassiodorus there appears to be a gap in the record of nearly 500 years until the Arabic manuscript description of an eight- geared mechanism by Al Biruni in 996 AD [53]. Hill suggests that the diffusion from Byzantium to the Arabic world occurred in the first part of the ninth century BC. The structure of Al Biruni's described mechanism is so consistent with what is left of the Byzantine geared sundial, and so similar to a surviving Arabic geared astrolabe by Abi Bakr from 1221/2 AD that the basic technology and tradition of this particular kind of device can be clearly seen to persist between 500 AD and 1220 AD. A continuity of technology may also be inferred from accounts of automata in the classical, Byzantine and Arabic worlds.

The Abi Bakr astrolabe with gearing, made in Isfahan, is illustrated in Figure 10 based on details from Field and Wright [50], King [54], personal inspection and the website of its custodial Oxford museum (Museum of the History of Science [55] in the references). The Byzantine and Al Biruni devices showed the position of the Sun and Moon in the zodiac on separate dials, but it is noteworthy here in the Abi Bakr device, they are shown on the *same* dial – and hence reminiscent of the 'topographical' front dial of the Antikythera Mechanism, and seen later in mediaeval clock sun and moon displays. Inscriptions on the astrolabe's casing

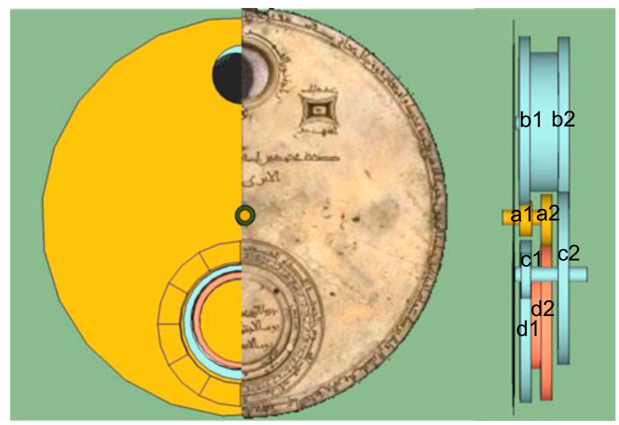

Figure 10. Schematic rear and side view of the Abi Bakr geared astrolabe from Isfahan 1221/2 AD, made in brass with triangular-toothed gears. It is about 185 mm diameter. The front of the device is an astrolabe, but the rear (shown left) is a geared display of the lunar phase (top aperture) by rotation of circles on the back face of gear b1 past a circular aperture – there are two black circles on opposite sides of the axis – and numbers showing through a small aperture give the age of the Moon in the lunar month. The gearing is shown side-on at right, with the depth exaggerated. The motion of the Moon around the zodiac is shown by a black dot (probably originally silvered) on the annular or ring gear (d2, shown pink), and the motion of the Sun by a gold dot on the face of the annular gear wheel d1 (shown light blue). The mechanism would have been operated by turning the central axis. The train to the lunar phase display is a1(8)−b1(64), the train to the lunar position in the zodiac is a2(13)−d2(48), and the train to the solar position is a1(8)−b1(64) + b2(64)−c2(64) + c1(10)−d1(60). N turns of the shaft carrying a1 and a2 a will give $N/4$ lunations, 13 $N/48$ lunar orbits and $N/48$ solar orbits. Thus the sun will go around the zodiac once in 48 turns, while the moon will go around 13 times with 12 lunations. The implied year is a pretty inaccurate 354 days, but the motions are elegantly demonstrated.

A fine animation is available at http://www.mhs.ox.ac.uk/almizan/AstrolabeAnimation.htm

Image of astrolabe by permission and copyright of the Museum of the History of Science, University of Oxford. Image inventory No. 48213.

mention ‘different motions [of the heavenly bodies] with a single mover’ – although the reference here was intended as predominantly theological rather than philosophical.

