The new findings from Antikythera mechanism front plate astronomical dial and its reconstruction

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Fig. 1 - Extreme ''depth of field'' images, of the back face of Fragment C. The fossilized Lunar Disc on the back face of the front plate is clearly detectable. Credits: National Archaeological Museum, Athens. A. Voulgaris - Copyright © Hellenic Ministry of Culture & Sports/Archaeological Receipts Fund.

This paper refers to the investigation of the Zodiac scale and the Egyptian calendar ring of the Antikythera Mechanism front plate, based on the known surviving fragments of the Mechanism, mainly of Fragment C (National Archaeological Museum, Athens, inventory number X.15087). Fragment C is the preserved part of the front plate of the Antikythera Mechanism, located in front and above the large gear *b1*. Until now, only a portion and other isolated smaller fragments of the front plate survive.

The front plate dial was the cadran of the Annual and the Astronomical – calendar of the Mechanism. The manufacturer engraved on the front plate the information about the recurring events of every year on the Egyptian calendar ring and the Zodiac scale. During its revolution (1 turn/year), the pointer of the *Golden Sphere - Sun (Gnomonion)* pointed on the Egyptian Calendar ring, traversing the 12 months with 365 subdivisions and simultaneously the 12 zodiac constellations, engraved in arcs with subdivisions around the inside ring, just next to the Egyptian ring. The pointer - *Gnomonion* of the Sun – *Golden Sphere* (a bronze sphere with a pointer, which was possibly placed close to the perimeter of the annual gear *b1) (*Voulgaris et al 2018*)*, as it traversed the two rings, informed the user about the position of the Sun on the sky, (on Zodiac Constellation), during the corresponding Egyptian month and day.

Ophthalmoscopic examination of Fragment C shows that the front plate had a large hole in the center (Bitsakis and Jones 2016). Two plates with engraved inscriptions of the parapegma were on the top and on the bottom of the front plate of the Mechanism (Anastasiou et al 2013; Freeth and Jones 2016; Bitsakis and Jones 2016). In Fragment C, an

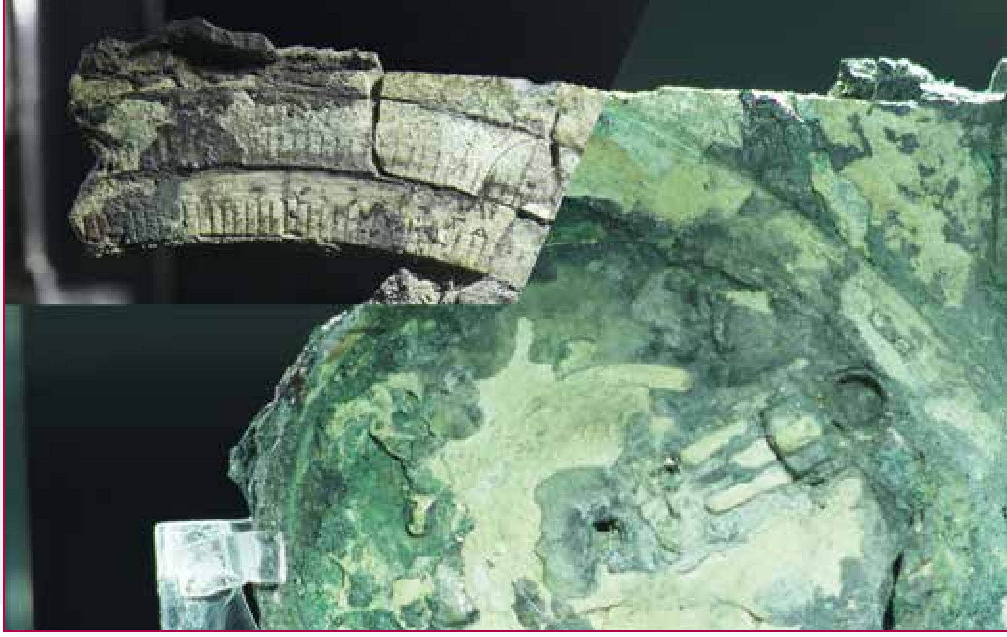


Fig. 2 - In the Isogeometrical-Multilayer Image, are presented parts of the front and rear faces of Fragment C. On the left of the image are clearly seen the two dial rings and on the right, the Bearing Base ring. It is evident that only the half width of the Egyptian calendar ring is supported on the Bearing Base ring. Close to the ''Moon Sphere'' the only one preserved staple is detected. Right above is clearly seen the sliding catch. Credits: Copyright © Hellenic Ministry of Culture & Sports/Archaeological Receipts Fund, A. Voulgaris

almost well preserved part of the parapegma inscriptions, is situated fossilized in front of the surviving dial rings and the Lunar Disc (Ptolemy; Wright 2012 notes; Carman and Di Cocco 2016). On the back side of Fragment C, lies the Lunar Disc, also fossilized (Fig.1), which was at the center of the mechanism before the ancient artifact was destroyed. By hand rotating the Lunar Disk (Voulgaris et al 2018), the user was also informed about the phases of the Moon, looking at the Moon Phases Sphere.

DATA MINING

Critical and determinant for our investigation, was the design and construction by A. Voulgaris of an optomechanical device with a modified camera lens, mounted on a micro moving x-y-z axes for tilting and aiming of the lens. This setup is capable to capture images of the fragments with extremely different position angles up to 83˚, eliminating the defocusing problem arising from the limited depth of field, which is strongly detected in conventional-non modified camera lenses (Fig. 1, 4, 5).

We also captured high resolution – *''isogeometrical''* images of the front and rear faces of Fragment C. We named our images *''isogeometrical''* because the capturing was done with the same optical system, in almost the same distance and perpendicularity from the well detected center of the fragment, so the parallax is the same and totally minimized on all of the images. So the images of the front and the rear faces are all of about the same scale and orientation. After the digitally processing (*mirror invert* in y axis) by the one the two images, we adding together and we constructed the *Master Isogeometrical, Multilayered - high resolution - (visual) Image* (Fig. 1,5). Then we added some of the corresponding AMRP X-ray tomographies (Figures 3,7). The very accurate-precise aligning of the set of these images was achieved by aligning on some distinctive - sharp areas of the boundaries of the fragment and especially the side to side mechanical (perpendicular on the plate) holes and other formations, avoiding aligning on the random cracks of the material or deformed areas. Therefore the *Master Isogeometrical Multilayer Image* offers the simultaneous selective observations of the front and rear areas of Fragment C.
After the digital processing, some very important new data about the design, the construction of the astronomical dial of the front plate, the handling and the using of the Mechanism were detected. Also some crucial differences from the published bibliography about the design and the role of the front plate dial have resulted.

THE DESIGN OF THE ANTIKYTHERA MECHANISM FRONT PLATE DIAL

The information about the annual astronomical events was engraved in the front plate of the Antikythera Mechanism (parapegma) and also in the two concentric rings: the Egyptian months ring and the Zodiac Constellations ring. The front plate of the Antikythera Mechanism was divided into three separate sections: the two *Rectangular Sections*, where the star events of the parapegma were inscribed

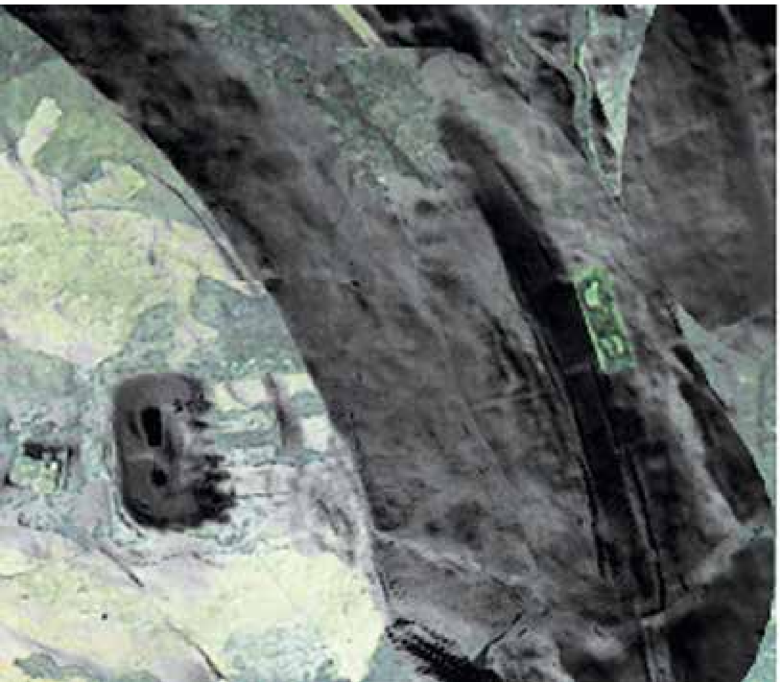


Fig. 3 - The Multilayer Isogeometrical Image of the Fragment C, in combination with corresponding (multi combined) CT of the AMRP. On the left it is detectable the stabilizer of the Egyptian calendar ring (front face) and the position of the staple (rear face). On the right are presented the form of the stabilizer. Credits: Copyright © Hellenic Ministry of Culture & Sports/ Archaeological Receipts Fund, A. Voulgaris-©AMRP.

