# The Antikythera Mechanism And A Modern Reproduction

Stephen Phillips, April 2024



# **Agenda For The Presentation**

- **General Introduction** ٠
- **Recap On The Solar System** ۲
  - Planetary Movement, including retrograde motion
    Solar & Lunar eclipses
- ٠
  - The Antikythera Mechanism

    Where and when it was found and what remains exist
    - The analysis done on this to understand how it worked
    - The main components of the mechanism.
- My reconstruction of the mechanism ۲
  - How this was designed and manufactured
- How the original mechanism might have been ٠ made.
- Recent updates on the analysis of the ٠ Antikythera Mechanism (time permitting)
- **Question and Answer Session** •



# Stephen Phillips, B Eng, C Eng, MIET

- I am a chartered engineering with a degree in mechanical engineering from Sheffield University,
  - I did a thick sandwich degree course funded by the Ministry of Defence, working at RAE Farnborough, NGTE Pyestock, Rolls Royce and then the Royal Ordinance Factory, Leeds working on the Shir 2 tank which subsequently became Challenger.
- I then did a Fellowship in Manufacturing Management post graduate course at Cranfield, and moved into electronics initially at Systime Computers in Leeds
  - Then Schlumberger Test Equipment in Dorset and final at Lucas in Cirencester, fully retiring in 2018 from what had then become part of ZF
- I have always made things in my workshop at home, and in 2015 embarked on making my first orrery
  - Which led on to the Antikythera Mechanism, several more orreries and clocks, the most recent of which are stepper motor driven with Raspberry Pi
    micros to drive them.
- I am not an expert on Astronomy, but will try to describe the solar and planetary motions related to the Antikythera mechanism before going on to examine the original mechanism and my later reproduction in more detail.



# **The Solar System – Planetary Motion**

- It was not till Copernicus in the 17<sup>th</sup> Century that we understood that the planets revolve around the sun
  - The Greeks has speculated about this but it was the work of Newton, Galileo and Kepler that lead to Copernicus' work
  - Copernicus developed a mathematically predictive heliocentric system, with planets in elliptical orbits and the sun at one of the focal points of the ellipse





Distances of selected bodies of the **Solar System** from the Sun. The left and right edges of each bar correspond to the perihelion and aphelion of the body, respectively, hence long bars denote high orbital eccentricity. The radius of the Sun is 0.7 million km, and the radius of Jupiter (the largest planet) is 0.07 million km, both too small to resolve on this image.

# **The Solar System – Retrograde Movement**

- When viewed from earth some of the planets show retrograde motion
  - The planet appears to move backwards in the sky as earth moves relative to it
  - As <u>Earth</u> (blue) passes a superior planet, such as <u>Mars</u> (red), the superior planet will temporarily appear to reverse its motion across the sky.
- The Greek's recognised this, and tried to model the system as they saw it in the Antikythera Mechanism





# **Retrograde Planetary Motion Simulation**

- When viewed from Earth the planets appear to move backwards at times
  - Caused by the Earth and Planets moving relative to each other.
- This Retrograde Motion was known by the Greeks



#### **Lunar Movement**







Apsidal precession—The major axis of Moon's elliptical orbit rotates by one complete revolution once every 8.85 years. In this image, the elliptical shape of the Moon's orbit is vastly exaggerated from its almost circular shape to make the precession visible.

# The Solar System – Solar & Lunar Eclipses

- The Greeks were also familiar with solar and lunar eclipses
  - And managed to predict when these would occur, and of what type they would be.
- We now understand that these eclipses are due to the 5 degree difference in the planes of the orbits of the earth and moon around each other coupled to the elliptical orbit of the moon
  - When these are in a specific alignment then an eclipse occurs
  - The Saros cycle was develop to predict these occurrences





# The Solar System – The Saros Cycle

- The Saros is a period of approximately 223 synodic months (approximately 6585.3 days, or 18 years, 11 days, 8 hours), that can be used to predict eclipses of the Sun and Moon.
  - One saros period after an eclipse, the Sun, Earth, and Moon return to approximately the same relative geometry, a near straight line, and a nearly identical eclipse will occur, in what is referred to as an eclipse cycle.
  - A series of eclipses that are separated by one saros is called a saros series
- What you actually see depends on where you are on earth as well as the Saros cycle



