Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 46 (2010) 552–556

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Antikythera Calculator advances modern science of 19 centuries

Giovanni Pastore

Freelance engineer and Lecturer Department of Engineering, Potenza University – Italy, Via Monte Bianco, 14, I-75025 Policoro, Matera, Italy

Received 20 January 2008; received in revised form 12 March 2009; accepted 31 March 2009

Abstract

The Greek astronomic calculator, discovered in the depth of the sea in a naval wreckage of the 1st century B.C. in front of the island of Antikythera, is the most amazing among the archaeological discoveries of last century. The mechanism immediately appeared like a device out of its time. After years of study this devise is still provoking a discussion between scientists and archaeologists because of the complexity and the modernity of the scientific knowledge the work presupposes. Its epicyclical gearings show the high level of the scientific culture reached in that period of history.

The knowledge of the planetary motion, necessary to the design of the epicyclic gearing of the Calculator of Antikythera, presumes that ancient Greek scientists knew the planetary motion of the celestial bodies and had already achieved the same results that have been attributed to scientists 19 centuries later. The scientific value of this gear mechanism is indisputable because the inventor of the Calculator of Antikythera had the knowledge that was "re-discovered" centuries later as the heliocentric theory proposed by Niccolò Copernicus in 1543 (*De revolutionibus orbium coelestium*), the universal gravitation law formulated by Isaac Newton in 1687 (*Philosophiae Naturalis Principia Mathematica*), and the kinematic study of the epicyclical gearings published by Robert Willis in 1841 (*Principles of mechanism*).
© 2010 Published by Elsevier Ltd. on behalf of COSPAR.

Keywords: Antikythera Calculator; Astronomical history; Epicyclic gearing

1. Archaeology, technology and science of the Calculator of Antikythera

The Calculator of Antikythera, found in a naval wreckage of the 1st century B.C. in the waters in front of Antikythera in the Aegean Sea and shown in Fig. 1, is one the most amazing archaeological discoveries of the last century. The mechanism immediately appeared to be extremely advanced for that period of history. After years of study it still provokes discussion among scientists and archaeologists because of the complexity and the modernity of the scientific knowledge that the work implies. The epicyclic gearing with which it was built shows the elevated level of the scientific culture reached in that period. The design of this special gear makes scientists and historians suppose that Hellenistic scientists knew the calculation of the planetary motion of the celestial bodies similar to the knowledge that was achieved in more modern times. The mechanism is constituted of a handle operating about 32 bronze gears into a wood box, as large as a shoe box. These gears could rotate the hands of special quadrants. Perhaps it was made in Rhodes by the astronomer Geminus or his teacher Posidonius (135–51 B.C.).

After its recovery in 1902, for 50 years the purpose of the instrument was not understood. In 1951 Derek John de Solla Price (1922–1983) started, for the first time, to study the mechanism in detail. A radiography he obtained of the gears is shown in Fig. 2. After about 20 years of research he understood its working to be an astronomic calculator. It had the function to reproduce the lunar phases and the movement of the Sun and the Moon among the constellations of the zodiac. Probably it could also represent the motion around the Sun of the planets visible to naked eye (Mercury, Venus, Mars, Jupiter, Saturn). It could be used for both an instrument for the navigation and for astronomic investigations.

E-mail address: giopastore@katamail.com

0273-1177/$36.00 © 2010 Published by Elsevier Ltd. on behalf of COSPAR.
doi:10.1016/j.asr.2010.04.002

Fig. 1. Antikythera mechanism (National Archaeological Museum of Athens – Greece).

