An Extraordinary Journey

I would like to thank our hosts very much for inviting me here and for including the Antikythera Mechanism as part of the 7th Platsis Symposium. I am a passionate advocate for this unique part of the Greek legacy—the most important surviving technological artefact from ancient times. It is an object that challenges all our preconceptions about the capabilities and technologies of the ancient Greeks.

It has been a 100-year journey of discovery to get from the crumbling remains of the object that was pulled out of the sea by the Greek sponge divers in 1901 to the complex and richly detailed model that we have today. The last few years in particular have been exciting times for Antikythera research and I would like to give you some insight into the research that we have been undertaking.

The Mechanism in History

First, I would like to take you back 2,000 years to an era of astronomy before the telescope to see where the Mechanism fits into a historical perspective. Our best estimate of the date of the Antikythera wreck is in the range 80 – 60 BC, judging by the archaeology of the wreck. We believe that the date of the Mechanism itself is between 150 – 100 BC—we have no definite date, but we are fairly sure that it was made around the era when the Greek empire was ending and Rome was becoming the dominant force in the Mediterranean. In terms of astronomy it fits into a period after the great Archimedes, probably towards the end of the life of Hipparchos, one of the greatest of Greek astronomers. Other names that have been associated with the Mechanism are Posidonios and Geminos, but in truth we do not know who made it or where it was made—though some intriguing clues have emerged from our most recent research, as I will tell you.

Nature papers

What I want to concentrate on is the recent research. This was the result of an extraordinary international collaboration, which resulted in two papers in the prestigious science journal Nature. The first, published in 2006, announced a revolutionary new understanding of how it worked and what it did as well as a major step forward in reading the inscriptions that cover its surfaces. It was received with a
The Antikythera Mechanism: Decoding an Ancient Greek Mystery
Tony Freeth, Antikythera Mechanism Research Project     University of Michigan, Ann Arbor, 2008

storm of international publicity. The second paper in Nature, published earlier this year, found a surprising cultural origin and changed our view about how the Mechanism predicted eclipses. Again this publication received great publicity. It has been a fascinating process of discovery. I want to give you some insight into what our work has involved.

Research Context

Price & Karakalos

The starting point for all modern research on the Antikythera Mechanism is Derek de Solla Price, a British physicist, who became a very distinguished historian of science and a professor at Yale University in the USA. In the early 1950s, he became interested in the Antikythera Mechanism and his interest developed into a passion. He carried out an extraordinary 20-year odyssey of research, culminating in a truly great paper, Gears from the Greeks, which was published in 1974. This paper gives a clear picture of the Mechanism’s historical significance and it defined the understanding of how it worked for a generation.

The Mechanism itself is now split into many fragments. Building on earlier research, Price assembled the main fragments into a coherent structure and he described the basic architecture of the Mechanism. It is about the size of a large dictionary. It has a front dial with two scales: a Zodiac scale with the signs of the Zodiac in Greek and a Calendar scale that shows the Greek names of a 365-day Egyptian calendar. On the back are two dial systems, with the main dials consisting of what appear to be concentric rings and small subsidiary dials inside them.

Crucially, Price teamed up with a leading Greek radiologist, Charalampos Karakalos, to do the first X-ray study of the Mechanism. Inside the main fragment, Fragment A, they made the astonishing discovery of 27 precision gearwheels and they found three more gears in other fragments. However, Karakalos’ X-rays were two-dimensional and all the gears overlapped in a very confusing puzzle. Karakalos and his wife Emily counted the teeth of the fragmentary gears and estimated their tooth counts.

Price’s Model from Gears from the Greeks

One of Price’s greatest insights was that the Antikythera Mechanism is an astronomical calculating machine—the first known mechanical calculator in history. The ancient astronomers had discovered that there are repeating cycles of the Sun and Moon and the genius of the ancient Greeks was to realize that these could be incorporated into a geared machine. In order to understand what the Mechanism calculated, the tooth counts were critical. Karakalos counted one gear, which we call d2, as having 128 teeth—not an interesting number astronomically since it is simply a power of 2. But Price suggested that the gear has 127 teeth, which is a much more interesting number. Our modern X-rays show sufficient teeth to be sure that it does have 127 teeth. The reason for its significance is that it relates to a cycle of the Moon, called the Metonic Cycle, after the 5th Century BC Athenian astronomer, Meton of Athens.