#### The Antikythera Mechanism

- The Antikythera Mechanism was on board a ship laden with fine bronze and marble sculpture and glassware, which sank within a few years after 70 BC off the island of Antikythera, between Crete and the Greek mainland.
- The shipwreck site was discovered by Symiote sponge divers in 1900 and salvaged by them, under Greek government supervision, in 1900-1901.
- In 1902 fragments of the Mechanism were noticed among unsorted bronze pieces from the wreck at the National Archaeological Museum in Athens.
- Since then a number of scientific investigations have been carried out on the mechanism to try to understand it purpose and functionality.
  - One of the most recent of these was reported in ISAW Papers 4 (February, 2012) "The Cosmos in the Antikythera Mechanism" by Tony Freeth and Alexander Jones

(https://dlib.nyu.edu/awdl/isaw/isawpapers/4/#,~:text=Abstract%3A%20The%20Antikythera%20Mechanism%20is.the%20inscriptions%20on%20its%

- This work proposed an overall arrangement and functionality for the mechanism based on deduction from the surviving parts of the mechanism
- The BBC made a good documentary on this charting the investigations and some of the models made
  - <u>https://www.youtube.com/watch?v=3T1n7RjCMfQ</u>



#### The Antikythera Mechanism Fragment

- The Antikythera Mechanism was contained in a wooden box, which had bronze front and back covers.
  - A small portion of the wooden box, as well as a wooden sub-frame, survive in some of the fragments
  - There are now 82 separate fragments, of which Fragment A is by far the largest fragment and contains twentyseven of the surviving thirty gears.



#### An Extensive Analysis Was Done On These To "Reverse Engineer" the Design

- Images shown are from X-ray CT scans done by the 2005 Antikythera Mechanism Research Project
  - Who studied the physical structure and then related this to a mathematical model and design reconstruction based on tooth count etc.







#### **Computer Tomography Study Of The Antikythera Mechanism (1)**



https://www.youtube.com/watch?v=hkXNbCeoQS0 – rotating view of scan of mechanism fragment

#### **Computer Tomography Study Of The Antikythera Mechanism (2)**



<u>https://www.youtube.com/watch?v=6Wp3wL8g2Eg</u> – plan view of fragment.

#### The Antikythera Mechanism – Exploded View Of A Reconstruction

- Mechanism had display dials on both sides
  - Driven by a crank handle at the side
- The whole mechanism was packaged into a wooden box so that it could be easily transported



#### **The Mechanism and The Front Plate**

- The evidence for the Front Cover is from Fragment G and a number of other small fragments.
  - These establish that the Front Cover had inscriptions facing outwards.
  - The Front Cover may have covered the whole of the front or just the central dial
- The front plate was divided into three sections.
  - A central dial system displayed outputs from the Mechanism on a Zodiac Dial, marked with 360° scale divisions and a Calendar Dial, marked with 365 days.
  - The Calendar Dial was designed to be moveable, so that the Mechanism could accommodate the fact that four Egyptian calendar years fall short of four 365.25 day solar years by one day.
- Above and below the dials, were plates covered in inscriptions in the form of a Parapegma (star calendar).
- At the right-hand side of the Mechanism there was an input, and we assume that this was turned by hand with some sort of handle or crank, though only the keyway for the input remains



#### The Mechanism and The Rear Plate

- Beneath the removable Back Cover there were two major dial systems (top and bottom) in the form of spirals, divided into lunar months, with subsidiary dials inside them.
- The top dial showed a 19-year Metonic calendar, divided into 235 lunar months.
  - Inside this dial was a subsidiary dial, showing the 4year panhellenic games cycle and (conjecturally) a dial showing the 76-year Callippic cycle.
- The bottom dial showed a 223-month eclipse prediction dial, based on the Saros cycle.
  - This dial included glyphs that indicated information about the predicted eclipse possibilities, including time of the eclipse.
  - Inside this dial was a subsidiary Exeligmos Dial, designed to adjust the eclipse times for successive turns of the Saros Dial.