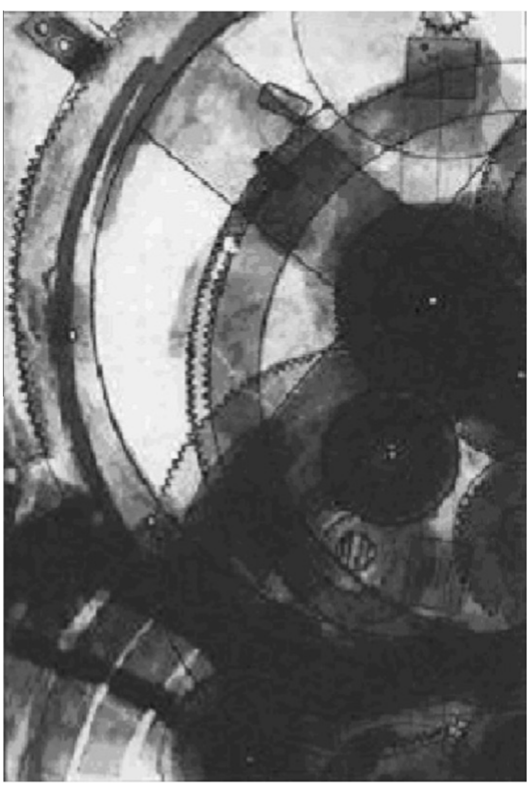

Fig. 2. Radiography of the gears – epicyclic gears [from Price (1974)].

The bronze gears had been made with the technology available in those times, probably by *investment casting*, but this method is considered inadequate evidence for the precision evident in Fig. 2. The regular working of sophisticated gear mechanisms like this required an elevated precision, achievable only with modern technology.

1.1. The astronomic calculator in the classical literature

The Calculator of Antikythera is the only planetarium available to us, but the Latin literature quotes another older one, built by Archimedes in the 3rd century B.C., also presumably with gear mechanisms. Cicero (106–43 B.C., contemporary to the sinking of the Calculator of Antikythera) reports that after the conquest in Syracuse in 212 B.C., the Roman consul Marcello carried in Rome a celestial globe and a planetarium built by Archimedes (287–212 B.C.): *De Re Publica*, I, 14, and besides also 21 and 22; *Tusculanae disputationes*, I, 63.

This planetarium was mentioned also by Ovidio (1st century B.C.) in the *Fasti* (VI, 263–283), Lattanzio (4th century A.D.) in the *Divinae institutiones* (II, 5, 18) and in a Claudiano epigram (4th century A.D.) entitled *In Archimedis Sphaeram*. Particularly, Claudiano adds that the instrument was contained in a starry sphere of glass. Unfortunately any detailed description of the mechanisms that animated the planetarium has been lost. What we know about this mechanism has been saved as the work of Archimedes *On the construction of the Sphere*, in which he described the principles adopted in the construction. These literary topics, however, show that the construction of these mechanisms was very diffused for centuries.

1.2. The most ancient analogical calculator of history

The Calculator of Antikythera worked as a portable calculator to a fixed program, just like a slide rule, in the sense that if they inserted some data (turns of the crank, corresponding to days) and the machine, already “programmed in the hardware” for that computational algorithms, directly gave the connected information: the positions of the Sun and the Moon in comparison to the constellations (and perhaps also the positions of the other planets). Currently it appears to be the most ancient analogical calculator in history.

2. Antikythera Calculator advances modern science

The heliocentric planetary system, proposed in modern times by Copernicus in 1543, had been anticipated in ancient times from Aristarchus of Samos (310 ca.–230 B.C.). The studies of the heliocentric planetary system, however, were opposed for many of the following centuries, allowing the assertion of the Aristotle (384–322 B.C.) geocentric theory and of Claudius Ptolemy (100 ca.–170 ca. A.C.), that, discusses it in his *Almageste*. Only a few scientists supported Aristarchus, some contemporaries of him like Archimedes in Syracuse (287–212 B.C.), which quotes the Aristarchus heliocentric theory in his book the *Arenario*, and from Seleucus of Seleucia (2nd century B.C.).

The heliocentric theory could have been supported also by Eratostene of Cirene (276–196 B.C.), who calculated the diameter of the Earth with extraordinary precision, from

Apollonius of Perga, (261 ca.–190 B.C.), author of the fundamental essay of geometry "*The Conic*" where he refers to the "epicyclic movement", and by Hipparchus of Nicea (2nd century B.C.), who discovered the precession of the equinoxes and the slow motion of the stars, considered fixed up to the 18th century when such a motion was ascertained by Edmund Halley (1646–1742). The chronology of the most important Greek scientists is illustrated in Fig. 3.

