The Role of Astronomy in Society and Culture
Proceedings IAU Symposium No. 260, 2009
D. Valls-Gabaud & A. Boksenberg, eds.

doi:10.1017/S1743921311002225

The Antikythera Mechanism: The oldest mechanical universe in its scientific milieu

Xenophon Moussas

Astrophysics Laboratory, Faculty of Physics,
National and Kapodistrian University of Athens,
Panepistimiopolis, GR 15783 Zographos, Athens, Greece
email: xmoussas@phys.uoa.gr

Abstract. In this review the oldest known advanced astronomical instrument and dedicated analogue computer is presented, in context. The Antikythera Mechanism a mysterious device, assumed to be ahead of its time, probably made around 150 to 100 BCE, has been found in a 1st century BCE shipwreck near the island of Antikythera in a huge ship full of Greek treasures that were on their way to Rome. The Antikythera Mechanism is a clock-like device made of bronze gears, which looks much more advanced than its contemporary technological achievements. It is based on mathematics attributed to the Hipparchus and possibly carries knowledge and tradition that goes back to Archimedes, who according to ancient texts constructed several automata, including astronomical devices, a mechanical planetarium and a celestial sphere. The Antikythera Mechanism probably had a beautiful and expensive box; looking possibly like a very elaborate miniature Greek Temple, perhaps decorated with golden ornaments, of an elegant Hellenistic style, even perhaps with automatic statuettes, 'daemons', functioning as pointers that performed some of its operations. Made out of appropriately tailored trains of gears that enable to perform specialised calculations, the mechanism carries concentric scales and pointers, in one side showing the position of the Sun in the ecliptic and the sky, possibly giving the time, hour of the day or night, like a clock. The position of the Moon and its phase is also shown during the month. On the other side of the Mechanism, having probably the size of a box (main part $32 \times 20 \times 6$ cm), are two large spiral scales with two pointers showing the time in two different very long calendars, the first one concerning the eclipses, and lasting 18 years 11 days and 8 hours, the Saros period, repeating the solar and lunar eclipses, and enabling their prediction, and the 19 year cycle of Meton, that is the period the Moon reappears in the same place of the sky, with the same phase. An additional four-year dial shows the year of all Greek Festivities, the so-called 'games' (Olympic, Pythian, Isthmian etc). Two additional dials give the Exeligmos, the 54 year and 34 day cycle, which provides a more accurate prediction of eclipses. It is possible that the Mechanism was also equipped with a planetary show display, as three of the planets and their motion (stationary points) are mentioned many times in the manual of the instrument, so it was also a planetarium. From the manual we have hints that the mechanism was probably also an observational instrument, as having instructions concerning a viewfinder and possibly how to orient the viewfinder to pass a sunbeam through it, probably measuring the altitude of the Sun. There are fragmented sentences that probably give instructions on how to move the pointers to set the position of the Sun, the Moon and the planets in their initial places in the ecliptic, on a specific day, or how to measure angular distances between two celestial bodies or their coordinates. This mechanism is definitely not the first one of its kind. The fact that it is accompanied with instructions means that the constructor had in its mind to be used by somebody else and one posits that he made at least another similar instrument.

Keywords. instruments, planets, Moon, eclipses

"*The origin of all technical achievements is the divine curiosity [of Plato] and the play instinct of the working and thinking researcher as well as the constructive fantasy of the technical inventor.*"

Albert Einstein, radio speech on August 22, 1930
Opening of the 7th Deutsche Funkaußtellung in Berlin†

1. Introduction

To understand the Antikythera Mechanism it is necessary to have certain understanding of the knowledge of astronomy of that time in the Greek World of the second century BCE, more than a century after the death of Alexander the Great and at least 50 years after the death of Archimedes. It is necessary to understand the development of science, and astronomy in particular, which are two very important components of humanity and its history. Perhaps civilisation started with the need for calendars, which are necessary for humans from early prehistoric times, when they were still gatherers –hunters and fishermen. Astronomy becomes a necessity with the advent of agriculture, as otherwise without the proper timing of the tropical year agricultural societies find themselves in the great risk of famine. Initially, prehistoric societies see gods everywhere, and explain all phenomena in terms of acts of gods. The leap from a prescientific society to a society that develops science is gigantic. The West, starting from the Romans, who were a pre-scientific society, was unable to understand science, to distinguish between myth and non-myth, to accept causality at an abstract level of description, with generalisations, that includes all nature, to understand and accept that there are laws of physics, and eventually to understand that they govern nature, even at a cosmic scale. This is the reason there have been several laws introduced by Roman emperors against astronomy and astrology, mathematics and chemistry, as Romans were not in position to understand science that they were afraid of. The chemical books in the library of Alexandria were considered dangerous; as they were giving the power of knowledge to the Greeks, and others, who having this know-how, might transform minerals and metals to gold, they issued edicts to destroy such books in the Library of Alexandria (emperor Diocletian 296 BCE, see Berthelot 1888; Gibbon 2009).

The roots of science and Natural Philosophy, as well as mathematics, go back to prehistoric times. Greeks like to personify everything, as initially they had a god or hero behind every action. This helped to pass easily from a prescientific to a proto-scientific society in a way that science can be accepted, or at least not rejected, by all. According to Greek mythology Prometheus is the archetypal image of human existence that takes science from the gods and gives it to humans, to use Carl Kerényi's and Ralph Manheim's poetic view. Orpheus (2nd millennium BCE) the king of Thrace and Macedonia (northern Greece) is the first one that tames nature, develops music further than predecessor in music god Hermes (Mercury), and domesticates animals.