Fig. 4 - Extreme ''depth of field'' image, shows the two rings which are located in the same level with the Middle Section of the front plate. Credits: National Archaeological Museum, Athens, A. Voulgaris. Copyright © Hellenic Ministry of Culture & Sports/Archaeological Receipts Fund.

Fig. 5 - On the top left: the Fragment C image with extreme depth field of view. The equal level of the two dial rings is shown and the rear stopper with a central hole. On the right: AMRP X-ray tomography in sideways direction. Bottom left: the stopper position compared to the boundaries of the two dial rings. Credits: National Archaeological Museum, Athens, A. Voulgaris. Copyright © Hellenic Ministry of Culture & Sports/Archaeological Receipts Fund and ©AMRP.

Fig. 6 - Left: A clock cadran digital composition of eleven frames on time 30s-31s, 35s-36s, 40s-41s, 45s-46s, 50s-51s and 55s. The pointer of the seconds it is not in the correct aligning in relation of the 6th, 7th, 8th and 9th subdivision of the cadran, because the lack of the calibration. The clock cadran needs an offset CCW rotation about 1.5˚, so the distinct positions of the pointer of the seconds to be aligned with the corresponding subdivisions. Right: On the ''24 hours clock'', the two pointers are in opposite ''line'' direction (i.e. 12 o clock), but the clock cadran needs an offset CCW rotation about 6˚, so the positions of the two pointers to be aligned with the corresponding subdivisions (24th and 12th). A. Voulgaris Collection.

(Anastasiou et al 2013; Freeth and Jones 2016; Bitsakis and Jones 2016) and the almost square *Middle Section*, with the central hole (Bitsakis and Jones 2016; Wright 2012). Around the central hole of the *Middle Section*, the Egyptian calendar and the Zodiac Constellations were engraved in circular distribution. As shown in Fig.2, from the *Master Isogeometrical Multilayer Image* of Fragment C, three totally independent rings surround the central hole of the Middle Section:

The *Bearing-Base ring* (Wright shows this as not in dependent from the *Middle Section* and present this as a sink digged on the Middle Section, (Video presentation at 50:55" and 50:58").

b) The inlaid Egyptian calendar ring

c) The *Zodiac Constellations ring* (totally independent), (Wright shows in https://www.youtube.com/watch?v=cSh551cdIEY at 50:55" and 50:58"and also Bitsakis and Jones (2016) and Jones (2017) refer to this, as a not independent part from the *Middle Section*, i.e. a ''solid body'' with the *Middle Section*).

The detection from CTs that the *Zodiac Constellations Ring* and the *Bearing Base ring* is an independent ring, it is not easy, because of strong fossilization, which transformed the rings as ''one body'' with the Middle Section. The Bearing-Base ring is stabilized to the almost square *Middle Section* by staples, from which only one from the four survives (Fig.2). As detected from the *Master* Isogeometrical Multilayer Image and the composition of the corresponding CT by the AMRP, this staple is the rear edge of (one of the four, preserved and detected in CTs (Bitsakis and Jones 2016) peripheral stabilizers of the Egyptian calendar ring Fig.3. These stabilizers prevent the Egyptian Calendar ring from falling outside.

In X-ray CT scans, out of a possible total of 365 holes, 87

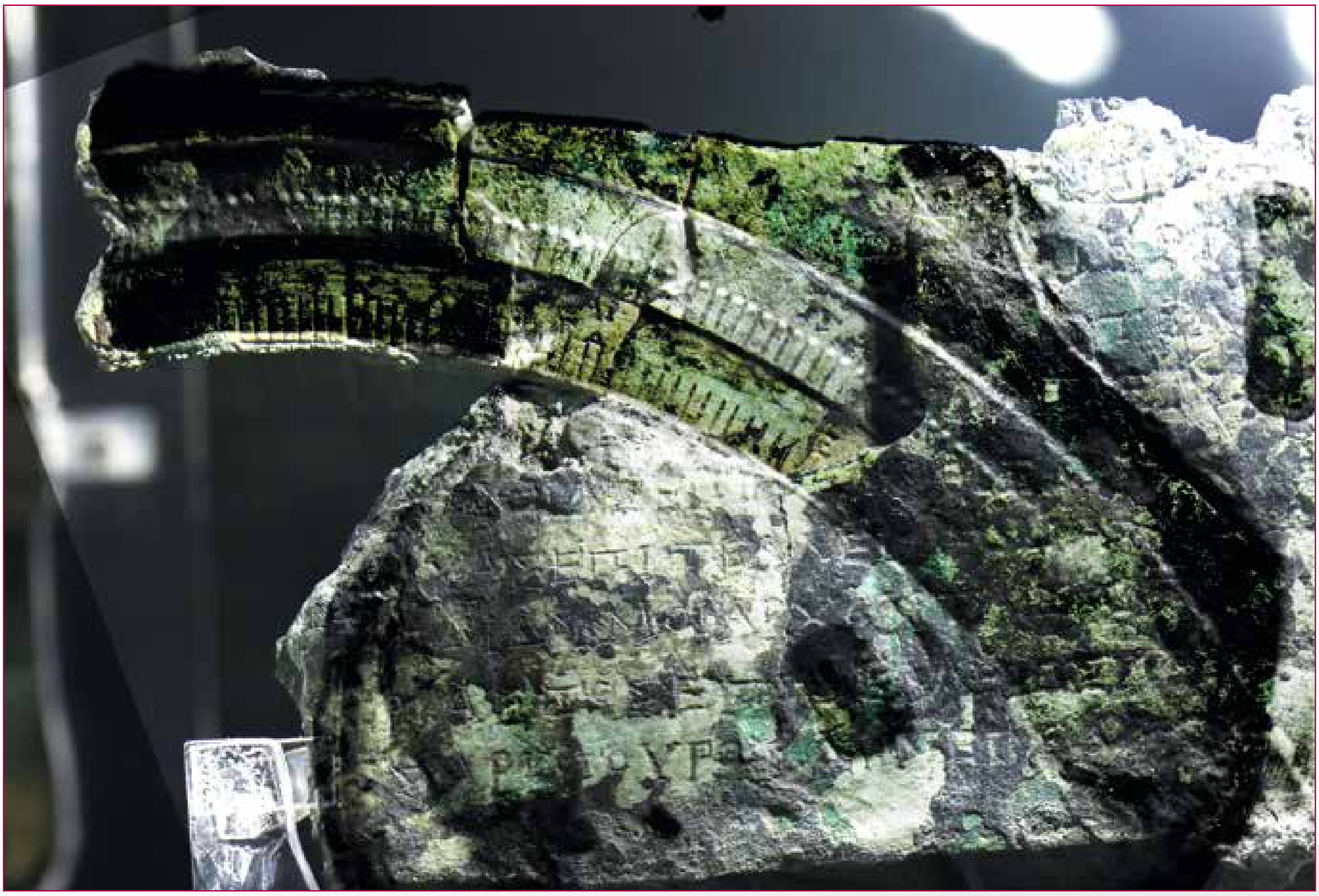


Fig. 7 - A digital synthesis of front face of the Fragment C with the corresponding X-ray CT by AMRP. The preserved ''day'' holes of the Bearing-Base ring are located between the subdivisions of the Egyptian calendar ring. Credits: Copyright © Hellenic Ministry of Culture & Sports/Archaeo logical Receipts Fund, A. Voulgaris - and © AMRP