Most of the Aristarchus writings have been lost, and it is not possible to know the elements adopted by him to support his theory.

The knowledge of the planetary motion, necessary for the design of the epicyclic gearing present in the Calculator of Antikythera could have been, instead, one of the reasons induced by Aristarchus and a small number of Hellenistic scientists supporting the heliocentric theory. It is supposed that the epicyclic gearing can have been used, for the similar peculiar kinematics, as the mathematical models for the calculation of the celestial planetary motion. The mathematical model of the epicyclic gearings is illustrated in Fig. 4.

To calculate the planetary motion of the Earth, the Sun can be considered positioned on the central wheel, that is fixed (solar gear), and the Earth positioned on the planetary wheel epicyclic (planetary gear), that turns around the solar wheel. The value of the wheelbase i (distance of the Earth from the Sun) is calculated resolving the simple system of two equations. From this you obtain:

$$\begin{cases} \tau = \frac{r_1}{r_2} \\ i = r_1 + r_2 \end{cases} \qquad i = (1+\tau)\cdot r_2 \cong 149{,}580{,}000 \text{ km}$$

Also the third law of Johannes Kepler (1571–1630), was used by Isaac Newton (1642–1727) who formulated in 1686 (published in 1687) the law of universal gravitation. This referred to the orbit of the planets, assumed previously to be circular, but whose dimension was measured from the length of the maximum diameter of the elliptical orbit, technically known as the greater axis.

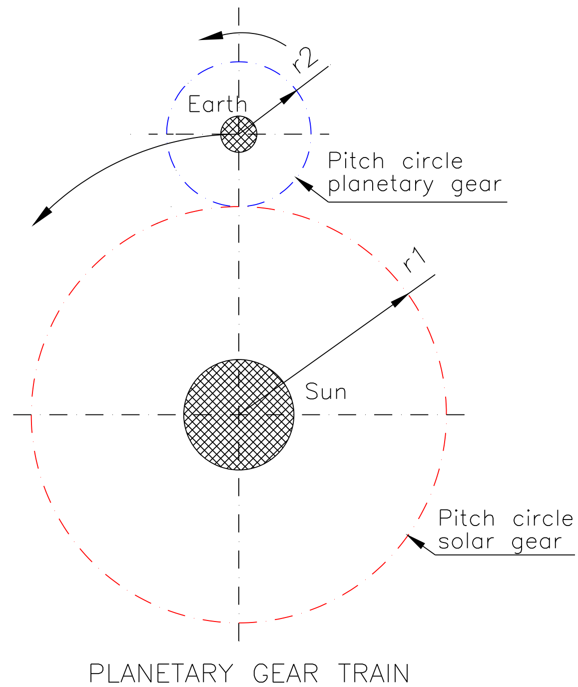

Fig. 4. Mathematical model of the epicyclic gearings (Giovanni Pastore © Copyright 2006).

The value of the distance of the Earth from the Sun could have been verified in the ancient times with measures of stellar parallax or with other procedures unknown to us. The distances of the Earth and the Moon from the Sun, knowing the cyclical times, allows the calculation of the speeds of the Earth and the Moon.

It is possible that the ancient scientists were also able to calculate the strengths of attraction (gravity) because they knew that in the rotational motion of the planets the strength of gravity is equal to the centrifugal force

