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BABYLONIAN TIMINGS OF ECLIPSE CONTACTS AND THE STUDY OF EARTH'S PAST ROTATION

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Abstract: Long-term changes in the length of the day are investigated using an extensive series of Late Babylonian timings of lunar and solar eclipses. The dates of these observations range between about 700 BC and 50 BC. In recording the times of eclipse contacts, the Babylonian astronomers reported time intervals rather than specific moments. Hence scribal errors tend to be cumulative. To reduce this effect, I have concentrated in this paper almost exclusively on first contact observations. Analysis of these measurements leads to a result for the parameter ΔT of 31.7 ± 0.3 sec/cy/cy and a mean rate of change in the length of the day over the selected interval of 1.74 ± 0.03 ms/cy.

Keywords: Babylon, Earth rotation, eclipses

1 INTRODUCTION

The publication of transliterations, and translations into English, of the extant Late Babylonian eclipse (and other astronomical) records of known date is now essentially complete (Sachs and Hunger, 1988, 1989, 1996, 2001, 2006; Huber and de Meis, 2004). Unless an unexpected archive comes to light, little further progress seems likely in the next few decades. It is thus appropriate to reconsider the eclipse observations in detail to investigate long-term variations in the Earth's rate of rotation.

Over many centuries, the cumulative effect of these variations, termed ΔT, amounts to several hours. It can thus be readily detected from ancient observations, even those of low precision. The parameter ΔT is defined as the difference between Terrestrial Time (TT), as defined by the motion of the Moon and planets, and Universal Time (UT), as measured by the Earth's spin. Throughout the whole of the pre-telescopic period, eclipses have proved to be the only astronomical observations which are of real value in the study of Earth's rotation. By comparison, occultations and planetary conjunctions are of little utility.

2 THE OBSERVATIONS

For several centuries, Babylonian astronomers systematically recorded eclipses of both Moon and Sun. Although only a small percentage of the original records has been recovered, observations of nearly one hundred separate eclipses are preserved. Nearly all of these records range in date from about 700 BC to 50 BC. Steele (2000) identified a single later eclipse which probably dates from 10 BC. The various observations were recorded on clay tablets using a cuneiform script. Practically all of the extant texts are in the British Museum, having been recovered from the site of Babylon (latitude = 32.55 deg N, longitude = 44.42 deg E) during the 1870s and 1880s. Most tablets are very fragmentary, but thanks to the painstaking work of a number of scholars, the various inscriptions are well understood.

Over the period covered by the Late Babylonian texts, very few eclipse observations from any other part of the world are of comparable value for the investigation of ΔT. A few untimed observations of total or near-total solar eclipses are preserved in the histories of ancient China and Europe (Stephenson, 1997). However, the place of observation is frequently in doubt. Several careful Greek measurements of lunar eclipse times (mainly from Alexandria) are recorded in the *Almagest*, but none is earlier than about 200 BC. Prior to about 700 BC, allusions to eclipses (notably from China and Western Asia) are extremely rare and are sometimes of dubious reliability. In this paper I shall concentrate specifically on the set of Babylonian data from 700 BC to 50 BC.

The Late Babylonian observational texts are of three main kinds: (i) astronomical diaries summarising the observations made over a period of several months; (ii) lists of eclipses compiled by the Babylonian astronomers, often extending over many years; and (iii) so-called 'goal-year' texts used in the preparation of almanacs. The data in texts in categories (ii) and (iii) were compiled from the diaries. Occasional duplication of observations can thus be found in the extant texts.

When reporting eclipses, the astronomers of Babylon noted both predictions and observations. In most texts, predictions can be readily distinguished from observations. In the case of predictions, little more than the expected time interval of first contact relative to sunrise or sunset is recorded; there is usually a comment that the observer 'did not watch' (on account of unfavourable weather) or that the eclipse 'passed by'. Use of this latter term indicated either an eclipse occurring when the appropriate luminary was below the horizon or an unsuccessful prediction—e.g. when the shadow of the Moon at a solar eclipse passed completely to the north or south of Babylon. Observations of eclipses frequently contain much more detailed information. This typically includes timings of each phase of the eclipse as well as other data, such as an estimate of the eclipse magnitude and whether the Sun or Moon rose or set whilst eclipsed. When an observation of first contact is reported, the corresponding predicted time is never cited, having been superseded by measurement.