Humans observe the sky since the birth of Humanity. The very word *anthropos*, human in Greek [$AN\Theta P\Omega\Pi O\Sigma$, from $\alpha\nu\alpha\theta\rho\epsilon\acute{\iota}$ α $\acute{o}\pi\omega\pi\epsilon$] means the one who contemplates on what s/he observes consequently means the one who observes the sky. There was a time when humans used to watch the sky at night, as there was no TV available at that time. They wondered the motion of the Sun, day by day, including the change in altitude of our nearest star, during the year that leads to the seasonal changes, winter and summer from solstices, spring and autumn on equinoxes. At night humans watch and memorise the positions of the stars. They group them in constellations to refer to them and educate

† http://www.einstein-website.de/z_biography/speechfunkausstellung.html

the young, they become familiar with their harmonic motions, the rising and setting of stars, and the seemingly anomalous motions of the planets, with their stationary points, the point in the sky where they appear to stop and change direction in the sky as we see them from our planet. They master the motion of the Moon, its phases that govern their lives, the growth of trees, the periods of fishing and hunting, to mention a few. Humans are able in this way to find regularities and beauty in the Cosmos, and eventually to understand and explain the phenomena. Eventually humans understand that there is causality and that the laws of nature help us to foresee and predict natural phenomena, such as the rising of a star or of the Sun.

It is interesting to have a look at some ancient texts, not only scientific. The very popular, initially to the Greeks, and to all Europeans at later times, the *Orphic Hymns*, are the collection of some very old Greek texts that reflect early scientific attempts, attributed to at least the 5th or 4th century BCE, and according to some traditions, have their roots in the 2nd millennium BCE†. It is interesting to note that according to the hymn *The Law* it is the Law that governs nature: *ΟΥΡΑΝΙΟΝ ΝΟΜΟΝ ΑΣΤΡΟΘΕΤΗΝ* [celestial law that puts the stars in their position and motion, my translation, see Papathanasiou (1978)]. Let us read a part of the hymn (in my translation):

The Hymn to the Law.

I call the King of all, mortal and immortal, Celestial Law that sets the stars in their position and motion, righteous and equitable seal, of the seas and the Earth, [law] that never deviates or changes, and what looks uncertain in nature becomes inescapable as it follows the laws of nature

Another very early and characteristic text is the *Derveni Papyrus* (Laks & Most 1997; Betegh 2004), which is the oldest European text that survived in its original form, partially burnt in a tomb of the 4th century BCE, and found in Macedonia, Greece. It contains important philosophical treatises and seemingly commentary on *Orphic Hymns* that seems to reflect Ionian philosophical views on natural philosophy (e.g. Anaxagoras) and discusses the nature of the Cosmos and the celestial bodies.

2. The birth of science

It was in Greece, in Ionia, the western coast of the Aegean Sea, Anatolia (Asia Minor, today's Turkey), where primitive practical astronomy gradually transforms from traditional avocation of life to proper observational astronomy and astrophysics and natural philosophy, inquiring the nature of stars, the Sun and the Moon and at the same time is mathematical and theoretical, thus becoming an exact science, probably the first one. The Ionian Science established by Thales who introduces the theoretical reasoning with proofs used in Mathematics, followed later by Anaximander, Anaximenes, Heraclitus and Xenophanes. Philosophy interwoven with science moves to Athens, where Anaxagoras, Socrates, Plato, Aristotle, to name a few; give it a new perspective that remains forever since. At the same time philosophy spreads to Macedonia (Aristotle) and Thrace (Democritus) and northern Aegean (Protagoras) and Italy that was then named Great Greece, where Pythagoras, Parmenides, Zeno, Empedocles, established their schools. As the Greek world extends with colonies all around the coasts of the Mediterranean Sea, so does philosophy and science.

Physics probably started with Pythagoras' experiment with hammers that I believe led to the development of experimental physics in conjunction with mathematical the-

† see at the website `http://www.sacred-texts.com/cla/hoo`, the text, translation and notes by A. Athanassakis (1988) as well as at `http://remacle.org/bloodwolf/poetes/falc/orphee/hymnes.htm`

ory. According to the legend as Pythagoras passed by a blacksmith heard the hammers producing harmonic sounds, almost like music. He measured the weights of the hammers of 12, 9, 8, and 6 units respectively. Then with the use of mathematics he explains the harmony and continues with new experiments using a monochord, a musical instrument with one string with a division to variable lengths and variable tension. He discovers musical scales, among them the pentatonic scale. Naturally after this he was convinced that the essence of nature is described by mathematics, and hence Pythagoreanism was born. The Pythagoreans were a very important school of thought that includes Plato and many of his followers and I am sure many of the readers will agree with me when I say to the first year students of Physics that *you will become more Pythagoreans than Pythagoras himself*.

Mathematics and physics become more and more part of astronomy and astrophysics as time passes and science progresses. Leucippus introduces the idea that mater is made of small indestructible and indivisible particles, the atoms. Leucippus' atomic theory (adopted by his disciple Democritus) is incorporated in his cosmology, the theory of creation of the Universe, the stars, the Sun, the Earth. All of these are formed by various sizes of cosmic vortices. A large vortex makes the Universe. Every cosmic vortex heats up as it spins faster and faster. The heavy atoms of the vortex tend to go to the center of the Universe, the lighter follow an up going road. The mechanism of vortices creates the stars. Every star spins up and this produces heat and light, while at the same time the heavy atoms go to the center, which becomes thicker and denser, while lighter atoms go up. Another similar vortex creates the Sun that heats up because of its fast rotation. The Earth has a similar origin. It is really a great surprise for us to read ideas of modern astrophysics and cosmogony (creation of planets) in the very ancient texts of Leucippus.

Plato, although an opponent of Democritus and Leucippus and their atomic theory, probably because he is a Pythagorean, hence everything has to be described in terms of mathematics, introduces his own "*atoms*", or rather what we call today in modern physics elementary particles and quarks, his two orthogonal triangles that construct all his chemical elements in the form of the platonic solids, the five platonic regular polyhedra. Plato's Academy and Aristotle's *Lyceum* or *Peripatetic School* (recently discovered in central Athens) as well as the astronomers associated with their schools in Athens and elsewhere develop advanced mathematical methods to describe accurately astronomical phenomena, among them the rising and setting of stars at particular geographical latitude on Earth. After the time of Alexander the Great, philosophy, astronomy and mathematics spread in Alexandria and Rhodes. Alexandria became a new center of philosophy and technology for centuries to come.