have been detected on the *Bearing-Base ring* with diameter 0.7mm - 0.8mm (Wright 2012; Evans et al 2010). These holes well drilled by the manufacturer in a circular allocation on the *Bearing-Base ring* with excellent accuracy (Fig.7).
Some of these holes were also detected in our visual photographs of Fragment C, with the help of the X-ray images. From our photographs with extremely sideways capture angle, it is evident that the *Zodiac Constellation and the Egyptian calendar rings* are on the same level with the *Middle Section* of the front plate Fig.4 (Wright Video presentation; Bitsakis and Jones 2016; Jones 2017). About half of the width of the Egyptian calendar ring is positioned on the half of the width of the *Bearing-Base ring* Fig.7, while the *Zodiac Constellations ring* does not have any contact with the *Bearing-Base ring*. It is of course mandatory that the *Zodiac Constellations ring* is somehow supported.
In Fig.5 behind the two rings, just at their contact boundaries, a formation is detected, which seems it could well be one of four (or three) rear stops. This elongated formation-stopper has a cylindrical perforated cross section and it is curved following the circular boundaries between the contacts of the two rings. This formation could be stuck (soldered?) on the rear face of the *Zodiac Constellations ring* (or on the Egyptian calendar ring, but it is not easily evident from the tomographies), preventing this ring from falling outside (or inside). We also assume that of 3 or 4 stops acting also as little pointers (needles), stuck on the front side of the *Zodiac Constellations ring* (or on Egyptian calendar ring) were necessary to prevent this ring from falling inside (outside). These totally necessary front and back stops placed the *Zodiac Constellations ring* on the same level with the Egyptian calendar ring and allowed its free rotation.
The free - independent rotation of the *Zodiac Constellations ring*, offers the ability of the very precisely aiming and calibration of the ring, in relation to the positions of the *Golden Sphere- Sun pointer* and the *Lunar Disc pointer* (see chap…..). It also offers the ability of correction of the Callippic calendar which requires the subtraction of one day every four Metonic cycles (Theodosiou and Danezis 1995; Freeth et al 2008): after four Metonic cycles, the user can rotate the independent *Zodiac Constellation Ring* CCW by one subdivision (one day). A similar ability can be detected on the clocks cadran: after the assembling of a clock, it is possible that the pointer of the seconds does not coincide exactly with the clock's cadran subdivisions (usually 1 subdivision/5 sec-min) (Fig.6). The clock maker must calibrate the clock: he can rotate the clock cadran CW or CCW to achieve the absolute coincidence of the pointer of seconds with the subdivisions of the cadran.
The three rings of the front plate of the Mechanism, had engraved measuring scales with subdivisions or holes, so it is logical to assume that they were sequentially made by dividing, engraving, drilling machines (Voulgaris et al 2017; Irby 2016). According to our precise measurements about the drilling process of these holes, the dividing error must be $< 0.3^{\circ}$ to avoid overlapping of the holes. Even today the dividing and drilling of 365 holes with a diameter of 0.8mm with mechanical conventional tools, is an arduous work and requires extreme accuracy and attention. The *FRAMe Project* team designed and constructed the conventional cutting-dividing-drilling machine for the *Bearing-Base ring* and studied the procedure and the duration of the drilling on the *Bearing Base ring*.
The central section of the front plate was secured with four sliding caches (Wright 2012; Bitsakis and Jones 2016), of which only one is preserved. The sliding pin was secured on the rear face of the two rectangular parts of the parapegma (upper and bottom). In Rehm's photograph of Fragment A,

Fig. 8 - Digital reconstruction of the Middle Section (AMRP radiography) of Fragment C, in relative scale of Rehm's image of the Fragment a (Bayerische Staats bibliothek Rehmiana III/9). In Rem's image we also added digitally the (lost) wooden outline on the right part. From this reconstruction it is obvious that the Middle Section is not supported on the lower part of the wooden outline and supported on the left-right wooden outline. On the lower part of the wooden outline is supported the parapegma rectangular plates.

taken on 1904/5 (Rehm 1906), some preserved wooden linear formations, in vertical and horizontal positions (a part of wooden outline there is Fragment F via radiography of AMRP) (Fig.8) (Wright 2012). Based on the preserved Fragment C photographs and CTs, we digitally reconstructed the possible view of the Middle Section of the ancient prototype Fig.8. In this digital reconstruction, we also added Rehm's reconstructed photograph of Fragment A. In Figure 8 it seems that the vertical fossilized wood acts as a bearing spacer between the Front Middle Section and the Medium plate. The lower boundaries of the Middle Section plate are not matching with the wooden horizontal outline formation. The horizontal wooden outline formation acted as a bearing spacer of the lower Rectangular Section (parapegma).
By measuring the dimensions of the preserved deformed, distorted and incomplete parts of the Mechanism, the possible true dimensions of the Front Plate of the Mechanism (including the partially preserved wooden outline, as detected from the radiographies of the Fragment B) were at least 200mm X 330mm. In our functional models we chose the ratio of the sides equal to the golden ratio $\varphi=1.618$, which was used by ancient designers, sculptors, mathematicians and applied in a lot of constructions in ancient Greece (Hambidge 1924; Euclid).

THE EGYPTIAN CALENDAR RING

The inlaid freely rotating ring represented the Egyptian months ΘΩΘ (*Thoth*), ΦΑΟΦΙ (*Phaophi*), ΑΘΥΡ (*Athyr*), ΧΟΙΑΚ (*Hoiak*), ΤΥΒΙ (*Tybi*), ΜΕΧΙΡ (*Mechir*), ΦΑΜΕΝΩΘ (*Phamenoth*), ΦΑΡΜΟΥΘΙ (*Pharmouthi*), ΠΑΧΩΝ (*Pachon*), ΠΑΥΝΙ (*Payni*), ΕΠΙΦΙ (*Epiphi*), ΜΕΣΟΡΙ (*Mesori*) of 30 subdivisions each (days) and 5 induced (epagomenai) days. According *Figure 2* the Egyptian calendar ring was adapted onto the *Bearing Base ring* (see the previous chapter)

and was held in place by four peripheral stabilizers (Bitsakis and Jones 2016). Setting the disc in a given position, the fixation was probably done by inserting one (or two) pins, applied in one (or two opposing) of the 365 peripheral holes of the *Bearing-Base ring* (Wright 2012). The user removed the pins every four years or 53.4 full rotations of the *Lunar Disc* (sidereal months), rotated the Egyptian calendar ring anticlockwise by one hole and placed the pins back, thus accounting for the slide of the Egyptian calendar ring relative to the solar year.
The Egyptian calendar had 365 days per year and did not account for a correction over the actual duration of 365.25 days. This meant that it preceded the actual year by one day, every four years or 6 months in 720 years and essentially the seasons and the risings and settings of the stars did not occur in the same Egyptian date overtime. Every 1460 years, namely during a *Sothic Cycle* (Theodosiou and Danezis 1995) or *Canicular Period* (Murray 1828), the Egyptian calendar would return to its original starting position. The *Sothic Cycle* began with *1st Thoth* (the first month of the Egyptian calendar) at the first day of the morning rising of Sirius. Censorinus and Theon of Alexandria report that on July 19, 139 AD (Theodosiou and Danezis 1995), a new *Sothic Cycle* began on the morning rising of Sirius (when the Sun was at 24th day in the constellation of Cancer). The start of the previous *Sothic Cycle* was on July 9, 1321 BC (according to the *Starry Night* planetarium software program), when Menefres Ramsey I or one of his successors, Seti II or Meneftha II, was the pharaoh of Egypt.
The gap between 139 AD and 150 BC (an hypotethical date of construction of the Mechanism), is 289 years. So, *1st Thoth* of 150 BC should point at the third subdivision of the month ''Χηλαί'' (Libra). By examining the surviving fossilized Egyptian calendar ring and the *Zodiac Constellations scale ring* of the Fragment C, *1st Payni* points to 18th subdivision (day, see next chapter 2.3) of Libra and this correlation happened on 569 BC (see also Price 1974).
The position of the Egyptian calendar ring does not affect and is not related with the measurement system of the Mechanism, the pointers or with the gears. Its role is ''more passive'' and its position depended entirely from the other scales-calendars.
As described below, the Mechanism was constructed so it could be readily used at any given date and year and it is possible that it was set to this specific date by the user and the Egyptian calendar ring position followed the position of the rest rings and pointers.

