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Visual Aspects of the Transmission of Babylonian Astronomy and its Reception into Greek Astronomy

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Summary

Evidence for the transmission of Babylonian astronomy into the Greco-Roman world is well attested in the form of observations, numerical parameters and astronomical tables. This paper investigates the reception of Babylonian astronomy in the Greco-Roman world and in particular the transmission, transformation and exploitation of the layout of texts and other visual information. Two examples illustrate this process: the use of Babylonian lunar eclipse records by Greek astronomers and the adaptation of Babylonian methods of eclipse prediction in the Antikythera Mechanism.

Contents

1. Introduction

The initial decipherment of Babylonian astronomical sources written in cuneiform in the last part of the nineteenth century was quickly followed by the realization that parts of ancient Greek astronomy could be traced back to Babylonian antecedents. For example, Kugler in his *Babylonische Mondrechnung* (1900) noted that the value for the mean length of the synodic month attributed by Ptolemy to Hipparchus in *Almagest* IV 2 (29;31,50,8,20 days) equals the mean value of column G in what is now called Babylonian System B lunar theory, and more generally that all the fundamental parameters of Hipparchus's lunar theory can be derived from System B.[1] Subsequent research by Neugebauer, Jones and others have revealed that much of Babylonian lunar and planetary theory was known in the Greek world, alongside several astronomical and calendrical period relations.[2] Further, the rediscovery of cuneiform astronomy allowed the comparison of reports of observations made in Babylon given by Ptolemy with original Babylonian material, providing evidence that these reports

[1] F. X. Kugler, *Die Babylonische Mondrechnung. Zwei Systeme der Chaldäer über den Lauf des Mondes und der Sonne* (Freiburg im Breisgau, 1900). See also G. J. Toomer, 'Hipparchus and Babylonian Astronomy', in *A Scientific Humanist. Studies in Memory of Abraham Sachs*, edited by E. Leichty, M. deJ. Ellis and P. Gerardi (Philadelphia, 1988), 353–62.

[2] See e.g. O. Neugebauer, *A History of Ancient Mathematical Astronomy* (Berlin, 1975), A. Jones, 'Evidence for Babylonian Arithmetical Schemes in Greek Astronomy', in *Die Rolle der Astronomie in den Kulturen Mesopotamiens*, edited by H. D. Galter (Graz, 1993), 77–94, A. Jones, *Astronomical Papyri from*

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are genuine if sometimes occasionally misunderstood by Ptolemy (or the Greek source on which he relied).[3]

The route by which astronomical material was transmitted to the Greek world is currently unknown. All that can be said for certain is that it must have involved direct contact by one or more Babylonian scribes versed in cuneiform astronomical texts—what we might call 'Babylonian astronomers'—with Greek astronomers. Cuneiform astronomical texts include too much technical language for an average scribe to have been able to read and explain their content.[4] It is of course possible that a Greek astronomer could have learnt to read cuneiform, but he would still have had to be taught the specialized language found in astronomical texts from an astronomical scribe and even this would not have been enough to be able to understand large parts of Babylonian astronomy because the astronomical cuneiform texts generally do not provide sufficient information to readily understand the astronomy they deal with. We must assume that an oral tradition went alongside the written astronomical texts that would explain to someone learning to work as an astronomer the necessary background to understanding the procedures outlined in texts. It therefore seems unavoidable to conclude that the transmission of Babylonian astronomy to the Greek world required direct contact between Babylonian astronomers and Greek astronomers. But where, when and how this contact took place is not known: Greek astronomers may have visited Babylon, Uruk or other cities in Mesopotamia where astronomy was practiced, one or more Babylonian astronomers may have travelled to the Hellenistic World, or a combination of the two possibilities may have taken place. The conquest of Babylonia by Alexander no doubt increased the possibilities for contact between Babylonian and Greek astronomers, but it is clear that cultural transmission between the Greeks and the near east was widespread also before and after the time of Greek rule.

In this article I discuss an aspect of the transmission of Babylonian astronomy and its reception in the Greek world that has not previously been addressed in any detail, namely visual aspects of the presentation of astronomical texts—their layout, structure and chosen content—and the role these played in the transmission and transformation of astronomical knowledge. I take as an example the case of a group of Babylonian eclipse texts (both observational and predictive) and explore how their particular structure was on the one hand exploited by Greek astronomers to obtain additional information not explicitly given in the texts and on the other transformed to highlight different information than had been of interest to the Babylonians.

2. Late Babylonian eclipse texts

Beginning in the eighth century BC, Babylonian astronomers regularly observed and recorded eclipses of the sun and moon. In addition, predictions of eclipses that were not seen (generally because they took place when the eclipsed luminary was below

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Oxyrhynchus (Philadelphia, 2000), A. Jones, 'Babylonian Lunar Theory in Roman Egypt. Two New Texts', in *Under One Sky*, edited by J.M. Steele and A. Imhausen. *Astronomy and Mathematics in the Ancient Near East* (Münster, 2002), 167–74, D. Pingree, 'Legacies in Astronomy and Celestial Omens', in *The Legacy of Mesopotamia*, edited by S. Dalley (Oxford, 1998), 125–37.