#### **Virtual Reconstruction Of the Antikythera Mechanism**



# The "Pin In Slot" Mechanism Was Used to Give Retrograde Planetary Motion

- Each outer planet is pointer is driven by 4 gears (G for Mars)
  - A fixed gear (G1 with 37 teeth for Mars) that is fixed to the front plate
  - 2<sup>nd</sup> mating gear (G2 with 79 teeth) that rotates with the main wheel, and has a pin mounted to it
  - A 3<sup>rd</sup> lower gear (G3 with 69 teeth) which is driven by the upper gear pin which moves in a slot in this gear
  - A 4<sup>th</sup> gear (G4 with 69 teeth) that is connected to the planetary pointer
- The sizes of these gears give the relative rotational speeds of the planets to each other
  - Jupiter gears have 76, 83, 86 and 86 teeth respectively
- The pin in slot mechanism gives the retrograde motion where the planet positions appear to move backwards and forwards when seen from the earth



Mars-based on 37 synodic cycles in 79 years.



Jupiter-based on 83 synodic cycles in 76 years.



#### **Gears & Proposed Arrangement by Freeth & Jones**

- The Antikythera Mechanism Research Project proposed an overall general arrangement is based on the existing fragments
  - But extrapolated to what the full mechanism might have looked like in particular for the outer planet gearing



#### Front Dial Planet Outputs – Freeth & Jones Model

- The Freeth & Jones model includes pointers for all five planets on the Zodiac Dial.
- In order to be consistent with the "little golden sphere" inscription on the Back Cover, these pointers include conjectural spherical marker beads in different metals and semiprecious stones
  - Which are placed at different distances along the pointers.
- These then create a "cosmos" for Sun, Moon and planets in the order:
  - Moon (silver),
  - Mercury (turquoise),
  - Venus (lapis lazuli),
  - Sun true position (gold),
  - Mars (red onyx),
  - Jupiter (white crystal)
  - Saturn (obsidian).
- Two additional pointers give current date and moon position and state



#### **Rear Dial with Metonic & Saros Cycles**

- The main epicyclic gearbox, rotating once per year, drives the rear face dials from gear B2
- The Metonic, Calippic and Olympiad pointers are driven by intermediate gears L, M and P
  - The gear ratios give the different cycle lengths of 19 years (235 lunar months) for the Metonic, 4 years for the Olympiad and 76 Years (ie 4 x 19) for the Callipic.
- The large gears E3 (223 teeth) and E4 188 teeth convert the 235 month Metonic cycle into the 223 month Saros cycle
  - Again with intermediate gears F and H giving the exact ratios required for the Saros and Exeligmos pointers
  - The Exeligmos pointer is designed to adjust the eclipse times for successive turns of the Saros Dial (4 spirals).



#### Moon Drive Including Anomaly Adjustment

- The moon pointer uses a complex geartrain to give a rotation every 27.3 days
  - With a pin in slot mechanism provide an anomaly adjustment
- Gear B2 on the epicyclic gearbox drives through intermediate gears C and D to the E1/E2/E3/E4 group
  - The E gears are all 50 teeth but revolve on the large E gear and have a 1mm offset pin in slot to create the lunar anomaly
  - Gear E1 then drives B3 at the centre of the coaxial shafts which drives the moon pointer
- The top lun1 to lun4 gears then show the moon phase
  - A later design shows a simpler arrangement for this function



#### Metonic & Saros Cycles & Gearing

- Gearing is shown in a cascading format
  - With resulting periods in days and years
- Metonic & Saros displays use spirals to cover the full periods
  - 5 turns for the Metonic and 4 turns for the Saros
- Shaded items were not in the parts recovered but have been proposed by later analysis



