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The influence of Hipparchus in Antikythera mechanism

Ioannis S. Diolatzis*, Gerasimos Pavlogeorgatos[1]

Department of Cultural Technology and Communication, University of the Aegean, University Hill, building of Geography, off. 2.14, 81-100, Mytilene, Lesvos, Greece

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ABSTRACT

Around 1900, a group of sponge divers, pulled out from an ancient Roman shipwreck, near the Antikythera island, a piece of a hardly distinguishable geared mechanism which is known since then as “The Antikythera mechanism”. Until now the exact use of some of its survived gears is investigated and there are speculations about its missing parts. In 2005 two revolutionary technical methods were applied on Antikythera mechanism. The first is known as : (3D) X-ray computed tomography (CT) by X-Tek Systems Ltd, with the use of which many hidden details under the corrosion, came to light. The second is known as : Polynomial Texture Mapping (PTM) which was applied by HP Labs, revealing engraved symbols and letters on Antikythera mechanism surfaces. After all these years of research, a more comprehensive picture of this machinery was built, leading to the conclusion that it was used as a multi functional “astronomical calculator” according to Freeth et al. (2006b) with many impressive capabilities such as:

- a prediction of upcoming Solar and Lunar eclipses
- a calculator of the four astronomical cycles (Metonic cycle, Callippic cycle, Saros cycle, Exeligmos cycle)
- moon phases indication
- Sun and Moon position in zodiac

The whole mechanical construction seemed covered by a wooden case with a front and a back door with engraved inscriptions on them. According to Freeth et al. (2006b) “The inscriptions support suggestions of mechanical display of planetary positions” proving the existence of a missing planetary subsystem. In this decrypted text, according to Freeth et al. (2006b), astronomical terms have been recognized like stations "ΣΤΗΡΙΓΜΟΣ" like statio,conjunctions and according to Jones (2017), there are references about the names of the five known planets. Researchers are trying for years to present planetary activity on their models suggesting different solutions with a common characteristic. In all models of planetary motion, the *epicyclic theory* is applied. Although this theory is precise enough for planets with negligible eccentricity, fails to demonstrate the real recorded apparent orbit of planets with significant eccentricity, like Mercury’s which is 0.205. On the other hand in Antikythera mechanism remains, there is an advanced device, known as the “*pin & slot*”, which simulates the non-uniform motion of the moon. According to Moussas (2009)...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 .... So if the constructor used a specialized gearing to model the moon’s orbit eccentricity which is 0.0549 why not do the same for Mercury’s case with an eccentricity of 3.7 times bigger? Many speculations about the Antikythera mechanism’s purpose have already been expressed, but nevertheless, accuracy is its undeniable feature which should be reflected in the mechanism’s astronomical indications. So, there’s a question that might be answered. ”Is it possible, the planets eccentricity can be simulated using the *pin & slot* device?”. This research tries to find an answer and proposes a feasible epicyclic gearing which can simulate the geocentric apparent path of Mercury. The construction is taking seriously the planet’s eccentricity, trying to minimize the discrepancy between expected and indicated measurements. Our proposal is based on theories known at the time Antikythera mechanism was constructed.

* Corresponding author.
E-mail addresses: ctd15003@ct.aegean.gr (I.S. Diolatzis), gpav@aegean.gr (G. Pavlogeorgatos).
[1] Director of the CHMLab, Department of Cultural Technology and Communication.

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1. Introduction

In ancient times astronomers kept watching the night sky being astonished by the weird motion of the planets. They recorded periodically the synods of the planets and they measured from time to time the (*stations*) of their retrograde[2] motion. Two Greek astronomers Hipparchus[3,4,5] and Apollonius[6] managed to predict these periodical phenomena by introducing the *epicyclic theory*.There is no extant treatises about Apollonius and Hipparchus but there are references in Ptolemy's Almagest. This is highlighted by Neugebauer (2013)... "Again, from the Almagest, we know that half a century before Hipparchus, Apollonius had proved important theorems concerning epicyclic and eccentric motion. ..." According to *epicyclic theory*, geocentric planetary motion is the superimposition of two circular motions. This is quite sensible if we consider that the geocentric motion (since it is observed from Earth) is the synthesis of two independent motions, one of the planet orbiting the Sun and the other of the apparent Sun orbiting the Earth. In other words the *epicyclic theory* is based on circles and not on ellipses. That's why planets apparent orbits with negligible eccentricity, like Venus, can be satisfactorily modeled by this theory. The problem appears in planets whose orbits are ellipses and the circular orbit approach, creates a considerable discrepancy in measurements. This research gives a solution to this problem by using the *eccentric-circle theory* which was applied by Hipparchus to explain the inequalities of the epochs. According to Ghosh (2018) "The deferent– epicycle model was also used as an alternative to Hipparchus's eccentric circle theory to explain the apparent non-uniformity of the sun's motion". Specifically, according to Fraser (2006) "Hipparchus explained the variable solar motion by assuming that the Sun moves about the Earth on a circle whose center is displaced slightly with respect to the Earth". Also, the *eccentric-circle theory* was applied from Antikythera mechanism's constructor, to modulate the non uniform lunar motion around the Earth using the previously referred *pin & slot* device. In this article it will be suggested a collaboration between *epicyclic theory* and *eccentric-circle theory*, especially for a planet with significant eccentricity like Mercury, in order its simulated apparent trajectory to be as real as possible. A specialized gearing is proposed as a final product of our research which could be applied to any planetary subsystem of Antikythera mechanism. We recommend this mechanical reconsideration especially for planets whose eccentricity should not be neglected (like Mercury and Mars) achieving accuracy in time measurements and reliable indications.