3. Astronomy, the rhythms of the Cosmos and mathematical models of the universe

It is very probable that humans are able to understand rhythms and mathematics before their birth. We become familiar with mathematics and rhythms as we listen to the beats of the heart of our mother and ourselves. I once performed an experiment with my yet unborn daughter, taping my wife's belly once or twice and observing the six month fetus responding with one or two kicks respectively. So I assume that mathematics is embedded in our minds or we could say in our DNA.

It is no surprise that humans develop mathematics and understand the rhythms of astronomical phenomena. An interesting aspect of the history of astronomy is the introduction of theoretical reasoning based on more and more advanced mathematics. Eudoxus was an excellent mathematician known for his curve, given by the formula

$k^2 x^4 = m^4(x^2 + y^2)$. Eudoxus solved several problems, such as the eclipses, the reappearance of the lunisolar phenomena in the sky every eight years (*octaetiris*), a period that is very useful for keeping an accurate calendar, which tries to overcome the problem that the tropical year does not contain an integer number of lunar months. Eudoxus wrote a treatise on the motion of the planets and their variable velocities during the years. Most important of all are his planetary models of motion during the years, which are combinations of 27 nested moving spheres for every planetary object, the Moon, the Sun and the planets. Meton introduces a lunisolar period of 19 years that takes the Moon, with its complex wobbling motion in the sky, to reappear in the same place of the sky with the same phase (new Moon, full Moon etc). Callippus advances further the model of Eudoxus for planetary motion using a total of 34 spheres. The spheres account for the motion of every planet around the Earth and the fact that every planet trajectory is on a different plane that makes an angle with respect to the ecliptic; the plane of the Earth's trajectory around the Sun. Aristotle adopts the Callippian model. Callippus improves Meton's 19 year cycle and replaces it with a 76 year one, which gives more accurate predictions.

I believe that probably advanced science started as a result of the effort of humans to create accurate calendars that take into account the complicated motion of the Moon and the fact that the year does not last an integer number of lunar months. For this astronomers had to develop complicated calendars in their effort for keeping the beginning of the tropical year fixed with respect to the stars and the solstices, as well as the lunar months and phases.

Another good example of the advance of mathematics in astronomy is given by the works of Autolycus of Pitane, a theoretical astronomer who wrote two books that we could say are the oldest surviving books of theoretical physics (mechanics), based exclusively on theorems, that describe the rotation of a sphere, with applications to the celestial sphere, the rising and setting of stars at a given location on Earth. Euclid few years later publishes in his Catoptrics the mathematical theory of mirrors, in his *Optics* a treatise on perceptiveness and in his *Phaenomena* spherical astronomy.

4. Alexander the Great and science

The extent of the Greek world to Asia (Babylon and Persia, Central Asia, up to India) and Africa (Egypt) with the Empire of Alexander and his successors induces several multi-faced developments in philosophy, science, mathematics, technology, and astronomy in particular. Alexander is accompanied by a large group of scientists, as he learned for many years by his professor Aristotle that science and philosophy are very important to statesmen because they provide happiness, fulfill mental needs, satisfy the divine curiosity of Plato, and are a source of power. Greek science gathers all astronomical observations, huge amounts of tables of astronomical phenomena and all information available in the known World. Greek astronomers and mathematicians based on measurements and practical knowledge from Egypt, Babylon, Persia, Samarkand and Asia in general improve their understanding of astronomical phenomena, start to introduce new parameters and perform more accurate measurements. Another unexpected for the unaware factor, that led to the development of science was the Greco-Egyptian bureaucracy that was necessary for running the enormous state Alexander the Great, the *King of the World*, as it was its title, has created. In the new city of Alexandria in Egypt it was necessary to have many well-educated people keeping record of all transactions, commerce and shipping. This led to a large demand for educated people and education that was previously unknown, so it led to new types of education and this eventually led to advances in science and philosophy. Education was previously limited only to few and in the post Alexander era it becomes a necessity for many.

5. An eccentric world: the epicyclical motions for the celestial bodies

Good measurements on the brightness of the planets that varies with time and their relative position to the Earth, hinted the necessity of revising the system of the nested spheres developed by Eudoxus. The Epicyclic System for the motion of planets, the Moon and the Sun has been probably introduced by Hipparchus to model the changing brightens of the planets over time, caused by the changes of the relative distance of the planets and the Sun and the Moon from Earth, and their variable velocity. For this he introduces the eccentricity in their orbits and their retrograde motion and hence solves several serious problems of the Eudoxian system, keeping circles as basic components of the geometrical solution to the problem of modeling the planetary motions. Two circles are used for every planet. Later the number of circles becomes larger to increase accuracy of the motion. Circles are used because they are simple and they can be reproduced using gear mechanisms. It is certain that all astronomers new about the heliocentric system of Aristarchus. But we do not necessarily need it to reproduce planetary motions as seen from Earth. Archimedes describes the heliocentric system and even mentions that Aristarchus states that the *gravity* of the Earth keeps the Moon in its orbit around our planet. Good measurements of the variable position and variable velocity of the Moon during the month, and the Sun over the year, made accurately by Hipparchus, possibly using Rhodes large petal shaped stadium as a measuring device, helped him to calculate the eccentricity of their orbits, their variable speed and their changing angle in the sky. It was inevitable for an astronomer like Hipparchus to introduce an eccentric model for the motion that reproduces realistically the motion of the planets, the Moon and the Sun and saves the phenomena (to reproduce the phenomena even if you do not understand the nature and the mechanism), as the Greeks liked to say.

