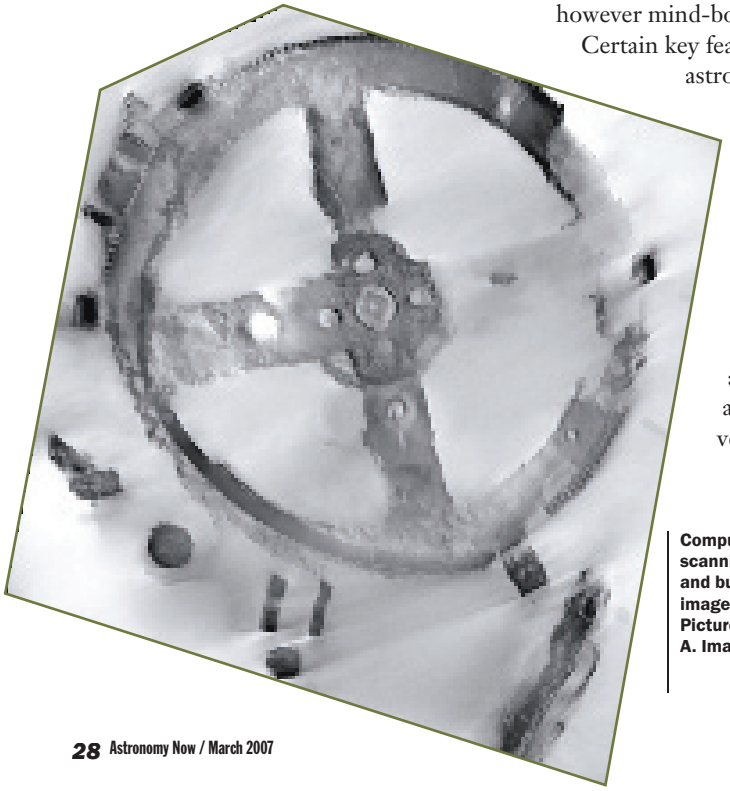
Decoding the Antikythera mechanism

In 1900, a Greek diver named Elias Stadiatos discovered fragments of an unusual mechanical device in an ancient Greek shipwreck near the island of Antikythera. Known ever since as the Antikythera mechanism, it has revolutionised our thinking of the sophistication of the ancient Greek astronomers. **Nick Kollerstrom** investigates the latest findings.

A recent Athens conference has re-evaluated and – dare one say it – probably fathomed the Antikythera mechanism. The re-inspection has turned out to be extraordinarily productive and an inspiring example of how the study of the history of astronomy ought to function. An article in *Nature* last November, timed to coincide with the conference, generated a worldwide storm of interest. Everything happened so quickly, starting in September 2005 when eight tonnes of X-ray apparatus clunked into the National Archaeological Museum at Athens. Nervous officials had twice refused permission for its use – after all, might it not damage the fragile, priceless ruins of their mechanism, which had lain dormant beneath the Mediterranean ocean for two millennia?

Historians have puzzled over its function ever since it was recovered off the seabed between Crete and Greece at the turn of the twentieth century. Quite a lot of text has now been read off from its casing - all astronomy, with no theology, astrology or poetry. It has two thousand years of accretions around it and has now come apart into 82 separate fragments. It is the remains of a sophisticated solar–lunar calculating engine from the second century BC, however mind-boggling that may be.

Certain key features link it to the astronomical school of Hipparchus on the island of Rhodes.

