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THE ARTISTIC COMPLEXITY OF THE ANTIKYTHERA MECHANISM: A COMPREHENSIVE TUTORIAL

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ABSTRACT

Recovered in 1901, from a first-century BC shipwreck, the Antikythera Mechanism is considered to be the oldest extant complex geared device. It was constructed in ~150 BCE and was essentially an analog computer, an astronomical and calendrical device, designed to predict astronomical phenomena, such as lunar and solar eclipses, to maintain calendar accuracy and to predict the dates of Panhellenic Games. The device was operated manually by a user, setting a date in a dial. All necessary calculations were made using a set of gears (at least 39), while the results were displayed on several scientific scales. The Mechanism's miniature size, the elaborate gear trains, the use of eccentrical gears and the employment of a pin–and–slot gear system to calculate the anomalous orbit of the Moon, demonstrate that the Greek mechanicians of the Hellenistic period had become far more skillful in designing geared devices than the surviving written sources imply. Geared devices matching the complexity of the Antikythera Mechanism would not appear again in Europe until the mechanical clocks of the thirteenth century. The aim of this paper is to present this ancient elaborate device in the most comprehensible way.

KEYWORDS: Antikythera Mechanism; Gear Device; Gears; Ancient Astronomy; Ancient Technology; Egyptian Calendar; Metonic Cycle; Saros

1. INTRODUCTION

Like many great discoveries, the Antikythera Mechanism was found by accident. In 1900, sponge divers came across a shipwreck off the coast of the Greek island of Antikythera, and over the next year or so, they retrieved a number of artifacts—statues, coins, jewellery, and so on. One item they brought to the surface was not immediately recognized: a lump of corroded bronze and wood, broken into several calcified fragments.

The artifacts were all sent to the National Archaeological Museum of Athens for cataloguing and restoration, but the bronze lump sat almost unnoticed (Seiradakis et al., 2018; Jones, 2017; Kaltsas et al., 2012; Zafeiropoulou, 2007; Archaeological Ephemeris, 1902). When researchers finally turned their attention to it, they couldn't agree on what it was. The bronze lump seemed to contain gears and dials, suggesting it was a navigational device or perhaps even a clock. Some archaeologists suggested that it was a mechanism too advanced for the date of the shipwreck—the first century B.C.—and thought it might have been lost at sea more recently.

In time, however, analysis using X-ray and other advanced imaging revealed its true nature, and the Antikythera Mechanism is now considered as important for technology and sciences as the Acropolis for the architecture and arts. The object is the remains of the earliest known analogue computer.

Now we know that it was an extremely advanced mechanism that could be used to calculate and predict astronomical events. Detailed studies of the mechanism by various researchers have shown that it could predict with astonishing accuracy the position of the sun, moon, and the planets on the sky. It could also determine the phases of the moon, adjust the calendar, determine the dates of the ancient Olympic Games, and predict solar and lunar eclipses (Seiradakis et al., 2018; Jones, 2017; Kaltsas et al., 2012; Zafeiropoulou, 2007; Archaeological Ephemeris, 1902; Price de Solla, 1974; Wright, 2005; Ramsey, 2007; Malzbender et al., 2021; Freeth et al., 2006; Efstathiou et al., 2012; Efstathiou M. et al., 2013; Anastasiou et al., 2014; Efstathiou et al., 2018; Anastasiou et al., 2013; Anastasiou, 2014; Efstathiou M., 2018; Efstathiou M. et al., 2017; Basiakoulis et al., 2017).

From the letters and the symbols of the inscriptions, it can be concluded that it was built in the first half of the 2^{nd} century BC., possibly in Rhodes, where at that time, the science of astronomy flourished. In addition, two of the greatest astronomers of antiquity lived there during that period. Hipparchus died in Rhodes in 120 BC, as well as the Stoic philosopher and astronomer Poseidonios the Rhodian, who is mentioned in a work by Cicero as the maker of a celestial globe – planetoscope (Kaltsas et al., 2012).

The Mechanism was assembled in a wooden box (compass) measuring 32 cm x 16 cm x 10 cm. The front and back views were covered by bronze plates with calendar or astronomical scales and pointers. These surfaces were protected by two wooden outer covers, to which densely inscribed bronze plates were attached. The basic structure of the Mechanism is shown in Figure 1, in which it is displayed an accurate replica of the Mechanism (Efstathiou et al., 2012; Efstathiou M. et al., 2013).

Figure 1. The front and the back view of an accurate replica of the Antikythera Mechanism

It contained more than 39 cooperated gears. Some of them are shown in Figure 2 as they were recorded from the tomographies of fragment A. During the function, gears moved 7 pointers simultaneously, in order to predict the astronomical phenomena in the corresponding scales.

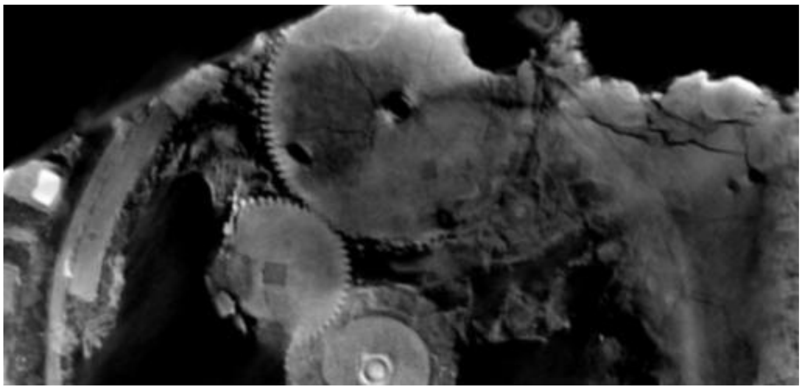

Figure 2. One of the tomographies of the fragment A of the Antikythera Mechanism

At the centre of the front plate, the Mechanism had two concentric circular scales (Figure 3). The outer scale had 365 subdivisions, which corresponded to the 365 days of the year and the names of the 12 lunar months in the Egyptian language with Greek characters (THOTH, FAOFI, ATHYR, CHOIAKI, etc.) (Spalinger, 2015). The inner scale had 360 subdivisions and the names of the 12 zodiac constellations (AQUARIUS, PISCES, ARIES, TAURUS, etc.) (Seiradakis et al., 2018; Jones, 2017; Kaltsas et al., 2012; Zafeiropoulou, 2007; Archaeological Ephemeris, 1902; Price de Solla, 1974; Wright, 2005; Ramsey, 2007; Malzbender et al., 2021; Freeth et al., 2006).

Figure 3. Front plate of the Antikythera Mechanism

At the centre, ended the Sun-Date pointer and the Moon pointer (Figure 4), which were rotated by the 39 gears. These pointers showed on the inner scale (constellation scale) the position of the Sun and the Moon in the sky for each day of the year. The specific day corresponded to the indication of the Sun index on the external scale of 365 days.

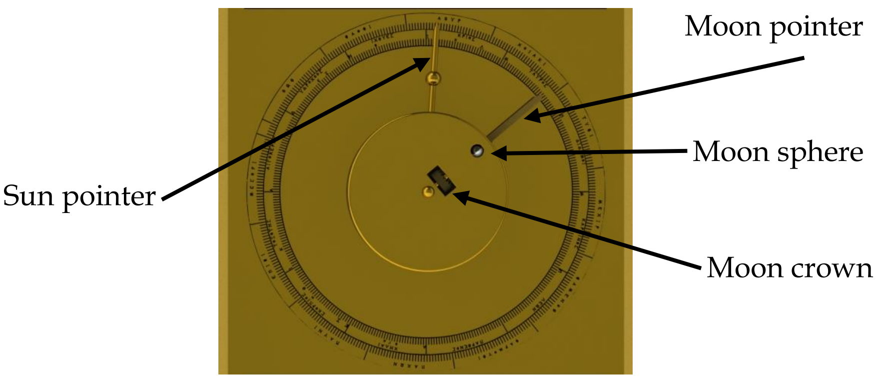

Figure 4. The centre of the front plate of the Antikythera Mechanism

Under the outer annual scale, which was a detachable ring (Figure 5, right), there were 365 holes (Figure 5, left). Every four years the operator could detach the ring and by turning it counter clockwise, move it one hole to account for leap years.