Shading denotes gear not found in the mechanism parts recovered

#### **Functionality – The Epicyclic Gearbox**

- The epicyclic gearbox is mounted on the main gear B1 and generates the motions of the planets as viewed from the earth
  - The main gear rotates once per year, and uses fixed and moving gears to give the relative planet speeds and positions
  - Pin in slot mechanisms are used to get the back and forth movements of the planets as seen from the earth.
- The inner planets are driven from fixed gears at the base of the mechanism
  - Gears Mer1, Ven 1 and Sun 1.
  - Which then are output on coaxial shafts driven by levers with slots running on pins
- The outer planets are driven from fixed gears at the top of the mechanism
  - Gears Sat1, Jup1 and Mars1
  - Using 3 further gears per planet with pin in slot mechanisms to give the correct speed and relative motion.
- As the overall gearbox rotates mounted on the large gear B1 the fixed gears give relative outputs through coaxial shafts to pointers on the front dial



#### **Planetary Drive Proposal**

- Mercury drive used a pin-in-slot mechanism carried on the main wheel to give the correct period and retrograde movement.
- Later analysts (Freeth & Jones) have proposed how this could be extended to the other planets and sun true-position
  - Using 4 gears per planet in a compact epicyclic gearbox

	Gear	Period Yrs	Period Days										
Input Drive	A1	0.2	79	48	Input Gear (replaced by worm drive in the reproduction)								
	B1	1.0	365		223	Main Wh	eel						
Mercury	Mer 1	Fixed	Fixed			104							
Driver	Mer 2	0.32	116				33	Mercury Pointer (pin & slotted lever drive)					
Venus	Ven 1	0.63	228			64	Venus P	nus Pointer (pin and slotted lever drive)					
	Sun 1	Fixed	Fixed			40							
True Sun	Sun 2	1.0	365				40						
Drive	Sun 3	1.0	365					40	True Sun	Pointer (p	in & slotte	ed lever d	rive)
Mars Drive	Mars 1	Fixed	Fixed			37							
	Mars 2	1.9	687				79	Pin in slo	ot drive (1)	)			
	Mars 3	1.9	687					69	Pin in slo	t drive (2)			
	Mars 4	1.9	687						69	<b>Mars Point</b>	er		
	Jup 1	Fixed	Fixed			76							
Jupiter	Jup 2	11.9	4328				83	Pin in slo	ot drive (1)	)			
Drive	Jup 3	11.9	4328					86	Pin in slo	t drive (2)			
	Jup 4	11.9	4328						86	<b>Jupiter Poi</b>	nter		
	Sat 1	Fixed	Fixed			57							
Saturn	Sat 2	29.5	10768				59	Pin in slo	ot drive (1)	)			
Drive	Sat 3	29.5	10768					60	Pin in slo	t drive (2)			
	Sat 4	29.5	10768						60	Saturn Poi	nter		

Shading denotes gear not found in the mechanism parts recovered

#### **Physical Implementation – Original Mechanism**

- In the original Antikythera mechanism all the gears were approximately 2mm thick, and rested on top of each other
  - Minimising the overall thickness but increasing friction in the mechanism which would need to have been well lubricated.
- The gears were generally about Modulus 0.5 (typically 1mm long teeth), but this varied slightly across the whole mechanism
  - Requiring quite tight tolerances and some very small gears only 6.5mm in diameter
- The Tony Freeth CAD reconstruction of this tried to model all the original epicyclic gearbox mounting points with those on the fragments
  - And to show that this was a mechanism that could have been manufactured and would work





#### **Modern Interpretation of the Antikythera Mechanism**

- The modern interpretation of the Antikythera mechanism attempts to reproduce most of the functionality of the original but with key changes
  - Gears are 3mm thick and spaced apart so that the mechanism can be viewed more easily
  - Some gears have been increased to Modulus 0.9 (1.8mm teeth) so that they can be manufactured with the available tools
    - Primarily driven by the diameter of the small gears.
  - The rear face dials have been updated to "current" dates and eclipses starting in January 2015.
    - And with manually adjustable pointers rather than
      pointers moving in spiral grooves
  - The front face dials have been simplified without moving calendar rings
    - With engraved pointers to show the functions.
  - The case has been made open to show the internal functionality so that this can be more easily understood.
- The following CAD diagrams and photographs show this modern interpretation in more detail