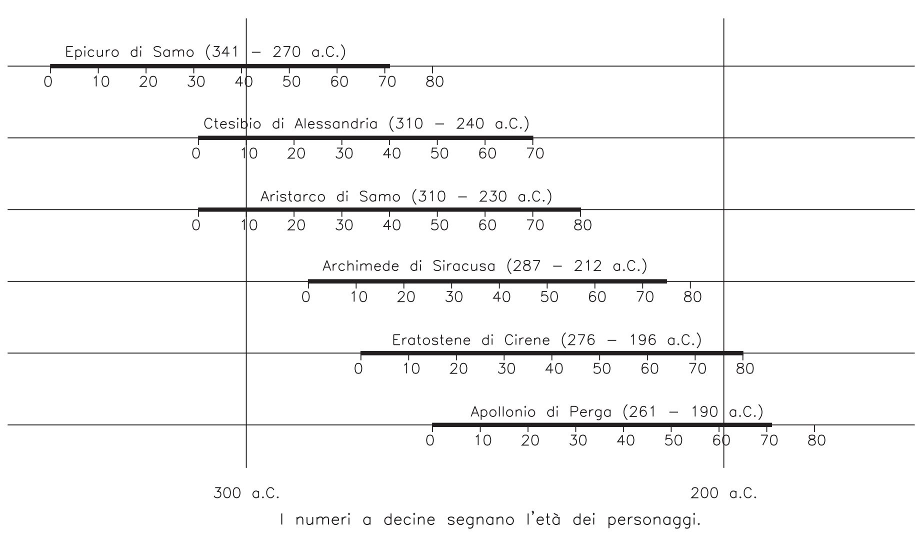

Fig. 3. Chronology of the most important Hellenistic scientists (Giovanni Pastore © Copyright 2006).

(Plutarche: *De facie quae in orbe lunae apparet*). In modern times centrifugal strength has been formulated from Christiaan Huygens (1629–1695).

The same Isaac Newton, considered himself a discoverer of ancient knowledge, in *De mundi systemate liber* (1728) attributing the knowledge of the law of the inverse squares to Pythagoras, making the analogy with the law of sounds by the monochord.

In other manuscripts not edited by Newton, but included in the preface to the *Astronomiaes physicae et geometricae elementa* (1702) by his pupil David Gregory, states that the ancient people (Chaldeans, Babylonians, Hebrews, Egyptians) knew that the gravitational strength was the inverse of the square of the distance. It has been attributed to Newton the worth of demonstrating this law, putting together the third law of Kepler and the formula of Huygens on the centrifugal strength, equalizing the period of the rotation of the two formulas and including the mass of the Sun in the universal constant "K" of Kepler. Here the mathematical model and the analytical development for brevity are not included, but they are broadly shown by Pastore (2006).

Consequently it is supposed that some sublime minds of the ancient times, with the knowledge of the equations of the epicyclic gearings that the construction of the Calculator of Antikythera implies, were able also to calculate the distance of the Earth from the Sun and accordingly the speed of the Earth and the Moon and their strength of gravity, the same results reached achieved by applying Newton's law

The values of the speeds and the gravitational strengths calculated with both algorithms converge to the same result, as numerically shown in Table 1. The differences between these two sets of calculations are negligible. From these calculations it appears that the ancient Greeks anticipated, by 19 centuries, the results of the law of the universal gravitation formulated by Isaac Newton in 1687 in his publication *Philosophiae Naturalis Principia Mathematica*.

Besides, the mathematical model of the epicyclic gearings used for the construction of the Calculator of Antikythera, presents many kinematics analogies with the "Theory of the vortexes" used by modern and contemporary scientists to simulate the formation of the solar system.

The model of the universe to "vortexes" has been hypothesized in the modern epoch by Cartesio (*Principia Philosophiae Naturalis*, 1644), then taken back, on a new basis, by Immanuel Kant (*Allgemeine Naturgeschichte und Theorie des Himmels – Universal Natural History and Theory of Heaven*, 1755) and subsequently re-elaborated by Pierre-Simon de Laplace (*Exposure of the system of the world*, 1796; *Mécanique céleste*, 1799–1825). The theory of Kant, will be then acquired by the History of the Science like nebular hypothesis of Kant-Laplace.

The model to "vortexes" on the origin of the universe and of the solar system was proposed also recently (1944) by the German Carl Friedrich von Weizsäcker (1912–2007). The study has then been enriched and completed by the Dutch Gerard Pieter Kuiper (1905–1973). The genial intuitions of the scientists of 17th and 18th centuries were confirmed by the discoveries made in recent years with the Hubble space telescope, launched into orbit around the Earth by NASA in 1990.