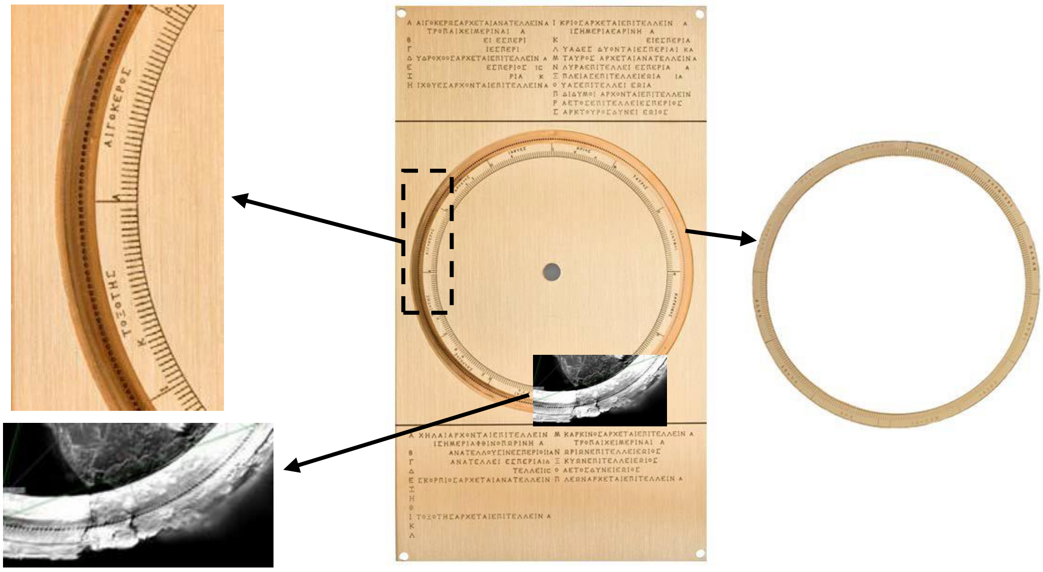

Figure 5. Front plate of the Antikythera Mechanism with the detachable ring and the tomography of a segment of the 365 holes

The Moon's pointer had two indications. In addition to the position of the Moon in the sky, it also displayed its phase (full moon, new moon, etc.). To achieve this, a rotating sphere (Figure 4) half white-half black was fitted to the pointer which rotated with the help of a crown gear.

The top and bottom of the front plate of the Mechanism were covered by inscriptions, which constituted a Parapegma (Figure 6). Parapegmata were essentially diaries of astronomical and meteorological events, which were widely used in ancient Greece. These astronomical events relate the rising and setting of stars or constellations in the sky to the rising or setting of the Sun. The realization of these events once during a solar year and their constant temporal repetition, contributed to the use for the determination of practical activities such as agriculture and navigation (Anastasiou et al., 2013; Anastasiou, 2014).

Figure 6. Parapegma of the Antikythera Mechanism

At the back bronze plate (Figure 7), the Mechanism bore five scales, the scale of Meton, the scale of eclipses or Saros Dial, the scale of Callippus, the scale of Exeligmos, and the scale of the Panhellenic Games.

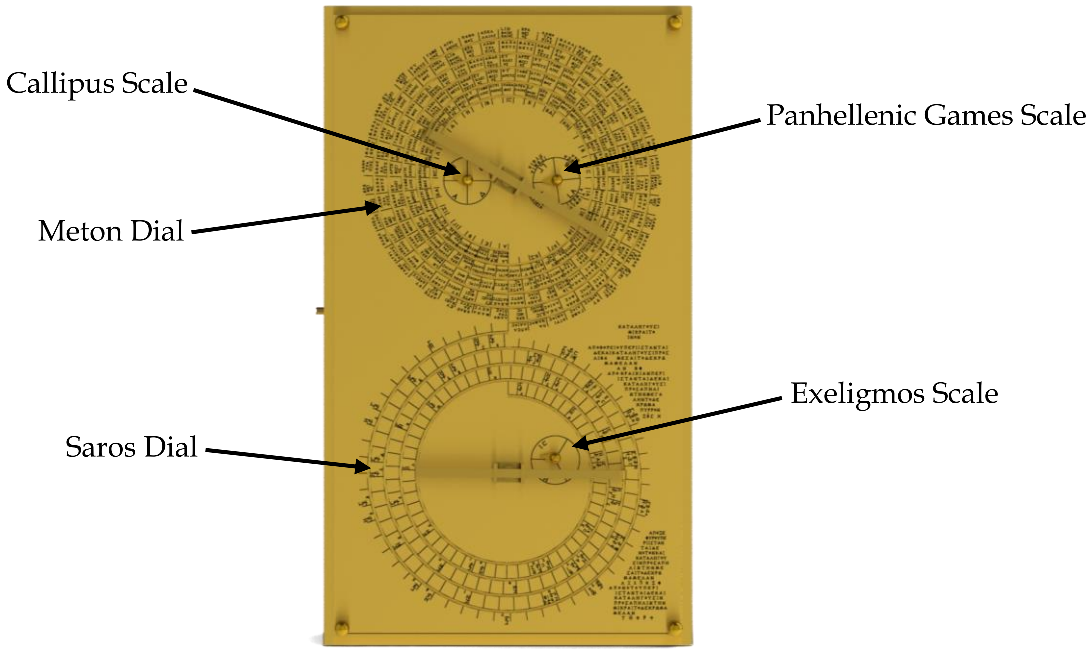

Figure 7. Back Plate of the Antikythera Mechanism

Meton's scale was a spiral with five turns (Figure 7). Its total length was divided into 235 sections, which correspond to the 235 months of the period of Meton's calendar. The ancient names of the twelve lunar months were engraved on these sections (Figure 8) and were repeated until all 235 months (19 years) were completed. Inside the spiral, there were two small circular scales, the Calyppic pointer and the Panhellenic games pointer. Callippus, an astronomer and mathematician who lived about a century after Meton, addressed Meton's work by calculating a correction which subtracted a day every 4 Callippic cycles, that is, every 76 years. This correction was made with the help of the pointer in the left part of the interior of Meton's scale. The pointer rotated counter-clockwise (opposite to the spirals' pointers) (Anastasiou, 2014).

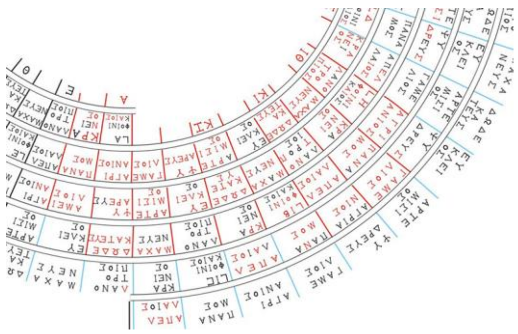

Figure 8. Part of the Metonic spiral

The pointer in the right part of the interior, displayed the ancient Greek panhellenic games in a four-year Olympic cycle. The letter "L" symbolizes the year which was written inside each quadrant. The games OLYMPIA, PYTHIA, ISTHMIA, NEMEA, NAA and ALIEIA were written at the periphery of the scale (Figure 9) (Efstathiou M., 2018; Anastasiou, 2014).