THE ZODIAC MONTHS SCALE - RING

Concentric to the Egyptian Calendar ring, was the smaller inlaid and freely rotating *Zodiac Constellations ring*. On this ring were engraved the zodiacal constellations *Libra (ΧΗΛΑΙ), Scorpio, Sagittarius, Capricorn, Aquarius, Pisces, Aries, Taurus, Gemini, Cancer, Leo and Virgo*. Of the 12 zodiacal constellations, *Libra* (by naked eye) and *Scorpio* (by CTs) are completely preserved in Fragment C, with 30 subdivisions each and also parts of *Virgo* and *Sagittarius* survive (Bitsakis and Jones 2016). Because of the existence of the subdivisions, this ring was also a measuring scale.
According to Price 1974, the Zodiac scale was probably divided into 12 equal arcs, with 30 subdivisions each, therefore was divided into 360 subdivisions i.e. degrees (Wright 2002b). If the Zodiac scale was divided into 360 equal subdivisions, then the solar anomaly could not be represented (Evans et al 2010).We will argue that the Zodiac ring was divided into 365 (equal) subdivisions (or less possibly in 364 divisions + 1.25, a more extended one) i.e. days (and not degrees), with 12 zodiac (unequal arcs) months, with an

Fig. 9 - The old analog multimeter with the concentric scales and the common pointer. The three inside scales (black, red and red arcs) have equal subdivisions of Volts/milliamperes (DC-AC). Note that the concentric scales of Ohms and Decibels do not have equal subdivisions.

uneven number of days, depending on the duration of each zodiac month, for the following reasons:

1) The fact that the rotation of the *Lunar Disc* and the revolution of the *Golden Sphere-Sun* with its pointer, traced the 365 subdivisions-days of the Egyptian calendar ring, indicates that the Mechanism acted as an astronomical calendar-time measuring device. Thus, in the front plate, the quantum unit of the front dial measuring system was one day (time unit) and in the back plate was one synodic lunar month.
The *Egyptian Calendar ring* and the *Zodiac Constellations ring* seem to be concentric and both of these have engraved subdivisions. The pointer of the *Golden Sphere* traced simultaneously the subdivisions of the two scales during its revolution.
A characteristic paradigm of a measuring machine - device with two concentric scales with a common central pointer is the old analog voltage-current multimeter Fig.9. An analog multimeter measures the electrical current in Amperes (A) and with the addition of some electrical resistances it can also measure the voltage in Volts (V). The current and the voltage scales with equal subdivisions are in concentric circular arcs. The center of the common pointer is placed on the center of the two circular scales. Using the multimeter for a measurement, the angle declination of the pointer from the ''zero'' position, is given by the equation $\varphi^{v}= k*V$ *(1)* for the Voltage measurement and $\theta^{A}= n*A$ *(2)* for the current measurements (where *k* and *n* are constant numbers). By dividing the equations *(1)* and *(2)* we argue that $\varphi^{v}/\theta^{A} = k/n * V/A \rightarrow \varphi^{v}/\theta^{A} = k/n* R$ *(3)* (V/A=R, Resistant). This ratio *(3)* is a constant number. So the two arc scales can be concentric with a common pointer, because their ratio is a constant number i.e. the two scales are related with a constant ratio or they have the same units.
Because the *Zodiac Scale* and the *Egyptian calendar ring* of the Mechanism are circular and concentric with a common pointer (*pointer-Golden Sphere*), the ratio of their measuring units (subdivisions) must be a constant number. If the measuring unit of the Egyptian month dial ring is ***days*** (t^{days}) and the zodiac scale units is ***x***, the ratio $t^{days}/x^{(units)} = a$ *(4)* must be a constant number. If we assume that the zodiac scale had 360 subdivisions i.e. angle degrees, the equation *(4)*

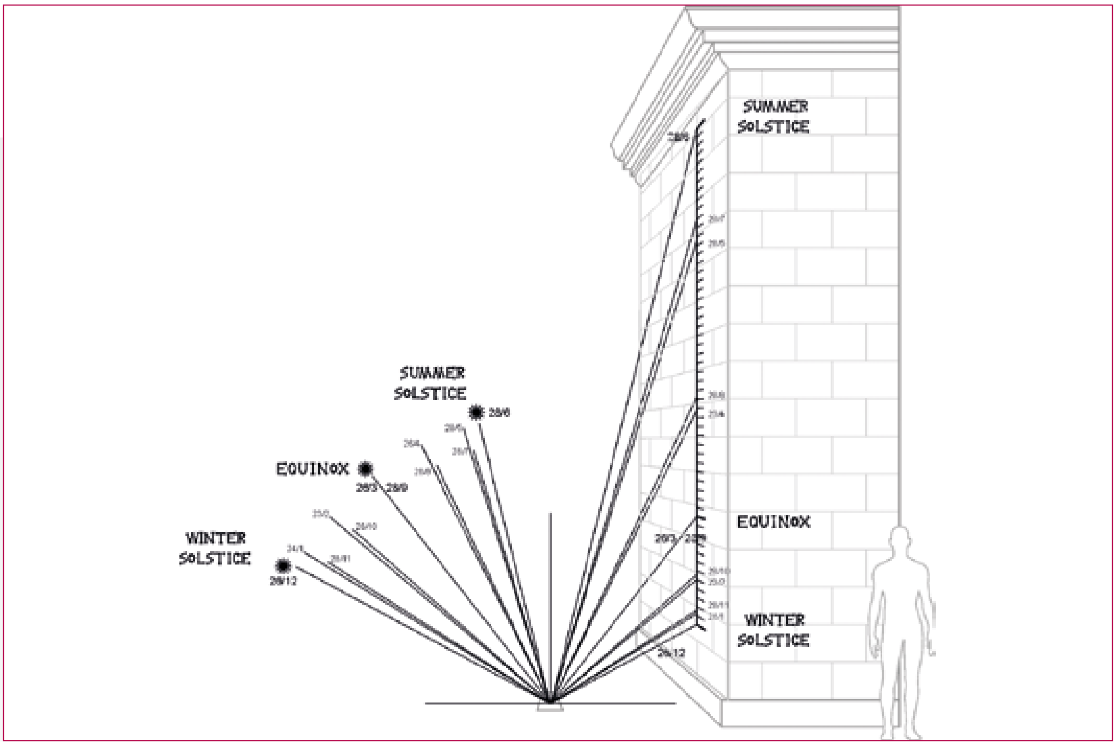


Fig. 10 - Representation in relative scale of a possible set up of the Meridian Wall that could be used by Meton and Callippus, for measuring (at the wall) the height of the sun at noon during the seasons, using a mercury mirror.

is written in an analog function: *($x^{degrees}$) = $a*t^{days}$ (5)*. The time (t^{days}) that the Sun takes to cross an angular distance of *d*˚ in the zodiac circle in the sky, is given by the equation

$t^{days} = d^{\circ} / v^{sun}$ (6). Because of the solar anomaly, Sun's velocity v^{sun} is not constant, so the equations *6* and *5* cannot be constant. Therefore, the hypothesis that the zodiac scale had 360 equal subdivisions of degrees is not correct.

2) The parapegma of the Mechanism (Anastasiou et al 2013) referred to observations on specific dates (i.e. days) when the risings/settings occurred. The manufacturer engraved the numbering of the risings/settings of the stars of the parapegma, on some of the subdivisions of the zodiac scale with index letters (in Fragment C, 12 index letters are preserved on some zodiac scale subdivisions) (Bitsakis and Jones 2016). The user read the index letters on the zodiac subdivisions and simultaneously these letters were engraved on the beginning of each parapegma corresponding sentence of the star event.