Underlying Principle of the Mechanism

First let me discuss how this gear fits into the Mechanism. If we look at Price’s model of the Mechanism, on the right-hand side is a hand-turned input. On the front Zodiac Dial is a pointer that shows the position of the Moon in the Zodiac. The input is geared to the large wheel with four spokes at the front of the Mechanism. This large gear turns once a year. Rigidly attached to this gear is another gear (which you can't
see without X-rays) that has 64 teeth. This engages with another gear, called \(c_1\), that has 38 teeth. The result is that \(c\) turns at a rate of \(-64/38\) rotations per year. This is simply a consequence of the basic law of meshing gears. The minus sign is because \(c_1\) turns in the opposite direction to \(b_2\). Adding another gear, \(c_2\), to the axis of \(c_1\), we can start to build up even more complicated output ratios. We multiply and divide the tooth counts as we go along. (We cannot do addition or subtraction with fixed-axis gearing.)

It was the genius of the ancient Greeks to chain gears together like this to create ever more sophisticated mechanical calculation. It is a key step in the history of technology. Science is about theories that make predictions. This is the first known instance in history that such predictions have been mechanized.

Returning to our gear train, we can eventually incorporate the large 127-tooth gear that Price identified, which engages in turn with a small 32-tooth gear called \(e_2\). The net result is that \(e_2\) turns at a rate of \(-254/19\) rotations per year. But why is this so significant?

### The Metonic Cycle

The important cycle of Sun and Moon, called the Metonic Cycle, was known in Greek astronomy from at least the 5\(^{th}\) Century BC, and probably earlier in Babylonian astronomy. The cycle comes in two equivalent forms. The first form of the Metonic Cycle states that in 19 years, the Moon goes through the Zodiac of ‘fixed’ stars 254 times. This period of the Moon is called the *sidereal month* and is about \(27 \frac{1}{3}\) days. \(254 = 2 \times 127\). So Price's 127-tooth gear is part of a gear train that calculates the position of the Moon in relationship to the stars. In its second form, the Metonic Cycle states that in 19 years, the Moon goes through its phases from New Moon back to New Moon 235 times. (Notice that \(254 = 235 + 19\).) This period of the Moon is called the *lunar month* and is about \(29 \frac{1}{2}\) days. The reason that this is a longer cycle of the Moon than the sidereal month is that, when the Moon has gone right round the Zodiac to complete the sidereal month, it still needs to catch up with the Sun (which has moved in the mean time) to get back to the Moon's same phase. It takes just over two days to do this. The Metonic Cycle is one of the two basic keys that unlocks our understanding of the gears. The fundamental importance for the Mechanism of the Metonic Cycle was one of Price’s great discoveries.

### Price’s Model

From this work, Price developed a famous model of the Mechanism. If we look at a diagram of all the gears, it is clearly very complex and difficult to understand. As we have discussed, Price said that it used the Metonic Cycle to show the position of the Moon in the Zodiac. He also claimed that it contained a ‘Differential’ gear system that involved ‘epicyclic’ gears whose axes moved on other gears—a remarkably sophisticated proposal for its era. This he asserted calculated the lunar month. We no longer believe Price’s proposed Differential: it was a beautiful idea, but it is wrong. However we are sure that the Mechanism contained epicyclic gearing—a quite astonishing concept for its era. Price’s model was of very great importance, but we don’t believe in most of his proposed gear trains. Why has it got so many gears? The basic problem with the model is that it much too complex for its relatively simple outputs, which could be obtained with much simpler gearing. We now believe that Price got many things wrong. He had some remarkable insights, but he was also in the habit of throwing away many of his best ideas. However, he is still revered by researchers because he understood the essence of the Mechanism as a calculating machine and because he understood its supreme importance in the history of science.
and technology. Price died of heart attack in 1983 at the young age of 62, leaving a very important but unresolved research legacy.

**Bromley & Wright**

Two more important pioneers took Price’s legacy forwards. Allan Bromley (now deceased) was an Australian professor of computing science who was an expert on a much later pioneer of computing called Charles Babbage, who lived 2,000 years after the Antikythera Mechanism. Michael Wright was formerly Curator of Mechanical Engineering at the Science Museum in London. They became sceptical of Price’s model and determined to get the three-dimensional X-ray information that Karakalos’ X-rays lacked in order to understand the 3-D positions of the gears. In 1989/90 they carried out a new X-ray study using an early 3-D x-ray technique, called “linear tomography”. It was invented in the 1930s and was used in the last war to find the 3-D positions of shrapnel fragments in the human body. It was a pioneering study, but in many ways the technique was compromised compared with modern X-ray methods. However, they found important proof that Price’s model was wrong and that his Differential could not work in the way Price had proposed. Allan Bromley died of cancer in 2002. But Michael Wright was very persistent and went on to do very significant research—some of which was crucial for our own work, as we shall see.