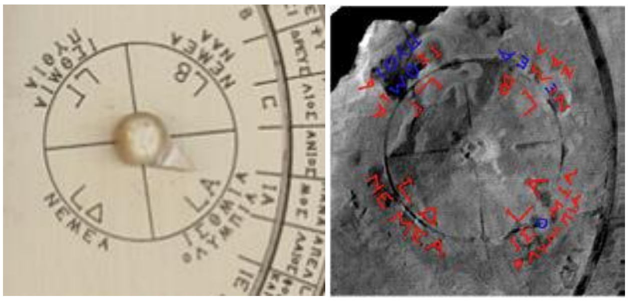

Figure 9. Panhellenic games' pointer in a replica of the Antikythera Mechanism, as well as in a tomography of the fragments

At the bottom of the back plate of the Mechanism was a spiral with four windings (Figure 10). Its total length was divided into 223 sections, corresponding to the 223 months of the eclipse/Saros period. In the months where eclipses occur there were engraved symbols. Each symbol has a specific interpretation. The symbol **H** denotes a solar eclipse. Accordingly, **Σ** denotes a lunar eclipse. The symbol means time and is followed by a letter e.g., which indicates the numerical value of the time (=8) at which the eclipse will occur. Symbol is also used which symbolizes the word day and denotes a lunar eclipse that takes place during the day and therefore is not visible.

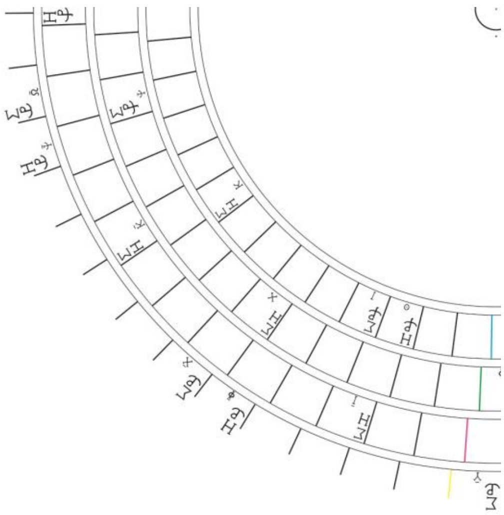

Figure 10. Part of the Saros spiral

Likewise, NY symbols that a solar eclipse occurs at night and is not visible. The day of the eclipse was determined on the front plate of the Mechanism by the Sun-date pointer on the day the Sun and Moon pointers were aligned (Anastasiou, 2014).

Inside the lower spiral scale of eclipses, there is the scale of *Exeligmos* (Figure 7) which is divided into 3 parts. On the two subdivisions are engraved the symbols H and IC, which correspond to the numbers 8 and 16, while on the third subdivision there is no inscription and essentially corresponds to the number 0. This scale corrects the time of eclipses which listed in the subdivisions. The numbers 0, 8, and 16 indicate the number of hours to be added to correct the time of an eclipse.

This is the basic structure of the Antikythera Mechanism, showing the complexity of the device as well as the wealth of scientific knowledge it contains. Below is an overview of the scientific background during its construction as well as the time of its discovery and its investigation to obtain all this information from its fragments, which remained at the bottom of the sea for almost 2000 years.

2. SCIENCES AND ARTS INVOLVED IN THE CONSTRUCTION, DISCOVERY, STUDY, DECODING AND RECONSTRUCTION OF THE ANTIKYTHERA MECHANISM

The complexity of the Mechanism requires the appropriate knowledge of almost twenty scientific fields. Specifically, during the design and the construction of the device (approximately 2nd century BC), astronomy, mathematics, geometry, engineering, metallurgy, manufacturing, geography, meteorology, artistic design as well as the specific dates of religious, social and agricultural activities and traditions had to be acknowledged. Accordingly, from 1900 up today, a number of sciences had taken part in the discovery, study, decoding and reconstruction of the Mechanism (Figure 11).

Design and construction of the Mechanism, 2nd century BC
Astronomy Mathematics Geometry (Euclidean geometry, Descriptive geometry, Solid geometry) Engineering Metallurgy Manufacturing Geography Meteorology Knowledge of religious, social and agricultural activities and traditions Artistic design

Discovery, study, decoding and reconstruction of the Mechanism (1900 - today)	
Astronomy Mathematics Geometry (Euclidean geometry, Descriptive geometry Solid geometry) Engineering Metallurgy Manufacturing Geography Meteorology Knowledge of religious, social and agricultural activities and traditions Artistic design	Archaeology, Underwater Archaeology Physics and Chemistry History Epigraphology Navigation Philology of ancient Greek and Latin Specialized new technologies (Tomography, PTM technology)

Figure 11. Sciences and arts involved in the construction, discovery, study, decoding and reconstruction of the Antikythera Mechanism

2.1. *Design and construction of the Mechanism, 2nd century BC*

❖ ***Astronomy***

The history of astronomy is intertwined with the course of man on Earth. With his first steps on Earth, man turned his gaze to the starry sky full of awe and questions. The rising and setting of the Sun, the phases of the Moon, the changing of the seasons, the movement of the planets in the sky, the appearance of comets and the shocking phenomenon of eclipses were the first stimuli to begin the systematic observation of the heavenly bodies.

As a science, astronomy began, like all sciences, with observations aimed at determining the positions and movements of the heavenly bodies. Thus, at the beginning, the astronomy of the position of celestial objects develops, and then mathematical astronomy, which essentially dominates until the middle of the 19th century. It is true that our knowledge of the universe advanced unimaginably during the 20th century, but astronomy began 3,000 years BC, with the simple observation of the sky. The Moon, the Sun, the planets, the stars and the constellations of the sky were the first things to be observed, with the aim on the one hand of creating calendars and on the other hand of connecting celestial bodies with the Gods.

If we look back 5,000 years, we see two major periods of scientific achievement in the field of astronomy. The one period is at the beginning of this era in the Greek world of Anaximander, Aristotle, Aristarchus Samius, Hipparchus and Claudius Ptolemy. The other period is in the last five centuries. Especially in the 20th century the achievements of astronomy are enormous.

It is generally accepted that geometrical astronomy was founded and matured in ancient Greece. The ancient Greek astronomers founded the science of astronomy and set the guidelines on which it is still based.

The Greeks many centuries or even millennia before Christ knew how to interpret astronomical phenomena and the celestial dome. In fact, attempts at celestial mapping are reported as early as the 2nd millennium BC. Early Greek astronomy was developed and promoted by great people of the Greek spirit. During the period of early Greek astronomy, the main characteristic that stands out in the thinking of the thinkers of the time is the eviction of the supernatural element from the conceptions of the world and its creation. It is the time when for the first-time man tried to submit the natural phenomena to a rational process which would give him explanations, without depending on the previous supernatural concepts. After Orpheus, Hesiod and Homer, the scientific development of astronomy begins in Greece, with Thales around 600 BC, which is characterized by the attempt of a series of astronomers (Table 1) to formulate laws for the observed astronomical phenomena.

Table 1. Famous astronomers of ancient Greece and the most likely time period they lived.

Name	Date (B.C.)
Meton	5th
Philolaus of Kroton	~ 470 – 385
Evdoxos of Knidos	~ 407 – 335
Kallipos	370 – 300
Aristarchus of Samos	310 – 230
Hipparchus of Rhodes	190 – 120
Poseidonios of Rhodes	~ 135 – 51

The Presocratic philosophers were the first to begin to investigate natural phenomena in this way. In this effort, they also developed various hypotheses regarding the structure and beginning of the universe (cosmology) (Nikoli, 2012).

The first phase of the development of astronomy is connected with serving purely practical needs, such as the existence of a calendar, orientation on land and at sea, etc. and more generally with determining time. The first unit of time intuitively developed by man is that of day-night, i.e., the time it takes the Earth to make one revolution on its axis. This primordial unit of time has remained intact over the centuries. All civilizations that created time measurement systems not only kept this first unit but tried to have the basic magnitudes be integer multiples of the day. For many years the seasons, with their different climates, were also a very important unit of time measurement because they played a crucial role in people's lives. However, it was gradually found that the exact starting time of each era could not be determined. For this reason, people turned to more stable natural phenomena to base their calendars. One of these phenomena was the rising and setting of some bright stars.

The Egyptians and the Chaldeans used 36 bright stars whose rising marked the beginning of 36 decades of the year (36 x 10 = 360 days). The Greeks at the time of Hesiod in the 8th century BC, before the formation of their regular calendar, used the stars as a unit of time as well.