We do not think that the manufacturer converted the dates of the star events (days) in the corresponding degrees and then engraved the letters on the subdivisions of the zodiac scale, using a different scale unit than days. The ratio 365 days/360˚= 1.01388888 days/degree and this conversion creates periodically errors during the dividing-engraving of the subdivisions, because of the rounding error, which downgrades the accuracy: in the beginning of the two scales (Egyptian-days and Zodiac-''degrees''), the subdivisions are coincident, but as the subdivisions proceed the two scales

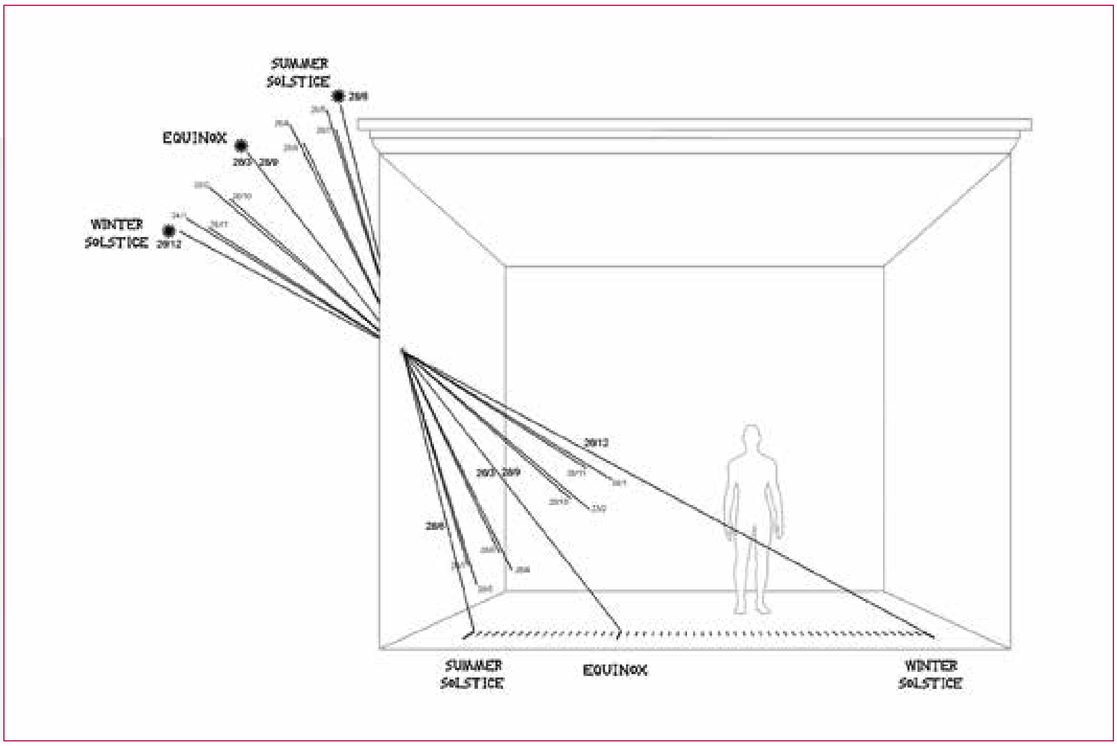


Fig. 11 - Representation in relative scale of a possible set up, that could be used by Meton and Callippus, for measuring (at the floor) the height of the sun at noon during the seasons, using a camera obscura-pinhole camera.

Seasons	Era 432 BC	Days	Era 330 BC	Days	Era 130 BC	Days	Era 80 BC	Days
Autumn Season	28/9-25/12 (perihelion 29th Noe)	89	27/9 - 24/12 (perihelion 30th Noe)	89	26/9 - 23/12 (perihelion 1st Dec)	89	26/9 - 23/12 (perihelion 30th Noe)	89
Winter Season	26/12-25/3	90	25/12 - 24/3	90	24/12 - 22/3	89	24/12 - 22/3	89
Spring Season	26/3-27/6 (aphelion 29th May)	94	25/3 - 26/6 (aphelion 30th May)	94	23/3 - 24/6 (aphelion 31st May)	94	23/3 - 25/6 (aphelion 30th May)	95
Summer Season	28/6-27/9	92	27/6 - 26/9	92	25/6 - 25/9	93	26/6 - 25/9	92

Tab. 1 - The dates of the Solstices and Equinoxes and the duration of the seasons for different Eras.

diverge, e.g in 73th day the difference is 1 subdivision (73rd day= 72˚).

3) Taking into consideration the constructional techniques at that time, it would be more precise and easy to simultaneously divide and engrave two concentric rings, attached to a common center. The probable divisional machine of the manufacturer was already calibrated in 365 subdivisions for engraving the ring of the Egyptian months and for drilling the 365 holes on the *Bearing Base ring*. If the zodiac scale had 360 subdivisions, then he would need to recalibrate the dividing machine tool for 360 divisions. This task at that time was quite painful and slow.

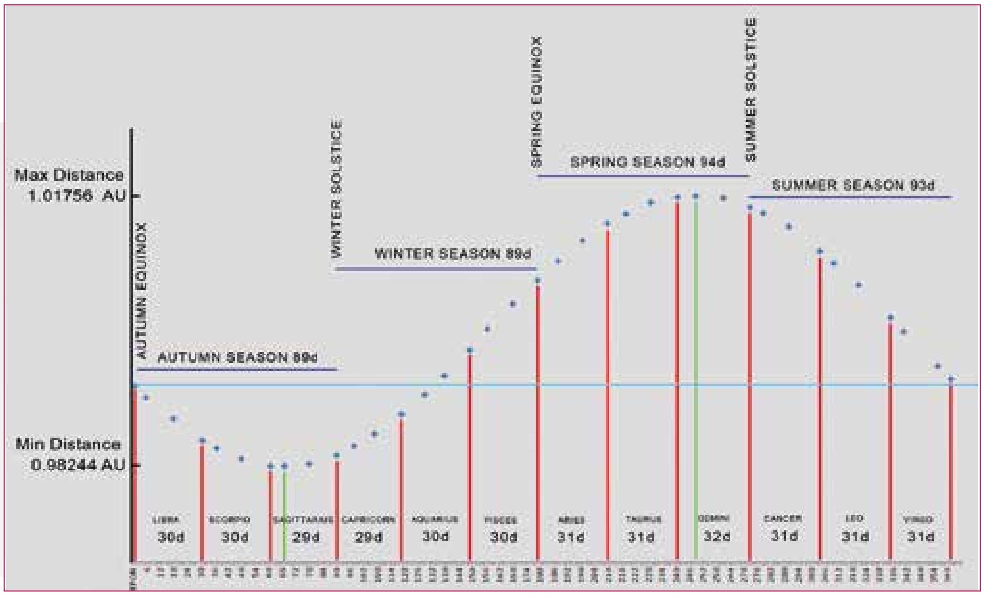
4) If the Zodiac scale had 360 subdivisions in degrees, then to account for the solar anomaly, it would require 360 unevenly distributed subdivisions (closer spaced at the months that the Sun's velocity is faster). We consider this hypothesis unlikely, because we must assume more hypotheses and more structural-constructional modifications of the front plate (Evans et al 2010). This contradicts *the principle (philosophy) of the fewest assumptions*, as first stated by pythagoreans philosophers and later known as the Occam's razor (https://plato.stanford.edu/entries/logical-construction).