Michael Wright also produced a new model of the Mechanism. At the front, it shows not only the positions of the Sun and Moon in the Zodiac, but also the Moon phases with a semi-silvered ball and all five planets known to the ancients. The Moon phase device was a feature that had been seen since the early work of Svoronos in 1902 but not understood for more than 100 years until Wright suggested its function. There is an on-going debate about Wright’s highly ingenious planetary arrangement and I don’t have time here to discuss this speculative system. At the back of the Mechanism, Wright resurrected one of Price’s brilliant but discarded ideas with the suggestion that the Upper Back Dial is a calendar dial based on the 19-year Metonic Cycle, which I will discuss later. He also suggested that the Lower Back Dial showed another form of month, the *draconitic month*. But this idea was greeted with considerable scepticism by another group of researchers, who would subsequently prove it to be wrong.

**Antikythera Mechanism Research Project**

**Academic Team**

In early 2000, a friend of mine called Mike Edmunds, who is a leading international astronomer and was at Cardiff University in Wales asked me I had ever heard of the Antikythera Mechanism. I had never heard about it. He told me its extraordinary story and asked me if I thought that it might make a good TV documentary. (At the time, I was a documentary filmmaker.) I thought that it was a wonderful idea. We were not at that stage successful with the TV idea, but I became fascinated with the Mechanism. I had formerly been a research mathematician and I ended up writing an academic paper called *Challenging the Classic Research*. During this stage, Mike contacted a fellow academic, the distinguished Greek professor of astronomy John Seiradakis, who is at the Aristotle University of Thessaloniki. It is a nice coincidence that John’s aunt is Marika Seiradake, who became Mary Platsis, and was one of the co-founders of this Symposium. John in turn contacted his old friend and colleague, Professor Xenophon Moussas at the National & Kapodistrian University of Athens. He in turn recruited a physicist, Yanis Bitsakis, as a researcher on the team. Yanis would end up doing a lot of the work on the inscriptions with Dr Agamemnon Tselikas, who is
Director of the National Bank of Greece Cultural Foundation. We came to be known as the Antikythera Mechanism Research Project.

Our main frustration with studying the Mechanism was lack of data. We didn’t even have a good set of still photographs. In 2001, early in the process of the formation of our academic team, I had seen a fascinating article in New Scientist magazine about a technique for looking at surfaces, which enhanced all the details. The article showed an example of a Babylonian tablet, whose surface features could be seen much more clearly using the new technique. I thought that this would be ideal for looking at the inscriptions on the surface of the Antikythera Mechanism. After four years of frustration and difficulties, a great team from Hewlett-Packard (USA), led by the inventor of the technique, Tom Malzbender, came to Athens with special equipment to study the Mechanism. Another item in New Scientist magazine triggered our other main investigations. I saw a false-colour X-ray image of a goldfish with all its tiny bones visible. This in turn led more than four years later to another great team coming to carry out high-resolution 3-D X-rays of the Mechanism. This was led by Roger Hadland, then proprietor of X-Tek Systems (UK), who are world leaders in microfocus X-ray tomography. The Antikythera Mechanism is in the care of the National Archaeological Museum in Athens. Two of its senior staff were responsible for the new scientific investigations, which we carried out in autumn 2005. Dr Eleni Mangou is Head of Chemistry at the Museum and Mary Zafeiropoulou is a senior archaeologist in the Department of Bronzes. In all the research team had expanded to 17 people and they are the co-authors of our first paper in Nature.

Data Gathering

The Fragments

In the earliest publication on the Mechanism in 1902, Svoronos had named the main fragments as A, B, C and D. We also knew from Price’s work that there were about fifteen smaller fragments and some other pieces. In 2005, Mary Zafeiropoulou called us to say that she had found some more boxes of fragments in the Museum basement store. Would we be interested? Of course we were interested! To our astonishment, we have now ended up with a total of 82 fragments that probably all belong to the Mechanism. It is a daunting jigsaw puzzle and we are still in the process of doing it.