But even this way of measuring time was overcome with time. The stars were not always visible due to weather conditions. To solve this problem, but also for other mysterious reasons, the creation of calendars was based on the periodic phases of the Moon as well as the periodic movement of the Earth around the Sun. Based on the phases of the Moon a second unit of time was also discovered which was the week of 7 solar days and about 9 hours, the time during which each lunar quarter evolves.

The great issue which led to the creation of plenty and complex calendars in all civilizations, was that these periods of time for the completion of the phases of the moon did not consist of a whole number of days (Theodosiou, 1995). To solve this problem, these calendars divided the political year into 12 lunar synodic months of 29 or 30 days whose duration is equal to the time of the moon's revolution around the Earth (about 29.5 days e.g., from one full moon to another). Although the division of the year into lunar months was a natural division of the year, it had the disadvantage that the solar year - the time it takes the Earth to make one complete revolution around the Sun - did not coincide with the twelve orbits of the Moon around the Earth (Theodosiou, 1995). So, a lunar year has 12 lunar months with 354.367068 days and differs from the solar year by 10.8751 days (about 11 days).

The solution to the problem of harmonizing the solar year with the lunar months was given by the Athenian astronomer and mathematician Meton in 432 BC. Meton calculated that in the time period of 19 solar years there are 235 lunar months or 6940 days (Koetsier Teun, 2009). But 19 solar years x 12 lunar months = 228 lunar months, not 235. To solve the difference of these 7 months - resulting from the difference of 11 days in each solar year compared to the lunar years – he added to seventh of the nineteen years an additional month, known as the "*εμβόλιμος μήνας*" or intercalary month. Thus, the problem of matching the lunar months with the solar years was solved.

Kallipos, 200 years later, had calculated that Meton's calculations had to be corrected. Precisely, as the Metonic cycle is a periodical phenomenon, you must subtract one day every 76 years or every four Metonic cycles (4 x 19 = 76). These calculations are performed by the Mechanism and are displayed on two scales at the back side of the Mechanism. In one of the few references regarding the Mechanism, Cicero noted that he visited the laboratory of Poseidonios in Rhodes, where he admired a celestial sphere made by Poseidonios.

Another fundamental philosophical and scientific controversy in human history was the definition of the center of the Universe and the place of the Earth in it. This controversy began around the 6^{th} century BC until the beginning of the 18th century AD. The main theories were the Geocentric, the Pyrocentric and the Heliocentric models. The Geocentric model was based on the interpretation that Earth was at the center of the Universe, was spherical and stationary. The main exponent of this theory was Aristotle. The Pyrocentric theory holds that Fire was the first Principle of the Universe. So, after the Creation, the Fire was concentrated in the center of the World and the attraction it exerted on various other bodies created a formation that led to the Universe. Pyr (fire) stands at the center of the Universe and around it Antichthon, the Earth, the Moon, the Sun and the planets moved in a spherical orbit. The main exponents of this theory were Philolaus of Kroton and other Pythagorean philosophers (Busoutas – Thanasoulis, 2010). The formulation of the Pyrocentric theory was based on a revolutionary view for that time, that the Earth is not at the center of the Universe but Fire. The 'dethroning' of the Earth from the center was a very big step for the subsequent development of a theory that would place the Sun at the center. The two aforementioned theories (Geocentric, Pyrocentric) could not give the astronomers of the time the possibility to clearly explain the retrograde course of the planets Mars, Jupiter and Saturn. The answer was given by Aristarchus, a Greek astronomer and mathematician, born in Samos. He is the first scientist who, in his attempt to explain the retrograde course of the planets, proposed the heliocentric model of the Solar System, placing the Sun and not the Earth at the center of the known Universe (Evans, 1998). Aristarchus' theory of Heliocentrism, although correct, was not accepted until the 15^{th} AD. (see on heliocentric versus geocentric systems and ancient beliefs in Liritzis and Coucouzeli 2007).

This is due, according to researchers, to the superstitious view of the time, that since the residence of the Gods was on Earth, then the Earth must be in the center and be stationary so as not to disturb the tranquility of the Gods. In fact, this view was accepted and strengthened by the Christian Church. Another reason was that man, from his direct experience as an observer of the sky and the heavenly bodies, considers himself, and therefore the Earth, stationary, while the rest of the bodies revolve around him. This experience combined with the philosophical authority of Aristotle left no room for questioning the Geocentric theory for more than two millennia.

Later researchers, supporters of the Geocentric theory, tried to provide answers to the disadvantages of this theory. Apollonius the Pergaeus (~260 BC – 170 BC) and Hipparchus the Rhodian (190 BC – 120 BC) in their attempt to solve the retrograde course of the planets introduced the system of the carriers of circles and epicycles (Koetsier Teun, 2009; http://www.noesis.edu.gr/aet/thematic_areas/p346.html). Thus, they explained the changing angular velocity of the moon as it revolved around the Earth, as well as the retrograde turns of the planets. Additionally, Hipparchus calculated the size of the Earth, the Sun and the Moon and the transient motion of the Earth which lasts almost 26,000 years. Another important calculation mentioned in written sources as being made by Hipparchus is the determination of the distance between the Earth and the Sun as well as the Earth and the Moon.

The Antikythera Mechanism was built in 200-150 BC. It is not certain whether it is based on the geocentric or the heliocentric theory since the phenomena are calculated by taking into account the relative motion of these celestial bodies to each other, whether one is at the center of the universe or the other. The important thing is that written sources prove that the scientists at the time of the construction of the Mechanism had the knowledge to calculate the positions and the movements of the heavenly bodies accurately, whether they were supporters of one theory or the other.

In addition, they knew the phenomena of solar and lunar eclipses. The Babylonians had observed and recorded for many years the phenomena of the eclipses. From their observations they knew that to have a lunar eclipse we must have a Full Moon, while to have a solar eclipse we must have a New Moon. Around 575 BC, having records of eclipses over a period of more than 500 years, they discovered that eclipses repeat in the same order every 223 synodic months. In fact, they knew that in a period of 223 synodic months, they had 38 lunar eclipses. To determine the months in which an eclipse would occur, they used a schematic sequence of 8-8-7-8-7. Their distribution showed that in the Saros cycle the first eight eclipses occurred every six months. At the end of the eighth eclipse, they had a period of 5 months without an eclipse. Then a cycle of 8 eclipses at six-month intervals was repeated, and then they had a five-month gap, followed by a cycle of seven eclipses at six-month gaps, and so on. So, in each set of 8 eclipses, we have 47 months, while in each set of 7 eclipses we have 41 months. So, 47+47+41+47+41= 223 months.

This period of 223 synodic months is called the Saros cycle and took its name from Sir Edmund Halley, while the ancient astronomers called it Periodicity. The cycle of Saros corresponds to 6,585 and 1/3 days. To arrive at a whole number of days, astronomers before Hipparchus tripled the cycle of Saros and derived a period of 19,756 days which they called an "Exeligmos-*Εξελιγμός" or* Evolution (Koetsier Teun, 2009; see also Voulgaris et al., 2021). Saros and Exeligmos cycle are both displayed in the back side of the Antikythera Mechanism. It is worth mentioning that the Mechanism could predict not only the date of eclipses but even whether they would be visible or not (day or night) as well as the exact time they would occur.

- ***Mathematics***

The aforementioned knowledge in the field of Astronomy obviously presupposed an excellent knowledge of the science of mathematics, so that they could calculate all these phenomena and pass from the stage of observation to the production of equations so that they could make predictions about these phenomena in the future.

But this knowledge was really important even in the production stage of the Mechanism. Knowledge of Mathematics was necessary to determine the necessary gears, their size and the appropriate number of teeth, as well as to design the gears and other complex parts of the device, such as the two dials on the back of the Mechanism (Metonic and Saros) that appeared on two spiral scales.