6. Automata, *Deus ex machina*

In the mean time the Greeks have developed several automata from antiquity. In Homer we read *ΑΥΤΑΓΡΕΤΟΣ* [Homer, Odyssey, I. 148], i.e. a device that can take decisions and change a function accordingly, e.g. a ship that automatically turns to the right direction according to the direction of the wind that blows, using an automatic system that turns the sails and the ship. In Greek temples automatic doors and other automatic devices from very ancient times also existed. Archimedes constructed several automata, many weapons (including a hot steam canon) that enabled him to keep the Romans out of Syracuse single-handed. As we read in many ancient authors including Cicero and Plutarch, he has constructed a mechanical celestial sphere and a planetarium [Proclus, *In primum Euclidis Elem. Comment.*], as well as a very complicated clock (Stamatis 1974). Sextus Empiricus [*Adv. Mathem.*] writes that looking at Archimedes' sphere we wonder how the Sun, the Moon and the planets move ... and the Latin manuscript *Tusculanae Disput.* [I. XXV] adds that the motions have variable velocities and Claudius Claudianus in *Carminum minorum corpusc.* adds "*when Zeus saw the aether in the little sphere of Archimedes made of glass to what extend humans moke me with this fragile sphere? [...] some unknown force moves the variable trajectories of the planets that move like they were alive. Moves an artificial zodiac and an artificial Moon ...*". A similar description on variable velocities for the planets is given by Lactantius [*Divinorum Institutiorum*] "*Archimedes constructed a sphere made of copper, a simulation of the*

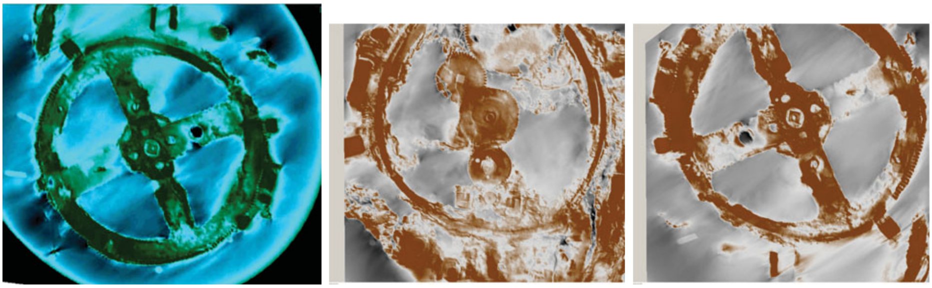

Figure 1. Fragment A with the main wheel that drives the Sun and eventually all gears. Images created by the author using X-ray tomography of `X-tek` raw data and Volume Graphics software.

Universe, a mechanical Universe, with solar, lunar and planetary motions similar to the real ones and not just moving forward backward, while at the same time the of the fixed stars sphere moves turns". Vitruvius [*De architectura*] says that Archimedes and Scopinas of Syracuse (his follower) constructed several instruments and clocks [*organicas et gnomonicas*] based on appropriate calculations that follow the laws of nature. All these are based on actual facts and Philon of Byzantium (2nd century BCE) informs us that Archimedes addressed once to Ariston: "*My friend, I would like to explain to you how hydraulic clocks are constructed* [966, Arabic codex, Oxford]. It is important to know that Archimedes was the son of the astronomer Phidias, and he was astronomer himself. He estimated the distances of the Moon, the Sun and the planets as we read in Hippolytus and Macrobius. His death is probably related to an astronomical device, perhaps his planetarium, as Plutarch writes that Archimedes, after the fall of Syracuse, was carrying to the Roman general Marcellus (who according to some sources was an admirer of the great scientist) mechanical spheres, mathematical instruments, dials, angles, that enabled him to measure the angular diameter of the Sun, and while walking to Marcellus house Roman soldiers believing he was transporting gold in a box killed the great scientist. After the death of Archimedes Marcellus took the Planetarium and the Mechanical Sphere to Rome, where he put the Sphere in the circular Temple of Vesta in Capitolium, and the planetarium in his house. Cicero informs us that polyglot Posidonius (about 135 BCE to 51 BCE) astronomer, statesman, anthropologist and professor, accepted by many Greeks in ancient times as only second to Aristotle, had in his School in Rhodes, where Cicero studied, a mechanical planetarium that gave the positions of the Sun, Moon and the planets. Philon of Byzantium (ca. 200 BCE), a student of Ctesibios at the Museum used gears in water raising devices (Chondros 2009).

It is evident that the Greeks had real clocks, not only solar or water clocks, but also mechanical, as it so well documented in the works of Archimedes, in the Arabic manuscript (Stamatis 1974). The Antikythera Mechanism is the only good example we have in our hands, now on display at the National Archaeological Museum of Athens, Greece. Another extremely interesting example of ancient astronomical calendar device is the fragment of the disc of Chevroches (Devevey & Rousseau 2009), which is a circular convex disc, made of bronze, probably part of an astronomical device, around the 3rd century, discovered in the Gallo-Roman town of Chevroches (Nièvre), now at the Musée archéologique of Dijon, with a diameter of 6.5 cm, divided into twelve sections inscribed, with the Egyptian months written in Greek, whose the Greeks have been using for centuries, and in Latin the signs of the Zodiac and the twelve Roman months. It seems that the circle turns around a center that is slightly eccentric, possibly taking into account the

https://doi.org/10.1017/S1743921311002225 Published online by Cambridge University Press

eccentricity of the Earth's orbit and inequality of the seasons†. Recently in the ancient Greek city of Olbia in Sardenia, Italy, the archaeologist Rubens D'Oriano discovered in the market of this glorious city (Agora-Forum) a 3rd century BCE well-constructed part of a gear that has been studied by engineer Prof. Giovanni Pastore which I have named *Archimedes Gear* as it is constructed at the same period. In the literature we read (Cicero, Plutarch and others) that there have been several mechanisms of this type over the centuries and it seems that their readers are familiar with these instruments.