#### **CAD Model Of The Epicyclic Gearbox**



#### **CAD Model Animations**



#### **Antikythera Reconstruction – Front Plate with Planetary Movement**

- The front plate has been simplified from the original
  - Fixed calendar and astrological engravings
  - Simple moon pointer without showing the moon phase
- The planets do show the correct relative speeds and retrograde motion
  - The earth pointer rotates once every year, and shows current date.
  - The other pointers rotate relative to this, and show planetary position provided that they are correctly calibrated, but as viewed from the Earth!





#### The Planetary Display and Lunar Anomaly Drive in the Reproduction



# Antikythera Reconstruction – Rear Plate with Metonic and Saros Dials

- The Metonic Dial shows current calendar date
  - With a spiral to show the 235 month full Metonic cycle when read with the Calippic dial
    - Which effectively multiplies the spiral dates by a factor of 3
  - The Olympic pointer rotates once every 4 years to show where the games will be held
  - The Saros dial rotates on a 223 month cycle
    - Again with the Exigimos pointer multiplying the cycle by a factor of 3
    - This dial is engraved to show the solar and lunar eclipses starting from 1<sup>st</sup> January 2015



#### The Metonic & Saros Dials & Gears



### The Metonic & Saros Dials & Gears in the Reproduction



#### **But How Was It Made?**

- The design although complex uses fastenings and techniques that were available at that time
  - Square holes and shafts to give location/drive retained by pins
  - Gears with triangular teeth that could be made with files.
- A number of reproductions have been made including Michael Wright, who used to work at the Science Museum
  - This was shown in a very informative BBC video, including how he marked out and cut gears with odd numbers of teeth using only hand tools (<u>https://www.youtube.com/watch?v=3T1n7RjCMfQ</u>)
- The "Clickspring" website is making a faithful reproduction, and trying to use the tooling available to the Greeks
  - Files made by hand and case hardened by heating with a charcoal based covering
  - Holes drilled by a manual bow type drill using simple spade drill bits
  - Marking out and soldering using materials that were available to them.
- The site contains a series of videos showing the design progressing
  - Supported by other "Fragment" videos showing the tooling etc being made
  - The following 2 slides show some examples from this website

# Making The Original Antikythera Mechanism – The Gears

"Clickspring" uses a similar method but with a special marking out jig, which would have allowed "automation" in production.



<u>http://www.clickspringprojects.com/the-antikythera-mechanism.html</u>

# Making The Original Antikythera Mechanism – Spiral Grooves

 The spiral grooves turn out to not be true spirals, but offset semicircles, which can be made with relatively simple tooling



#### The Anitkythera Mechanism – A Computer Before Its Time?

- What the Greek's managed to achieve in 70BC is simply astonishing
  - Both in understanding the underlying cycles, planetary movement and eclipse predictions and in physically
    making a portable device that can model this.
  - It was not until the 17 century that Europeans started to really understand this and define the planetary system as we now understand it, making Orreries to display these motions
- How advanced would we now be if this knowledge had not been lost in the intervening period?





# **Recent Scientific Updates to the Antikythera Mechanism**

www.nature.com/scientificreports

- Papers have recently been published in Nature and the BHI Horological Journal
  - Nature article redefines some of the planetary gearing based on updated research
  - BHI articles redefine the calendar ring structure on the front of the mechanism

# scientific reports

https://www.nature.com/articles/s41598-021-84310-w

#### OPEN A Model of the Cosmos in the ancient Greek Antikythera Mechanism

Tony Freeth<sup>1⊠</sup>, David Higgon<sup>1</sup>, Aris Dacanalis<sup>1</sup>, Lindsay MacDonald<sup>2</sup>, Myrto Georgakopoulou<sup>3,4</sup> & Adam Wojcik<sup>1⊠</sup>

# The Antikythera Mechanism

Evidence of a Lunar Calendar – Part 1/2	C. Budiselic	A. T. Thoeni
	M. Dubno	A. T. Ramsey