[3] J. M. Steele, 'A Re-Analysis of the Eclipse Observations in Ptolemy's *Almagest*', *Centaurus*, 42 (2000), 89–108, J. M. Steele, 'Ptolemy, Babylon and the Rotation of the Earth', *Astronomy and Geophysics*, 46/5 (2005), 11–15, A. Jones, 'Ptolemy's Ancient Planetary Observations', *Annals of Science*, 63 (2006), 255–90.

[4] J. M. Steele, 'Applied Historical Astronomy: An Historical Perspective', *Journal for the History of Astronomy*, 35 (2004), 337–55.

the horizon—i.e. solar eclipses during the night and lunar eclipses during the day) were recorded alongside the observed eclipses.[5] These eclipse reports were included in the so-called 'astronomical diaries', texts containing night-by-night records of astronomical observations and predictions. Probably in part because regularly searching through the astronomical diaries to find eclipse records would be a rather time-consuming process, the astronomical scribes abstracted eclipse records from the astronomical diaries and created texts devoted only to eclipses, which can be collectively called 'eclipse texts'.[6]

The eclipse texts can be subdivided into three main groups: (i) tablets containing consecutive eclipse observations and predictions arranged in Saros cycles (the Saros is an eclipse cycle of 223 synodic months or a little over 18 years after which there is almost an exact return in lunar anomaly and latitude), (ii) tablets containing consecutive eclipse observations and predictions in a straightforward list format, and (iii) tablets devoted to a single eclipse observation.[7] The tablets in category (i) are of particular interest. These tablets are formatted with a characteristic grid layout defined by horizontal and vertical rulings (see Figures 1 and 2). Each cell of the grid contains a report of an observation or a prediction of an eclipse. Going down the columns, consecutive cells contain consecutive eclipse possibilities separated by either five- or six-month intervals (the Babylonian calendar is a luni-solar calendar so these correspond to synodic months). Along the rows of the grid, eclipse possibilities are separated by one Saros of 223 months (either 18 years or 18 years plus one month in the Babylonian calendar). The tablets arranged in Saros cycles are always devoted to either lunar or solar eclipses, never mixing the two. The structure of the tablets is governed by the Babylonian understanding of the periodic repetition of eclipses:[8] eclipse possibilities occur at six- or occasionally five-month intervals, and the Saros of 223 synodic months is an eclipse period after which eclipses recur with similar characteristics, but approximately eight hours later in the day.

Among the eclipse texts arranged in Saros cycles are preserved fragments of three tablets which formed part of a large compilation of lunar eclipse records.[9] This large compilation, which was probably written on eight tablets, contained eclipse reports covering 24 Saroi over the period from 747 to 315 BC. The tablets that formed this compilation are unusual in that they turn from left to right, rather than bottom to top as is normal for cuneiform tablets. Turning about a vertical axis highlights the importance of the Saros in their structure: eclipse possibilities in one Saros series continue along a horizontal line from the obverse to the reverse of the tablet. The eclipse records in this large compilation were almost certainly taken from the astronomical diaries or other eclipse texts: the few cases of the same eclipse preserved on one of the fragments of the large compilation and in another text generally agree as to the details of the eclipse (for details of the content of the eclipse reports, see below).[10] Furthermore, there are differences in the amount of recorded detail between the

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[5] On late Babylonian eclipse records, see P. J. Huber and S. De Meis, *Babylonian Eclipse Observations from 750 BC to 1 BC* (Milan, 2004) and J. M. Steele, *Observations and Predictions of Eclipse Times by Early Astronomers* (Dordrecht, 2000), 21–83 and 239–62.

[6] For editions of the eclipse texts, see H. Hunger, *Astronomical Diaries and Related Texts from Babylonia. Volume V, Lunar and Planetary Texts* (Vienna, 2001), nos. 1–33.

[7] See my appendix to Hunger (note 6).

[8] On Babylonian methods of predicting eclipses, see J. M. Steele, 'Eclipse Prediction in Mesopotamia', *Archive for History of Exact Science*, 54 (2000), 421–54.

[9] Hunger (note 6), nos. 2–4.

[10] Steele (note 5).