It seems that more complex designs with planetary displays did persist in the Arab world, as can be inferred by accounts of a gift made in 1232 AD by the Sultan of Egypt to the Holy Roman Emperor Frederik II. It ‘was made to resemble the celestial sphere [similitudinem sphaeraum caelestium] in which moved likenesses of the Sun, Moon and the other planets … set in motion by weights and wheels’. This excerpt [56,57, p. 350 note 1] is from a rather later account by the German abbot and historian Trithemius (1462–1516 AD), but is corroborated (North op. cit.) by other sources. Within another 70 years of the gift to Frederick, three manuscripts from around 1300 AD in northern Italy [56] describe the setting of gear ratios and some constructional details for making an ‘Opus quarundam rotarum mirabilium quibus sciuntur vera loca omnium planetarum …’ – a ‘device of certain remarkable wheels by which the true places of all the planets are known’. North (summarised, discussed and illustrated in King [54] and Lehr [58]) notes the possibility that this design, whose origin may date from some years before the surviving manuscripts, might share ancestry with Frederik’s present. He proposes a reconstruction as a mechanism with over 21 gears, showing the Sun, Moon and planets displayed on discs or annuli carried on concentric-tube axes. Motions were probably only mean period circles, except possibly for the Moon. Here is evidence of complexity almost to match the Antikythera Mechanism, and in the next section we will see the evidence of such complexity being exceeded (with a suggestive Greek connection) only 50 years later.

No attempt is made in this narrative to incorporate the invention and development of astronomical clocks in China from the seventh century AD onwards. Although pioneering, there seems little evidence that it had any major influence in the West. Some transmission of ideas may have come through the Islamic world after 1200 AD, and the interested reader is referred to the excellent book of Needham et al. [59].

8. The development of mechanical astronomical clocks 1250–1400 AD

It was around 1280 AD that the fundamental invention of the escapement was made, although where (northern Italy?) or by whom remains unknown. From antiquity, ‘clepsydra’ or water clocks had used fluid flow to regulate time. A consistent flow was difficult to maintain. The escapement provided time intervals needed for the regulation of a mechanical clock by the method of regular alternate stopping and release of a crown gear by two small vanes on an oscillating shaft (or ‘foliot’). The crown gear’s teeth are of a special shape which allows some of its rotational energy to feed through into keeping the foliot oscillating. It was not until 1656 AD that Huygens introduced the more accurate pendulum regulation. Although mechanical clocks may initially not have been as accurate as carefully-maintained clepsydra, Landes [60] points out two critical advantages that led to their dominance – they did not freeze (important in Northern European climates) and their technology could be miniaturised, eventually allowing portability while maintaining timekeeping. Mills [61] usefully outlines the basic physics of the limitations of clepsydra. The foliot escapement led to a century of clock building and innovation, well established by 1300 AD, and the timepieces were sometimes enhanced by coupled astronomical displays. Richard, Abbott of Wallingford left some extensive (but incomplete) details with gear ratios and diagrams (‘Tractatus Horologii Astronomici’ [62]) of a clock he was still constructing at the time of his death in 1336. It would certainly have shown Sun, Moon and eclipses, and was possibly intended to show the other planets. Reconstructions have been attempted by North (op. cit.) and by Lehr [58], his fig 236).

This was the era of the great cathedral and city clocks, often showing mean solar and lunar motions. Examples of construction dates are Norwich Cathedral Priory c 1322–1325, Strasbourg 1352–1354, Salisbury Cathedral c 1385 and Prague 1410.

The extent of new invention becomes apparent with the construction of a complicated ‘Planetarium’ or ‘Astrarium’ astronomical display clock by Giovanni di Dondi in Padua, northern Italy, completed in 1364. His father, Jacopo di Dondi, had already made an astronomical town clock for Padua in 1344. Giovanni left a detailed and fairly comprehensive account of his own construction which is preserved in several manuscripts (the name Planetarium or Astrarium varies between them), the earliest believed to date to 1389. A useful English translation with original diagrams was prepared by Baillie et al. [63] – rather harshly reviewed by Turner [64], and a French translation and facsimile published by Poulle [65]. The history of the device is covered by Bedini and Maddison [66], and its function discussed in King [54], chapter 3) and Lehr [58, figs. 238–264]. Several physical reconstructions have been made – e.g. see Figure 11. The Astrarium contained 107 gear wheels, was weight-driven and regulated by an escapement. Individual dials showed the diurnal motion of the stars and the annual motion of the Sun, and the positions of the Moon and each of the five planets in the Zodiac, with arrangements of gears with slotted arms and pins to allow retrograde motion. There was a dial showing the position of the Moon’s ascending node, allowing prediction of eclipse possibilities. This form of prediction is obviously mechanically different from the pointing to pre-calculated

Figure 11. A modern reconstruction of the astrarium clock of Giovanni de Dondi completed in 1364 AD. This is the first known device that is more complicated than the Antikythera Mechanism. The seven faces on the upper part show the daily motion of the stars and annual motion of the Sun, and individually the motions in the zodiac of the Moon and five planets. At about 1 m high it was not nearly as conveniently portable as the Antikythera device.