- ***Mechanics (Metallurgy, Engineering, Manufacturing)***

The scientific community gives great emphasis on ancient Greek literature, mathematics, and philosophy as opposed to engineering. The discovery of the Antikythera Mechanism shows the high expertise of the ancient Greeks in metallurgy as well as in the creation of complex gear mechanisms. Pappus of Alexandria (290 AD – 350 AD), in his writings describes machines of earlier mathematicians and engineers such as Archimedes, Heron, etc. He mentions that Mechanics was divided into two parts, the theoretical and the applied. The theoretical part consisted of geometry, theoretical arithmetic, astronomy, and physics. The applied part consisted of metallurgy, construction, tectonics, painting, and their manual application (Efstathiou M., 2018; Spandagos, 2006).

  - *Metallurgy*

Humanity from the discovery and use of metals in order to manufacture tools and weapons entered a new technical-economic-social stage. The earliest organized metal mining appears to have taken place in copper mines in Egypt's Sinai Peninsula during the 4th millennium BC. Copper was the material that revolutionized man's equipment, as bronze replaced stone tools used to make weapons, utensils, clothing, and jewellery. New metal tools led to the development of new techniques such as marble carving and wood carving.

In the Hellenic world, the first metals appear around 5,000 BC whereas the use of metal objects occurred much later. From the archaeological findings, it is evident that the ancient Greeks used copper, gold, and silver for the manufacture of various decorations, jewellery, and coins. As usual, gold and silver as precious metals were used sparingly. Copper replaced gold in many applications, but it could not be used to make weapons and tools because it is a soft metal. For these implementations, they produced bronze, which is an alloy of copper with tin. There are many findings, which after analysis proved to be made of bronze (Tsaimou, 1997). Of course, the Antikythera Mechanism is included among them.

A characteristic reference is found in an inscription found in Eleusina (Figure 12), dating to the 5th century BC which describes an order for the manufacture of the copper links for the connection of the marble columns of the Philonia Lodge. There is a clear reference to the composition they should have: "...*The brass which shall come from Marion shall be an alloy of eleven parts of copper and one part* (1/12, that is 8.33%) *of tin*."

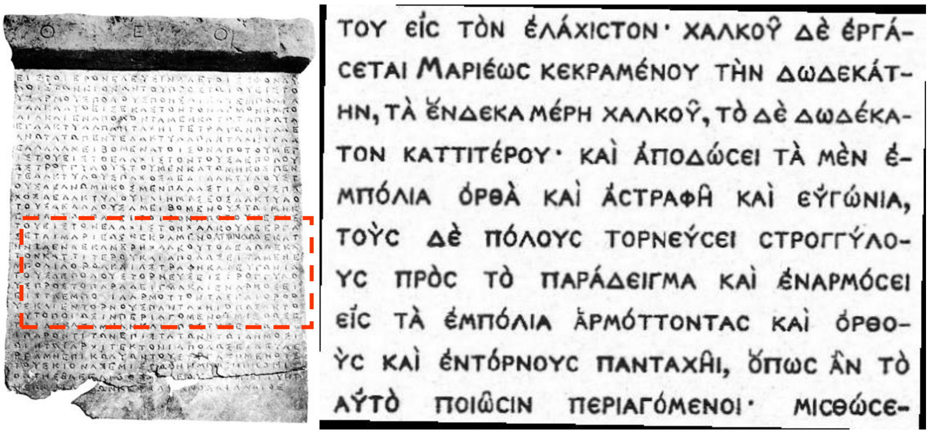

Figure 12. Inscription found in Eleusina, 5th century BC, Archaeological Museum of Eleusis, Greece

It is therefore clear that the ancient Greeks knew the production and use of bronze long before the construction of the Mechanism. The question that arises concerns the way in which the processing of the bronze took place. As for decorative pieces, statues, etc., they used methods that are known to them such as casting, engraving, forging, and rolling of bronze sheets, etc. However, for the manufacture of shafts or cylindrical parts that precision is required, such as e.g., the axes of the Mechanism, the use of a lathe is required. Although today we know of the existence of lathes for cutting soft materials such as wood, is it possible that there were lathes that used metal tools for the manufacturing of bronze parts? The above inscription (Figure 12) gives the answer to this question "...he will turn the (bronze) poles according to the pattern...". The information is important because it indicates the use of metal tools stronger than bronze, since to machine a part with a tool, the tool must be made of a stronger material than the part. The most common materials for this type of machining are steels, which are ferrous materials with a certain amount of carbon.

According to recent studies, steel has been known in western Iberia during the period between the Final Bronze Age (FBA, 1200–800 BCE) and the Early Iron Age (EIA, 800–600 BCE)[1] (Gonzalez et al., 2023), as well as in Greece since the 7th century BC (Efstathiou, M. et al., 2013). In Lavrio the metallurgy of iron and steel was developed, which were necessary for the manufacture of tools used in the mines but also in general in the arms and tools industry in Athens. The metallurgy of iron for the ancient metallurgist was quite a difficult process as high temperatures in the furnace could not be achieved (iron has a melting point of 1,540°). During the smelting of iron ores, the ancient metallurgist instead of liquid metal in the furnace, produced a spongy mass (the melt) in which the iron was enclosed in the form of pellets and the rust in a pulpy state. The rust was removed from the iron by forging at a high temperature of 1,200-1,300°C in a furnace. The melt was formed by forging into a continuous mass of iron. Steel was produced in the form of carbonized sheets. The forged thin sheets of iron with the above process were placed in clay sealed vessels with enough charcoal powder (Figure 13) (Tsaimou, 1998).

[1] Iron became common between 1100 and 900 BC, but by convention EIA archaeology begins around 1200, with the destruction of the Late Bronze Age (LBA) palaces. The period has existed as a scholarly construct since Schliemann's excavations in the 1870s. Petrie's 1890 synchronism between Mycenaean pottery and Egypt's Nineteenth Dynasty fixed the fall of the palaces around 1200, defining a 500-year interval between Mycenae and the archaic age. Some historians end the EIA in 776 BC, with the first Olympic Games, but most see a longer eighth-century transition, marked by population growth, state formation, colonization, and the return of literacy, representational art, and monumental architecture. (Morris 2007).

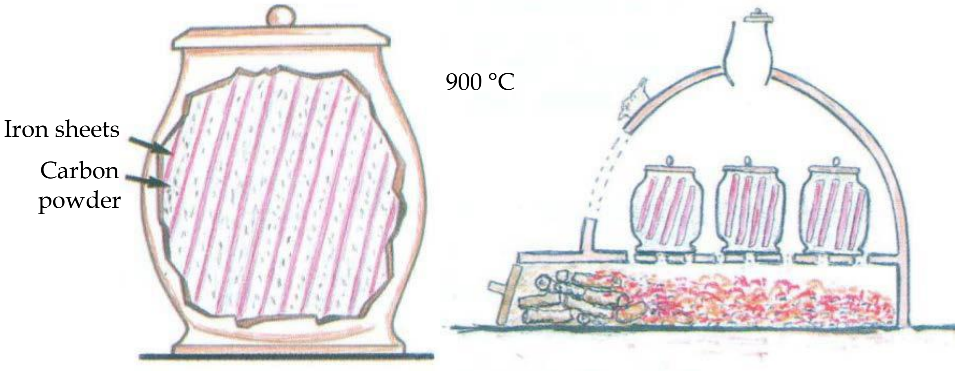

Figure 13. Representation of carbonization of iron in the form of thin sheets

In 1961 nuclear physicist Lyle Borst, known for his involvement in the development of the first atomic bomb, investigated three metal samples taken by himself from Sparta, dating back to 650 BC. Archaeologists believed that the metal fragments belonged to ancient coins, while he claimed that at least one of them was a spear fragment. The analyzes revealed that the samples were made of excellent-quality steel with minimal impurities. The elastic limit of the sample was calculated to be 358.5 MPa, about twice the elastic limits of today, while the carbon content was between 0.2-0.8%. After this analysis, he stated that the possession of this knowledge at that time corresponded in power to the possession of an atomic bomb in 1961 (Plumb, 1961). It is clear that at the time of the Mechanism's construction there was all the necessary know-how in metallurgy. The bronze from which the Mechanism was made was widely used during this period. Moreover, they had at their disposal the raw materials for their tools and the appropriate machines so to manufacture complex mechanical metal parts.