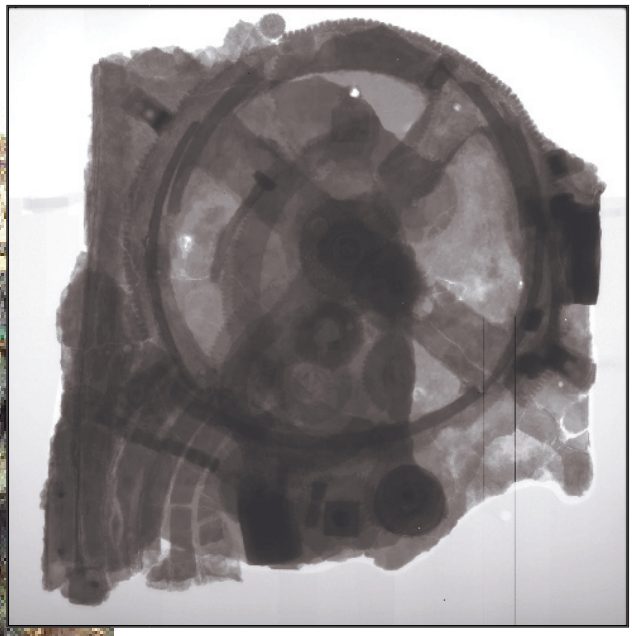


Computed Tomography works by scanning an object from all angles and building up a three-dimensional image from the individual slices. Pictured here is a 'slice' of fragment A. Image:

Historical artefact

It was a time when Roman ships were pillaging their empire for Greek artworks. Captured in a Roman merchant-vessel, the Antikythera mechanism was bound for Rome when it sunk, in a ship laden with Greek treasure, with bronze sculptures including the Youth of Antikythera (now in the National Archaeological Museum in Athens), heavy marble sculptures (which could well have sunk the boat), Rhodian amphorae full of oil, elegant glassware, pottery, jewellery and coins, the latter dated to 86 BC.

Carbon-14 dating (using the amount of radioactive decay of carbon-14 atoms to date objects) isn't applicable owing to the condition of the wooden framework in which the brass mechanism was enclosed. Instead the team used the skills of an epigraphy expert, who has given a dating based upon the style of the Greek lettering. This pushed it back somewhat earlier than previous estimates, to 150–100 BC. Other looted materials of the sunken ship had come from Rhodes, where Hipparchus, reputedly the supreme astronomer of ancient Greece, lived from about 140 BC to 120 BC. Poseidonius set up a school there,



Far left: Fragment A, the main remnant of the Antikythera mechanism. It is kept in the National Archaeological Museum in Athens. Image:

Left: An X-ray radiograph image of the front of the mechanism, clearly showing the cogs, dials and gears that make up this extraordinary example of ancient Greek engineering. Image:

continuing that tradition: Cicero studied on Rhodes and wrote that Poseidonius had built an instrument "which at each revolution reproduces the same motions of the Sun, Moon and the five planets that take place in the heavens, each day and night," supporting the idea of a mechanical-astronomical tradition there.

The team of British and Greek experts, led by Prof. Mike Edmunds and Dr Tony Freeth of Cardiff University, have plausibly figured out the sequencing of 37 gear-wheels of this mechanism, after applying state-of-the-art Computed Tomography and X-ray technology supplied by the X-Tek Group in Hertfordshire, plus surface imaging by Hewlett–Packard. There are 27 hand-cut bronze gears embedded in fragment A, plus two other separate gears in different fragments, all of which concern solar–lunar cycles. A thirtieth gear (with 63 teeth) is of unknown function but it may have driven a planetary wheel. The 17 authors of the letter to *Nature* have postulated seven extra, hypothetical gears to complete this wondrous device. A commentary on their work in the same issue remarked that their new model is "seductive and convincing in all of its details." The whole apparatus appears as exquisitely focused on the two 18–19 year solar–lunar periods, Saros and Metonic, both displayed on the 'back dial' of the mechanism. In both cases, the higher-precision multiples of these cycles, the Callippic and the 54-year 33-day Exeligmos cycles, are marked out with separate dials.