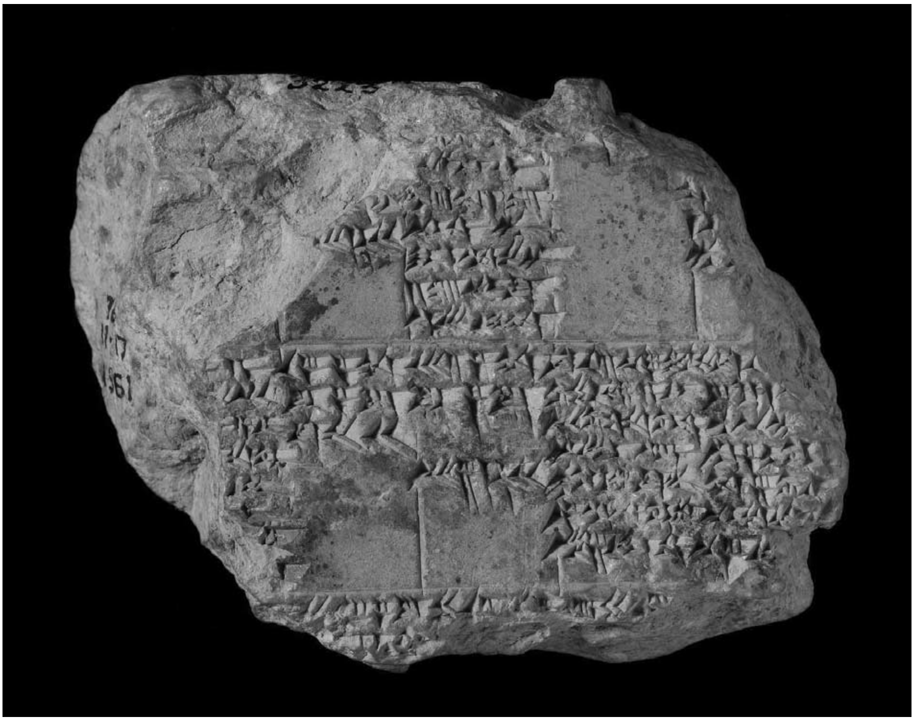

Figure 1. A fragment of the large compilation of lunar eclipse reports arranged in Saros cycles from Babylon (BM 32234 Obv; © The Trustees of the British Museum). Each cell of the compilation, marked by horizontal and vertical rulings, contains a report of an observation or a prediction of a lunar eclipse.

earliest eclipses in the compilation and the later eclipses, mirroring what is found in other texts and suggesting that no attempt was made to standardize the eclipse reports when they were copied into the large compilation.

Nabopolassar 16 XII 11 Mar 609 BC	Nebukadnezar 13 XII 22 Mar 291 BC	Nebukadnezar 31 XII 1 Apr 573 BC	Nabonidus 1 I 13 Apr 555 BC	Cyrus 2 II 23 Apr 537 BC
Nabopolassar 17 VI 3 Sept 609 BC	Nebukadnezar 14 VI 15 Sept 591 BC	Nebukadnezar 32 VI 25 Sept 573 BC	Nabonidus 1 VII 6 Oct 555 BC	Cyrus VII 17 Oct 537 BC
Nabopolassar 17 XII 28 Feb 608 BC	Nebukadnezar 14 XI 12 Mar 590 BC	Nebukadnezar 32 XII 22 Mar 572 BC	Nabonidus 1 XII_2 2 Apr 554 BC	Cyrus 3 I 13 Apr 536 BC

Figure 2. A schematic illustration of the dates of the eclipse possibilities in the fragment shown in Figure 1. The years and months of the eclipse possibilities corresponding to the entries in the fragment shown in Figure 1 are given in the Babylonian calendar together with the Julian date of the eclipse possibility.

Observed and predicted eclipses in the large compilation can often easily be distinguished without having to read the account of the eclipse by the relative lengths of the entries: descriptions of predicted eclipses are generally very brief, stating no more than the date (year, month and day), the expected time of the beginning of the eclipse, and that the eclipse was a prediction not an observation, which generally takes up no more than two lines of text in the cell of the compilation devoted to that eclipse possibility; entries for observed eclipses, however, usually extend over six or seven lines, filling the cell, and can contain in addition to the date and time of the eclipse a measurement of the length of the various phases of the eclipse, its magnitude, some estimate of the moon's position (either by zodiacal sign or by reference to a nearby star), the direction of the wind during the eclipse, and possibly more.[11] In addition, eclipse possibilities situated after a five-month interval are highlighted by the phrase 5 ITU '5 months' stated straight after the date, normally in the first line of a cell.

A second set of tablets arranged in Saros cycles is worth highlighting. These tablets, often referred to as the 'Saros Canon' and related texts,[12] contain dates (years and months only) arranged in Saros cycles. The dates are unaccompanied by any references to eclipses, but analysis of the dates indicates that they refer to eclipse possibilities, either lunar or solar depending upon the text. The dates of the eclipse possibilities were apparently determined using a theoretical scheme,[13] and do not agree with the dates of the observed and predicted eclipses recorded in the large compilation discussed above or other texts.[14] Because each eclipse possibility in the Saros Canon texts contains only the year and the month, which can be written on one line, there was no need to use horizontal and vertical rulings to delineate individual eclipse possibilities into cells. Instead, the Saros Canon texts generally employ vertical rulings between columns to separate eclipse possibilities at intervals of one Saros, and horizontal rulings to indicate the eclipse possibilities which are situated at a five month interval from the preceding eclipse (see Figure 3). This appears to be a deliberate attempt to highlight the importance of the five-month intervals within Babylonian eclipse theory.