Numerous eclipse (and other astronomical) texts are extensively damaged, but in many cases either the date is preserved or it can be confidently restored. Prior to the Seleucid Era (311 BC), years were counted from the accession of each ruler. However, all subsequent years were numbered continuously. Dates within a year are expressed in terms of the Babylonian luni-solar calendar. Most years had 12 lunar months, each of either 29 or 30 days. However, an occasional

13th month was intercalated, in order to keep the calendar in step with the seasons. The operational rules of the Babylonian calendar have been extensively studied and are well understood. Accurate tables for converting Babylonian dates to the Julian Calendar are available (Parker and Dubberstein, 1956).

Several major tablets contain collections of eclipse records at 18-year intervals. Here the occasional preserved date is usually quite sufficient to identify missing dates in the sequence. Other texts which contain lunar and planetary information enable the date to be computed—independently of the eclipse records. Among the extant texts, lunar eclipse observations far outnumber their solar counterparts. A partial explanation of this anomaly is the relatively higher frequency of lunar eclipses which are visible from any one location on the Earth's surface. However, the date range covered by Babylonian observations of lunar eclipses is about twice as long as for solar obscurations. This appears to be the result of chance—probably less than 10 per cent of the original archive has come to light.

The Babylonians systematically timed—possibly with a water clock, but the actual method is uncertain—the start (first contact) of both lunar and solar eclipses relative to sunrise or sunset, depending on which was nearer. The next phase of the eclipse (second contact in the case of a total eclipse and greatest phase for a partial eclipse) was then timed relative to first contact; other phases were similarly timed in steps. Times were measured in UŜ (time degrees, usually abbreviated to deg), where 1 UŜ was precisely equal to 4 minutes (cf. Stephenson and Fatoohi, 1994); there were 360 UŜ in a combined day and night. Before about 550 BC, measured times were quoted only to the nearest 5 or even 10 UŜ. However, all later measurements are expressed to the nearest 1 UŜ.

To give an example, the total lunar eclipse of 11 November 371 BC is recorded as beginning at 30 deg after sunset; after a further 22 deg it became total; the duration of maximal phase was 20 deg, while the Moon became bright after a further 21 deg. The duration from start to finish is confirmed in the text as 63 deg. We can readily compute the local solar time (LT) of sunset at Babylon as 17.35 h. Hence the LT of the four contacts may deduced as 19.35 h, 20.82 h, 22.15 h and 23.55 h.

3 SELECTION OF DATA

In the investigation of the Earth's past rotation, it is important to use eclipse reports which have been dated without recourse to retrospective calculation based purely on the eclipse observations themselves. Otherwise, there is a danger of circular reasoning: what Robert R. Newton aptly described as "… playing the identification game". In the present analysis I have concentrated on those eclipses for which the date is recorded directly or has been reliably established independently by other means (see Section 2 above).

In analysing the various Babylonian eclipse timings to determine ΔT, I have concentrated almost exclusively on first contact measurements. There are two main reasons for this choice. To begin with, there are many more preserved reports of first contact than for any other single eclipse phase. Furthermore, the way in which the Babylonian astronomers recorded eclipse times other than first contact can lead to systematic errors. As may be seen from the above example of the eclipse of 371 BC (Section 2), the Babylonian astronomers almost invariably expressed the times of all contacts apart from the first relative to the immediately previously measured moment. Hence any mistake in measurement, or scribal error, in recording the time interval between sunset (or sunrise) and first contact—or a damaged reading—will systematically affect the LT of each phase. Similarly, an error in the time-interval between first and second contact would affect the LT of second, third and fourth contacts, and so on. The use of all the available observations of each particular eclipse—rather than first contact alone—can thus lead to a higher proportion of faulty data which are not independent of one another.

The adverse effects of using all contact observations in the derivation of ΔT is displayed by comparing two diagrams in the monograph by Stephenson (1997). Comparison between the ΔT values obtained from single contact measurements (Figure 6.6) and from results derived from other contacts (Figure 6.7) reveals a considerable bias towards high values of ΔT in the latter diagram caused by observations of three total lunar eclipses (and hence twelve measurements in all) between about 300 and 200 BC; the precise dates are 13 December 317, 1 August 226 and 23 December 215 BC.