Metonic and Saros cycles

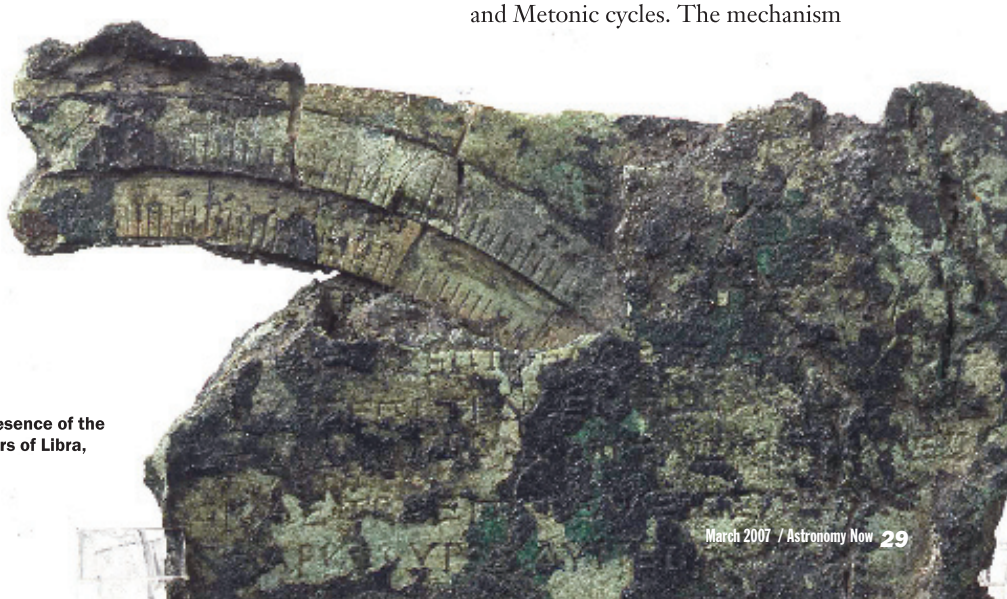
Ancient Greeks knew of the Metonic cycle, which embeds the sequence of lunar months into a solar calendar through a 19-year period. For precise working of a calendar one takes four such periods i.e. 76 years less one day, to give the 'Callippic' cycle. At the top-back of the mechanism, a dial spirals through five revolutions of 47 months to make up the 235 lunar months of the Metonic cycle, plus a small dial marks out the longer Callippic cycle. In December 2005, the 3-D X-rays of fragment 'F' revealed the words '235 divisions of the spiral' in Greek.

The team's first major breakthrough came in November 2005 when they realised that the big wheel on the lower back of the mechanism was indeed the 18 year, 11 1/3 day Saros cycle (an eclipse cycle used to predict lunar and solar eclipses), and not a monthly lunar cycle as earlier investigators had supposed. Was it not the first astronomical computer? It was clearly an eclipse predictor.

Nothing resembling an ancient Greek (or Babylonian) text describes both these cycles and evidence that ancient Greeks used the Saros cycle for eclipse prediction is rather scant. It would be hard to name any astronomer prior to, say, Edmond Halley, who could have explained these cycles in relation to eclipses.

The still-mysterious sequence of Saros eclipses both solar and lunar loom into view, wrapped around this four-level dial. The eclipses recorded have times on them and are fitted into the lunar months of the Saros-spiral, 1–223. So far, the team have found symbols representing five lunar eclipses, five solar and six both solar and lunar (i.e. both falling within one lunar month.) Curiously four of the lunar eclipses are given as falling in the daytime, perhaps indicating that they were not visible from the Mediterranean. As yet, the team has not found a specific Saros-chain that best fits these eclipses.

The gears involve key prime numbers: 19 (doubled to 38) and 47, both Metonic, 127 (the sidereal lunar month divides into the Metonic cycle exactly 254 times, i.e. twice 127), 223 (the Saros) and 53, a gear-count which appears thrice. The last of these is used to derive the nine-year apse rotation from the Saros and Metonic cycles. The mechanism



A fragment of the zodiac wheel on the front dial. The presence of the 'chelae' (claws) of the Scorpion, today known as the stars of Libra, help date this artefact to before the year 46 BC. Image:

thus has lunar periods expressed in the numbering of its gearwheels.

The juxtaposing of these two periods, Callippic/Metonic and Exeligmos/Saros, on the back dial gives an indication of some astronomical school rather more advanced than any recorded in the pages of history. Hipparchus (according to Pliny) showed that lunar eclipses can occur five months apart and solar eclipses seven months, and that the Sun can be hidden twice in thirty days, i.e. can be twice eclipsed. This is quite a way short of what is shown by the mechanism.