- *Mechanisms*

The ancient Greeks had complex lifting machines (Figure 14), which they used in the construction of huge building projects, such as e.g., in the construction of the Parthenon temple.

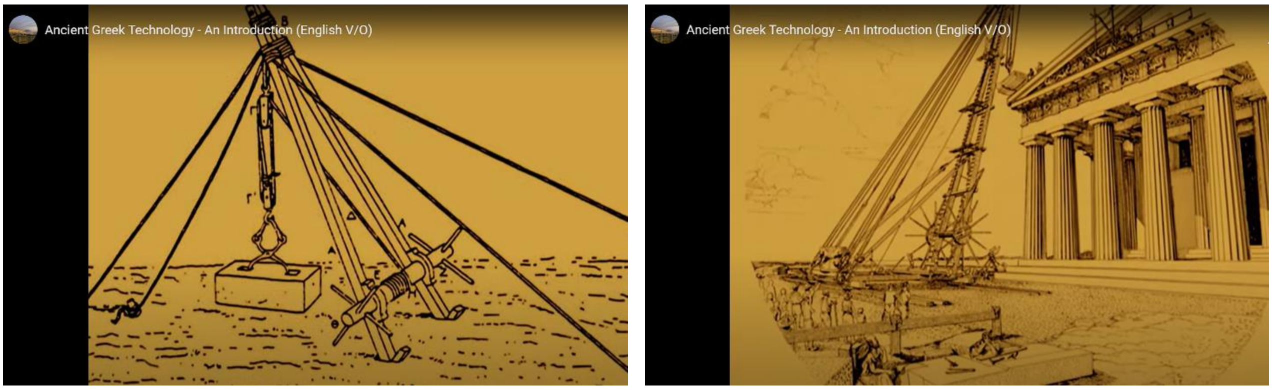

Figure 14. Heavy lifting machine and crane (Ancient Greek Technology 1997)_

Also, constant conflicts with powerful military forces such as the Persians, necessitated the construction of complex military machines (Figure 15) mainly for defensive purposes, but also for offensive ones, as in Alexander the Great campaign.

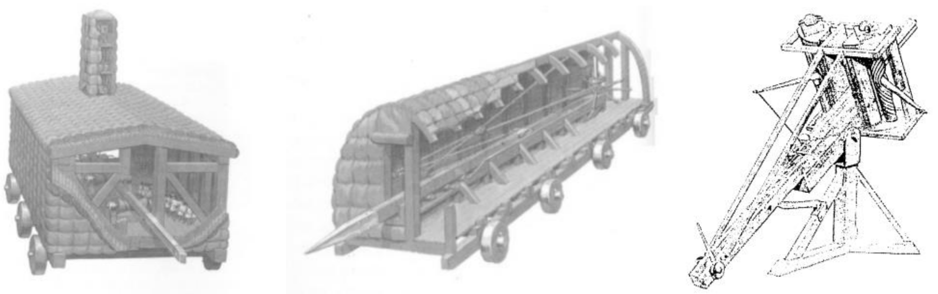

Figure 15. War machines built during Alexander the Great's campaign (Lazos, 1993)

But how did these machines work? Did they use pulleys, levers, belts, screws, or gears? Was this knowledge then available? The first references were some descriptions to jagged wheels in manuscripts, such as at the Aristotle's Mechanical Problems. There are also some sources refer to Archimedes as the constructor of war machines used similar wheels, around 250 BC. But the clearest references to toothed wheels, detected in an Alexandrian engineer Heron, as well as in Vitruvius, without naming their origin or discovery. However, Archimedes and Ctesivius are considered as the possible inventors of the jagged wheel.

The most important source on the knowledge and use of such mechanical components is found in the Mathematical Synagogue of Pappus of Alexandria. In this writing he describes the construction of a machine that uses gears to produce the necessary power to lift a certain weight (Figure 16). In the description he mentions that everything he describes has been proven in the works "On Balances" by Archimedes, "Mechanics" by Heron of Alexandria and "Mechanics" by Philo of Byzantium, of which almost nothing survived (Spandagos, 2006).

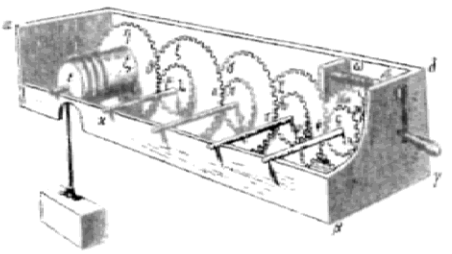

Figure 16. Heron winch with toothed wheels

Moreover, he refers to a basic coupling principle of two cooperating gears according to which in order for two gears to cooperate they must have the same module, i.e., have an equal ratio of diameter to the number of teeth. Accordingly, he sets a problem to be solved, in which the diameter and the number of teeth of one gear are known and students have to calculate the diameter of the second if the number of its teeth is known survived (Spandagos, 2006). Additionally, he refers to the work of Apollonius of Pergaeus "On screws or helixes" and explains the mathematical calculations to construct a gear with helical teeth and then describes how such a gear cooperates with an unending screw (Figure 17) (Spandagos, 2006).

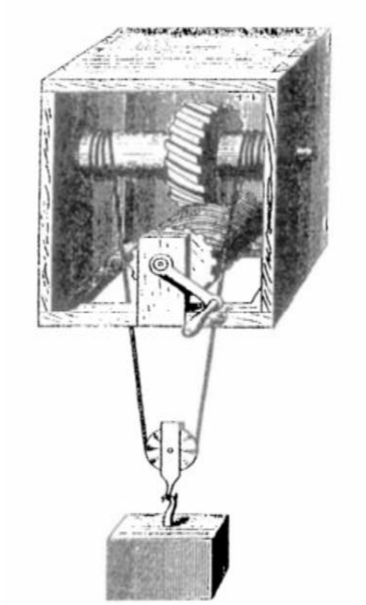

Figure 17. Winch using helical gear and worm gear

From the above references it is obvious that our ancestors had the knowledge of making and using gears at least 2 to 3 centuries BC. Arguably, these reports describe simpler constructions than the Antikythera Mechanism, but the find demonstrates the ability to develop such complex devices as well.

❖ ***Geography, Meteorology***

The date pointer refers to texts engraved on the surfaces of the back site dials of the Mechanism referring to directions such as (Figure 18) (Freeth, 2014): "From the North-North-West and they revolve and end towards the East ...". Price de Solla argued that the directions refer to winds (De Solla Price, 1974). Tony Freeth argued that the directions refer to directions of obscuration of Lunar eclipses (Freeth, 2014).