Therefore, the hypothesis that since both the two surviving constellations, *Libra* and *Scoprio*, were divided in 30 subdivisions, then all of the remaining constellations would also be divided in 30 subdivisions (degrees) is neither necessary, nor mandatory for the proper functioning of the Mechanism. Instead it hinders the functionality of the Mechanism. There is no reason to divide the zodiac scale in 360 subdivisions, since the dividing into 365 subdivisions is simplest, easier,

ZODIAC CONSTELLATION	Date on 130 BC	Equinoxes and Solstices	Duration of the Zodiac Months
Libra	27 September-26 October	Autumnal equinox	30 (Fragment C)
Scorpio	27 October -25 November		30 (Fragment C)
Sagittarius	26 November-24 December (perihelion on 1st December)		29
		autumn season duration	89 days duration
Capricorn	25 December - 22 January	Winter Solstice	29
Aquarius	23 January -21 February		30
Pisces	22 February -24 March		30
		winter season duration	89 days duration
Aries	25 March-24 April	Vernal equinox	31
Taurus	25 April-26 May		31
Gemini	27 May-26 June (aphelion on 31st May)		32
		vernal season duration	94 days duration
Cancer	27 June-27 July	Summer Solstice	31
Leo	28 July-27 August		31
Virgo	28 August-27 September		31 (parapegma inscriptions)
		summer season duration	93 days duration

Tab. 2 - The duration of the Zodiac Months.

Fig. 12 - The sinusoidal graph represents the variable distance of the Sun-Earth, in Astronomical Units, during the year, through the zodiac months, for the era of 130 BC (according to ''Starry Night'' program). The graph starts from zodiac month of Libra, in date of the Autumn Solstice. Because of the 2nd Kepler's law, during the minimum of the distance, the ''solar velocity'' and also the angular velocity is maximum.



without errors and fully functional.

So we believe that the Antikythera Mechanism was a time measuring machine and not a machine like a sextant (for angles measuring).

THE ANCIENT MEASUREMENTS OF A SEASONAL DURATION

The unequal duration of the seasons and also the different duration of each zodiac month were known in ancient Greece, from observations of *Meton* and his partner, *Euktemon* (Pavel 2006; Jones 2017). The calculation of the dates of the solstices and the equinoxes, was done from the hill of Pnyka in Athens, using their invention, the *Heliotropion* or *Helioscopion*. Meton identified the repetition of the positions of the Sun and Moon in relation to the sky (stars) in the era of about 432 BC, known as the 19 years Metonic cycle (Freeth et al 2008; Theodosiou and Danezis1995). About one hundred years after *Meton*, around the era of 330 BC, *Callippus* continued the observations and improved the accuracy of the calculation of the duration of the seasons and the dates of the Solstices and Equinoxes.

One possible setup of the *Helioscopion* and a method for calculating the dates of the solstices and equinoxes in ancient time, could be based on the use of an East-West aligned oblong container, filled with mercury, which acted like a permanent leveled mirror reflecting the sun's light Fig.5 (mercury as *cinnabar* was in use in ancient Greece and Egypt for the separation of gold ore) (Theophrastus). The observer secured the container to a fixed place on the ground in some distance from a wall several meters high (e.g. *The Horologion of Kyristos* - Ωρολόγιον του Κυρρήστου, known also as the *''Tower of the Winds''* in Pnyka of Athens, was 12m high) (Noble and Price 1968). By making observations for a few consecutive days and recording the maximum daily height of the reflection of the sun rays on the wall, he could determine a point of the ''reflected'' local meridian. Next, by using a plumb line cord *(''Σταφυλίς- Staphylis'')* (Orlandos 1955), he drew the local meridian on the wall, as a vertical line. The reflected sunrays from an oblong mirror have also oblong form, thus making the measurements easier and more accurate. The lowest height of the solar reflection was during the date of the *Winter Solstice* (Sun's Declination -23.4˚) and the highest during the date of the *Summer Solstice* (Sun's Declination +23.4˚). Using trigonometry (calculations on the *Meridian Wall* or using the local latitude), the observer could calculate the point on the *Meridian Wall* at the dates of the equinoxes (Sun's Declination 0˚). He could also design-mark other useful information of the celestial sphere e.g. the projection of the Ecliptic in different dates. If the distance between the two solstices on the wall was about 5m (i.e. the distance of the mirror from the wall was about 2.5m), the scale on the *Meridian Wall*, would be about 0.1˚/1 cm. This scale offers a resolution of about 4 arc min, enough for precise calculations. In this manner, also some nighttime lunar observations could be performed.

A second idea of how *Helioscopion* could be implemented is the pinhole camera-(*camera obscura*). The pinhole camera was known in Ancient Greece since Aristotle (Gatton 2016; Aristotle; Euclidis; http://paleo-camera.com/) . In a dark room with a small hole on the wall, located towards the meridian, the Sun's image was projected on the floor and the projection of the solstices was inverted: the Summer Solstice closest to the wall with the hole and the Winter Solstice farthest (Sutter 1964, https://www.youtube.com/watch?v=MnnntOVHw4Y) . The distance of 2.5m between of the hole and the floor offers the same resolution with the

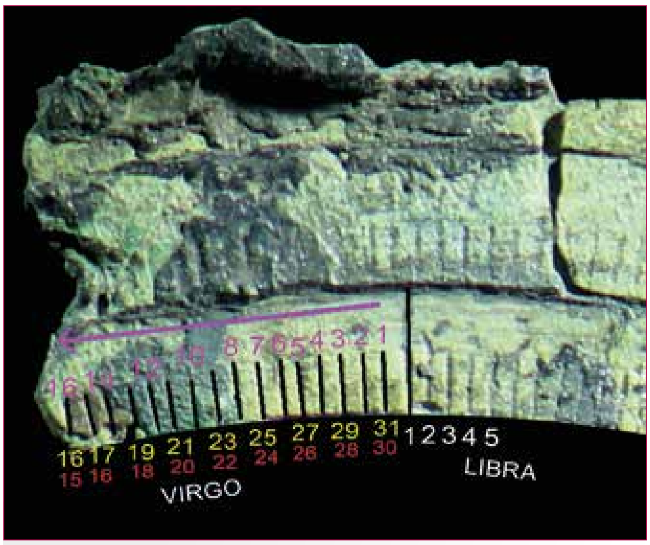


Fig. 13 - The numbered preserved part of Virgo zodiac Month. With purple numbers is the numbering beginning from the end, with red numbers the ''false'' measurement and with yelow the correct measurement of the subdivisions.

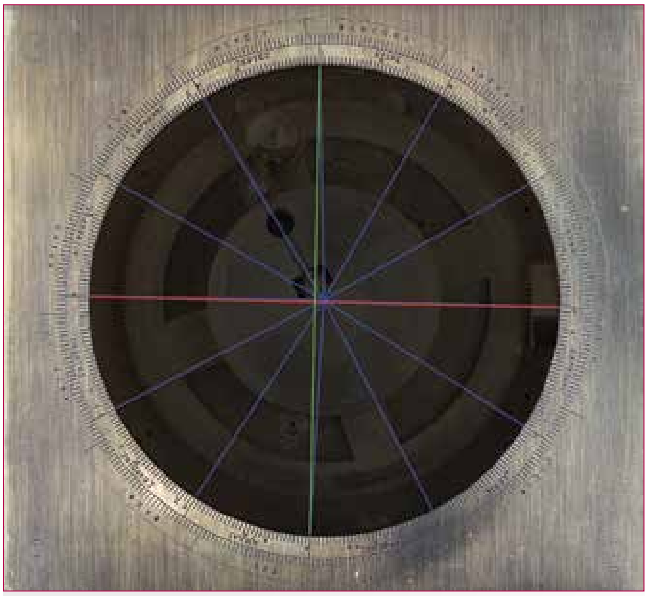


Fig. 14 - The Zodiac Months ring of the FRAMe model of Antikythera Mechanism. We correct align by tilting, our front plate model in an optical bench. The red line represents the line of solstices, the green line represents the line of equinoxes and the yellow line represents the line of apsides (perihelion-aphelion). The blue lines show the unequal central angles of the zodiac months with respect to the center of rotation of the Sun - Golden Sphere (and the Lunar Disc) i.e. Earth, which is also the center of the two dial scales. Because autumn and winter seasons had 89 days each, the line of Equinoxes is perpendicular to the line of Solstices, but their intersection does not coincide to the common center of the two dial scales, because of the solar anomaly.

Meridian Wall.
Moreover, if the distance between the pinhole and the projected image on the floor is large enough, then it is even possible to measure the diameter of the solar image (as a pinhole camera solar projection). For example for a hole-floor distance of 10m, the projected solar image has a diameter about of 93.5 mm on perihelion or about 90.5 mm on aphelion i.e. sufficient enough for someone to realize and measure the change of the apparent solar diameter from perihelion to aphelion.
We consider unlikely the possibility that the *Heliotropion,* designed-constructed and used by the excellent geometer-engineer *Meton,* could be only a high pillar, because the projected shadow on the ground is of too much low contrast with very extensive and blurred limits.

THE ZODIAC MONTHS RING RECONSTRUCTION

The division of the *Zodiac scale ring* into 365 equal subdivisions (days) converts it to a *Zodiac Months ring*. Each Zodiac Month begins when the Sun transits (projected on) the Zodiac Sign of the corresponding Zodiac Constellation and its duration is measured in days. The 12 arcs of zodiac months are not equal, because they have a different number of days, due to the solar anomaly. Of course we don't know which data, astronomical map, zodiac signs, observations and calculations about the duration of each zodiac month the manufacturer used.
We assume that on the ancient astronomical map used by the manufacturer, the Ecliptic was divided in 12 equal arcs of 30˚ each. Each of the 12 zodiac constellations began with its zodiac sign, as usually inscribed on most ancient astronomical/astrological maps of Babylon, ancient Greece and even on most recent maps until today (Theodosiou and Danezis 1995; Rogers 1998; Powel 2006).
For the calculation of the duration of each zodiac month in era of 130 BC (the possible era of the Mechanism's construction) (Freeth et al 2006), we firstly calculate the duration of each seasonal period.
Each seasonal period of three months, started with the date of the corresponding solstice or equinox. According to the ancient Greek calendar (Theodosiou and Danezis 1995), the beginning of every day was the time of the sunrise and for our calculations we used the exact time of sunrise (about 6 a.m. ± 1 hour, depending on the season). Using the re-calibrated astronomical planetarium software *Starry Night*

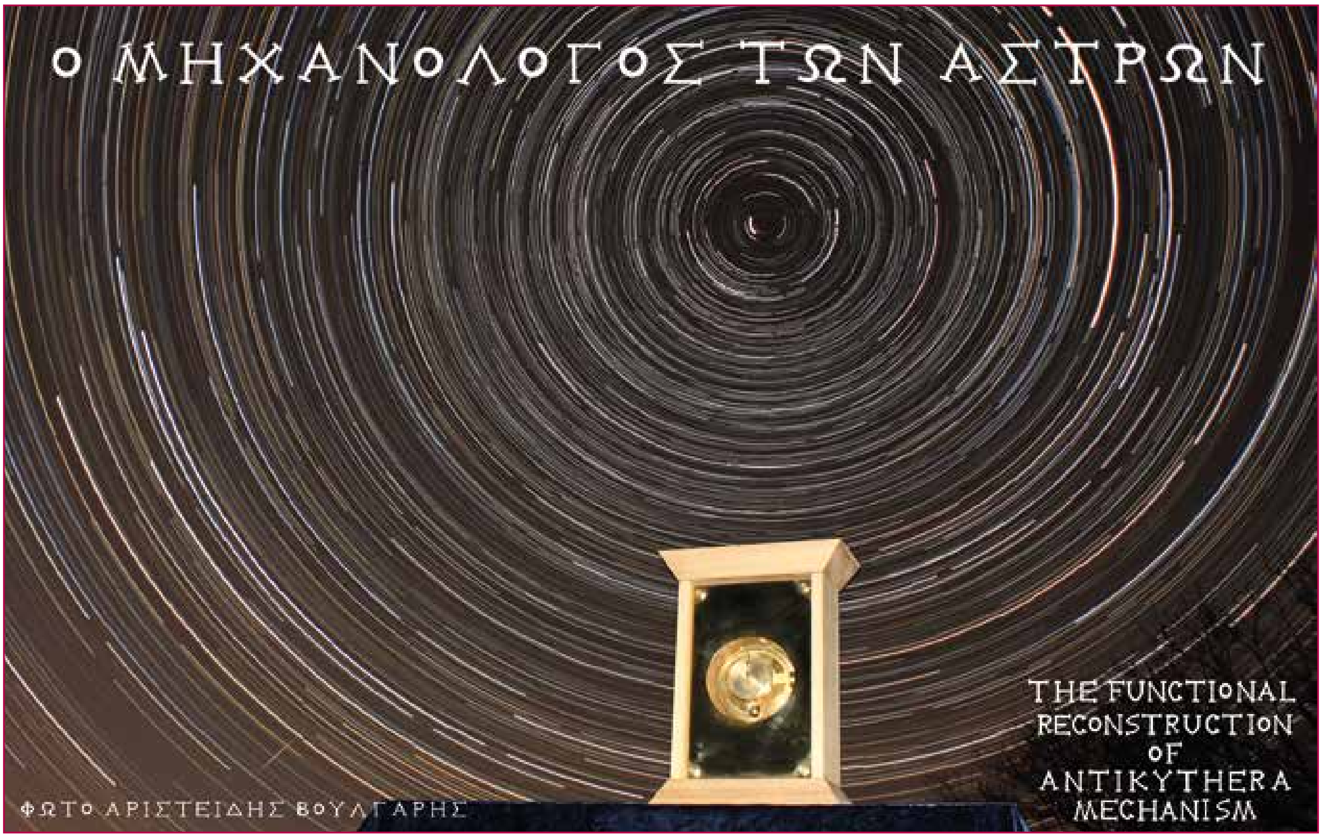


Fig. 15 The Mechanologist of the Heavens. Because of the Earth's rotation the star trails are visible. The total exposure time is about 3 hours.

(https://starrynight.com), we calculated the durations of the seasons and the perihelion/aphelion dates for the years 430 BC (Metonic Era astronomical observations), 330 BC (Callippic Era astronomical observations), 130 BC (possible era of the construction of the Mechanism) and 80 BC (possible era of the shipwreck) (Freeth et al 2006), (Table 1).
As seen from Table 1, the same seasonal period, calculated in different eras, has a different duration, because of the Precession. In every year, each seasonal period has a different duration, because of the solar anomaly. Afterwards we calculated the duration of each Zodiac Month, for 130 BC (Table 2-Fig.12).
In the era close to 130 BC, the autumn season duration was 89 days. The two zodiac months Libra and Scorpio fully preserved on Fragment C, each have 30 subdivisions-days (Bitsakis and Jones 2016). So the duration of Sagittarius (the third zodiac month of the autumn season) must be 29 days. In this way the zodiac month of Sagittarius, has the smallest duration in days, which is in correlation with the fact that it includes the date of perihelion i.e. the date when the Sun's velocity is in its highest value (so the duration of this zodiac month must be shorter).
The duration of the winter season is also 89 days. The duration of the three missing zodiac months of the winter season, were chosen to be of 29, 30 and 30 days respectively. These numbers were chosen because of the gradual decrease of the sun's velocity after the date of perihelion. As a result, the duration of each month of the winter season is in mirror - axial symmetry to the corresponding months of autumn season.
The spring season has duration of 94 days and the summer season of 93 days. In the same manner, we keep the pattern of the axial mirror symmetry of the duration of months with respect to the *line of apsides* (and also close to the Solstices). The month with 32 days (to account for the extra day of the spring season) was chosen to be the zodiac month of *Gemini*, because this month includes the date of aphelion, when the Sun's velocity is in its lowest value. The rest two months of spring season were chosen to be of 31 days each. Also for the summer season duration of 93 days we chose the duration of each month to be 31 days so that the axial mirror symmetry of the duration of months with respect to the *line of apsides* continues to apply.
Another proof of the above calculations is the crucial observation from the Front Dial inscriptions (Bitsakis and Jones 2016). In the preserved part of Fragment C of the constellation of *Virgo*, Bitsakis-Jones report the detection of two subdivision letters (index letters), Ψ on the 19th subdivision engraving and Ω on the 21st. The part of Virgo constellation arc with engraved subdivisions 1-14 is missing and the numbering of the index letters Ψ and Ω was calculated from the existing end of the month, counterclockwise, assuming the presence of 30 subdivisions (for Ψ*, 30-12=19th sub. and for* Ω*, 30-10=21th sub.*).
On the preserved Fragment 28, detected individual letters may be associated with the constellation of Virgo. Parts of words and two (date) numerals {IC and K[A,B….]} are preserved on fragment 28 (Bitsakis and Jones 2016):
Line 1: *[Zodiacal constellation begins ris]*ing [A]
Line 2: …… (male attribute) *[rises/sets in the even]*ing IC (i.e. in 16th subdivision of the zodiac month scale)
Line 3: …… (female attribute) *[rises/sets in the even]*ing K [A,B…]
Line 4: Rising ……… …….E…[K+1, KA+1, KB+1,…]
Bitsakis and Jones suggest the following star events associated with Fragment 28:
Line 1: Virgo begins to rise [A]
Line 2: …… (male attribute) *[rises/sets in the even]*ing IC (i.e. in 16th subdivision of the zodiac month scale)
Line 3: Capella (Αίξ-Αίγα) rises in the evening K or K[A,B…] (20th or 21th, 22nd,…. subdivision of the zodiac month scale) for ''Ψ'' index letter
Line 4: Arcturus rises in the morning [KA or K(B,Γ…..)] (21th or 22nd, 22nd or 23rd, ….) for ''Ω'' index letter
The correlation between Fragment 28 and the preserved index letters of Virgo in Fragment C, leads us to the conclusion that the index letters Ψ and Ω must be at the 20th (K) (Line 3) and the 22th (KB) (Line 4) respectively engraved subdivisions and not at 19th and 21st subdivision. So in the Zodiac Month scale, the arc sector of Virgo, must had 31 subdivisions i.e. 31 days (Fig.13).
If the zodiac month of *Virgo* has a duration of 31 days, then the two previous months should also have at least 31 days each (see below) (because they are closer to the date of aphelion). As a result, the summer season had a duration ≥ 93 days. The 93 days of the summer season is valid for 130 BC, but not for 432, 330 and 80 BC (see Table 1) and also not for the era of 150 BC (according to *Starry Night* program). So the astronomical data used for the construction of the *Zodiac Month scale* by the manufacturer, must originate from observations made at about 130 BC (or a few years later) (Hipparchus age c. 190-c. 120 BC). At that time the access to astronomical information was slow and delayed for a few years, since the publication of the observations was time consuming and expensive. So we believe that the date of the construction of the mechanism was between 125 and 100 BC.
According to Table 2, we reconstructed the *Zodiac Months ring*. The division of the *Zodiac Months ring* scale into 12 zodiac unequal months and 365 equal subdivisions creates unequal arcs of the zodiac months, depending on the number of days in each zodiac month. Therefore with this design, the calculation of the solar anomaly is included in the Antikythera Mechanism mechanical model, without any other assumptions. Figure 14 shows the possible representation of the *Zodiac Months ring* of the front plate with 365 subdivisions of the 12 unequal zodiac months.
Because the *Zodiac Months Ring* was free to rotate, it is obvious that the position of the four seasonal columns of the parapegma does not correlate with the preserved position of the *Zodiac Months Ring* (Price 1974; Freeth and Jones 2016; Bitsakis and Jones 2016). So it is possible that on the top left position of the parapegma, the summer season star events were engraved (*Cancer, Leo, Virgo*) and not the winter season star events, because the Callippic Cycle started at the Summer Solstice (Theodosiou and Danezis 1995, Evans 1998).

ANTIKYTHERA MECHANISM AS A TIMELESS COMPUTER

As we mentioned above, the Zodiac Months Ring was also independent and free to rotate. Although the manufacturer could engrave the zodiac months around the perimeter of the central hole in a fixed position, he did not do so.
The mechanical system of the engaged gears that moved the Moon and the Sun was fixed (''closed'' system), therefore it was impossible to accurately rotate the *Golden Sphere* independently to the *Lunar Disc-Moon* Sphere to any position (date), without disengaging some of the gears. It is obvious that the manufacturer designed the Zodiac Months-Sky, as an independent ring, so that he could quickly set the front plate dial to a specific date (by turning *''the sky''* of the Mechanism) starting the mechanism in any desired date, as a perpetual computational calendar mechanism with very extensive time limits. With this process, it seems that the mechanism had the ability of fast recalibration and of necessary minor adjustments, to account for mismatches

between the actual calendar date and front plate dial indications caused by mechanical errors (Edmunds 2011; Jones 2017) and also the subtraction of the one day in every Callippic cycle (Freeth et al 2008).
Moreover, to move forward in Time, the Mechanism should be rotated clockwise from the *Lunar Disc*. For the past dates, the user needed to rotate the *Lunar Disc* counter clockwise. This change in the direction of the rotation introduced some mechanical problems between the teeth of the gears, a lot of ''backlash effects" and aiming errors of the pointers (especially in ''slower" pointers) (Edmunds 2011). All of these errors disappear, if the *Lunar Disc* was continuously rotated (only) clockwise, as the Time moves forward: for a desired date of the Past, the user rotated the *Zodiac Months ring* (just on the desired date) and then continued the clockwise rotation of the *Lunar Disc*.
For example the ancient user could start the Mechanism from the date of the total solar eclipse on 15th August of 310 BC (i.e. during the 20th year of the first Callippic cycle, the first day of the third synodic month of the ancient Greek calendar, in the corresponding 18th day of Zodiac Month of Leo, for 310 BC), known as the *eclipse of Agathocles* (https://eclipse.gsfc.nasa.gov/SEsearch/SEsearchmap.php?Ecl=-03090815 ; www.mreclipse.com ; Stephenson 1997). Firstly the ancient user, via clockwise rotation set the pointer of the *Lunar Disc*, aiming to the *Sun-Golden Sphere* (New moon). Then he rotated the independent *Zodiac Months ring* up to the pointer of the Golden Sphere aiming to the 18th zodiac day of Leo. After this calibration, he started the back dial plate calibration (Voulgaris et al under writing). Finally he rotated the Egyptian calendar ring to the corresponding date. After the calibration of the Egyptian calendar ring, the user knew the dates of the equinoxes /solstices on the corresponding Egyptian dates.
The Mechanism was a *''time measuring machine computer"* (Fig. 15), designed and constructed so as to minimize all the mechanical and calendrical errors. Because of the engraved days on the *Zodiac Months Ring* and its freedom to rotate, we argue that the tropical year was known and in use (as a measured part of the 1/19 of the Metonic Cycle) in Ancient Greece, but the synodic month was more usable in that era. We strongly believe that the Mechanism was constructed for some governmental or administrative authority of that era. This hypothesis is enhanced by the detection of the pointer and the indications of the Stephanites Games, engraved at the back plate of the Mechanism (Freeth et al 2008): several synodic months before the starting date of the *Olympic Games*, the *''spondophoroi messengers"* (Σπονδοφόροι Αγγελιοφόροι) traveled to the Greek cities to announce the starting date of the Olympic Games on the 2nd full moon after the Summer Solstice (Perrotet 2004).
The new findings of the front astronomical dial, shows us that the Mechanism could calculate the positions of the Sun, the Moon and also the Moon Phases and that it entailed all of the astronomical knowledge known in antiquity (Moussas 2009), like a ''bronze astronomical book", equipped with all the parameters required to perform astronomical calculations, thus making it a real astronomical calendar-time computer.

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Abstract

The present study aims to investigate the astronomical calendar-dial display of the Antikythera Mechanism Front Plate. The design, position and role of the Zodiac ring, are investigated and discussed. Special photographs taken from the ancient prototype, give us new information about the design and operation of the front dial. From these new findings about the Zodiac ring, we conclude that the user of the mechanism was able to easily perform astronomical calculations at any selected time - of past or future date. Based on the new findings during ''The Functional Reconstruction of Antikythera Mechanism Project" (FRAMe), we reconstructed the new bronze front plate and we placed it in our functional model of the Antikythera Mechanism.

Keywords

Antikythera Mechanism; Front Plate; Zodiac Month; Zodiac Ring Front Dial; Egyptian calendar ring

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