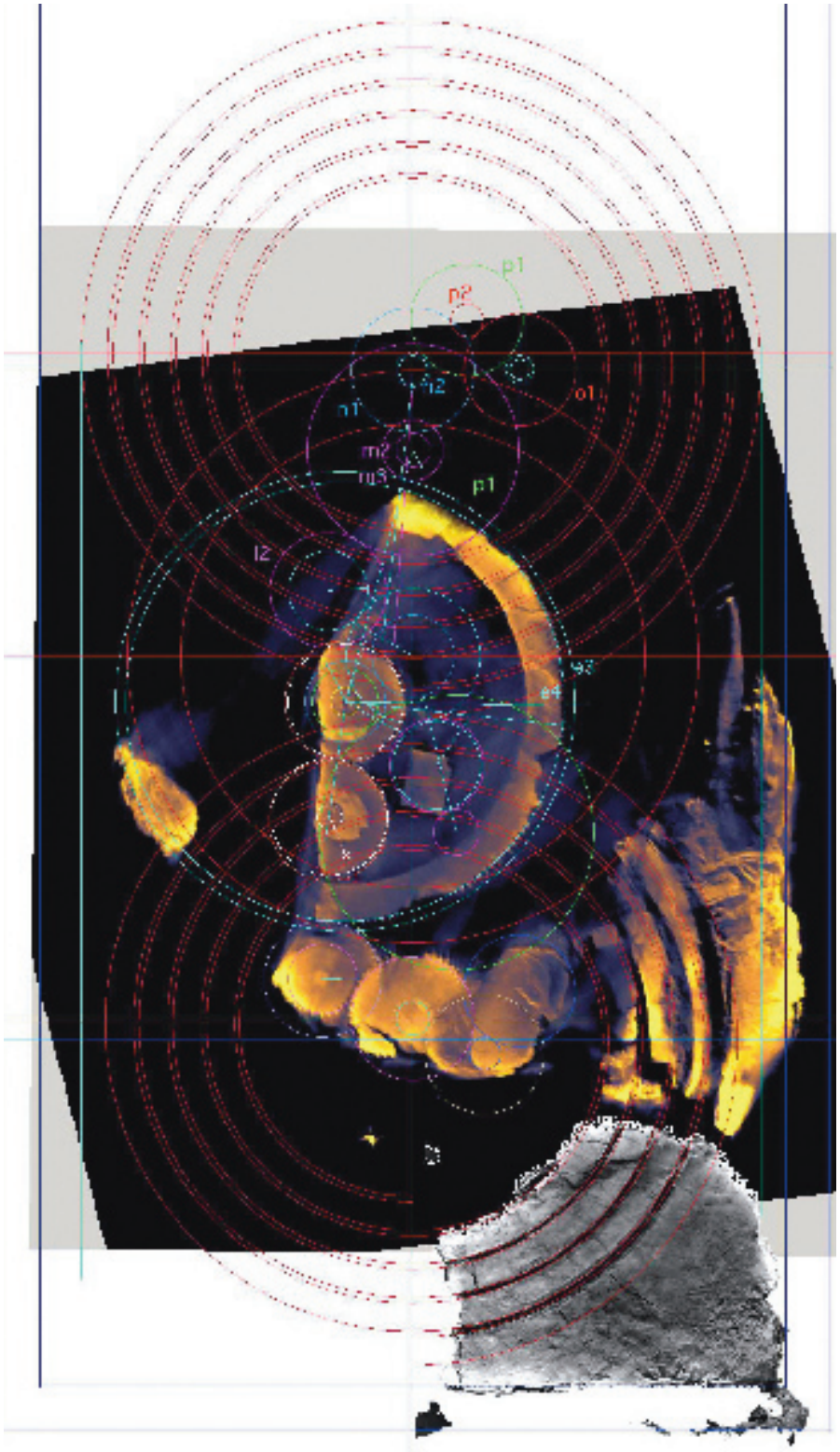
Zodiac dial

The front dial has a zodiac around which a solar pointer revolved yearly and the one clear inscription of a zodiac sign name is 'chelae', meaning 'claws'. What we now call Libra the zodiacal Scales between the Virgin and the Scorpion were, in ancient times, the claws of the huge, powerful Scorpion that lay in wait for the Sun at the autumn equinox. These stars were 'Chelae' to the Greeks and Romans until the time of Julius Caesar's calendar reform in 46 BC. This antique use of the term 'chelae' firmly anchors the mechanism in those centuries.