3. Greek use of Babylonian eclipse observations

In the *Almagest* Ptolemy discusses 10 lunar eclipses said to have been observed in Babylon.[15] He makes use of seven of these eclipse observations in his own derivations of lunar parameters and reports and discusses Hipparchus's use of the remaining three (Ptolemy remarks that Hipparchus also used two of the other eclipses; it is quite possible that Hipparchus used all of the Babylonian eclipses that Ptolemy cites). The

[11] For a description of the contents of the accounts of eclipse observations, see A. J. Sachs and H. Hunger, *Astronomical Diaries and Related Texts from Babylonia. Volume I, Diaries from 652 B.C. to 262 B.C.* (Vienna, 1988), 23–4 and Huber and De Meis (note 4), 7–17.

[12] See most recently A. Aaboe, J. P. Britton, J. A. Henderson, O. Neugebauer and A. J. Sachs, *Saros Cycle Dates and Related Babylonian Astronomical Texts*, Transcations of the American Philosophical Society 81/6 (Philadelphia 1991).

[13] A. Aaboe, 'Remarks on the Theoretical Treatment of Eclipses in Antiquity', *Journal for the History of Astronomy*, 3 (1972), 105–18.

[14] Steele (note 8).

[15] For a more detailed discussion of Ptolemy's use of the Babylonian eclipses and the problems he may have faced, see J. M. Steele (note 4).

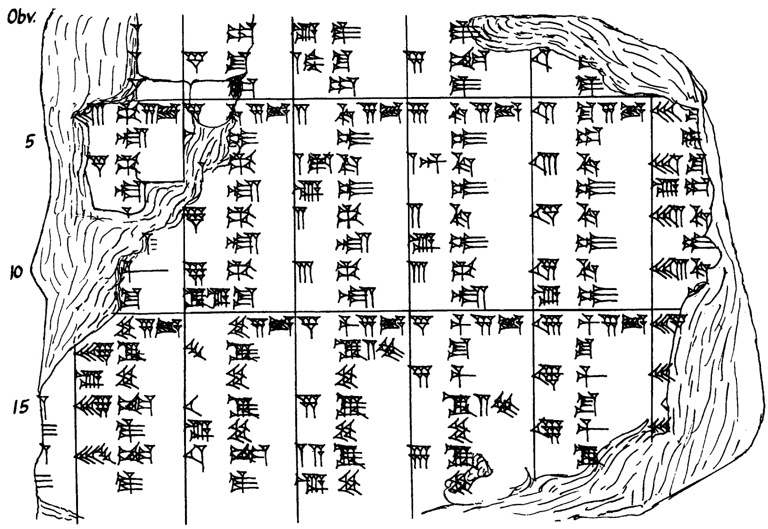

Figure 3. A copy of the so-called Saros Canon (BM 34597) drawn by T. G. Pinches at the end of the nineteenth century (© The Trustees of the British Museum). The Saros Canon gives dates of eclipse possibilities arranged in Saros cycles. Eclipse possibilities five months after a previous eclipse possibility are indicated by the horizontal rulings.

source from which Ptolemy obtained these observations is not known: it is possible, for example, that Ptolemy only had access to eclipse reports that had been discussed by Hipparchus or other Greek authors. But it is more likely that Ptolemy had a considerable collection of Babylonian eclipse observations with which to work from which he selected those that he discussed,[16] which suggests that he had access to a compilation of Babylonian eclipse records stretching from at least 721 to 491 BC (the earliest and latest Babylonian eclipses he uses), plus the three eclipses of 383 and 382 BC he knew from Hipparchus. He clearly did not have access to the original Babylonian records himself as the accounts he quotes differ in some significant respects from the type of accounts we know from Babylonian texts, most obviously in the use of seasonal units of time measurement. Ptolemy himself is unlikely to have converted the Babylonian observations into seasonal hours as his first step when using the observations is to turn them back into equinoctial time-reckoning.[17] This suggests that Ptolemy was working with a Greek version of a compilation of Babylonian lunar eclipses which had already changed some of the observational data to make it more like the other pre-Ptolemaic Greek eclipse records reported by Ptolemy which give times in seasonal hours.[18]

Although the Greek compilation of Babylonian lunar eclipse records is not preserved to us we can make a plausible case that it was a Greek translation of the large compilation of lunar eclipse reports arranged in Saros cycles covering the

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[16] J. P. Britton, *Models and Precision: The Quality of Ptolemy's Observations and Parameters* (New York, 1992), 151.

[17] Steele (note 4), 339.

[18] Steele (note 5), 101.

period 747 to 315 BC discussed above.[19] It is inconceivable that a Greek astronomer working in conjunction with a Babylonian scribe worked his way through several hundred years worth of astronomical diaries searching for eclipse records (which could only have taken place in Babylon); this large compilation, by contrast, contained over 400 years worth of eclipse reports on a mere eight tablets, which could be easily copied, a copy transported from Babylon to another part of the Greek world if necessary, and translated quickly and easily by a Babylonian astronomical scribe. The eclipse reports contained in this large compilation would have included reports of all of the eclipses cited by Ptolemy or known to have been used by Hipparchus. It seems almost certain that a Greek version of this large compilation provided the source material from which Ptolemy and other Greek astronomers drew their observations of lunar eclipses.