2. The apparent motion of the planets and the "epicyclic theory"

According to epicyclic theory, the planet P performs a complex motion while it is rotating uniformly on the small red circle called *epicycle* (ΕΠΙΚΥΚΛΟΣ) and simultaneously the center E of the epicycle is rotating uniformly on the large blue circle called *deferent* (ΦΕΡΩΝ ΚΥΚΛΟΣ)(see Fig. 1-a). The planet P is revolving the center E of epicycle, like planets revolving the Sun. For that reason E could be considered as Sun. Except for these two circles (epicycle and deferent) there are two others also, which are involved in the synthesis of P motion. The first one is a large black circle labeled x of radius x centered and fixed at D and the other one is a small black circle labeled y of radius y, centered at E. The y-circle is rolling on the circumference of x-circle. The question that might be raised here is: "What is the relation between epicycle and y-circle?". These two circles have common center (E) and the epicycle is fixed on y-circle. That means that while y-circle is rolling on the x-circle, the epicycle is forced to follow, and thus is revolving the E with the same angular velocity. The noteworthy in this theory is that an appropriate ratio of radii x and y and a specific epicycle radius R_E can reproduce the apparent trajectory of the planet P.

Now lets name ω_P the angular velocity of the rolling y-circle which is also the angular velocity of point P (fixed on epicycle) and ω_E the angular velocity of the epicycle's center E, around the center D. It is obvious that the point P is participating in a compound motion consisted from a local rotation around E with angular velocity $\frac{x}{y}\cdot\omega_E$ and a rotation around D with angular velocity ω_E. So for the real world the angular velocity of P will be:

$$\omega_P = \frac{x+y}{y}\cdot\omega_E \tag{1}$$

Now the point E could be considered as Sun orbiting the D which could be considered as Earth. On the other hand, the point P represents the planet P. Therefore $\omega_E = \frac{2\pi}{T_E}$ and $\omega_P = \frac{2\pi}{T_P}$, where is the mean sidereal period of Earth around the Sun (equal to the time that it takes for the true Sun to make a complete circuit of the ecliptic[7]) and T_P is the mean sidereal period[8] of the planet P around the Sun. So, $\omega_E = 2\pi$ rad/year and the Eq. (1) will be transformed into:

$$\boxed{\frac{1}{T_P} = \frac{x+y}{y}} \tag{2}$$

3. Determination of radii x and y

In Fig. 1-b the planet P inferior to Earth, appears in two successive superior conjunctions[9]. The time interval between these two successive superior conjunctions is the synodic period[10] of the planet.This section will be a logical consequence of the previous one. So, since the planet P which belongs to the epicycle with center E, in one synodic period, is rotating around E at $(2\pi + \theta_s)$ rad, it yields that:

$$\theta_S + 2\pi = \omega_P\ T_S \tag{3}$$

where T_S is the synodic period of planet P.

Since in T_S the radius DE is rotating at θ_S rad, then:

$$2\pi\ T_S + 2\pi = \omega_P\ T_S \tag{4}$$

or

$$T_P = \frac{T_S}{T_S + 1} \tag{5}$$

From the Eqs. (2) and (5) it is concluded that:

$$\boxed{\frac{y}{x} = T_S} \tag{6}$$

4. Determination of epicycle's radius and the Mercury's apparent orbit

The angular distance between Sun C (center of epicycle) and the planet P is called *elongation*. This angle has its greatest value when the

[2] Retrograde motion, in astronomy, is an apparent motion of a body in a direction opposite to that of the (direct) motions of most members of the solar system or of other astronomical systems with a preferred direction of motion.

[3] A station is the point when a planet appears to stop moving in the sky as it observed from Earth.

[4] An apparent meeting or passing of two or more celestial bodies. The Moon is in conjunction with the Sun at the phase of New Moon.

[5] Hipparchus was a Greek astronomer and he was born in Nicaea. He lived from about 190 B.C. to approximately 125 B.C.

[6] Apollonius was a Greek Geometer and astronomer who lived from about 262 B.C. to approximately 190 B.C.

[7] The ecliptic is the circular path on the celestial sphere that the Sun follows over the course of a year.

[8] Sidereal period of a planet is the time interval needed for the planet to return to same position relative to the fixed stars as seen from a fixed point outside the system.

[9] Superior conjunction occurs when a inferior planet passes behind the Sun as viewed from the Earth.

[10] Synodic period of a planet is the time interval needed for the planet to return to same position relative to the Sun as seen from Earth.