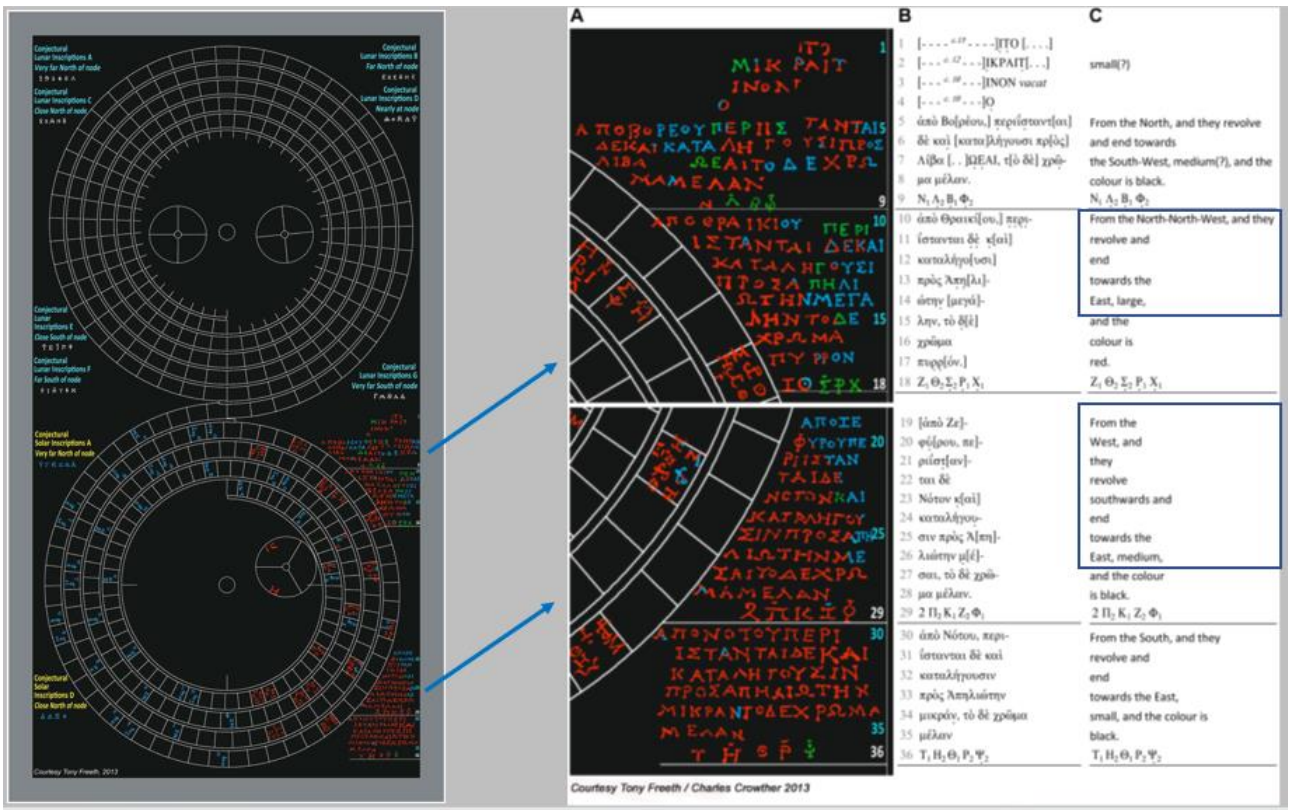

Figure 18. Texts engraved on the surfaces of the back site dials of the Mechanism

❖ ***Knowledge of religious, social and agricultural activities and traditions***

Knowledge on religious, social and agricultural activities and traditions was necessary to design the Parapegma of the Mechanism as well as the scales of the Panhellenic games (see the introduction pages 2-6). The Parapegma contributed to the use for the determination of practical activities such as agriculture and navigation. Hesiod mentions that the harvest period begins, on the day it will appear the constellation of Pleiades for the first time in the sky.

2.2. Discovery, study, decoding and reconstruction of the Mechanism (1900 - today)

It is obvious that the use of the forementioned Sciences and knowledge, were also necessary for the discovery, study, decoding and reconstruction of the Mechanism from 1900 up today. Moreover, were necessary Sciences and knowledge considering Archaeology, Underwater Archaeology, Physics, Chemistry, History, Epigraphology, Navigation, Philology of ancient Greek and Latin and Specialized new technologies (Tomography, PTM technology). For example, making use of these scientific fields it was possible to determine the celebration date of the Pythian games (Thursday 24 August 2023) assuming that they were taken place in modern era (Efstathiou et al., 2022).

❖ ***Archaeology and Underwater Archaeology***

In first century BC, a large Roman ship battled with the waves on the rough sea between the mainland of Greece and Crete. Finally, the boat sank on the shores of the small Greek Island Antikythera. The ship was loaded with works of art and other precious artifacts. Two thousand years later, at the Easter of 1900 AD sponge-divers from the Greek Island Symi, discovered accidentally the ancient shipwreck off the coast of the Greek Island of Antikythera. Underwater excavation began at the end of November 1900 (Figure 19), and a few months later, important findings were recovered, now exhibited at the National Archaeological Museum of Athens (Kaltsas, 2012).

Figure 19. 1900 underwater excavation on the shores of the Greek island of Antikythera

Among the findings, a strange bulk of material, broken, worn and calcified, was located with obvious signs of bronze plating (Figure 20) (Kaltsas, 2012). In the first publication of the Antikythera shipwreck (Archaeological Ephemeris, 1902), the existence of the Mechanism was mentioned with the suggestion that it was an astronomical instrument. The Antikythera Mechanism, after 2000 years on the seabed, was expected to change the accumulated knowledge so far on the technological skills of the ancient Greeks.

Figure 20. The fragments of the Antikythera Mechanism, National Archaeological Museum of Athens

- ***Chemistry, and Metallurgy***

Chemistry, and Metallurgy were necessary for the chemical analysis of the parts, found in the fragments and the identification of the material used for the construction of the Mechanism and to choose corresponding material for the reconstruction of the Mechanism.

The material used to construct the various parts of the Mechanism, except for its wooden mounting box, is bronze, a copper - tin alloy. The chemical analysis showed that the fragments were made of bronze, with a tin content of about 5% (Kaltsas, 2012). Newer analyses by Panagiotis Mitropoulos in 2018 (Kaltsas, 2012) revealed three alloys, the main components of which are copper, tin and lead. The shares of copper tin and lead varied. It can be assumed that the individual parts of the mechanism consist of copper alloys of different composition (Vlachogianni, 2015).

- ***History and Epigraphology.***

The necessity of having Historian experts is an obvious need. Epigraphology was used to estimate the date of the construction of the Mechanism. The epigraphic research carried out, for the study of the types of letters of the texts (inscribed) in the fragments of the Mechanism, has shown that the Antikythera Mechanism must have been constructed approximately between the second half of the 2nd century BC. and the beginning of the 1st century BC, i.e. between 150 - 100 BC, with an error of ± 50 years (Freeth et all., 2006).

- ***Geography and Navigation.***

Knowledge on Geography and Navigation combined with History knowledge were necessary to determine probable courses of the sunken ship on the shores of Antikythera. Relevant studies have shown that most probably the ship started from the eastern Aegean, probably from Pergamon, with stops on various islands such as Rhodes and then headed west, traveling north of Crete and south of Peloponnese, red line on Figure 21. It sank between Peloponnese and Crete. The usual course of these ships continued north along the coasts of western Greece to the height of Corfu and from there southwest to Syracuse with a final destination in Rome, blue line on Figure 21 (Seiradakis, https://clioturbata.com/%CE%B1%CF%80%CF%8C%CF%88%CE%B5%CE%B9%CF%82/chiradakis_antikythera_mechanism/).

Figure 21. Probable course of the ship

❖ *Philology of ancient Greek and Latin.*

Knowledge on **Philology of ancient Greek and Latin** was necessary for researching ancient Greek and Latin sources for information related to the Mechanism. Some of the most important examples are the followings:

References to mechanisms similar to the Antikythera Mechanism in ancient Greek sources

Two examples of Greek bibliographic sources are:

1. Pappus of Alexandria: Mathematical *Collection, Book H΄:*

Μηχανικούς δέ καλοῦσιν καί τούς τάς **σφαιροποιίας** [ποιεῖν] ἐπισταμένους, ὑφ' ὧν εἰκών τοῦ οὐρανοῦ κατασκευάζεται…. Κάρπος δε πού φησιν ὁ Ἀντιοχεύς **Ἀρχιμήδη** τόν Συρακόσιον ἓν μόνον βιβλίον συντεταχέναι μηχανικόν τό κατά την σφαιροποιίαν, τῶν δέ ἄλλων οὐδεν ηξιωκέναι συντάξαι.

2. Proclus: A Commentary on the First Book of Euclid's Elements:

... ὑπό δέ τήν μηχανικήν ἐστίν… καί η **σφαιροποιία** κατά μίμησιν τῶν οὐρανίων περιφορῶν, οἵαν **καί Ἀρχιμήδης** επραγματεύσατο, και όλως πάσα η της ὕλης κινητική.

Both writers use the term **Σφαιροποιία**, which refers to the construction of celestial globe or sphere that represent the movements of celestial bodies in the sky, like the Antikythera Mechanism. They also refer to Archimedes **(Ἀρχιμήδης)**.