3. Summary

While shown in more detail by Pastore (2006), the proof of the use of epicyclic model in the construction of the Calculator of Antikythera and the kinematics analogies of the model tend to hypothesize that the ideas of the modern and contemporary scientists on the origin of the universe must be backdated many centuries. The discovery of the Calculator of Antikythera has led to the conclusion that ancient individuals promoted two principal ideas:

- The heliocentric nature of the solar system was opposite of the geocentric concept of the solar system.
- The formation of the solar system based on the "Theory of the vortexes".

The scientific value of this gear mechanism is indisputable because the inventor of the Calculator of Antikythera must have anticipated, by 19 centuries, the results of the law of the universal gravitation formulated by Isaac Newton in 1687 (*Philosophiae Naturalis Principia Mathematica*), that anticipated and used the heliocentric theory proposed by Copernicus in 1543 (*De revolutionibus orbium coelestium*), and anticipated the cinematic study of the epicyclic gearings published by Robert Willis in 1841 (*Principles of mechanism*).

Consequently it is possible also to calculate the speed of the Moon in the position of "Total Eclipse of Sun", that results to be of 28.798 km/s, inferior only by 3.5% in comparison to the speed of escape required to gravitate around

Table 1
Comparation of the ancient Greek and Newton's law computations.

Comparison of the computational results	Middle speed ($\frac{km}{s}$)			Gravitational force $N(\mathrm{kg}\frac{m}{s^2})$	
	Cinematic calculation based on the acquaintances of the Greek period	Calculated with Newton law	Measured	Cinematic calculation based on the acquaintances of the Greek period	Calculated with Newton law
Of the Moon around Earth	1.006	0.988	1.011	0.0182×10^{22}	0.0176×10^{22}
Of the Earth around Sun	29.782	29.786	29.790	3.544×10^{22}	3.545×10^{22}

the Sun. If the Moon, in the position of Eclipse of the Sun, had the absolute speed of 29.827 km/s (approximately equal to the peripheral speed of the gearing made ordinary, 29.701 km/s), it would be easily introduced in the orbit around the Sun because it is a preferential run. In such case also the third law of Kepler results were verified.

Nevertheless, this small difference of speed allow us to understand why ancient people were frightened of the consequences of the eclipse of the Sun if, in such a position, the Moon might escape the Earth's gravitation. If the Moon escaped the terrestrial gravitation to enter the orbit of the Sun as a planet, this would change the dynamic equilibriums of the Earth–Sun system and the Earth would start rotating more quickly, with catastrophic consequences easily imaginable, because of the diminution of the moment of inertia around its axis. And this is what happens, for example, to a dancer rotating on herself, if she closes her arms; her angular speed increases because the moment of inertia decreases.

$$Q = I_0 \cdot \omega = \cos t$$

It is obvious that the increasing of the speed, also of only 1 km/s, considered the big mass of the Moon, should require a big momentum. The possible impact of an asteroid on the Moon could alter such dynamic equilibrium. The direction of the impact would be fundamental.

The mathematical model and the analytical development for brevity are not included, but Pastore (2006) broadly shows them in the book *Antikythera E I Regoli Calcolatori*. The study of Giovanni Pastore on the Calculating of Antikythera, published in Rome in February 2006 in the book *Antikythera E I Regoli Calcolatori*, is based on the presence of the epicyclic wheel emerged from the studies of Price (1959, 1974). Subsequently, on 30th November 2006, a team of researchers (Freeth et al., 2006) has hypothesized other cinematic solutions that, however, do not invalidate the theory discussed above.

References

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., Ambisco, W., Edmunds, M.G. Decoding the ancient Greek astronomical calculator known as the Antikythera mechanism. Nature 444, 587–591, 2006.

Pastore, G. Antikythera E I Regoli Calcolatori, Tecnologia e scienza del calcolatore astronomico dei Greci, Istruzioni per l'uso dei regoli calcolatori logaritmici matematici, cemento armato e speciali, con numerosi esempi di calcolo. Privately published, Rome, February 2006. Available from: <http://www.giovannipastore.it>.

Price, de Solla Derek John, An Ancient Greek Computer. Scientific American, pp. 60–67, June 1959.

Price, de Solla Derek John, Gears from the Greeks: the Antikythera mechanism, a calendar computer from ca. 80 B.C. Transactions of the American Philosophical Society, November 1974.