# **Nature Article Presents New Planetary Information**

- Decoding of more text on the front and rear covers led to a revised proposal on the planetary gearing
  - Based on the periodicity etc defined in the text including some key numbers on Synodic Periods for the planets.
- Very little of this can be proven from the remaining fragments
  - Ŏnly some elements related to the framework and inferior planet mechanisms



# **Proposed Gearing Is Now More Complex**

- To give the required periodicity for each ۲ of the planets and pointers
  - The planets return to the same point as seen from Earth in their "Synodic Period" These periods can be related to a number
  - of years
    - Mars has 133 Synodic Periods in 284 years.
- The team used complex mathematics ٠ to find ratios which could be represented by specific geartrains
  - Including wherever possible shared gears which could be related to the fragments of the mechanism.
  - And explain how the mounting features might have worked
- This resulted in up to 7 gears for the ٠ outer planets
  - Compared to the 4 in my reproduction.



Inferior planet:  $g_1 \sim g_2 + g_3 \sim g_4 \sim g_5 \oplus follower$  Superior planet:  $g_1 \sim g_2 + g_3 \sim g_4 \sim g_5 \oplus g_6 \sim g_7$ 

е	Spoke	poke Function		Years	Factors	Factors	Mult.	Epicyclic gear train
	А	MERCURY	1513	480	17x89	2⁵x3x5	x 3	51 ~ 72 + 89 ~ 40 ~ 20 ⊕ follower
	В	NODES	98	93	2 x 7 <sup>2</sup>	3 x 31	x 32	<u>49</u> ~ <mark>62</mark> + 64 ~ 48
	с	VENUS	289	462	17 <sup>2</sup>	2x3x7x11	x 6	51 ~ 44 + 34 ~ 26 ~ 63 ⊕ follower
	D	MEAN SUN	1	1	1	1	n/a	None

f	Α	SATURN	427	442	7x61	2x13x17	x 8	<b>56</b> ~ <b>52</b> + <b>61</b> ~ <b>40</b> ~ <b>68</b> ⊕ 86 ~ 86
	В	JUPITER	315	344	3 <sup>2</sup> x5x7	2 <sup>3</sup> x43	x 8	<u>56</u> ∼ <mark>64</mark> + 45 ∼ 40 ∼ 43 ⊕ 65 ~ 65
	с	MARS	133	284	7x19	2 <sup>2</sup> x71	x 16	<u>56</u> ∼ <mark>64</mark> + 38 ∼ <b>40</b> ∼ <b>71</b> ⊕ 80 ∼ 80
	D	TRUE SUN	1	1	1	1	x 56	<u>56</u> ~ 52 ~ 56 ⊕ follower

# **Projected Gearing**





# **Revised Planetary Display Concept**

- With rings for the planets and ulletpointers for the sun, moon and time displays.
  - And a new display of the lunar nodes
- Text does state that the  $\bullet$ planets were displayed by semi-precious stones
- Nature has a good video of • the revised design concept. - <u>https://vimeo.com/518734183</u> - <u>https://www.facebook.com/NaturePortfolioJourn</u>

  - als/videos/a-model-of-the-cosmos-in-the-ancientgreek-antikytheramechanism/343710920407596/



#### Tony Freeth and Jen Christiansen (graphic), UCL Antikythera Research Team (model)

https://www.scientificamerican.com/article/an-ancient-greek-astronomical-calculation-machine-reveals-new-secrets/



# **CAD Model Of Latest Proposals**





# **British Horological Institute Papers 2021**

- The papers focussed on the display scales on the planetary display With a detailed analysis of hole spacing and count.
- Resulting in a revised proposal for the holes and calendars that they • represent
  - And a possible lunar pointer design





# **Updated Conclusions**

- Our understanding of the Antikythera mechanism is still growing.
  - And with each new discovery if becomes even more complex and outstanding in its capabilities.
  - The Nature and Clickspring reconstructions will probably provide an even better understanding of both the device and how it was made.
  - But I have no current plans to update my replica which is now outdated!