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information on the Saros dial that is employed in the Antikythera Mechanism. It comes from the fact that the Moon's orbit about the Earth and the Earth's orbit about the Sun (the ecliptic) are not coplanar, so an eclipse can only occur when the moon and Sun are at or very near one of the two crossing points or 'nodes'. The positions of the nodes precess around the ecliptic, so prediction must be based on calculating the positions of nodes, Sun and Moon. Richard of Wallingford's clock was also based on this method. The Astrarium does use the 19 years of the Metonic cycle in a mechanical perpetual calendar of Christian moveable feasts that had 19-link chains. Although some gear wheels still show triangular teeth, there are other gears with blunt-nosed teeth, and to reproduce irregularities some are intentionally oval in shape or with varying tooth spacing. The Astrarium is chronologically the first known device that is definitely more complicated than the Antikythera Mechanism. De Dondi does not make explicit reference to sphaerae in his account, but does give credit to the Greeks for their astronomical achievements, and his clock was referred to as 'a sphere … for celestial movements' in 1385 [66]. It is known that both he and his friend, the scholar and poet Petrarch, were familiar with the works of Archimedes and Cicero [67]. Even more suggestive of a direct link is a letter of 1388 to de Dondi from his friend Giovanni Manzini of Pavia (quoted in [66], and referring to Reference 3A in our Table 1) –

> I saw your … clock … Cicero tells how Posidonius has constructed a sphere which revolved showing, through the Sun, Moon and five planets what happens in the heavens … I do not believe there was such competency in art at that time, nor was there such a mastery of skill as is shown in this.

We suggest that Manzini is not claiming that the Greeks couldn't do it, but simply that de Dondi is doing it better and that de Dondi would already have been familiar with the Cicero reference – indeed that he took his inspiration from the Greek sphaerae tradition.

9. The influence of mechanism 1400–1720

The mechanical inspiration continued, in that there is good evidence that the major figures of the Copernican Revolution would have been familiar with astronomical clocks and mechanical devices, and their classical roots. Johannes Muller von Königsberg, known as Regiomontanus and 'arguably the best mathematical astronomer of fifteenth century Europe' [68] was an influence on Copernicus and a key critic of the shortcomings of the Ptolemaic system. Regiomontanus suggested that 'to restore the heavens … [we must] remove the rust from the heavenly spheres' (Swerdlow [69]). In 1463 he saw, and was very impressed by, De Dondi's Astrarium [70]. Bedini and Maddison [66] and Zinner claim that clock still survived (although no longer working) in 1529, and was on display in Pavia in north Italy (where Regiomontanus had seen it) until at least 1495. Copernicus was in Bologna in 1496–1500 and Padua 1501–1503, and even if he did not see de Dondi's clock himself, he must surely have heard reports of it. A copy of de Dondi's account of the clock was sent to Cracow ca. 1494 [66].

Although de Dondi's clock is lost, there are others with strong similarities from 150 to 200 years later which do survive. The oldest is that in the Bibliothèque Sainte-Geneviève in Paris, said to have been restored by Oronce Fine in 1553 for the Cardinal of Lorraine, but of which parts – particularly the planetary display dials – probably date back as far as the beginning of that century or the last years of the fifteenth century [71,72]. It has dials, with slotted arms and wheels to allow retrograde motion where appropriate, showing individually the position in the zodiac of the five planets, Sun, Moon and nodes. The slightly later 1554–60 Tübigen clock by Philippus Immser [54, p. 71] has a 'topographical' dial analogous to the front of the Antikythera Mechanism, combining the display of the position of the planets, Sun, Moon and nodes by pointers on one dial. These devices are of course geocentric.