One of the problems faced by a Greek astronomer attempting to use Babylonian observations would have been converting the date of the observation from the Babylonian calendar into a calendrical system within which he could work such as the Egyptian calendar used by Ptolemy. A luni-solar calendar was in use in Babylonia in which months could either have 29 or 39 days and years comprised 12 or 13 months. Intercalation of the 13th month in certain years was governed by a 19-year cycle (the 'Metonic' cycle) from about 500 BC onwards but greater randomness in intercalation took place before that date.[20] Before the commencement of the Seleucid Era at the end of the fourth century BC, years were given from the ascension of a king to the throne.[21] All three aspects of the Babylonian calendar potentially posed problems for a Greek astronomer wanting to use Babylonian observations. Theoretically, a complete record of 29- and 30-day months was preserved in the astronomical diaries, but using that data to obtain a running count of days back to, say, the sixth or seventh century would not have been practical. Similarly, details of the occurrence of intercalary months and the lengths of king's reigns stretching back to the eighth century could be abstracted from the astronomical diaries, but abstracting and using this information would again not have been practical.

If the Greek astronomers had access to a translation of the large compilation of lunar eclipse records which preserved its format, as I have argued, the layout of the text itself would have provided the means to allow the astronomer to reconstruct the necessary information about the Babylonian calendar. The regular format of six- or occasional (and always noted) five-month intervals between eclipses meant that the number of months between any two dates given for eclipse possibilities could be easily and precisely determined. For example, if the month of an eclipse report in year 10 of a particular reign was given as Month X, and the following eclipse report was for Month IV of the year 11 of the same king, then there cannot have been an intercalary month XII in year 10. If the second eclipse was dated to Month III of year 11 but the eclipse was stated to be at a five-month interval, then again there cannot have been an intercalary month XII in year 10. If, however, the second eclipse

[19] See Steele (note 4) and C. B. F. Walker, 'Achaemenid Chronology and the Babylonian Sources', in *Mesopotamia and Iran in the Persian Period: Conquest and Imperialism 539–331 BC*, edited by J. Curtis (London, 1997), 17–25.

[20] J. P. Britton, 'Calendars, Intercalations and Year-Lengths in Babylonian Astronomy', in *Calendars and Years: Astronomy and Time in the Ancient Near East*, edited by J. M. Steele (Oxford, 2007), 115–32.

[21] For further details of the Late Babylonian calendar, see R. A. Parker and W. H. Dubberstein, *Babylonian Chronology 626 B.C. – A.D. 75* (Providence, 1956).

was again dated to Month III of year 11 but there was no statement of a five-month interval (and recall that this can always be restored even if the text was broken since eclipse possibilities at five-month intervals will be in the same row of the compilation), then in this case there must have been an intercalary Month XII in year 10. Similar arguments would hold in the case of an intercalary month VI. Thus, all intercalary months within the period covered by this large compilation (747–315 BC) could have been identified simply from the dates of the eclipse possibilities in the text and the layout of the text. In exactly the same fashion, the length of king's reigns could be abstracted directly from the large compilation. Even if small parts of the compilation were lost or corrupted, it would be possible to reconstruct the missing or corrupt parts from other data in the text and knowledge of its layout. This implies, for example, that all of the pre-Hellenistic part of Ptolemy's royal canon could have been obtained from the material given in the (Greek translation of the) large compilation.[22]

At first sight it would appear that a bigger problem was posed by the variability in the length of the month in the Babylonian calendar. The large compilation does not contain information on the length of every month. However, the format of the compilation itself provided a solution to the problem of the count of days. Neighbouring eclipse possibilities along the same row of the large compilation are separated by one Saros or 223 months. It was well known to both Babylonian and Greek astronomers that a Saros was also equal to about 6585 one-third days (the excess over a whole number of days actually varies between about six and nine hours, something that was well known to the Babylonians).[23] Thus, if the equivalent date of a single eclipse in one row of the large compilation were known, the number of days separating that eclipse from other eclipses in that row could be determined simply by successively adding or subtracting 6585 one-third days. For example, if the equivalent dates of all the eclipses in the final column of the large compilation were known, which is not too farfetched as this coincides with the period when Babylonia was under Greek rule, the dates of all other eclipses in the compilation could be determined.

It seems likely, therefore, that at some point after 315 BC, a Greek translation of the large compilation of lunar eclipse records from Babylon was made and that this translation preserved the format of the original compilation. The format of the compilation itself was then used to resolve the calendrical problems facing a Greek astronomer who wanted to use Babylonian observations.[24] The transmission of Babylonian eclipse observations in a way that was useful to Greek astronomers relied not only on translating the eclipse records contained in the compilation but also—and crucially—upon preserving the layout of the original compilation. It is worth noting that there are no errors in the Egyptian dates of the eclipses cited by Ptolemy.

[22] Steele (note 4), 343. On Ptolemy's royal canon, see G. Toomer, *Ptolemy's Almagest* (London 1984), 11 and L. Depuydt, 'More Valuable Than All Gold: Ptolemy's Royal Canon and Babylonian Chronology', *Journal of Cuneiform Studies* 47 (1995), 97–111.

[23] See, for example, J. M. Steele, 'A Simple Function for the Length of the Saros in Babylonian Astronomy', in *Under One Sky: Astronomy and Mathematics in the Ancient Near East*, edited by J. M. Steele and A. Imhausen (Münster, 2002), 405–20.

[24] Of course it is almost certain that the Babylonians themselves also used the format of the compilation to resolve calendrical problems in similar ways.

4. The display of eclipse predictions on the Antikythera Mechanism

The Antikythera Mechanism is an ancient Greek geared device for computing or tracking the longitudes of the sun, moon and (probably) the planets, dates in the Egyptian and Callipic calendars, and the months of eclipse possibilities.[25] The front dial of the mechanism is marked with degrees of longitude and days in the Egyptian calendar. Pointers, moved by internal gearwork, traced the positions of the sun, moon and possibly the five planets, although the pointers and most of the gears necessary for the planets are now lost. Alongside certain positions on the ring representing longitudes are letters that correspond to a parapegma text found inscribed elsewhere on the mechanism. The back of the mechanism contains two primary dials along with at least two (probably at least three) smaller subsidiary dials located within the primary dials. The two primary dials on the back of the mechanism are in the form of spirals: the upper dial is a five-turn spiral, the lower a four-turn spiral. The spirals are divided into cells, each cell representing one month. The upper spiral dial is divided into 235 cells, representing the 235 months of the 19-year Metonic cycle. The lower dial has 223 cells representing the 223 months of the Saros cycle (see Figure 4).[26] The subsidiary dial within the upper spiral dial is divided into four and marks the four-year cycle of Greek athletic games; the subsidiary dial within the lower cycle is divided into three and represents the cycle of three Saroi, known as the Exeligmos.[27] Evidence from the inscriptions on the mechanism suggest that a second subsidiary dial in the upper spiral marked the four Metonic cycles which make up a Callippic cycle of 76 years.

Some of the cells within the lower dial contain short inscriptions. These inscribed cells denote the months within the Saros cycle which contain eclipse possibilities.[28] The purpose of the lower dial was to indicate the months in which lunar or solar eclipses might take place. Because the dial is divided into 223 months, once the pointer had moved through the whole dial, it could be returned to the beginning and would predict the eclipse possibilities for the next Saros of 223 months, after which the process could be repeated once more. The subsidiary dial indicated whether the current month was in the first full circuit of the dial, in the second, or the third. Because the Saros is about one-third of a day longer than an integer number of days, eclipses in a Saros series will take place about one-third of a day later than the preceding eclipse in the series. After another Saros the cumulated time difference will be two-thirds of a day, and after the third Saros the time difference will reach a full day, meaning that the eclipse will once more take place at the same time of day. The subsidiary dial is divided into three parts that indicate whether the time of the predicted eclipse should be increased by 8, 16 or 0 hours depending upon whether we are in the first Saros, the second Saros or the third Saros.[29]

[25] For details of the Antikythera Mechanisn, see T. Freeth *et al.*, 'Decoding the ancient Greek astronomical calculator known as the Antikythera Mechanism', *Nature*, 444 (2006), 587–91 and M. T. Wright, 'The Antikythera Mechanism Reconsidered', *Interdisciplinary Science Reviews*, 32 (2007), 27–43, with references to earlier work.

[26] Freeth *et al.* (note 25).

[27] T. Freeth, A. Jones, J. M. Steele and Y. Bitsakis, 'Calendars with Olympiad and Eclipse Prediction on the Antikythera Mechanism', *Nature* 454 (2008), 614–17.

[28] Freeth *et al.* (note 25). The distribution of lunar eclipse possibilities within a Saros is identical to what we find in Babylonian sources but the solar eclipse possibilities seem to have been determined from a theoretical model of nodal elongation with unequal north and south eclipse limits. See further Freeth *et al.* (note 25), supplementary notes.

[29] Freeth, Jones, Steele and Bitsakis (note 27).

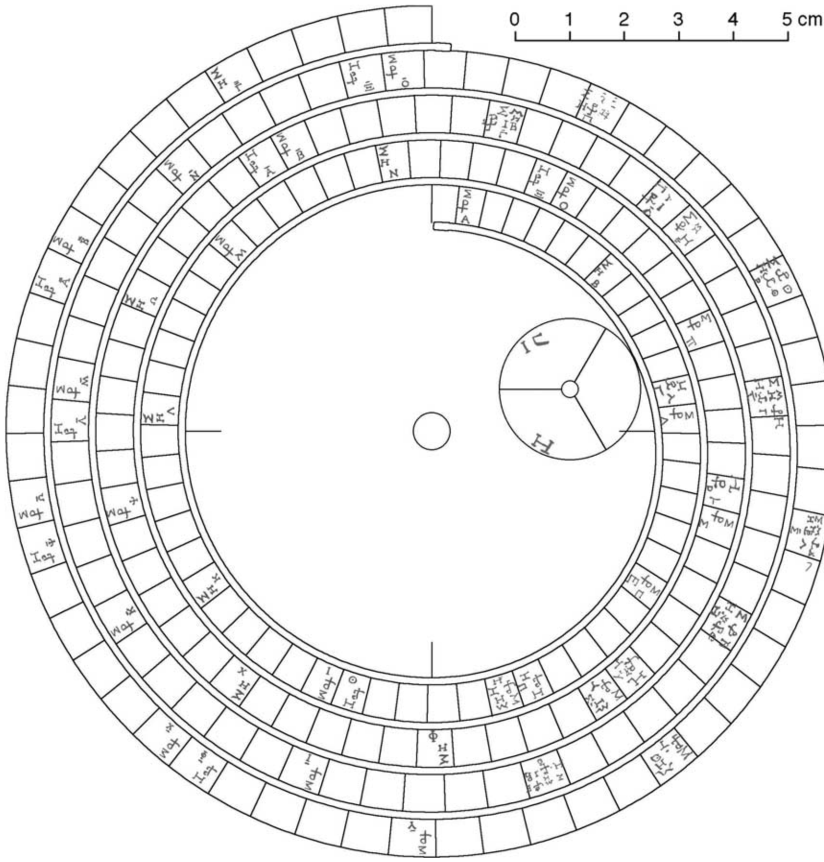

Figure 4. Reconstruction of the lower back dial of the Antikythera Mechanism (Reproduced with permission from Freeth, Jones, Steele and Bitsakis (note 26), Supplementary Notes (revised)). The dial is a four-turn spiral divided into 223 cells. Each cell corresponds to one lunar month. Months containing lunar or solar eclipse possibilities are inscribed with 'eclipse glyphs'.

The Saros dial on the Antikythera Mechanism relies upon several ideas that have a Babylonian origin: the Saros itself, the notion of eclipse possibilities (months in which an eclipse may take place contrasted with months at which an eclipse will not), and the approximately eight-hour time difference between successive eclipses in a Saros series. As we have seen above, all of these ideas are found in the Babylonian eclipse texts arranged in Saros cycles, and it seems very likely that these texts were the ultimate source of the method of eclipse prediction used in the Antikythera Mechanism Saros dial. Papyrus sources from Greco-Roman Egypt (one Demotic, one Greek) show similar awareness with Babylonian methods of eclipse prediction using the Saros.[30] However, the way that the underlying method is used and the

[30] O. Neugebauer, R. A. Parker and K.-T. Zauzich, 'A Demotic Lunar Eclipse Text of the First Century BC', *Proceedings of the American Philosophical Society* 125 (1981), 312–27; A. Jones (note 2), no. 4137.

method of presentation of the eclipse predictions on the Antikythera Mechanism reflect differences from the Babylonian material.

The first, and perhaps most obvious, difference is in the presentation of the months of the eclipse possibilities. Instead of listing the months containing an eclipse possibility and omitting the other months, as would be done in a Babylonian text, the pointer moving around the Saros dial on the Antikythera Mechanism sweeps through empty cells, indicating the months when there is no eclipse possibility, and then enters a cell with an inscription, indicating that there is an eclipse possibility that month. This difference, of course, is governed simply by being a mechanical device with a uniformly moving pointer. Related to this is that Saros dial itself does not give any specific dates. The Saros dial is, in essence, a template for eclipse possibilities that required the calendrical information indicated elsewhere on the Mechanism in order to relate it to actual dates. The subsidiary Exeligmos dial indicates that the Saros dial was intended to be used for more than one Saros cycle. Because the Saros is not equal to a whole number of calendar years (223 synodic months can be either 18 years or 18 years plus one month in a luni-solar calendar) some of the month names given on the Saros dial would have been incorrect the second time the dial was used. Babylonian eclipse texts, by contrast, always give specific dates for the eclipse predictions.