On 'fragment C' one can faintly read 'ΧΗΛΑΙ' for Chelai, and to the left two of the last letters N and N of the 'Parthenon' – the sign Virgo, reminding us that the goddess of the Parthenon's Acropolis was 'the Virgin,' Athena. Then to the right, I was shown, using the X-ray viewing method that goes below the surface, all the letters of 'ΣΚΟΡΠΙΟΣ', the sign Scorpio (Note: this is a new discovery, not hitherto reported in the literature on this mechanism). Thus its zodiac revolved clockwise. The letter 'alpha' can be read next to the zero degrees Libra (autumn equinox) position, suggesting that this zodiac was tropical, in accord with the Hipparchan innovation of starting at zero degrees Aries for the spring equinox.

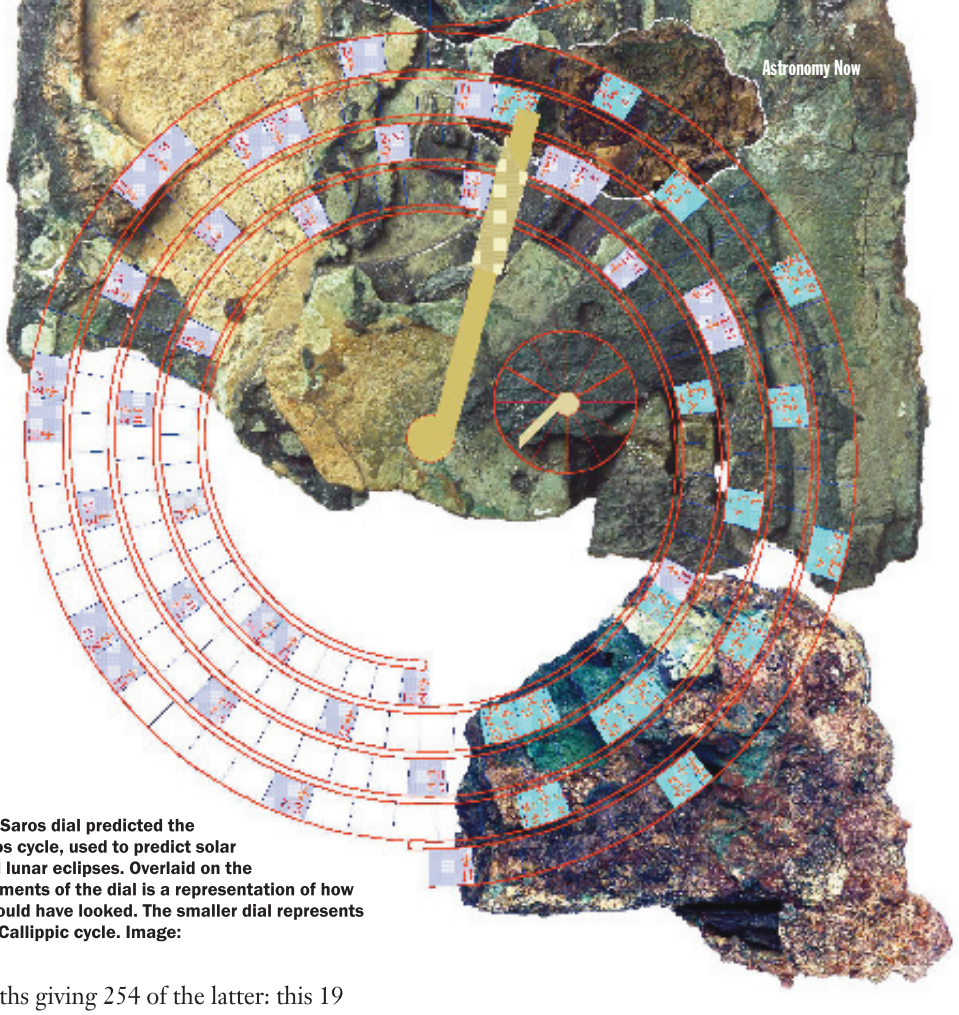
The X-ray scan of this zodiac fragment showed a ring of 365 holes, under the calendar ring. This image is some three millimetres below the previous surface X-ray image. It is assumed that these holes were for a locating pin in the moveable calendar scale, which enabled the leap-year adjustments every four years. There are also 'parapegma' on the front dial, i.e. star-rising dates, which may have given calendar dates corresponding to the zodiacal degrees.