An extremely interesting work by Henriksson (2011) shows that the data of eclipses mentioned in the scale of Saros in the Mechanism (months and hours of every eclipse) can be dated accurately using his method that takes into account relativity effects to 150 to 100 BCE and that the eclipses are visible at the hours mentioned in Sicily, hence giving a very good proof that the Mechanism is based not only on technology of the great mathematician Archimedes, but also on observations of eclipses by him and his disciples like Scopinas. (Henriksson 2011) uses five *Exeligmos* cycles that started in 351, 297, 243, 189 and 134 BCE that he has determined by identification of 10 solar eclipses, of which the hour of the eclipse can only be read in 9 eclipses records in the Mechanism scale. He compares the predicted solar eclipses on the mechanism with his predictions for Syracuse, Taormina, Athens and Rhodes, computed for 600 BCE to 2. He concludes that the solar eclipse predicted for the 72th month of the first Saros cycle in the last Exeligmos in the Mechanism took place in 129 BCE and it was observed as total in Syracuse and magnitude 0.999 in Taormina. Hence he proves that the mechanism probably has been calibrated in Sicily at the time of Archimedes (287-212 BCE). The timing error was only 3 minutes in Syracuse, 50 minutes in Athens and 84 minutes in Rhodes. This is a very important discovery that adds one very clear signature of Archimedes in the Mechanism. I do not think that this particular Mechanism was made to be used in Sicily. Naturally it is based on data from Sicily, but it was meant for Greece mainland, where it was found. Except if the Mechanism that Cicero mentions that he saw in Posidonius hand as a student at his School in Rhodes, was the one of Archimedes that Marcellus took to his villa in Rome has been taken by Posidonius to Rhodes to prepare it. Posidonius was a very influential personality in politics. He was *prytanis* (president) of Rhodes and has served to Rome as an ambassador (87 BCE to 86 BCE) where he was influential, as he managed to keep Rhodes independent for very long. Cicero, Pompey, Velleius, Cotta, and Lucilius were all friends and to an extend pupils of Posidonius in his Rhodes school. It is worth mentioning the Pompey visited Posidonius in Rhodes in 66 BCE during his war against the pirates of Cilicia and later in 62 BCE and asked Posidonius to write his biography, as he wanted it to have it from an excellent writer and philosopher. Another interesting aspect of the story is that the pirates of Cilicia dominated for very long all Mediterranean Sea and had an important naval base in Antikythera, a base that initially was a naval base of the Persians during their war against the Greeks and it becomes Greek at the time of Alexander the Great. Let us speculate about the shipwreck, that shank at that time. The ship was either a Greek, or a roman merchant ship that went to the port of Antikythera to avoid a bad weather that is frequent there, or it captured by pirates or a pirate ship, because as we said the Island of Antikythera was an important base of pirates that the Romans destroyed at that time.

Clocks, some of them quite complex, ornamental and with elaborate automata, continue to exist for long after Archimedes era, as it is inferred from the literature at all times, in the Greek World, the Roman empire, in the Byzantium, in the Arabic world and then in Western Europe, where they went as gift to kinks from Byzantium and then as

† see also the contribution by Devevey *et al.* in this volume, page 806.

war lute. Some of them with human figures with functions related with time events. The existence of human figures in Arabic clocks hints that they are of Greek origin or that they continue a Greek tradition already spread in all the known Mediterranean World.

Clocks become a fashion in Western Europe (Venice, Prague and elsewhere) after the fourth crusade (1204, when they destroyed Constantinople). This is the time the art of automata and clocks spreads from the Greek world to Western Europe together with Greek literature and philosophy, partly through the Arabs and the Jews in Spain.

7. What is the Antikythera Mechanism?

The Antikythera Mechanism is a very complicated astronomical instrument with many functions that can characterise it as a scientific instrument and a dedicated astronomical analogue computer. It is made of bronze gears that are designed to perform calculations. It gives the position of the celestial bodies at a particular time, possibly for given latitude, and as far as the Moon is concerned, for given longitude and local time. It has been studied extensively over the year since its discovery in 1901-2. Rediadis (1903), described also by Rehm (1907), believes that it is a complicated astronomical device and notices the pin in slot mechanism that –as we know today using modern techniques, especially computer tomography(Freeth *et al.* 2006)– gives the variable velocity to the Moon. Rados (1905) also believes that it is an astrolabe device, Theofanidis (1934) who constructs the first working model in bronze, a clocklike mechanism that costed him a fortune (priv. comm. Theophanidis, J., 2006) and that gives the position of some planets and, Price (1956, 1974), together with H. Karakalos perform radiographs and reconstruct a model. More interesting results came from tomographies by Bromley, Wright and Mangkou (Bromley 1986, 1990a,b,c; Wright *et al.* 1995; Wright 2002, 2003, 2005a,b,c, 2006a,b) and more recently by Freeth *et al.* (2006, 2008) with a more accurate computer tomography advance even further our understanding of the Mechanism, and that read several parts of the manual of the instrument written in the almost every available surface of the mechanism, hidden in the rust in it since it sunk in the sea during the second century BCE. See Marchant (2009) and Freeth (2009) for an account of the story.

The Mechanism is:

(*a*) Astronomical instrument suitable for observations.

i. It measures the altitude of a celestial body, i.e. the angular distance between the horizon to the astronomical object;

ii. The angular distance between any two astronomical objects;

iii. There are many words in the fragmented text of the manual referring to motion of planets and fragments of sentences or just words concerning how to move a pointer from one place to another, and hence to perform measurements.