An important difference between the Babylonian eclipse texts and the Antikythera Mechanism is that the Mechanism presents both lunar and solar eclipse possibilities together on the same dial. The Babylonian eclipse texts arranged into Saros cycles always deal only with lunar or solar eclipse possibilities. Mixing both together made practical sense for the designer of the mechanism, who would otherwise have had to find space and get gear-trains to two identical (except for the inscribed cells) dials. However, by mixing both the lunar and solar eclipses together the designer of the Mechanism made it considerably more difficult to identify the five-month intervals between eclipse possibilities of the same kind. As I have discussed, the Babylonians considered the five-month intervals to be sufficiently important to always note them either by a written comment or by a ruling on the text. For the Greek designer of the Mechanism, the five-month intervals had lost their importance. However, another feature of eclipse possibilities appears to have been worth highlighting for the Mechanism's designer: by making the Saros dial a four-turn spiral, cells along the same radius from the centre of the dial have the moon at syzygy at almost exactly the same phase in its cycle of lunar anomaly.[31] Each turn of the spiral contains 223/4 months and therefore each quarter turn of the spiral 223/16, which is very close to 14 months, a well-known period of approximate return of lunar anomaly. Therefore, cells located in the same angular position in each spiral will correspond to months where the lunar velocity is approximately the same. This was apparently a deliberate choice made by the designer of the Mechanism as it would have been possible to make the Saros dial a spiral with a different number of turns.

The text inscribed within the cells that refer to eclipse possibilities ('eclipse glyphs') bear both similarities to and differences from what we find in cuneiform texts. Whereas the cells of the large compilation contain a short prose account of the eclipse, the eclipse glyphs on the Antikythera Mechanism are highly abbreviated, using single letters or ligatures to convey meaning rather than complete phrases,

[31] Freeth, Jones, Steele and Bitsakis (note 27).

probably because of the small amount of space available within each cell. A typical eclipse glyph contains only the letters H or Σ standing for the Greek works Helios and Selene indicating a solar or lunar eclipse respectively (some glyphs have both, meaning that both a solar and a lunar eclipse could take place that month), a statement of the time of the eclipse in hours of day or night, and an index letter which cycles through the Greek alphabet from A to Ω as we move around the glyphs in the dial. Because there are more eclipse glyphs than letters in the Greek alphabet, the cycle of index letters repeats about two and a quarter times.[32] Index letters which are from the second time through the alphabet have a small bar over the letter; it is not known if any further mark was made for the index letters the third time through the alphabet as no examples are preserved.

Comparing the eclipse glyphs with details of the eclipse possibilities in the Babylonian large compilation we can see that both place a strong emphasis on the time of the eclipse. On the Antikythera Mechanism, the time is the only piece of information (apart from whether it is lunar or solar) that is given for the eclipse within the glyph. In the Babylonian large compilation, the time of the eclipse is always given for both observed and predicted eclipses.

The most significant difference between the display of eclipse possibilities on the Antikythera Mechanism and the eclipse possibilities given in the Babylonian Saros texts is the use of the index letters in the Antikythera eclipse glyphs. The purpose of the index letters is not entirely clear. Most likely they referred to text inscribed somewhere else on the Mechanism which contained further details about the eclipse possibilities. Index letters are used analogously on the dial on the front of the Mechanism to refer solar longitudes on the dial to the text of the parapegma inscribed in the remaining space on the front plate surrounding the dial. The use of index letters to refer to text written elsewhere is almost certainly a Greek innovation. It is not something found in cuneiform sources and indeed it is hard to see how the cuneiform writing system, which is not alphabetic and has no formal ordering of signs,[33] could be used in such a way, except hypothetically by the use of numbers (numbers were occasionally employed in cryptographic cuneiform texts to stand for whole words and a few number-syllabaries are preserved,[34] but I know of no cases where they are used to link one piece of text to another in the manner of a footnote). In Greek sources the use of index letters to refer from one piece of text to another is rare, but not unattested. A fragment of a Greek sundial from Istropolis on the Black Sea, attributed to the third century BC, has 13 short lines marked with Greek letters dividing the meridian.[35] Similar letters inscribed on a sundial are referred to in an inscription from Alexandria.[36] However, the practice was evidently not widespread.[37]

The Antikythera Mechanism presents a very clear example of the ways in which Babylonian astronomy was transformed when it was used by Greek astronomers.

[32] Freeth, Jones, Steele and Bitsakis (note 27).

[33] Standard sign-lists, known today as syllabaries, were used in scribal education in Mesopotamia, but they do not offer a simple ordering of signs in the way the alphabet does with letters.

[34] L. Pearce, 'The Number-Syllabary Texts', *Journal of the American Oriental Society*, 116 (1996), 453–84.

[35] S. Gibbs, *Greek and Roman Sundials* (New Haven, 1976), no. 1044.

[36] E. Breccia, *Inscrizioni Greche e Latine*, Catalogue Général des Antiquités Égyptiennes du Musée d'Alexandrie Nos. 1–568 (Cairo, 1911), no. 185.

[37] I distinguish here between index letters which refer to another piece of text and labels on a diagram which exist in their own right and do not refer to the reader to another piece of text.

One aspect of this transformation was the way that the astronomy was presented. Most obviously, of course, the Antikythera Mechanism differs in its use of dials and pointers to display information, but in addition, the designer of the Antikythera Mechanism was interested in highlighting different astronomical features of the months of eclipse possibilities (e.g. the periods of lunar anomaly rather than the five-month intervals between certain eclipse possibilities) to the Babylonian scribes. In doing so, he transformed not only the way astronomical phenomena were calculated (mechanically rather than numerically), but also the way information was presented to the user.

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