References to mechanisms similar to the Antikythera Mechanism in ancient Latin sources

The most known reference to celestial spheres is made by Cicero, who also mentions **Archimedes** and the astronomer **Posidonius** from Rhodes.

1. Cicero in his work "Tusculanae Disputationes I, Paragraph 63"

Nam cum **Archimedes** lunae, solis, quinque errantium motus in sphaeram inligavit, effecit idem quod ille, qui in Timaeo mundum aedificavit, Platonis deus, ut tarditate et celeritate dissimillimos motus una regeret conversio. quod si in hoc mundo fieri sine deo non potest, ne in sphaera quidem eosdem motus Archimedes sine divino ingenio potuisset imitari.

2. Cicero in his work "De Natura Deorum II, xxxiv Paragraph 88

Quodsi in Scythiam aut in Britanniam sphaeram aliquis tulerit hane quam nuper familiaris noster effect **Posidonius**, cuius singulae conversions idem efficient in sole et in luna et in quinque stellis errantibus quod efficitur in caelo singulis diebus et noctibus, quis in illa barbaria dubitet quin ea sphaera sit perfecta ratione?

3. Cicero in his work "De Republica, xxxiv Paragraph 88 - translation of Treatise on the Republic from Duke of Wellington, pp. 158-160"

... I had often heard this celestial globe or sphere mentioned on account of the great fame of **Archimedes**. Its appearance, however, did not seem to me particularly striking. ….

4. Publius Ovidius Naso in his work «Fasti VI» (translation)

There stands a globe hung by Syracusan art in closed air, a small image of the vast of heaven, and the earth is equally distant from the top and bottom. That is brought about by its round shape….

- ***Knowledge on Physics and on specialized new innovative technologies.***

In order to be able to see the internal parts and features of the fragments of the Mechanism as well as to read the engraved on the fragment's texts, specialized new innovative technologies were used.

In September 2005, was conducted a major new investigation of the Antikythera Mechanism, using an innovative and state of the art high power micro-focusing X-ray tomographer (see left part of Figure 22), especially constructed by X-Tek Systems (Ramsey, 2007) and the Hewlett Packard, USA, PTM Dome technique (see right part of Figure 22) (Malzbender, 2021). PTM Dome's innovative digital image capture mechanism (Advanced photography for reading texts., made possible the reading of also captured faded and worn inscriptions and other details of the surface of the fragments of the Antikythera mechanism even if they were not visible with the best systems of conventional and digital photography. In November 2006, the results of the investigation were announced during an international conference in Athens and published in the international journal Nature (Freeth et al., 2006). The three-dimensional images that were obtained when the fragments of the ancient mechanism were examined revealed internal details of gearing and inscriptions that remained hidden on the seabed of the Antikythera more than two thousand years. All inscriptions are written in Greek. A new font (True type font, Figure 23) has since been developed at the Aristotle University of Thessaloniki, Greece, reproducing the fine art letters (Anastasiou 2014).

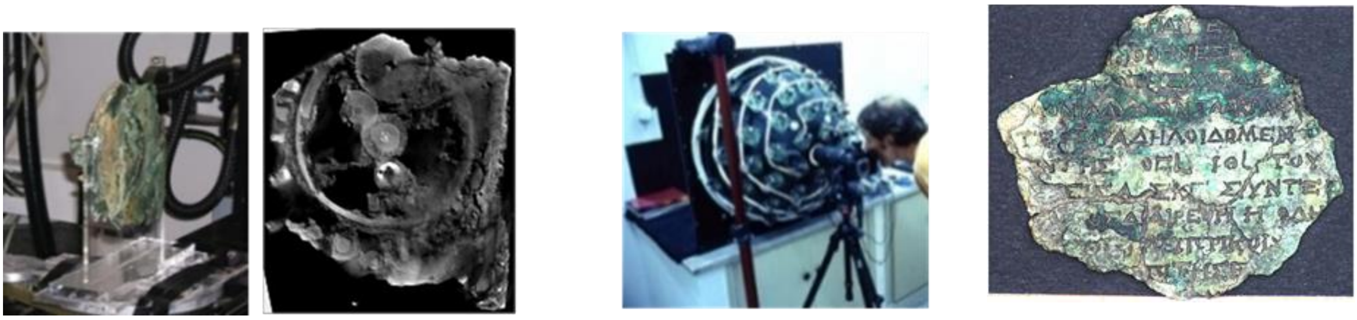

Figure 22. X-ray tomography of the fragment A by Roger Hadland (**left**) and investigation of the fragment 19 using the PTM Dome technique by Tom Malzbender and Dan Gelb (**right**)

Figure 23. The Antikythera Mechanism True type font

3. STEM, STEAM, STEMAC AND THE ANTIKYTHERA MECHANISM

The Antikythera bronze device (mechanism) has been investigated thoroughly on an interdisciplinary manner. A multi-scientific effort has been corroborated to reconstruct and date this extraordinary world earliest "computing" device ( ). In fact this study is an example of STEM which is an educational approach that combines technology and engineering together with science and mathematics, which are important for understanding the laws of the universe. *"STEAM (STEM working together with Arts) values the benefits of science-technology-engineering-mathematics (STEM) and fulfils the set by merging these principal disciplines. STEAM rises up STEM to the next level: it provides students to network their learning in these critical areas together with arts* *concepts and practices, design principles, and standards in such a way to provide the whole floor of learning at their disposal" "STEMAC aids the transculturation via STEM in a globalized society preserving the cultural roots and interrelated the beginnings and common traits of humanity, diversified from various environmental factors"* (Liritzis, 2018). *"Using proper tools from STEM applied to Arts & Culture could refer to some interesting topics, such as teaching astronomy from astronomical significant monuments, and artifacts, deciphering and simulating myths related to cultural heritage measurements"* (Liritzis, 2018).

As described above, the construction, discovery, decoding, and reconstruction of the Antikythera Mechanism spans a multitude of disciplines (Astronomy, Mathematics, Engineering, Archaeology, Physicς, Chemistry, History, Philology, Specialized new technologies, Artistic design etc.) Thats make the Antikythera Mechanism the prime example for STEMAC education.

DISCUSSION AND CONCLUSION

The Antikythera Mechanism, a complicated device of the 2nd century BC, has been thoroughly examined using multi-scientific and interdisciplinary approaches since its discovery in 1900. Scientists from various scientific fields and specialties such as archaeologists, historians, philologists, astronomers, archaeo-astronomers, mathematicians, palaeogeographers, navigators, physicists, chemists, mechanical engineers etc. have all participated in its long-term research. Over almost a century and a quarter of study, the emerging technologies available to those scholars have been used to study its structure, such as x-rays, PTM technologies, CT scans, chemical analyses, and simulations of its operation with the help of CAD systems, VR, AR, etc. These investigations have concluded that the Mechanism was assembled in a wooden box with its front and rear covered by bronze plates with a calendar, astronomical scales and pointers. These metal surfaces were protected by two wooden outer covers, to which densely inscribed bronze plates were attached. Internally the Mechanism contained at least 39 cooperated gears which moved several pointers simultaneously, predicting astronomical phenomena in the corresponding scales. Its operation could predict the position of the sun, moon, and planets, moon phases, solar and lunar eclipses, adjust the calendar for leap years, and determine the dates of famous ancient festivities. Perhaps the most remarkable fact of the Mechanism is not its uniqueness in the archaeological record, but that it represents the apogee of Ancient Hellenistic World engineering created from the accumulated expertise and knowledge in Greece. It demonstrates that the Greek mechanicians of the Hellenistic period had become far more skillful in designing geared devices than the surviving written sources imply. It would not be until the development of mechanical clocks in the thirteenth century that geared devices matching the complexity of the Antikythera Mechanism would appear again in Europe; and as one of the main Mechanism researchers, the astronomer John H. Seiradakis, used to say the Antikythera Mechanism is as important for technology and sciences as the Acropolis for architecture and the arts. It is no wonder, therefore, that Antikythera Mechanism is considered to be the earliest known analogue computer.

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