Copernicus' heliocentric de Revolutionibus was published in 1543, although a 'preprint' version of the ideas – the Commentariolus [73] – had been written ca. 1507 and circulated around Europe. The continuing but evolving use of mechanical analogy on the way to mathematical models may be seen in Tycho Brahe's (1546–1601) remark (Rosen op. cit., footnote to page 12):

> But really there are no solid spheres in the heavens … those which have been devised exist only in the imagination*, for the purpose of permitting the mind to conceive the motion which the heavenly bodies trace in their course* and, by the aid of geometry to determine the motion numerically through the use of arithmetic. [our italics]

We would interpret this as mechanical models acting as an essential conceptual prop, irrespective of their fidelity to the 'actual' physical structure – but it might alternatively be argued that Brahe is trying to reject any interpretation other than a mathematical one. The direct influence of mechanism on Brahe's successor Kepler is easier to establish. There is his well-known comment in a letter from 1605 'My aim is to show that the heavenly machine is not a kind of divine, live being, but a kind of clockwork … in so far as all the manifold motions are … taken care of by one single force' [74, p. 136], and a little earlier in 1598 [54, p. 92, 75] he had informed the astronomer Michael Mästlin that he proposed to construct a heliocentric planetarium-type device with the paths of the planets traced out by arms supported on a 'set of coaxial tubes rotated by wheelwork [i.e. gears] at the lower ends' and he gives calculated values for the gear ratios. It would have incorporated some kind of representation of the elliptic nature of the orbits. He is believed to have given up the project in 1599. The Greek connection is clearly evident from another letter to Mästlin in the same year (Letter 99 in Caspar [76]) in which Kepler discusses Archimedes' and Posidonius' sphaerea using references 2, 3A and 14 of our Table 1.

We shall only briefly sketch the further development of mechanical models, for details see King [54]. By 1600 in Amsterdam W.J. Blaeu was producing a simple geared 'tellurion' or 'tellurian' to show the motion of the Earth around the Sun and the Moon around the Earth. The first views through a telescope of the changing positions of the satellites of Jupiter in 1609, hastily published by Galileo [77], must have suggested a 'solar system in miniature', and a geared 'Jovilabe' or 'Jovilabium' was designed by in 1672 by Ole Rømer (who is best known for the first determination of the speed of light from observations of Jupiter's moons). The device reproduced Galileo's view by incorporation in a box with a suitable viewing aperture. Rømer had designed a full heliocentric planetarium by 1680, and Huyghens built an extant planetarium with offset circular orbits in 1682, whose design he later published in 1703 in 'Descriptio Automati Planetarii'.

It was of course Newton's Principia of 1687 with a 'field' theory of gravity which provided a mathematically rigorous and causal explanation for the elliptical orbits of the planets. The Principia was not easy for non-specialists to understand – indeed, some claimed that Newton had intentionally made it abstruse to avoid being taxed by 'little smatterers' in mathematics. However, more popular accounts spread its influence rapidly, and by the first years of the eighteenth century it had created a demand for exposition on which flourished geared models, both of the Sun-Earth-Moon system and of the whole known Solar System. Prominent were the devices by clockmakers George Graham and Thomas Tompion c 1704–1709 which led Charles Boyle, 4th Earl of Orrery (in Ireland) to commission one from John Rowley around 1712, with 'Orrery' subsequently sticking as the name for such devices. Their power for 'outreach' activity was beautifully captured in the ca. 1766 painting 'A Philosopher Lecturing on the Orrery (1764–1766)' (image widely available on the WEB) by Joseph Wright of Derby. Indeed, Westman [78] suggests that 'the orrery … contributed importantly to the naturalisation of the Copernican system in the eighteenth century' – showing the continuing value of mechanical visualisation in astronomical thought.

10. Conclusions

It is hoped that the recent resurgence of interest in the Antikythera Mechanism will result in more artefacts of gearing being discovered or recognised in collections, both public and private. We have two surviving forms of 'sphaerea' in the Antikythera mechanism and the lunar/solar displays of geared astrolabes and sundials. It seems likely that there would have been both intermediate and even more advanced forms, but speculation without more evidence is likely to be rather fruitless.

One perhaps surprising aspect is that, apart from the late (fifth century AD) and rather garbled reference by the poet Nonnus (Table 1 reference 17), there is no evidence of use of sphaerea for astrological, rather than astronomical, purposes. Throughout the AMRP investigations, a watch was kept for astrological function (e.g. a mechanisation of the 'lot of fortune') or inscription, but none has so far been found. This does not mean that the machine could not have been used for astrology, but probably implies that it was not its prime purpose.

For the Antikythera Mechanism itself the major unknowns are whether it incorporated variability of the solar motion, and the exact form of the planetary display. The function of the 63-tooth gear (r1) remains unknown. There is some uncertainly about the detailed scheme of eclipse time prediction used to produce the Saros dial. It is worrying that the small crown gear (q1) in the lunar phase display is apparently the wrong way round in its mounting, assuming a simple reconstruction. This might indicate either a more complicated device, or evidence of incompetent ancient repair.

Where was the Mechanism made? Possibilities include Alexandria, Pergamon and Syracuse. The latter had the advantage of any heritage left by Archimedes, but the problem that it was sacked in at the time of his death in 212 BC, although something may have remained. The best candidate must be Rhodes, a port at which the Antikythera ship had called (judged by some of its cargo) not long before its wreck. Rhodes was a highly technological naval centre around 100 BC with a fine bronze industry and an astronomical tradition. It is also one place where we know that a similar contemporary device was reputedly made and seen. What form of workshop or workshops produced sphaerea is an open question, with its eternal conundrum – within some concepts of Greek society – of requiring close co-operation of astronomical and mathematical knowledge with technological expertise and craft, skills that perhaps had to be combined in a single individual. What is certain is that the tradition of 'sphere making' lasted for a very long time, and could have flourished in different places at different times.

We will end with a summary of the philosophical implications. Sphaerea were mechanical representations of the Universe that were causal, deterministic and regular, driven by a single 'prime mover' and also in some cases showing 'regular irregularity'. Irrespective of the extent to which they were regarded as a true representation of comic structure, their demonstration of the possibility of mechanical explanations for heavenly motions must have been a major driver of philosophical and cosmological argument. Even as a spur for the conscious rejection of mechanical explanations they were influential. The realisation of the complexity and sophistication of the mechanical design of the Antikythera Mechanism, and the evidence that the knowledge of such mechanisms were reasonably widespread, forces us to acknowledge the influence of mechanical models in stimulating ideas of a mechanical universe not only for the Renaissance, but as far back as Plato. Design elements within the Mechanism may even hint at symbolic traditions carried through from the Bronze Age.

The use of mechanical models or analogies continues to this day – a good example is the damped harmonic oscillator, used as a conceptual model for a wide range of applications from tides to spectral line shapes. But physics may have grown away from physical models, and it could be that the lack of good mechanical analogies for much of quantum mechanics contributes to the apparent difficulty of comprehension – indeed in a 'Copenhagen' interpretation such models would be impossible. Maxwell made considerable use of rather complex mechanical models in developing a dynamic field theory of electromagnetism c 1865 – a recent illustration can be found in Morrison [79, p. 31]. A quote from Freeman Dyson [80] seems relevant:

> The scientists of that time, including Maxwell himself, tried to picture fields as mechanical structures composed of a multitude of little wheels and vortices extending throughout space … If you try to visualise the Maxwell theory with such mechanical models, it looks like a throwback to Ptolemaic astronomy with planets riding on circles and epicycles in the sky. It does not look like the elegant astronomy of Newton … Maxwell's theory becomes simple and intelligible only when you give up thinking in terms of mechanical models. Instead of thinking of mechanical objects as primary … you must think of the electromagnetic fields as primary …

Perhaps 'throwback' is the wrong word here. The Antikythera Mechanism and other spearae of the classical world, with their later legacy, serve as a reminder that mechanisms and machines have not only been important in the development of technology but also a critical aid in the development of our comprehension and visualisation of the Universe and its physical behaviour over the last 2500 years.