Some of the imaging of the mechanism was done using computed tomography (CT) scanning, courtesy of X-Tek, to generate three-dimensional images so the team of scientists could fathom the meaning of the dials and gears. Representations of the dials have been overlaid onto the image, with individual gears labelled. You can see where the gears all fit in on the master gear diagram on the opposite page. Image:



Three lunar months

The lunar dial, mounted on the front, revolves with what the writing on the back door calls its 'silver sphere' around the zodiac. The team came to apprehend, in May 2006, the 'Hipparchan' lunar theory used here: the pointer revolves once per sidereal month of 27.3 days and on top of that it oscillates ±6.5 degrees per anomalistic month (the 27.554 days between the Moon successively passing through perigee, the point in its orbit when it is nearest Earth) due to an ingenious pin-and-slot device, the latter having been discovered quite recently by Michael Wright. Two gearwheels mounted eccentrically have the same period (k1, k2; see the master gear diagram, right), and the rather awesome result is an interaction between the



The Saros dial predicted the Saros cycle, used to predict solar and lunar eclipses. Overlaid on the fragments of the dial is a representation of how it would have looked. The smaller dial represents the Callippic cycle. Image:

27.3 day sidereal axial drive and the anomalistic 27.5 day drives that generate, by differential motion, the nine-year apse rotation period. That eccentric oscillation was transmitted onto a drive that caused the lunar pointer to rock back and forth by the apogee–perigee cycle, as its angular speed peaked at perigee each month. One axle ('e'on the master diagram below) carries three different rotations! The fundamental sidereal period on its innermost rod, then the nine-year apse rotation on its second layer, then lastly the combined motions transmitted through to the front dial. One could imagine the watchmaker John Harrison executing such a subtle, economical design, in the mid-eighteenth century.

The lunar 'silver sphere' was half silver and half dark and it revolved by a differential drive once per synodic month to show the lunar phase. This lunar phase period was ingeniously derived as the differential between the two pointers for the solar year and sidereal lunar month.

Use of sidereal rather than synodic periods is a mark of advancement in astronomy, because the synodic period (e.g. Moon phase) is directly experienced, whereas the orbit-period (i.e. sidereal) is a more theoretical concept. The primary-drive input into this mechanism gave the solar year. The old chestnut, as to how the lunar–sidereal period may be derived from that, is here resolved to high precision via the Metonic cycle. Every year sees precisely one more sidereal month than there are synodic months, i.e. just over 13 of one and 12 of the other; so that there are 235 lunar months every 19 years, plus an extra 19 sidereal months giving 254 of the latter: this 19 to 254 ratio is embodied in the gearing, to give a solar/lunar speed ratio of the front dial hands exact to 99.998 percent!

Did the solar pointer also have a variable rate, moving it faster in winter than in summer? If so, the remains of bearings on the main drive wheel b1 may be all that is left of it. On the front door of the mechanism, a kind of casing, is a partially read description of the synodic cycle of Venus in its appearances and disappearances. That is the one planet whose motion seems to be described, but so far no mechanism associated with it has been found. The astronomy of this mechanism is geocentric, and solar–lunar, resolving their motions by elegant, whole number ratios. Pliny wrote that 'Hipparchus foretold the course of both the Sun and the Moon for hundreds of years (*Nat. Hist.* **ii**, 12). The Antikythera mechanism would have helped him accomplish that.

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This is the master gear diagram, showing the complexity of the front and back dials of the mechanism and how all the gears interlock to create the most sophisticated device from the ancient world ever found. Image: