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Thales of Miletus, Archimedes and the Solar Eclipses on the Antikythera Mechanism

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Abstract: Thales of Miletus (640?-546 BC) is famous for his prediction of the total solar eclipse in 585 BC. In this paper, the author demonstrate how Thales may have used the same principle for prediction of solar eclipses as that used on the Antikythera Mechanism. At the SEAC conference in Alexandria in 2009, the author presented the paper "Ten solar eclipses show that the Antikythera Mechanism was constructed for use on Sicily." The best defined series of exeligmos cycles started in 243 BC during the lifetime of Archimedes (287-212 BC) from Syracuse. The inscriptions on the Antikythera Mechanism were made in 100-150 BC and the last useful exeligmos started in 134 BC. The theory for the motion of the moon was from Hipparchus (ca 190-125 BC). A more complete investigation of the solar eclipses on the Antikythera Mechanism reveals that the first month in the first saros cycle started with the first new moon after the winter solstice in 542 BC. Four solar eclipses 537-528 BC, from the first saros cycle, and three one exeligmos cycle later, 487-478 BC, are preserved and may have been recorded in Croton by Pythagoras (ca 575-495 BC) and his school.

Key words: Solar eclipse, exeligmos cycle, saros cycle, seasonal hour, equinoctial hour.

1. Thales' Predictions of the Solar Eclipse in 585 BC

Many attempts have been made to understand which method Thales used when he made the famous prediction of the total solar eclipse during a battle between the Lydians and the Medes, first mentioned by Herodotus in History [1] (Figs. 1 and 2). This solar eclipse may even have ended the battle that took place in 585 BC, somewhere between the River Halys and Lake Tatta, east of Ankara in modern Turkey.

Clement of Alexandria (ca 150-215 AD), wrote in Stromata I, 65: "Eudemus observes in his History of Astronomy that Thales predicted the eclipse of the sun which took place at the time when the Medes and the Lydians engaged in battle, the King of the Medes being Cyaxares, the father of Astyages, and the King of the Lydians being Alyattes, the son of Croesus; and the time was about the fiftieth Olympiad." [580-577 BC] [2]. Eudemus (370-300 BC) was considered to be the first Historian of Science.

Thales was the first among the Greeks to investigate the cause of eclipses, according to Plinius the elder (23-79 AD) in "Naturalis historia" (XII, 53), and in the fourth year of the forty-eighth Olympiad (585/4 BC), "He predicted an eclipse of the sun which took place in the reign of Alyattes in the year 170 AUC." [2]. (Ab urbe condita, "from the founding of the city" of Rome).

Thales visited Egypt and Babylon, but it was only the Babylonian astronomers who were able to predict eclipses and they had access to a long record of eclipses. However, they were probably only able to set up rules of thumb, mainly based on the saros cycle of 18 years, 11 days and 8 hours (223 synodic months), and the 3 saros cycles, called the exeligmos cycle of 54 years 33 days. The exeligmos cycle is 669 synodic months, 40 minutes less than 19,756 days.

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Fig. 1 1/3 stater, from ca 600 BC in alluvial electrum, a naturally occurring gold-silver alloy. The ALYA to the left of the lion proves that it is from the reign of King Alyattes of Lydia (610-560 BC). According to the catalogue: "It is not by chance that the head of the lion of this coin has a disk on the forehead, which can only be the solar disk, later replaced by a radiate setting or rising sun on the anonymous 1/stater (trites), usually attributed to Alyattes. With permission from Stella Dreni 2013.

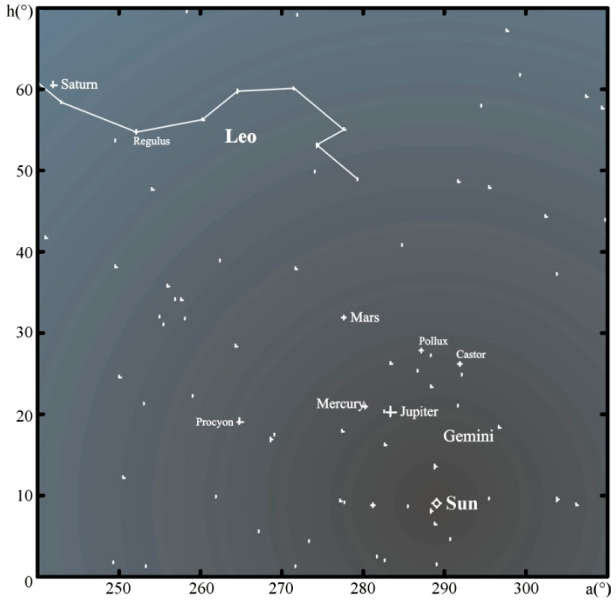

Fig. 2 The western sky during the total solar eclipse on 22 May 585 BC, at 18.12 local mean solar time at the battle field between River Halys and Lake Tatta, predicted by Thales of Miletus.

At the SEAC conference in Alexandria in 2009, the author presented the paper "Ten solar eclipses show that the Antikythera Mechanism was constructed for use on Sicily." The Antikythera Mechanism was an advanced technical construction that was possible thanks to new mechanical inventions. However, the fundamental astronomical principles behind all the scales had not been possible to formulate without a great collection of data preserved on clay tablets and papyri. According to the Babylonian eclipse prediction schemes 38 eclipses took place during a typical saros cycle, 19 solar and 19 lunar eclipses. The author decided to test the hypothesis that Thales made his prediction according to the same principles used on the Antikythera Mechanism and based on solar eclipse observations recorded in Babylon. All solar eclipses, with magnitude greater than 0.01, visible in Babylon between 2 AD and 1100 BC, were calculated with my own computer program, see below. The table was searched for saros and exeligmos cycles including the solar eclipse in 585 BC. The simplest method to predict a solar eclipse is from the exeligmos cycle, but the solar eclipse in 585 BC was the first one in a new exeligmos cycle and there was no earlier eclipse from which to make a prediction (Table 1). The time is local mean solar time, the Julian day is for maximum eclipse and all dates are given according to the Gregorian Calendar.

All the 7 solar eclipses predicted by the exeligmos cycle in the first column are perfectly visible, but one saros cycle later there were only two eclipses visible above the horizon and if we add two saros cycles none was visible. However, if Thales had used the result from the solar eclipse in 603 BC (-602), on 11 May, at 09 h 15 m, he could predict, by adding 8 hours, that the solar eclipse in the next saros cycle, in 585 BC (-584), on 22 May, Gregorian calendar (28 May, Julian calendar), would take place about 17 h 15 m. The actual time for the central eclipse in Babylon was according to the calculations by the author 18 h 59 m, 1 hour and 44 minutes later than predicted. The sun was 1° below the horizon at the total phase, but the eclipse must have been clearly visible in Babylon. If Thales had used the saros cycle to predict the eclipse he had expected the sun to be completely above the horizon during the central phase.

It is not known which place Thales made his calculations for, but the most likely alternatives are Babylon or his home town Miletus. If he had observed

Table 1 Exeligmos and saros cycles calculated for solar eclipses in Babylon

Exeligmos				Exeligmos + 1 Saros				Exeligmos + 2 Saros		
Julian day	year	date	magn.	Julian day	year	date	magn.	year	date	magn.
1,540,826.6183	-494	15/ 7	0.0743		-476	Not	visible	-458	Not	visible
1,521,070.6779	-548	12/ 6	0.3755	1,527,656.0978	-530	23/6	0.5165	-512	Not	visible
1,501,314.7616	-602	11/ 5	0.8674	1,507,900.1669	-584	22/ 5	1.0081	-566	Not	visible
1,481,558.8411	-656	8/ 4	0.7311		-638	Not	visible	-620	Not	visible
1,461,802.8798	-710	6/ 3	0.5451		-692	Not	visible	-674	Not	visible
1,442,046.8499	-764	1/ 2	0.7477		-746	Not	visible	-728	Not	visible
1,422,290.7404	-819	30/12	0.6973		-800	Not	visible	-782	Not	visible

the solar eclipse on 11 May in 603 BC, from Miletus, he would had recorded the central phase at 08h 00m local mean solar time. The solar eclipse one saros cycle later could approximately be predicted to take place 8 hours later at 16h 00m and it would be easily observed from Miletus. The probability was indeed very high that there should be a solar eclipse in the evening of 22 May 585 BC and, according to Herodotus, Thales announced this solar eclipse publically to the Ionians, Herodotos (1.74) [1]:

"After this, because Alyattes refused to surrender the Scythians despite the ongoing pleas of Kyaxares, a war ensued between the Lydians and Medes over a period of some five years. They even engaged in a battle by night. While they were still struggling, it happened that when the fighting had been joined, day suddenly became night. A prediction that this inversion of the day was going to happen, was made publically by Thales of Miletus in announcements to the Ionian people; he proposed exactly the same period favorable for it as the one in which the omen actually occurred. When the Lydians and Medes alike saw that it had become night in place of day, they broke off the battle and hastened on both sides with even more speed to bring about peace for themselves."

One can get the impression from Herodotos' text that Thales also had predicted the complete darkness, but this may be a reconstruction afterwards to make a good story even better. In fact the eclipse was partial in Miletus with the great magnitude 0.970, but at the battlefield between the River Halys and Lake Tatta it was total, with magnitude 1.003, about 9° above the horizon. Thales could not have known the place of the battlefield in advance so his calculation must have been made for either Miletus or Babylon. (In Babylon the magnitude was 1.008, with the total phase just below the horizon.)

From the statement by Herodotos that the eclipse "was made publically by Thales of Miletus in announcements to the Ionian people; he proposed exactly the same period favorable for it as the one in which the omen actually occurred", we can safely draw the conclusion that the most likely place for Thales' calculations was Miletus. The successful prediction of this solar eclipse made Thales famous in the ancient world.

2. Earlier Investigations of the Thales' Eclipse

Many scholars have tried to understand the method used by Thales when he made his famous prediction of the solar eclipse in 585 BC. The great authority on ancient astronomy, Otto Neugebauer [3], wrote despairingly:

"Concerning the prediction of a solar eclipse in -584 (May 28) by Thales a few remarks may be made here though I have no doubt that they will remain without effect. In the early days of classical studies one did not assume that in the sixth century B.C. a Greek philosopher had at his disposal the astronomical and mathematical tools necessary to predict a solar eclipse. But then one could invoke the Astronomy of the ‘Chaldeans’ from whom Thales could have received whatever information was required. This hazy but convenient theory collapsed in view of the present knowledge about the chronology of Babylonian astronomy in general and the lunar theory in particular. It is now evident that even three centuries after Thales no solar eclipse could be predicted to be visible in Asia Minor—in fact not even for Babylon.”

The last statement is no longer valid after my identification of the oldest solar eclipses in the first saros cycle, beginning with the new moon on 2 January 542 BC, displayed on the Antikythera Mechanism, see below. This saros cycle started only four years after the death of Thales in 546 BC. When great authorities cannot find a convincing solution to a famous problem, they try to explain their failure by inventing different reasons as to why the problem must be impossible to solve, for instance uncertain chronologies, important people have been mixed up, important words in the actual text may have different meanings, the story is a legend with unknown connection to the real world or the story is pure fantasy.

Stephenson and Fatoohi [4] have also investigated Thales’ eclipse. However, they have not been able to confirm that the eclipse was total at the battlefield: “According to our computations, the eclipse of 585 B.C. was certainly total over much of Asia Minor about an hour before sunset (and incidentally would probably be total at Miletus, where Thales lived).”

Patricia O’Grady [5] has written the following in International Encyclopedia of Philosophy about Thales:

“Thales is acclaimed for having predicted an eclipse of the sun which occurred on 28 May 585 BCE. How Thales foretold the eclipse is not known but there is strong opinion that he was able to perform this remarkable feat through knowledge of a cycle known as the saros, with some attributing his success to use of the exeligmos cycle. It is not known how Thales was able to predict the eclipse, if indeed he did, but he could not have predicted the eclipse by using the saros or the exeligmos cycles. Some commentators and philosophers believe that Thales may have witnessed the solar eclipse of 18th May 603 BCE or had heard of it. They accepted that he had predicted the solar eclipse of 28 May 585 BCE and reasoned from the astronomical fact of the saros cycles and the fact that the two solar eclipses had been separated by the period of 18 years, 10 days, and 7.7 hours, and concluded that Thales had been able to predict a solar eclipse based upon the knowledge of that cycle. Two facts discount rebut those claims. First, recent research shows that the solar eclipse of 18th May 603 BCE would not have been visible in Egypt, nor in the Babylonian observation cities where the astronomers watched the heavens for expected and unusual heavenly events. The eclipse of 603 passed over the Persian Gulf, too far to the south for observation (Stephenson, personal communication, March 1999; and Stephenson, ‘Long-term Fluctuations’, 165-202).”

Some modern eclipse calculators, who cannot correctly calculate the Thales’ solar eclipse, have suggested alternative chronologies and convinced themselves that it was a total lunar eclipse, that is much easier to calculate Whorten [6].

John Steele, on the other hand, did not even mention Thales’ name in his ambitious book Observations and Predictions of Eclipse Times by Early Astronomers [7]. It is remarkable that the most famous and important total solar eclipse during antiquity is only indirectly included on page 3 as: “And eclipses have often been used to underline dramatic events”.

As can be seen from my Table 1, there should have been no problem for Thales to use the exeligmos and saros cycles. However, this seems impossible to the modern astronomers who are not able to perform correct calculations of the solar eclipses in 603 BC and 585 BC.

The time of the eclipse one saros cycle later is delayed by about 8 hours which means that only eclipses early in the morning can be used to successfully make a prediction, because the eclipse must take place before sunset. A typical problem in the methods used is that the early morning eclipses take place below the horizon and there is no eclipse to make a prediction from.

3. The Accuracy of the Author's Solar Eclipse Calculations

The Thales' eclipse in 585 BC has been used as a fundamental test of the formulae and methods for calculations of ancient solar eclipses because it was the earliest well documented solar eclipse.

The author's computer program for calculation of ancient solar eclipses was completed in June 1985 and has since been successfully tested against all well defined ancient observations back to 3653 BC. It is mainly based on the theory by Carl Schoch (1873-1929) with all the formulae expressed in UT (Universal Time) used by the ancient observers [8], and with my improvements concerning modern astrophysical parameters. The slowing down of the Earth's rotation can be calibrated by direct comparison with ancient observations.

In the mainstream theory used today the formulae are expressed in the so-called ET (Ephemeris Time), a time flow proportional to the motion of the planets in their orbits, and after 1955 Atomic Time. The combined time scale is called TT (Terrestrial Time). The advantage is that the time scale is uniform, but the great disadvantage is that UT must be reconstructed.

The transformation between TT and UT requires a set of useful timed records made by ancient observers to calculate the time difference $\Delta T = TT - UT$ and it is impossible to avoid circular arguments. Simon Newcomb introduced ET in his calculations of ancient solar eclipses and claimed that he had successfully calculated Thales' eclipse. However, P V Neugebauer [9] discovered in 1931 that Newcomb's "success" was in fact a calculation error.

The most exact documentation of an ancient solar eclipse can be found on two separate cuneiform tablets [10], in the British Museum, which tell us about a total solar eclipse in Babylon, 15 April (Julian Calendar) in 136 BC, with the time given for three different phases of the eclipse. The difference between mean of the time recorded in the cuneiform texts and the author's computed time is 0 ± 2 minutes.

The identifications of many solar eclipses depicted on Swedish rock–carvings from the Bronze Age were presented in 1996 at the Oxford V Symposium in Santa Fe [11]. The identification of two total solar eclipses in Babylon makes it possible to date the Old Babylonian Kingdom, the Old Assyrian Kingdom, the Old Hittite Kingdom and the 13th–20th dynasties in Egypt, presented at the SEAC 2002 Conference [12] and at the SEAC 2004 Conference in Kecskemet [13]. At the Oxford 8 and SEAC 2007 Conference in Klaipeda I presented my identification of the oldest Chinese solar eclipses that dated the Xia, Shang and Western Zhou dynasties [14]. At the SEAC 2008 Conference in Granada, I demonstrated that my method to calculate ancient solar eclipses is so exact that it is possible to test Einstein's general theory of relativity [15].

My computer program is useful, without corrections, even for solar eclipses close to the horizon, back to 3653 BC, with timing errors of just a few minutes, caused by quasi-periodic non-tidal effects.

4. The Solar Eclipses on the Antikythera Mechanism

An ancient ship was found by sponge–divers in 1900, close to the island of Antikythera, situated between the southern part of Peloponnese and Crete. Among a rich collection of ancient bronze statues, jewellery, amphorae and pottery, a mysterious highly eroded object of bronze was found. Its size was about 300 × 190 × 100 mm. After some months it fell apart by itself and then it became clear that it consisted of several corroded bronze gearwheels and plates covered by scientific scales and inscriptions in Greek. It was a great surprise to find such a complex mechanism together with well-known ancient finds of which the youngest could be dated to about 80-65 BC. The earliest known comparable mechanisms did not appear until the astronomical clocks at the medieval cathedrals were constructed.

Already in 1905, Albert Rehm, a philologist, understood that the Antikythera Mechanism was an astronomical calculator. After decades of careful cleaning the historian of science Derek J. de Solla Price started his investigation in 1951. Price suggested that the Mechanism was operated by turning a crank on its outside. All the pointers on the dials on the front and the back moved simultaneously to their corresponding positions. In an important study in 1974 by Price [16], he cooperated with the radiologist Charalambos Karakalos who used X-rays and gamma–rays to investigate the inner parts of the mechanism. Price could now describe 27 gears in the main fragment and improved the counting of the teeth. Rehm and Price suggested that the mechanism also contained epicyclical gearing that resulted in a variable speed of the pointer connected to the axis of the last gear. Such a mechanism is necessary to correctly display the variable velocity of the moon and some of the planets.

Michael Wright and Allan Bromley performed the first three–dimensional X–ray investigation. They realised that some of Price's conclusions were wrong while others could be confirmed. Wright [17, 18] found that the dials on the back are spirals and he discovered an epicyclic mechanism on the front that calculated the phase of the moon. He also supported the idea by Price that the upper dial on the back might be a lunar calendar, based on the 19 year cycle with 235 lunar months, introduced by Meton in Athens in 432 BC, earlier used by the Babylonians.

After these investigations it became clear that the Antikythera Mechanism was a highly complex ancient geared mechanism with more than 30 gears, the greatest of them with a diameter of 125 mm, Fig. 3 a-b. The mechanism was constructed to calculate the position of celestial objects and it has therefore been considered as the oldest known complex scientific calculator. It appears to be constructed upon mechanical inventions by Archimedes (287–212 BC) from Sicily and astronomical theories developed by Hipparchos (ca 190–125 BC) from Rhodes.

5. The Latest Investigations by Microfocus X–ray-computed Tomography

The mathematician Tony Freeth and the astronomer Mike Edmunds formed an international collaboration sponsored by Hewlett–Packard in California. In 2005

(a)

(b)

Fig. 3 (a) The Antikythera Mechanism, Fragment A. Photo A. Kinnander 2010; (b) The Antikythera Mechanism, Fragment A, backside with kog wheels. Photo A. Kinnander 2010.

they could use a microfocus X–ray CT (computed tomograph). It was now possible to isolate different layers inside the fragments and to study all the fine details of the revealed inscriptions and exactly count the number of teeth of the gears and how they worked together in the gear trains. Additional fragments have been found and there are now all together 82 known fragments of the Antikythera Mechanism [19].

The function of all dials was described on the inside of the covering doors. The new X–ray images revealed more than 2,000 new text characters that earlier were hidden deep inside the fragments. A total of 3,000 characters, out of perhaps 15,000 original characters, can now be interpreted and read. Xenophon Moussas and Yanis Bitsakis at the university of Athens and Agamemnon Tselikas of the Center for History and Palaeography in Athens discovered inscriptions that had not been read for more than 2,000 years. One of the inscriptions on the back door is translated as «the spiral divided in 235 sectors», confirming the earlier result that the upper dial on the back was a five–turn spiral describing the distribution of the 235 months in the Metonic 19–year cycle [20].

The computer improvements of these X–ray images made it possible to identify the names of all the 12 months. The series of month’s names was identical with the seven earlier known month names from Taurmina, modern Taormina, a former Corinthian colony on Sicily.

The index letters in each glyph on the saros eclipse prediction dial, at the lower half on the back, were studied in detail. The four turns of the dial was explained as the series of months in the saros cycle and the exeligmos dial indicated an addition of 8 hours to the predicted eclipse hour during the second saros, and 16 hours for the third saros. However, the investigators did not understand the principle for the generation of the eclipse time, given as integer hours, and found them to be contradictory.

We read in the Supplementary Information [20], “According to Haralambos Kritzas (Director Emeritus of the Epigraphic Museum, Athens) the style of the writing could date the inscriptions to the second half of the 2nd Century BC and the beginning of the 1st Century BC, with an uncertainty of about one generation (50 years). Dates around 150 BC to 100 BC are a plausible range.”

The results from all the earlier studies of the Antikythera Mechanism and from the latest investigation are published by Freeth et al. [20] and Freeth [21].

6. The Eclipse Prediction Mechanism

From the CT data of the large fragments A, B, and F it was possible to identify 48 scale divisions and to establish the existence of 223 divisions in the four-turn spiral starting at the bottom of the dial [19]. The 223 subdivisions were identified as the lunar months in a saros cycle corresponding to 18 years, 11 days and about 8 hours. Between the divisions they found 16 blocks of characters, which they call “glyphs”. They appeared at intervals of one, five and six months. These are predictions concerning lunar or solar eclipses, or both kinds of eclipses. On the first line Σ stands for “Selene”, Hellenic for “moon”, indicating a lunar eclipse and H stands for “Helios”, Hellenic for “sun” indicating a solar eclipse. On the second row the first letter shows if it is hours of the day or of the night, followed by the hour of the eclipse. The bottom line gave the number of the eclipse in the saros [21].

A small dial showed the actual saros cycles within the exeligmos cycles. During the first saros cycle the hour of the eclipse could be read directly on the glyph, but during the second saros the pointer showed that 8 hours must be added to that hour, and during the third saros that 16 hours must be added to the hour given on the glyph.

7. The Motivation for the Investigation by the Present Author

I have with great interest followed the progress in the studies of the unique Antikythera Mechanism made during the last 40 years. At the SEAC conference in Granada, in 2008, professor Xenophon Moussas offered me the possibility to arrange an exhibition on the Antikythera Mechanism in Uppsala. During my opening lecture of the exhibition, 31 January 2009, I mentioned that it in principle might be possible to determine for which place this mechanism was constructed and when, by identification of solar eclipses predicted by the saros cycles. When Moussas later visited Uppsala, to bring the exhibition back to Athens, he helped me to read the hours of the predicted eclipses.

The circumstances of every solar eclipse are in principle unique for a certain time and place on the earth. Of course, if we take into account the uncertainties and errors in the original records, our misunderstandings, and errors in the calculations of the circumstances of eclipses, the situation is only unique within certain margins of errors. My hope was that the combination of all errors was small enough to give a unique solution in this case.

The “historical data” used in 2006 by Freeth et al. [19] was good enough to show that the distribution of subdivisions with glyphs on the saros dial matched with the calculated interval between the eclipses. In this paper they believed that glyph times were constructed from the Babylonian Saros Canon, the only known source with sufficiently good data. However, in 2008, after an unsuccessful attempt to correlate the glyph hours on the saros cycle with the calculated times by Espenak [22], they assumed that this series of eclipse months and hours was based on purely theoretical speculations by the people who constructed the Mechanism. They write: “We conclude that the process of generation of glyph times was not sound and may remain obscure.” [20]

In my opinion they blamed the constructors of the Mechanism for their own failure. When we look at all the others details on the Mechanism, we can understand how they work, we are astonished by the advanced technical ability and intellectual level of the constructors. These modern investigators have overestimated the accuracy of their own calculations.

8. The Investigation by the Present Author

My computer program has an uncertainty in the calculated time of solar eclipses that is less than 2 minutes and the uncertainty in the calculated time of sunrise or sunset is less than one minute and depends mostly on the altitude of the unknown local horizon. It is unlikely that errors in my calculations will cause any problem for this investigation.

In antiquity the 12 hours of the day were reckoned from sunrise to sunset and the 12 hours of the night were reckoned from sunset to sunrise. The question is if they used seasonal hours with unequal length, depending on the season, or equinoctial hours with equal length.

A special computer program was developed that compared the pattern of months with solar eclipses marked on the Antikythera Mechanism, with solar eclipse tables, for different places, computed by my eclipse program. The appearance of solar eclipses is strongly dependent on the locality of the observer. This means that if the hours for the solar eclipses marked on the Mechanism are based on local observations, or generated by correct transformations of good observations made at another place, it should in principle be possible to determine the position of observation by looking for the place where the eclipse predictions work best. The best solution is also time dependent, which gives the dates for the basic solar eclipse observations. On the other hand, all lunar eclipses with the moon above the horizon could be observed with almost the same magnitude. It is therefore much easier to predict lunar eclipses than solar eclipses, but they give only low quality information about the observer’s location.

The computer program performed the identifications automatically and without any manual interventions. It was necessary to run the program many times to test

Table 2 Identified Exeligmos cycles calculated for Croton and Syracuse

M	1	13	25	72	78	119	125	131	184
Solar eclipses recorded in Croton by Pythagoras et al.									
EC_0	**2/1** **-541**	**(-540, 19/1)** 1,523,847.16	N. v.	**-536, 26/10** 1,525,588.94	N. v.	**-532, 13/8** 1,526,976.25	**-531, 9/1** 1,527,124.93	N. v.	**-527, 17/10** 1,528,866.85
EC_1	**3/2** **-487**	**(-486, 21/2)** 1,543,603.14	N. v.	**-482, 28/11** 1,545,345.10	N. v.	**-478, 15/9** 1,546,732.22	**-477, 11/2** 1,546,880.91	N. v.	N. v.
Solar eclipses recorded in Syracuse by Archimedes et al.									
ES_{-2}	**12/9** **-350**	**-349, 1/10** 1,593,863.78	**-348, 19/9** 1,594,218.01	N. v.	Night hours	Night hours	N. v.	Night hours	N. v.
ES_{-1}	**15/10** **-296**	**-295, 3/11** 1,613,619.83	**-294, 23/10** 1,613,973.97	N. v.	Night hours	Night hours	N. v.	Night hours	N. v.
ES_0	**17/11** **-242**	**-241, 6/12** 1,633,375.91	**-240, 24/11** 1,633,729.99	N. v.	Night hours	Night hours	N. v.	Night hours	N. v.
ES_1	**22/12** **-188**	N. v.	**-186, 28/12** 1,653,486.02	**-182, 16/10** 1,654,873.92	Night hours	Night hours	N. v.	Night hours	N. v.
ES_2	**24/1** **-133**	N. v.	**-131, 29/1** 1,673,241.99	**-128, 17/11** 1,674,630.07	Night hours	Night hours	N. v.	Night hours	N. v.

M = month numbers, N. v. = Not visible, **EC_0 – EC_1** and **ES_{-2} – ES_2** = identified sequence of Exeligmos cycles = 54 years 33 days, for Croton and Syracuse, respectively.

the result for different places and to set acceptable limits for the deviations of important parameters.

The calculations started with Taurmina on Sicily, as it seemed to be the most likely origin of the Mechanism since its series of month names agreed with the month names used in that city. The result from this first test was astonishingly good. I continued with Athens to get data from a somewhat more easterly longitude and northerly latitude and finally it was tested how the solar eclipse predictions on the Mechanism worked for the City of Rhodes, earlier considered as the most likely place of origin. When it was clear that the result for Taurmina was the only acceptable one and that an even better result could be expected for a place to the west or south of this city, there was one obvious candidate—Syracuse, the city on Sicily that was the home of the most famous ancient scientist and inventor—Archimedes. The result for Syracuse was even better than for Taurmina and in fact one could not expect to get a better result.

9. The Result of Calculations for Different Places

A solution that includes 10 calculated solar eclipses determines the dates for the beginning of five consecutive exeligmos cycles, by a successful matching of three time glyphs in the well–preserved beginning of the saros cycle dial. Only less than 25% of the circumference is preserved and the hour of the eclipses can only be read for 10 of the solar eclipse predictions. Xenophon Moussas made an independent interpretation of these time glyphs for me.

The predicted times for the eclipses is rounded off to the nearest hour on the saros dial. The observers must have used reflection in a water surface to avoid damage to the eyes during observation of partial solar eclipses. The time for the eclipses is better for the first saros cycle because the hour for the eclipse in the second saros is delayed by about 8 hours and for the third saros by about 16 hours. For this reason I decided to try to get matches only from the first saros in the exeligmos.

The number of identified solar eclipses and the completeness of the exeligmos cycles are very good for Taurmina and Syracuse, but incomplete for Athens and the City of Rhodes. The match is very good for Taurmina, with a median difference of only 4 ½ minutes, and the mean error of the mean corresponds to about 15 minutes. The median difference is 50 minutes for Athens and 84 minutes for the City of Rhodes with the mean error of the mean of about 25 minutes. The two most deviating points have been excluded because errors of three hours cannot be real observational errors. Such great deviations are probably caused by intrinsic limitations in this method, as the saros cycle is, in fact, only a simple rule to predict eclipses.

The best fit is obtained for Syracuse. The median deviation is only 3 minutes and the mean error of the mean corresponds to 15 minutes, which is a very good result for the best eight identified predictions on the Antikythera Mechanism calculated for Syracuse. The mean value for the deviations, +22 minutes, is acceptable as deviations from the predicted time of the maximum phase because the time on the Mechanism is only given in hours.

10. The First Saros Cycles on the Antikythera Mechanism started in 542 BC

During my first investigation, in 2009, it was clear that there also existed four solar eclipse observations from a saros cycle that started already in 542 BC and three observations one exeligmos cycle later. These eclipses were not discussed in my first paper, presented in Alexandria 2009, because the conclusion that the Antikythera Mechanism was constructed for use on Sicily was more important.

The author’s main hypothesis concerning the oldest solar eclipses is that Pythagoras already in 542 BC could have observed and collected records of solar eclipses from Croton, in south-eastern Italy, where he founded his school. These records may have been preserved in the library in Alexandria where Archimedes copied them before he returned to Sicily. He used them on his mechanical globes for calculation of solar eclipses. Cicero (106-43 BC) described a globe constructed by Archimedes (De Re Publica 1.21-22): “…Thus the same eclipse of the sun happened on the globe as would actually happen …”, translation by Keyes [23]. This incident happened in 166 BC when a Roman consul, Gaius Sulpicius Gallus, was at the home of Marcus Marcellus, the grandson of the Marcellus who conquered Syracuse in 212 BC. The eclipse in 166 BC took place on 14 May and could have been observed by Archimedes, one exeligmos cycle earlier, on 10 April, 220 BC. The records on this globe may later have been used on the Antikythera Mechanism.

In the author's first investigation of the saros cycle on the Antikythera Mechanism, it was assumed that the hours on the glyphs were given as equinoctial hours. The calculations showed that this assumption worked very well for the eclipses calibrated in Syracuse, probably by Archimedes around 240 BC. Archimedes must have constructed some kind of water clock, a clepsydra, that indicated equinoctial hours.

It is remarkable that the oldest identified series of solar eclipses is the most complete and that the reckoning of the months in the first saros cycle started with 2 January 542 BC, Gregorian calendar, Table 2. This means that the people who initiated this series of systematic recording of solar eclipses decided to reckon the first month in the saros cycle from the first new moon after the winter solstice in our year 542 BC. Unfortunately, the glyph with information from the first solar eclipse in this series, in month 7, on 25 July in 542 BC, with magnitude 0.596 in Croton, is not preserved. The second eclipse took place 6 months later in month 13, on 19 January in 541 BC. The glyph for month 13 is preserved, but does not have the original hour engraved because a new calibration for this month was performed in Syracuse on 6 December 242 BC. The next solar eclipse took place 12 months later, but the preserved hour glyph for month 25 is not original. It was calibrated in Syracuse on 24 November in 241 BC, probably by Archimedes himself (Fig. 4). The next preserved glyph was for month 72 and this is the only month with as many as four possible observations. These took place on 26 October 537 BC, 28 November 483 BC, 16 October 183 BC and finally 17 November 129 BC with total solar eclipse in Syracuse. The hour on this glyph was calibrated at this total solar eclipse. This means that

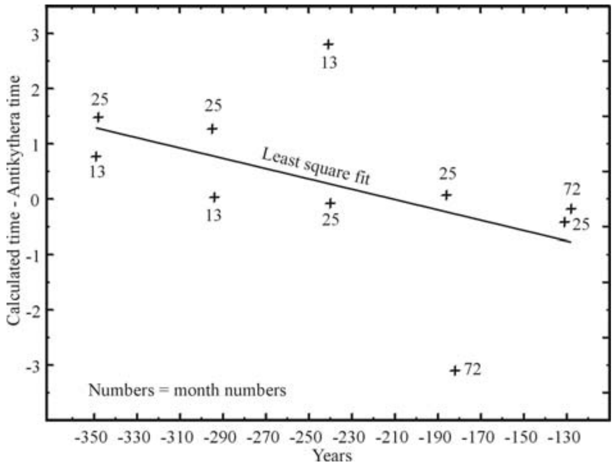

Fig. 4 The linear trend is expected because the exeligmos cycle is 0.7 hours shorter than 54 years and 33 days. The deviations for the solar eclipses in month 25 follow the linear rule, but there is a strange positive jump for last eclipse in month 13 and a similar negative jump for the first eclipse in month 72. This hour may have been updated after the total solar eclipse in 129 BC.

we have no hour recorded for month 72 from the older eclipses. However, it has been possible to reconstruct the hour for the eclipse in 483 BC, see below.

The hour for the solar eclipse on glyph 78 is given as the first “hour of the night”. During night hours the sun should be below the horizon and not observable. So far, no identification of solar eclipses in month 78 has been possible. This may be an example of a theoretical prediction that failed and was considered to have taken place during night hours.

The time for the solar eclipse on glyph 119 is marked as 10th “hour of the night”. Nevertheless, there is a match with the eclipses on 13 August in 533 BC and one exeligmos later on 15 September in 479 BC. The next preserved glyph corresponds to month 125. This glyph was calibrated on 9 November 532 BC and 54 years later on 10 February in 478 BC.

The hour on the next preserved glyph, for month 131, is the 9th hour of the night and no corresponding eclipse has been found. The glyphs for month 137 and 178 have also been preserved, but no solar eclipse has been possible to observe during these two months. The glyphs with solar eclipses during night hours must have been transformed from observations elsewhere or from a theoretical eclipse pattern. A “bar” above the index number as on number 119, 131 and 178 may have indicated the latter case, even if the eclipse on month 178 takes place during daytime, but there is no bar above glyph number 78.

The last of the preserved glyphs corresponds to month 184 in the saros cycle, with 223 months. The only visible solar eclipse in that month took place on 17 October in 528 BC.

In my first analysis I assumed that all the hours on the Antikythera Mechanism are equinoctial, which means of equal length. This assumption worked very well for the hours on the glyphs for the months 13, 25 and 72 calibrated in Syracuse by Archimedes and his followers, see above.

The author assumed that the oldest observations, from 537-478 BC, were made in Croton because the Pythagorean school was established in this city at that time. When I investigated the deviations between the hours for this old series, on the Antikythera Mechanism and my calculations, it became clear that the deviations were too big to be observational errors. These hours proved to be seasonal hours in which the interval between sunrise and sunset was divided in 12 hours of equal length, depending on the day of the year.

If seasonal hours were used, the mean value is +2.22 ±0.15 hours with the standard deviation 0.37 hours for 6 observations. The oldest observation from 537 BC is excluded because it deviates by 4 hours from the mean value of the other 6 observations. The reason is that the hour on glyph 72, which may have been observed in 537 BC, is not the originally recorded hour for that eclipse because the hour on this glyphs must have been recalibrated in 129 BC. The most reasonable explanation to the +2.22 ± 0.15 hour deviation of the mean value for the 6 observations in 533, 532, 528, 483, 479 and 478 BC is that a correction of 2 hours was subtracted from the hours recorded in an old table, when the glyphs on the Mechanism were engraved. This correction was probably based on the difference between the new observation, 8 hours, in month 72, performed in 129 BC, with a deviation of just –0.11 hours, and the earlier hour in the same month recorded during the solar eclipse in 483 BC. The original hour recorded in 483 BC should therefore have been 10. The original hours in the months 72, 119, 125 and 184 can be reconstructed as 10, 12, 4 and 3 respectively. The deviation in 537 BC will be -4.02 seasonal hours and cannot be explained as an observational error. However, this solar eclipse was very difficult to discover because of the small magnitude, 0.109 in Croton and 0.048 in Syracuse, and we cannot know if it ever was recorded.

The same calculations with seasonal hours have been performed for Syracuse and the resulting mean value for the deviations is +2.02 ± 0.17 hours with standard deviation 0.42 hours for 6 observations. The difference is not significant from the result for Croton, but I have preferred the hypothesis that the observations have been made in Croton by Pythagoras and his school, because no other competent observer and organization is known to have existed in Syracuse as early as 542 BC.

Seasonal hours were read from a sundial. Even if it has not been explicitly mentioned by the Greek or Hellenic authors, Thales must have used a sundial in 603 BC when he made his prediction of the solar eclipse in 585 BC. When Pythagoras from Samos (ca 575-495 BC) was about 20 years old he visited Thales (640?-546 BC) and Anaximander (610-546 BC) in Miletus. Thales had learned from the Babylonians how to calculate eclipses, and this knowledge had been transferred to Anaximander and Pythagoras. Another of Pythagoras' teachers was Pherekydes (ca 580-520 BC) of Syros. These teachers had constructed sundials and it is therefore likely that Pythagoras had learnt from them the art of construction of accurate sundials.

The oldest solar eclipses must have been observed and recorded in the area of Croton—Syracuse. The first months in the first saros cycle started with the appearance of the new crescent moon on 2 January in 542 BC (Gregorian calendar), with phase 26.18° at 18.00, local mean solar time in Croton (J.D. = 1,523,465.2025). The series of saros cycles on the Antikythera Mechanism is a direct continuation of this cycle.

11. Conclusion

Thales used exeligmos and saros cycles that had been developed in Babylon to predict eclipses. He used the solar eclipse in Miletus, on 11 May in 603 BC, to predict the solar eclipse on 22 May in 585 BC, Gregorian calendar. The fact that this eclipse was total at the battlefield between River Halys and Lake Tatta made him famous. The same method to predict eclipses was later used on the Antikythera Mechanism. A new exeligmos on the Antikythera Mechanism started on 16 November in 243 BC. The hours for the solar eclipses in month 13 and 25 have been calibrated in Syracuse during the lifetime of Archimedes (287-212 BC). The calibration in the 25th month, in 241 BC works for two earlier and two later exeligmos cycles. The calibration for month 72 has been made during the total solar eclipse in 129 BC and the Mechanism was probably constructed shortly thereafter. The hours for the months 119, 125 and 184 came originally from observations made by Pythagoras and his school in Croton, 537-478 BC.

The last exeligmos cycles started on 24 January in 134 BC, but the calibration did not work in 80 BC when the next exeligmos cycle was expected to start. The ship with the Antikythera Mechanism on board sunk about 80-65 BC. At that time the Mechanism may have been useless for eclipse predictions and was only considered as a valuable antiquity.

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