For some reason, recorded durations of totality are particularly subject to considerable error. The computed durations of lunar eclipses—unlike solar obscurations—are independent of ΔT. Of 18 reported durations in the compilation of Huber and de Meis (2004), 12 (of mean duration some 20 deg) are in fairly good accord with computation (average error 3 deg). However, on the remaining six occasions errors are serious: 14 deg instead of 23.7 deg in 501 BC, 25 deg instead of 16.7 deg in 501 BC, 7 deg instead of 21.6 deg in 327 BC, 5 deg instead of 20.9 deg in 317 BC, 22 deg instead of 11.0 deg in 284 BC, and 10 deg instead of 16.1 deg in 226 BC.

In the present investigation, although I have restricted my attention almost exclusively to first contact observations, I have also included a few observations in which the Moon or Sun rose very near the end of an eclipse. In these instances the observers directly estimated the (short) time interval between moonrise or sunrise and last contact.

In principle, restriction to little more than first contact observations may introduce what might be termed 'contact bias'—due to such factors as delay in catching sight of the start of an eclipse by inattentive observers or (specifically in the case of a lunar eclipse) difficulties in resolving the actual contact due to the 'fuzziness' of the Earth's shadow caused by the terrestrial atmosphere. However, the available evidence indicates that contact bias should not be serious. For instance, the Babylonian astronomers made systematic attempts to predict eclipses. As shown by Steele (2000), the average error in predicting the time of a lunar eclipse was about 2 hours, whereas for a solar eclipse it was about 3 hours. Intending observers thus knew roughly when to watch for first contact.

In my own personal experience, first or last contact for a lunar eclipse can be resolved with the unaided eye with tolerable precision, despite the indistinct edge of the Earth's shadow. For example, at the very small partial eclipse of 7 September 2006 (magnitude only 0.19), my estimate of the UT of last contact—made without taking advantage of advance predictions—proved to be within 2 or 3 minutes of the computed time.

Investigation of the durations of the individual partial eclipse phases as recorded by the Babylonian astronomers also indicates that contact bias may not be serious. In observing a partial eclipse the astronomers normally timed the interval between first contact and the moment when the eclipse appeared to reach its height. Then, a short interval was recognised—usually ranging from about 5 to 10 deg—during which the phase did not sensibly change. Finally, the interval between the end of this stage and last contact was measured.

For example, the record of the partial lunar eclipse of 28 April 239 BC was translated by Sachs and Hunger (1989: 85) as follows:

> At 80 deg after sunset, lunar eclipse; it began on the south and east side; in 15 deg night it made a little over 2/3 (?) of the disk; 10 deg of night maximal phase. When it began to clear, in 15 deg of night it cleared from the east to the west; 40 deg onset, maximal phase and clearing ...

For this eclipse, the computed magnitude was 0.41. The computed semi-duration of 17.8 deg was a little shorter than the measured figure of 20 deg. In examining the extant records of partial lunar eclipses, I note that the measured intervals between first contact and mid-eclipse (which I shall term first phase) and between mid-eclipse and last contact (last phase) averaged only about 0.4 deg (= 100 sec) less than their computed values. Furthermore, although only five sets of measurements of the durations for both the first and last phases are preserved, the systematic bias was only about 0.6 deg (= 140 sec).

In the case of solar eclipses, the Babylonian astronomers did not recognise an intermediate phase; they measured directly the interval from the start of an eclipse to maximal phase and from this latter moment to the end of the eclipse. The durations of both first and last phase are only preserved today for four solar eclipses: in the years 254, 190, 136 and 133 BC. Recorded semi-durations averaged about 16 deg, but the mean bias between the durations of the two phases was only 0.5 deg (= 120 sec). Hence for the purposes of the present study it seems feasible to ignore contact bias.