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Appendix 1. Gear evolution

Ratchet gears with characteristic asymmetric teeth are known from antiquity, used for example in catapults and in the geared Byzantine sundial described in Section 7 above. But for meshing metal disc gears there is no evidence before 1300 AD of anything other than triangular teeth, perhaps slightly rounded at the tip. Interpretation of copied manuscript diagrams is dangerous, since subsequent scribes may well have been influenced either by their knowledge of later machinery or their incomprehension of what they were copying, and so far as is known no original drawings of gearing have survived from the classical world. Early in the fourteenth century, Richard of Wallingford's designs still have gears with triangular teeth, but evolution to rather more sophisticated tooth shapes, and innovation in structure, is evident in a French geared astrolabe from around 1300 AD, considered in the Appendix to North [56] and in Lehr [58, his figs. 143 and 144]. The original probably contained 6–8 gears. Its functions of Sun and Moon position and age of moon (i.e. phase) are essentially the same as for the geared Arabic devices mentioned above, but the gear train and method of display are rather different. Indeed, it seems possible to distinguish a move to more efficient, smoother driving gears from around this date – certainly visible in some of di Dondi's gear designs – and probably catalysed by the demand for mechanical clocks. The invention of gear tooth forms which theoretically transmitted angular velocity perfectly smoothly came with cycloidal gears (associated with the names of Desargues, Rømer, and Hire c. 1644–1694 AD: [54, p. 108]) and in a more convenient, stronger form with involute gears (Euler, c 1755–1765 AD).

It is possible to make a rough comparison of the accuracy of the Antikythera gears. Suppose a gear is cut such that a linear tangential error of δ is made in placing a tooth on a gear of radius D. The angular error is then δ/D, and we may define a fractional error in the placing of the tooth by $\varepsilon = (\delta/D)/\theta$ where θ is the pitch angle of the gear, given by $2\pi/N$ where N is the number teeth. Re-arranging gives $\delta = 2\pi D\varepsilon/N$. If a given maker maintained a constant quality we might expect δ to be a constant for his gears. So we take $D\varepsilon/N$ as a measure of laying-out and manufacturing accuracy, with lower values indicating better quality. Values ε for the Antikythera gears (c150-60 BC) were estimated by angular measurement of images and model fitting of the teeth [35], and similar estimates have been made for gears from the Byzantine Sundial (c520 AD) and the Abi Bakr geared astrolabe (1221/1222 AD) described in Section 7. Estimates were also made for a gear from a Harrison Clock (the Royal Astronomical Society Regulator, 1776 AD), a modern twentieth century gear from laboratory equipment, and images of the 'Olbia' gear – a fragment found in Sardinia that has been suggested [81] to have originated in 'Archimedes' Planetarium'. Typical values of $D\varepsilon/N$ are: Antikythera 0.011–0.022, Byzantine 0.024, Abi Bakr 0.022, Harrison 0.007, Modern 0.006, Olbia 0.009. The Antikythera gears are comparable to – but a bit better than – the Medieval ones, but clearly not (as would be expected) as good as the eighteenth and twentieth century ones. The intermediate value of the Olbia gear, together with its non-triangular tooth shape, might argue that it is from a post-medieval clock.

Appendix 2. Mechanical calculation

Although it seems likely that the Antikythera Mechanism was built as a display device, it does have the function of analogue multiplication and division. This inevitably prompts the question of whether a full mechanical calculator might have been developed in classical times. There was an undoubted need for extensive calculation – for example, the Romans had huge administrative taxation and land survey requirements (Cuomo [82]). The abacus and slave labour may have been sufficient resource, and there is as yet no evidence that mechanical calculators were developed. The likely cumulative error implied by the accuracy of the Antikythera Mechanism technology [35] was probably too great for acceptable financial calculation. But its improvement by introducing a discrete 'click over' would not have been a huge one, and indeed a distance-measuring hodometer designed (but not necessarily actually built, [83]) by Vitruvius (85–20 BC) shows the idea of discrete counting in allowing pebbles to fall through holes in rotating wheels. That some mechanical geometric aids were developed is witnessed by the Byzantine architect Isidorus' of Miletus invention of an instrument to draw parabolas [84, p. 139]. The first record of geared mechanical calculation seems to be much later, in correspondence between Wilhelm Schickard and Kepler in 1632. Practical devices were developed by Pascal (the *Pascaline* 1642) and Samuel Moorland (the *Cyclologica* 1666), but it was not until the nineteenth century that mechanical calculators became widespread.