(*b*) Astronomical computer, 2nd Kepler's law

i. It gives the position of the Sun;

ii. The Moon, as it gives the position of the Moon and its phase during the month, the position of the Sun in the ecliptic (Zodiac);

iii. The age of the Moon (phase of the Moon)

iv. Predicts eclipses, both solar and lunar. For these functions the Moon moves following with a good approximation Kepler's second law using a train of four gears, two of which have slightly eccentric axles and are interconnected with a pin through a hole. The difference between Kepler's predictions on the angular velocity of the Moon during the month and the mechanism's prediction is of the order 1/400 (Gourtsoyannis 2010)

https://doi.org/10.1017/S1743921311002225 Published online by Cambridge University Press

(*c*) Calendar mechanism

i. It has a solar calendar, the tropical year, based on the Egyptian calendar

- It has instructions giving the name of a star that rises or sets together with the Sun on a given day of the year, enabling the user to know the exact day of every month.
- This was a universal way to keep a detailed accurate tropical year calendar

ii. It has a lunisolar calendar based on the cycles of eclipses, the Saros cycle and its triple and more accurate, the Exeligmos cycle. The Saros cycle is 223 lunar months, or 223×29.53 days, or 6,585.32 days, or 18,030 years i.e. 18 years, 11 days and 8 hours, while the more accurate *Exeligmos* cycle, predictions of eclipses, is equal to three Saros cycles or 19,755.96 days, or equivalently 54.090 years i.e. 54 years and 34 days. The period of 223 months appears in the fragmented text in the manual of the instrument.

iii. It has a lunisolar calendar based on the 19 year cycle of Meton, and 76 years of Callippus

- the period it takes the Moon to return to the same star in the sky with the same phase (e.g. full Moon, new Moon etc) and its more accurate Callippus cycle of 76 years, which is four Metonic cycles. Both 19 and 76-year periods appear in the manual.
- Meton's lunisolar cycle of 19 years is almost equal to 235 synodic lunar months (difference of two hours), or almost 255 draconic months (and hence can be used to predict eclipses), is used by the Greek orthodox Christians for the determination of Easter and by the Hebrew calendar.
- The lunisolar Callippus cycles 76 years, is a multiple by four of Meton's cycle and much more accurate.

(*d*) Meteorological or Climatological device. With its solar year calendar gives to the users exact dates of various agricultural activities.

(*e*) School/University demonstration and teaching device. Naturally such an instrument can be used in a school/university of that time. We know from Cicero that his professor Posidonius in his School in Rhodes, Greece, were he went to study rhetoric, astronomy etc. had in his possession a planetarium with a description similar to the one of Antikythera Mechanism.

(*f*) Luxurious object to show up to friends. Rich people spend excessive money (especially Greeks and later Romans) to impress their friends and visitors and this applies even more to Kings and rulers, who in the rooms that they invite foreign important visitors, in the sale of the throne, have impressive constructions including automata, like the clocks of Ctesibius, Heron and Prague.

(*g*) Instrument to measure geographic latitude

- Geographic latitude can be calculated if one has a table that shows the altitude of the Sun at noon for every latitude of the Earth, for every day of the year, or every ten days.
- The day of the year is determined using the manual and observing the stars that rise or set together with the Sun.
- The altitude of the Sun at noon can be measured by the angle of the Sun from the horizon, using the viewfinder [*stematia proetrimena* = pre-perforated viewfinder made of two perforated standing blades, as we read in the manual of the instrument] to pass sunrays [word in the manual] through them, as it is written.

(*h*) Cartographical instrument

(*i*) Possibly a navigational instrument? Naturally it can be used as such, but perhaps

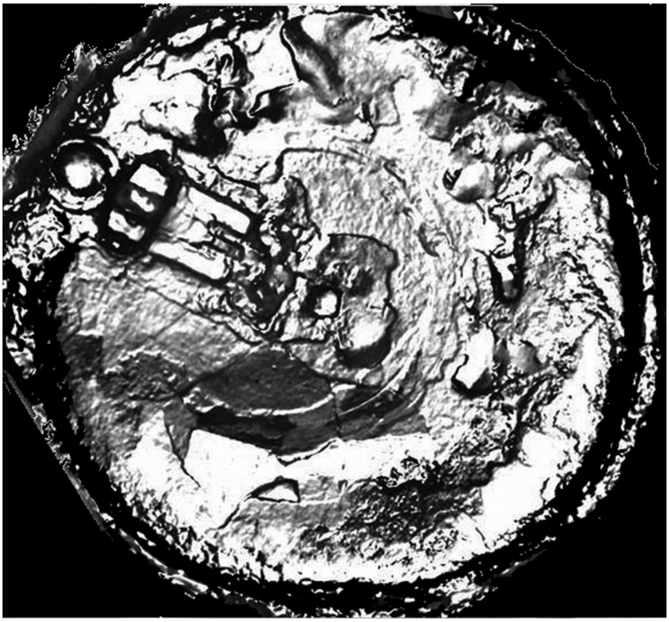

Figure 2. Image of the mechanism of the Moon. The Moon was a small silver sphere, as we read in the manual, attached in the hollow hemisphere seen at the top left. Created using 3D photographic PTM method by Malzbender *et al.* (2001) of Hewlett Packard, Palo Alto, California.

it is too expensive for this use, with the exception of a large ship or a fleet. A simpler version that has only some of its functions can be used for navigation.

7.1. *How it works*

The Mechanism works with trains of properly designed gears, using appropriate calculations. Trains of gears are used to perform certain calculations (wheel drives in windlasses in Aristotle, and on gears in Pappus 4th volume of Synagogue [Compendium of Mathematics], 340), like the ones needed to calculate the position of the Sun during the year, the Moon around the Earth during the month, the phase of the Moon in the sky. The eclipses are shown in the spiral scale of Saro s (223 months), which is divided in months with a pointer that slides along a spiral groove. If an eclipse is expected a sign is written in the appropriate month, Σ or H respectively, being the symbol for a lunar (SELENE) or solar (HELIOS) eclipse, together with the hour the eclipse takes place. The pointer slides in a groove moved by the turning of a gear that drives the largest of the gears moving the Sun. Another similar pointer moves in the spiral scale of Meton's cycle, where all the months are mentioned during the 19-year period (Freeth *et al.* 2006, 2008).