Hewlett-Packard (USA)

Tom Malzbender’s Hewlett-Packard team were the first to come to Athens in September 2005 to study the surfaces of the fragments. They used a specials dome covered in flashlights to take multiple digital images of the sample under different lighting conditions. Putting all this information together, using a technique from the computer gaming industry called Polynomial Texture Mapping (PTM), a computer can produce new ‘reflectance images’ of the surface that bring out fine details with extraordinary clarity.

X-Tek Systems (UK) (now part of Metris)

The second part of our investigations involved making 3-D X-rays of all the fragments. X-Tek Systems brought an eight-tonne X-ray machine to Athens called the Bladerunner, because its primary purpose was to detect defects in turbine blades. The machine had been modified with double the power of the X-ray source in order to penetrate the largest fragment, Fragment A. The technique is called Microfocus X-ray Computed Tomography (CT). It uses a very tiny X-ray source to project the sample onto a detector, which records up to three thousand X-ray images as the sample is
rotated on a turntable. Integrating these images with clever mathematics enables very high-resolution 3-D X-ray volumes to be produced. In practice the images are mostly used by viewing ‘slices’ through the X-ray volume.

A Detective Story

The result of our scientific investigations was nearly a terabyte of superb data. The text that covers the surfaces of the fragments is very difficult to read because it is confused by the texture and coloration of the highly corroded surfaces. Hewlett-Packard’s reflectance imaging enhances this text with great clarity and has enabled us to read much more of these crucial inscriptions, which we regard as an Instruction Manual for how the Mechanism worked. The microfocus CT showed us the structure of the gears and plates with great precision and has allowed us to make accurate models of the Mechanism. The other unexpected revelation that came from the CT was that we can read many inscriptions inside the Mechanism. Text that has not been seen for more than two thousand years is now readable in multiple CT slices. We believe that this is the first time that text has been read from inside an archaeological artefact. The data that has been revealed is at millimetre scales, remarkably preserved despite 2,000 years under water. Most of the text is less than 2 mm high. Our research has been a real detective story, piecing together multiple tiny clues to reveal a wider picture. I want to give you some examples of this exciting process.

Back Dials

Much of our recent work has concentrated on the Back Dials of the Mechanism, whose functions have been hotly debated for decades. Michael Wright discovered that these dials are not the concentric rings of Price’s model, but are in the form of spirals—and we have found some definitive evidence for this, which I will describe later. The Upper Dial has five turns and the Lower Dial has four. I would like to tell you what these dials do.

The fragments that witness the Back Dials are A, B, E and F. We now know how to solve this part of the overall jigsaw puzzle. Price discovered where B fits in relationship to A and, using our X-rays, we now know where E and F fit. Viewing an assembly of these fragments in X-rays clearly reveals the main structure of the Back Dial system with two main dials with spiral rings and smaller subsidiary dials inside these. So what do these dials show?

Upper Back Dials

Price suggested what the Upper Back dial might do—only to reject his insight and adopt the simplistic idea of a Four-Year Dial for his model. Wright resurrected Price’s good idea that the dial is a Metonic Calendar. In Fragment B, we can see a lot of scale divisions and we can assess how many scale divisions there are around the five-turn spiral. There are 47 divisions for each of the five turns, making a total of 235 divisions in all. You may remember the second version of the Metonic that in 19 years the Moon goes through 235 lunar months. So that is where our number 235 comes from, but why is it interesting? Our own calendar takes our word for the ‘month’ from the ‘Moon’, but we have lost any close relationship with the actual lunar month of 291/2 days, since most of our months are 30 or 31 days. We have simply forced twelve months to fill a year without regard for the actual cycle of the Moon. However, the ancient Greeks were far more concerned in their calendars to follow the real lunar month. The problem was that 12 lunar months do not fit exactly into a year—they are about 11 days short. So a calendar based on the Moon would rapidly go out of synchronization with the year. By using the Metonic Cycle which
fits an exact number of lunar months into 19 years, they could rescue the situation by constructing an artificial calendar that repeats every 19 years. Some of the years have twelve lunar months and some have 13 and these are fitted together in as regular a scheme as possible in a ‘luni-solar’ calendar. We now know that the Antikythera Mechanism had a 19-year luni-solar calendar as its Upper Back Dial. I will return to this later to fill in more details.

Wright made the plausible suggestion that the subsidiary dial inside the Metonic calendar follows the 76-year Callippic cycle—an improvement in accuracy of the Metonic cycle—but we have now shown that this is incorrect, as we shall see later.

Apart from the scale divisions, what makes us so confident that the Metonic Calendar is correct?

**Evidence from the Instruction Manual**

Fragment 19 is part of the Instruction Manual. It was seen and read by Price. Under Hewlett-Packard’s reflectance imaging technique, the text stands out clearly from the surface. We can easily read “76 years” (The Callippic Cycle); “19 years” (The Metonic Cycle); and the mysterious number 223—of which, more later!

Finding the 19-year cycle mentioned in the inscriptions adds much support to the idea of a Metonic Calendar, but we were to get definitive confirmation from the CT. In December 2005, Yanis Bitsakis (one of our core academic team) called me to say that in Fragment E, they had found the following inscription, “ΕΛΙΚΙ ΤΜΗΜΑΤΑ ΣΔΕ”, meaning “SPIRAL SUBDIVISIONS 235”. I nearly fell off my chair with surprise! Here we had in one short phrase confirmation of both the Metonic Calendar and Michael Wright’s proposal of spiral dials. Wright also proposed gearing, which would turn Price’s Metonic Dial at the correct rate, though at first we could not understand why the gear train was so complex.

**What is the Lower Back Dial?**

So we now were sure about the five-turn Upper Back Dial, but what is the four-turn Lower Back Dial? When I returned from our scientific investigations in Athens in October 2005, the first X-ray volume that I looked at was Fragment F. At first glance this small 8 cm fragment looks much like a pebble that you would pick up from the beach. And if you look at an X-ray slice, it doesn’t look much different. But if you go down through the fragment, viewing more X-ray slices, you start to see scales, which become clearly defined. And around the scales you begin to see scale divisions. This information not only showed us where Fragment F fits into the Lower Back Dials but it also suggested a strategy for understanding the function of the dial: look carefully at the scale divisions and estimate how many there would have been round the whole four-turn spiral. Fragment A also includes part of the Lower Back Dial and more scale divisions can be seen on the surface. In Fragment E yet more divisions are visible with the CT. We found nearly fifty scale divisions in all and this gave us a very reliable statistical estimate of the number of scale divisions. The remarkable answer was 223, which you may remember was the mysterious number on Fragment 19.

**The Saros Cycle**

223 is a number well known to experts on ancient astronomy. In Babylonian astronomy from at least the 7th Century BC onwards, they knew of an eclipse prediction cycle of 223 lunar months. The cycle works like this: if you have an eclipse of either the Sun or the Moon in a particular month and you look 223 months (18.03 years) later, then there is a strong possibility that you will get another similar eclipse. This cycle of eclipses goes on repeating for 12 to 15 centuries, so it is a really good
cycle. It must be said that, particularly for solar eclipses, you will not see the eclipse repeat in the same location on the Earth. In fact the cycle is \(6,585\frac{1}{3}\) days and the \(\frac{1}{3}\) day means that the eclipse repeats one third of the way round the world and about 8 hours later. And this explains the subsidiary dial inside our new Saros Dial. It shows a *Triple Saros Cycle*, known in ancient Greece as the *Exeligmos Cycle* that can be translated as “*Turn of the Wheel*”. It is remarkable to find an instrument with a pointer that goes round in a period over 54 years! After a single revolution of this dial, the eclipse repeat returns to much the same longitude and time of day. The Saros Cycle is the second of the two keys that unlocks our understanding of the gears. But how does the Saros Dial work?

**Glyphs and their meaning**

The CT of the scales in Fragment F revealed some new inscriptions of great significance. Between some of the scale divisions, we found blocks of text characters and symbols. Similar blocks can be seen on the surface of the back of Fragment A between the scale divisions of the Lower Back Dial. We can see what these look like using Hewlett-Packard’s beautiful surface imaging. We call them ‘glyphs’ and we now know what they mean. If we look at the Saros Dial, they are arranged round the dial at six-month intervals, five-month intervals or sometimes in adjacent months. This is exactly the pattern in which eclipses happen. So we realized that they must indicate the eclipse predictions round the dial. We have now found 18 of these glyphs, mostly using the X-ray CT. It took a long time to de-code these glyphs. One obvious feature was that all the glyphs contained Σ or Ηs or sometimes both. We soon realized that Σ stands for Σελήνη, the Greek for Moon and indicates a lunar eclipse and Η stands for Ηλιος, the Greek for Sun and means a solar eclipse. The anchor-like symbol we decoded as being a combination of ω and ρ, meaning ορα and indicating the hour of the eclipse. Η\\^M stands for Ημεροσ meaning ‘of the day’ and used to indicate lunar eclipses that happen in the day and so cannot be seen. Similarly Ν\\^Y stands for Νυκτοσ and is used for solar eclipses that happen at night and so cannot be observed. A typical line of one of the glyphs might read, Σ Η\\^M ωρ E—meaning a lunar eclipse in the day at the fifth hour. We had decoded nearly all the information in the glyphs, but not quite everything.

**AMRP Expansion**

After our first paper in Nature, we had organized a conference in Athens at the end of 2006 to announce our results. We were lucky that two of the participants in our conference were leading historians of astronomy, Professor Alexander Jones (Institute for the Study of the Ancient World, New York) and Dr John Steele (Brown University, Providence, Rhode Island). They joined the team to take the research forwards.

The glyphs are numbered by their month position round the 223-month scale of the Saros Dial. In the glyphs, we had seen letters at the bottom of each glyph, but we had not understood them. One of our new colleagues pointed out that they are index letters, in alphabetical order. For example, if we look at Glyphs 20, 25 and 26 on the left, they have the consecutive index letters, E, Z and H. (Zeta is always written on the Mechanism as an ‘I’ with long serifs.) How had we missed the fact that these letters are alphabetical? We assume that the letters referred to an indexed list related to the eclipse predictions, but we haven’t found any of it. The index letters have profound consequences for the arrangement of the glyphs round the dial. For example, in the gaps where our data is missing, they tell us how many glyphs there must have been.
This puts a tight constraint on any proposed reconstruction of the whole dial. However, we have finally managed to find a well-founded mathematical scheme of glyph generation that enables us to make a plausible reconstruction of the whole dial. The only elements missing are the times of the eclipse predictions, since we have not been able to make sense of the existing time data.

Now we knew that part of the Mechanism is an eclipse prediction machine and we knew how it worked.

**Structure of the Gearing**

Our new model of the function of the Saros Dial demanded answers to two key questions. Which gears turn the Saros & Exeligmos Dials? What are the two gears apparently stuck to the back of the large gear in Fragment A, which Price believed were part of his Differential. One of these appears to be an ‘epicyclic gear’—in other words, its axis is carried round by the large gear onto which it is fixed.

**Which gears turn the Saros & Exeligmos Dials?**

To turn the Saros Dial at the correct rate, we need a ratio of \(-\frac{4 \times 235}{19 \times 223}\). Since 223 is a prime number, which can’t be broken down into smaller factors, we must find a gear with 223 teeth. The only real possibility is the large gear \(e_3\) that is visible at the back of Fragment A. Our gear analysis confirmed that this gear has 223 teeth. A single conjectural gear with 27 teeth, meshing with the 223-tooth gear completed a gear train that would produce the correct ratio. So just a couple of months after gathering our data, we had a nice story about the Lower Back Dial. It is an eclipse prediction dial and we knew how it is turned by the gears of the Mechanism.

**A Huge Problem!**

This left us with a huge problem. Attached to the large gear \(e_3\) at the back of Fragment A are what looks like two gears, with the bottom one being carried round by \(e_3\)—so-called epicyclic gearing. However, Price had recognized that there are in fact four gears in this system and our CT confirms this. Just a millimetre in front of \(e_3\) are two gears \(e_5\) and \(k_1\). Another millimetre in front of these are two more gears \(e_6\) and \(k_2\). It is to the great credit of Price and Karakalos that they managed to distinguish these gears. The bottom gear, \(k_2\) has a slot in it. Rediadis noticed this in 1902, but he didn’t understand it. Price thought that it was evidence of a repair, which had dropped out. But Michael Wright had a much more important insight.

**A Critical Observation by Michael Wright**

Wright saw that there is a pin on the gear \(k_1\) behind \(k_2\). And this pin engages with the slot in \(k_2\). He suggested that the pin on \(k_1\) drags the gear \(k_2\) round via the slot. What’s the point of that you may well ask? If the gear with the pin simply drags the gear with the slot, they will turn at the same rate and you might as well fix them together. But what Wright suggested was that they turn on different axes. The axis of \(k_1\) is displaced by just over a millimetre from the axis of \(k_2\). This, Wright asserted, induces a small variation in the rotation of \(k_2\) while \(k_1\) turns at a constant rate. Since the gears turn on different axes, the pin on \(k_1\) is sometimes closer to the centre of \(k_2\) with the slot and turns it faster and sometimes further away and turns it slower. Wright had made a brilliant observation, but he discarded the idea because it didn't work in his model. His large gear \(e_3\) turned at much too fast a rate for it to make sense in his model. However, in our model, \(e_3\) turns in a period of about nine years. Could this Pin & Slot therefore be related to the variable motion of the Moon?
Theory of the Moon, attributed to Hipparchos—The First Anomaly

The Theory of the Moon, often attributed to Hipparchos, explains the variable speed of the Moon’s motion—called the Moon's first anomaly. In modern terms, we know that this is caused by the Moon’s elliptical orbit: when the Moon is closer to us it appears to move faster and when it is further away it moves slower. The ancient Greeks knew of this variable motion, but they did not know of the elliptical orbit.

Two cycles of the Moon are relevant to this theory. The sidereal month is the time for the Moon to return to the same place in the Zodiac—about $27^{1/3}$ days. The anomalistic month is the time for the Moon to return to the same speed of motion—about $27^{1/2}$ days. The anomalistic month is about one fifth of a day longer than the sidereal month. The reason for this (in modern terms) is that the major axis of the Moon’s elliptical orbit, called the Line of Apsides, is not stationary. It rotates with a period of about nine years. (Does this period remind you of anything?) The Moon takes about one fifth of a day to catch up with the Line of Apsides to complete the anomalistic month. The Theory of the Moon, attributed to Hipparchos, states that the Moon has a constant rotation with the period of the sidereal month, while the mean period stays at the sidereal month.

Don’t worry if the following discussion is not at all obvious! My experience talking to audiences is that this is the point where people tend to get lost. It should be said also it did take more than a hundred years to solve this problem!

The idea is that the variation induced by the Pin & Slot might model the variation of the Moon's motion. If the pin rotates at the rate of the sidereal month and the Pin & Slot is included directly in the gear train, the added variation would also have the period of the sidereal month. We want the variation to have the period of the anomalistic month, while the mean period stays at the sidereal month.

The stunning idea of the designer was to mount the Pin & Slot epicyclically on e3 in order to change its period of variation to the anomalistic month. What an incredible idea! In my view, this is a design of genius. What is necessary for this to work is that the rotation of e3 is the difference between the rotations of the sidereal and anomalistic months—this is a rotation with a period of about nine years and it can be calculated by combining the Saros Cycle (223 lunar months = 242 draconitic months = 239 anomalistic months) with the Metonic Cycle (19 years = 235 lunar months). You can try this yourself to discover why we found the prime factor 53 in this calculation. This explains why the surviving gears of the Mechanism include two gears with 53 teeth. We are also confident that the Mechanism must have contained a third gear with 53 teeth that has now been lost. Rotating e3 at the correct rate (including the factor 53 in the calculation) means that the Pin & Slot mechanism delivers its variation with a period that is the anomalistic month, as required by the first anomaly of the Moon.

The New Model of the Antikythera Mechanism

Putting all these ideas together enabled us to create an entirely new model of the Mechanism. It many ways it looks similar to Price’s model but it is even more complex and hard to understand. It works in an entirely different way. And it no longer suffers from the problem with Price’s model that it is much too complex for its functions—this is a complex model doing complex things. Our new model has coherence and unity and an ability to explain many puzzling features of the data, such as the role of the large gear e3 that has never been explained before. We have found two gears with the unusual tooth counts of 53 and we now know why they are there.
Nearly all the tooth counts of the Mechanism can now be accounted for by the Metonic and Saros cycles.

An animation of our new model reveals an astonishing geared mechanism. Its sophistication and harmony reveals the hand of an extraordinary design genius. It is a witness to a time in history when the human race was taking the first steps towards high technology. It is the forerunner of the scientific and technological revolutions that have created our modern world. It must surely rank as one of the greatest technological achievements of all time.

**Metonic Calendar & Olympiad Dial**

**Upper Back Dial**

I want to look again at the Metonic calendar and some new research that was part of our *Nature* paper this year. You may remember that it has a five-turn spiral scale with 47 divisions per turn, making a total of 235 lunar month divisions. It is a luni-solar calendar. We had known for some time that there are inscriptions between the scale divisions of this dial, which can be seen in the CT of Fragment B. If we look at multiple CT slices of Fragment B, we can see many text characters. Since it is a calendar dial, we thought that they might refer to month abbreviations or month numbers. One of our new experts on ancient astronomy discovered that they are month names, written over two or three lines. And we also found text referring to the beginnings of years round the 19-year dial. Some of the month names are unusual names and some of them very rare. After weeks of work we managed to piece together the whole calendar—all twelve month names. They contained an astonishing message. The month names are:

ΦΩΙΝΙΚΑΙΟΣ
ΚΡΑΝΕΙΟΣ
ΛΑΝΟΤΡΟΠΙΟΣ
ΜΑΧΑΝΕΥΣ
ΔΟΛΕΚΑΤΕΥΣ
ΕΥΚΛΕΙΟΣ
ΑΡΤΕΜΙΣΙΟΣ
ΨΥΔΡΕΥΣ
ΓΑΜΕΙΛΙΟΣ
ΑΓΡΙΑΝΙΟΣ
ΠΑΝΑΜΟΣ
ΑΠΕΛΛΑΙΟΣ.

Because of the origins of the other objects on the Antikythera wreck, it has always been assumed that the Mechanism was made for a culture in the eastern Mediterranean. Rhodes has often been mentioned because of long links with famous astronomers, such as Hipparchos and Posidonios. The month names tell us a completely different story. Greek calendars were very localized, with different cities have their own calendars and month names. The month names in blue are fairly common throughout the ancient Greek world. The month names in green are restricted to Dorian and northwestern Greek calendars. It’s the rare names in red that tell us about the cultural origin of the calendar—those in red are restricted to Corinth.
and Corinthian colonies, in such places as northwestern Greece and Sicily. The calendar of the Antikythera Mechanism is a Corinthian calendar. We don’t know for certain which city was its origin. One intriguing possibility is that it was made for Syracuse in Sicily, the home of Archimedes. It is known from the writings of Cicero that Archimedes constructed a similar Mechanism. He died at the siege of Syracuse in 212 BC, well before we believe that the Mechanism was made. So, it's almost certain that he did not make the Antikythera Mechanism. However, it could have been manufactured in a tradition of instrument making that originated with the great Archimedes.

Reconstructing the Metonic Calendar

We were only been able to decipher a small proportion of the text on the Metonic Dial. But with great luck we had been able to piece together all the month names. So we can now reconstruct the whole calendar, with reasonable assumptions about which years had twelve months, which had thirteen months and which months were repeated in the thirteen-month years.

Olympiad Dial

Fragment B contained another major surprise. I want to discuss the small subsidiary dial inside the Metonic Calendar. You may remember that Wright thought that this was a 76-year Callippic Dial. The first inscription that we read round this dial was ‘NEMEA’. I didn’t know what it meant. Again we benefitted from the expertise of our new colleagues, who told us that it refers to the Nemean Games. These were one of the major panhellenic games, like the Olympic Games. So this dial seems to follow the cycle of panhellenic games. We then managed to read parts of other games: the Isthmian Games in Corinth, the Pythian Games in Delphi and the minor Naiaean Games held at Dodona. And finally all the text of Olympia for the Olympic Games. The dial is marked with the year numbers of the four-year Olympiad cycle. We also found how the dial was driven. It turns anticlockwise and is powered by a single conjectural gear with 57 teeth on the axis of the Metonic Dial that engages with an existing 60-tooth gear that can be seen in Fragment B under the Olympiad Dial.

The Latest Model

Incorporating this new information into our diagram showing the structure of the gears shows a geared mechanism of extraordinary sophistication. Price wrote a very apt comment on the Antikythera Mechanism:

“It is a bit frightening to know that the ancient Greeks had come so close to our age, not only in their thought, but also in their scientific technology”

Professor Derek de Solla Price, Scientific American, 1959

We have discovered much, but it is still a deeply mysterious object. It is slowly giving up its secrets and we find that it is full of surprises. It embodies much of the astronomical theory of its time. It is the technological side of what is sometimes called the ‘Greek Miracle’. It is one of the true wonders of the ancient world.

Questions

I would be happy to answer any questions by email, but please look at our website first, which includes a Frequently Asked Questions section and is a rich source of information about the Antikythera Mechanism.
Thanks

Due to unforeseen circumstances, I was not able to come to Michigan to deliver my presentation in person. I would like very much to thank Professor Ulysses Balis for giving the presentation on my behalf. I would also like to express my great appreciation to Professor Vassillios Lambropoulos and his team for inviting me to the Platsis Symposium and for being so understanding when I was not able to come.

Tony Freeth
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