7.2. *When it was made?*

Books of various periods use different types of characters and one can guess when this book has been printed based on the font's type. The shape of the characters of Greek inscriptions can help to determine the date of construction, as epigraphologists use this method that is consider best for this case. Dr Ch. Kritzas, former director of the Epigraphic Museum in Athens, analysed the inscriptions and concludes that it was probably made around 150 to 100 BCE. The instrument is definitely older than the date of the shipwreck that is determined to be around 80 to 60 BCE, based on coins found there, on amphorae and Hellenistic pottery probably made 80-50 BCE, on carbon 14 analysis

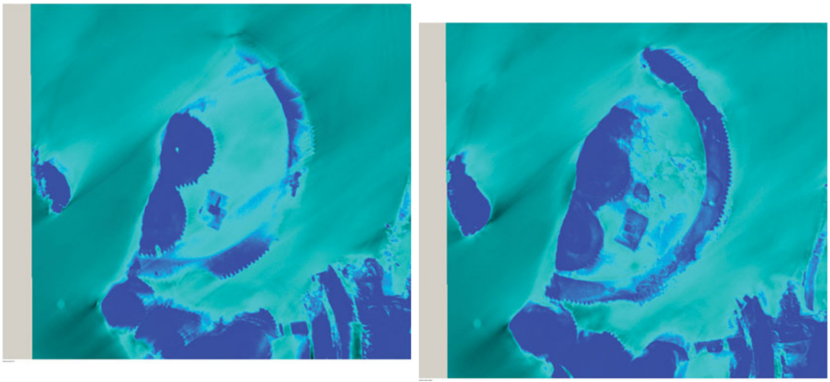

Figure 3. Four (now fragmented) gears that are in two parallel planes, two of them been slightly off-set (eccentric) and give variable velocity to the Moon during the month. The two eccentric gears drive one another using a pin attached to one (lower gear at right) and pulls the other gear using the pin that goes through the other through the slit (lower gear at left). Images created by the author using X ray tomography of `X-tek` raw data and Volume Graphics software.

of the wood of the ship revealing that it was cut around 220 BCE, i.e. 150 years earlier than the ship sunk. Wood is seasoned for very long before it is used in antiquity and ships are used for very long if serviced properly as they were covered with sheets of lead to protect from molluscs.

7.3. *Where and by whom was it made?*

Alexandria, Rhodes and the Ionian coast, and Syracuse have excellent tradition in philosophy, mathematics, science, astronomy, and technology –including metallurgy, chemistry, engineering, and automata. So these places are to be considered as possible places of the origin for such a mechanism and it definitely shares its roots in all these places. The Mechanism has the mathematical signature of Hipparchus in the lunar motion (epicycles). Hipparchus lived for long in Rhodes, and possibly for a period in Alexandria. Alexandria had an excellent tradition in astronomy and science in general. We know that Posidonius had such a mechanism in Rhodes and that the mighty Archimedes has created at least two different ancestors of the mechanism. The ship was on its way to Rome from Greece. It sunk near southern Peloponnese, in Antikythera, that served as a base of pirates for centuries. Hence we could infer that comes from the Aegean Sea, full of treasures meant for Rome, either as official lute and plunder or merchandise or even pirate booty. The coins found are from Pergamon in the Ionian coast. The ship was a very large one, full of treasures, about 60 to 70 m long, and 9 to 12 m wide (priv. comm. Admiral J. Theofanidis, 2006). It had almost one hundred statues (many of marble and some of bronze) and other treasures, like expensive furniture with bronze decoration, consequently it might very well have goods from many places, as the amphorae were from Rhodes, Kos and Italy or Spain (with Latin marks), thus the ship probably has visited these places.

Freeth *et al.* (2008) have discovered a Corinthian calendar in the Metonic scale and believe that is an Epirotic calendar (north west Greece), based on the coincidence of months of the Mechanism calendar with known calendar around the Greek World that covers all Mediterranean. Unfortunately very little is known about calendars around Greece, and frequently calendars differ substantially in cities or towns that are very close, with the best example found near Corinth itself, as the town of Sykion, that has a different calendar. Corinth was very rich and especially after the Peloponnesian war, when they defeat the Athenians, they have very many colonies all around the sea roads, i.e. from Cyprus to Marseilles, Sicily, Italy, Adriatic, to mention a few, and of course Syracuse.

Taking all these into account we could guess that the Mechanism has its roots in a long tradition in Ionia, Rhodes, Athens, Alexandria and Sicily. Great scientists like Archimedes, Hipparchus have their mathematical signature in the Mechanism.

7.4. *Why do we need such a mechanism, why do we need a mechanical universe?*

Humans need to know –and Plato's divine curiosity is really the answer to the question– why we are interested to understand the Universe and to model it with mathematics and mechanisms.

8. Codex Antikytherensis

Our study using non-linear computer tomography (Freeth *et al.* 2006) gave as expected a great part of the otherwise destroyed in the rust manual of the computer, that I have named *Codex Antikytherensis*. This text is fragmented, yet still extremely useful (Freeth *et al.* 2006). For a commentary see also Papathanassiou (2010).

Acknowledgements

The J.F. Costopoulos Foundation is gratefully acknowledged for generous support. The research that leads to the analysis of computer tomographs was carried out in collaboration with Prof. M.G. Edmunds, Prof. J. Seiradakis, Dr. T. Freeth, Dr. H. Mangou, Ms M. Zafeiropoulou, Mr. Y. Bitsakis, Dr. A. Tselikas and the National Archaeological Museum in Athens (Dr. N. Kaltsas, Ms R. Proskynitopoulou, Mr M. Makris and all the staff of the Museum, who enabled us to obtain the raw data). The X-ray data were gathered by a team from X-Tek Systems (UK), now Metris (NL), led by Dr. R. Hadland, special thanks are due to A. Ramsey and A. Ray. We thank the team from Hewlett-Packard (US), led by Dr. T. Malzbender, who carried out the surface imaging and for using his PTM excellent method for analyzing the surfaces of bodies and software. We appreciate the support of C. Reinhart of Volume Graphics. The photos have been produced using Volume Graphics software and our X-Tek data. Thanks are due to Dr Göran Henriksson for discussions on ancient eclipses, Dr Ch. Kritzas for estimating the age of the instrument based on the shape of the letters of the manual, Prof. Giovanni Pastore for many discussions on the Olbia Archimedes gear, Prof. Manolis Mikrogiannakis for drawing my attention to the Homeric word $AYTA\Gamma PETA$ which means automata [Odissey,I.148], Dr Irene Pajon Leyra for drawing my attention to the importance of Greek-Egyptian bureaucracy to literacy, Dr Arnold Lebeuf for discussions on Meton and Saros cycles and ancient calendars, Dr Alexandra Coucouzeli and Mr Panos Papaspirou for critical reading and many interesting discussions, Mr D. Kriaris for creating several bronze models, Dr F. Vafea, Prof. M. Papathanassiou for interesting long discussions on the Mechanism structure, astrolabes, ancient texts. Thanks are due to the University of Athens for support. Special thanks are due to Dr David Valls-Gabaud for organising the excellent conference at UNESCO for the International Year of Astronomy and editing this volume.

References

Berthelot, M. 1888, *Collection des Anciens Alchimistes Grecs* (Paris: Steinheil) `http://www.rexresearch.com/alchemy5/berthelo.htm` `http://remacle.org/bloodwolf/alchimie/table.htm`

Betegh, G. 2004, *The Derveni Papyrus: Cosmology, Theology and Interpretation* (Cambridge: Cambridge University Press)

Bromley, A. G. 1986, *Centaurus*, 29, 5
Bromley, A. G. 1990a, *Horological Journal*, 132, 412
Bromley, A. G. 1990b, *Horological Journal*, 133, 28
Bromley, A. G. 1990c, *Antiquarian Horology*, 18, 641
Chondros, T. G. 2009, in *International Symposium on History of Machines and Mechanisms*, H.-S. Yan & M. Ceccarelli (eds) (Berlin: Springer), p. 59
Devevey, F. & Rousseau, A. 2009, in *Cosmology Across Cultures* ASP Conference Series, Vol. 409, J.A. Rubiño-Martín, J.A. Belmonte, F. Prada & A. Alberdi (eds) (San Francisco: Astronomical Society of the Pacific), p. 172
Laks, A. & Most, G. W. (eds) 1997, *Studies on the Derveni papyrus* (Oxford: Oxford University Press)
Freeth, T., Bitsakis, Y., Moussas, X., Seiradakis, J.H., Tselikas, A., Mangou, H., Zafeiropoulou, M., Hadland, R., Bate, D., Ramsey, A., Allen, M., Crawley, A., Hockley, P., Malzbender, T., Gelb, D., Ambrisco, W., & Edmunds, M.G. 2006, *Nature*, 444, 587
Freeth, T., Jones, A., Steele, J. M., & Bitsakis, Y. 2008, *Nature*, 454, 614
Freeth, T. 2009, *Scientific American*, 301, 76
Gibbon, E. 2009, *The Decline and Fall of the Roman Empire* (Cirencester: CRW Publishing)
Henriksson, G. 2011, in *17th annual meeting of the European Society for Astronomy in Culture*, SEAC 2009 (Alexandria: Alexandria Library), in press
Gourtsoyannis, E. 2010, *Advances in Space Research*, 46, 540
Marchant, J. 2009, *Decoding the Heavens: a 2,000-year-old computer and the century-long search to discover its secrets* (Cambridge: Da Capo Press)
Malzbender, T., Gelb, D., & Wolters, H. 2001, in *SIGGRAPH 2001, Computer Graphics Proceedings* Annual Conference Series (New York: ACM Press) p. 519
Moussas, X., Seiradakis, J., Freeth, T., Edmunds, M., Bitsakis, Y., Babasides, G., Ioannidis-Vamvakas, D., Fasoulopoulos, G., Daniels, E. & Kriaris, D. 2007, in *Communicating Astronomy to the Public, IAU Commission 55 conference* 2007 (Athens) `http://www.communicatingastronomy.org/cap2007/abstracts.html`
Neugebauer, O. 1975, *A History of Ancient Mathematical Astronomy* (Berlin: Springer)
Papathanasiou, M. K. 1978, *Cosmological and Cosmogonical Notions in Greece during the 2nd millenium BCE*, PhD Thesis (Athens: University of Athens)
Papathanassiou, M.K. 2010, *Advances in Space Research*, 46, 545
Price, D.J. De Solla 1956, *Horological Journal*, 97, 811
Price, D. J. de Solla 1974, *Transactions of the American Philosophical Society (New Series)*, 64, part 7, 1
Rados, C. 1905, in *Comptes rendus du Congrès international d'archéologie classique, Athènes, [7-13 avril (25-31 mars)] 1905* (Athènes: Impr. Hestia), p. 256
Rados, C. 1910, *Peri ton Thesauron ton Antikytheron* (Athens: N/A)
Rediadis, P. 1903, *Der Astrolabos von Antikythera* (Athens: Beck & Barth)
Rehm, A. 1907, *Berliner Philologische Wochenschrift*, 27, 467
Svoronos, J.N. 1903, *Die Funde von Antikythera* (Athens: Beck & Barth)
Svoronos, J.N. 1908, *Das Athener Nationalmuseum* (Athens: Beck & Barth)
Stamatis, E. 1974, *The complete works of Archimedes* (Athens: Technical Chamber of Greece)
Theofanidis, J. 1934, *Praktika tes Akademias Athcnon*, 9, 140
Wright, M. T. 2002, *Horological Journal*, 144, 169 and 193
Wright, M. T. 2003, *Antiquarian Horology*, 27,270
Wright, M. T. 2005a, *Bulletin of the Scientific Instrument Society*, 85, 2
Wright, M. T. 2005b, *Antiquarian Horology*, 29, 51
Wright, M. T. 2005c, *Bulletin of the Scientific Instrument Society*, 87, 8
Wright, M. T. 2006a, *Antiquarian Horology*, 29, 319
Wright, M. T. 2006b, in *Proceedings Second International Conference on Ancient Greek Technology* (Athens: Technical Chamber of Greece), p. 49
Wright, M. T., Bromley, A. G., & Magkou, E. 1995, *Journal of the European Study Group on Physical, Chemical and Mathematical Techniques applied to Archaeology*, 45, 531