We have no knowledge of any method used by the Babylonian astronomers to dim the Sun when observing solar eclipses. However, it is interesting to note that the 1st century AD Roman writer Seneca, in his *Naturales Quaestiones*, remarked that in Italy it was the practice to view the eclipsed Sun by reflection in pitch. Owing to its viscosity, this liquid—which also had the advantage of low reflectivity, was not easily disturbed by wind, etc. Bitumen was readily available in Babylon and was regularly used there in building construction; possibly its optical qualities were also appreciated by the astronomers!

Lunar observations of first contact are of two main kinds. More usually, time-intervals were measured relative to sunrise or sunset, depending on which was nearer. However, after about 250 BC, times were also often measured relative to the culmination of any one of about 26 selected stars (or small star groups), known as 'ziqpu' stars. The identities of most of these stars are well established (for details, see Huber and de Meis, 2004: 32). Sometimes a lunar report of this type only states that the eclipse began when a particular star culminated. However, on several occasions it is implied that first contact occurred a few degrees (up to a maximum of about 7) before or after culmination of the reference star. The beginning of a solar eclipse was invariably timed relative to sunrise or sunset.

In compiling the data used in this investigation, I have extracted the various observations as the result of thorough searches through two major sources: the five volumes of transliterations and translations of Babylonian astronomical texts published by Sachs and Hunger (1988, 1989, 1996, 2001 and 2006) and the extensive compilation of Babylonian eclipse records compiled by Huber and de Meis (2004). I have carefully intercompared the two independent sets of translations. In the case of disputed readings, I have requested that other colleagues—notably Dr J.M. Steele—check the appropriate texts. I have rejected any records for which the interpretation—or reading of a key number—is doubtful. There are now many more observations available than was the case even a very few years ago. It is my hope that the present set of observations will prove to be definitive.

4 ANALYSIS OF DATA

In all eclipse computations in this paper, I have assumed a lunar acceleration of –26.0 arcsec/cy/cy, as derived from lunar laser ranging (Williams and Dickey, 2003). When the onset of a lunar eclipse was measured relative to sunrise or sunset, I have initially deduced the observed local apparent time (LT) at Babylon of first contact by calculating the LT of sunrise or sunset. Then I have derived the LT of first contact by adding or subtracting the measured time-interval. Finally, I have subtracted this result from the computed LT, based on the assumption that ΔT was zero. This difference gives the estimated value of ΔT at the date in question. In the case of lunar eclipse measurements based on ziqpu star observations, I have computed the LT of culmination of the appropriate star and then proceeded as previously. On the rare occasions when last contact has been used, I have computed the LT of moonrise or sunrise as necessary.

During a lunar eclipse, the appearance of the eclipsed Moon at any moment is virtually the same from any point on the Earth's surface where the Moon is above the horizon. Hence analysis of a lunar observation is a relatively simple matter. However, the derivation of ΔT from solar eclipse observations is more complex since the lunar shadow crosses the terrestrial surface and the appearance of the Sun is very much dependent on the observer's location. I have derived the observed LT of first contact as for a lunar eclipse, based on the measured interval after sunrise or before sunset. However, in order to deduce the value for ΔT, an iterative technique must be used. In this process, ΔT is progressively refined until the computed LT of contact matches the observed time.

5 ILLUSTRATIVE EXAMPLES

As examples, I have selected the following:

(i) The lunar eclipse of 17 October 537 BC is recorded as commencing 14 deg before sunrise. (Incidentally, it is also reported that when 2/3 of the disk was obscured the Moon set.) The computed LT of sunrise was 6.24 h, implying a measured LT of first contact of 5.31 h. Comparing with the computed LT of 10.54 h, based on a value for ΔT of 0, the result for ΔT = 18800 sec.

(ii) The lunar eclipse of 13 August 105 BC was reported to begin 7 deg (= 0.47 h) after the "bright star of the Old Man" (= α Per) culminated. At the time the R.A. of the star was 1.17 h, while that of the Sun was 9.28 h. Hence it may be derived that the LT of first contact was 12.00 + 1.17 – 0.47 – 9.28 = 3.42 h. Subtracting this result from the computed LT of 6.76 h (based on ΔT = 0) yields ΔT = 12000 sec.

(iii) The solar eclipse of 31 January 254 BC was observed to begin 56 deg before sunset. The computed LT of sunset on this occasion was 17.26 h, so the LT of first contact was 13.53 h. Using an iterative method, the computed LT of first contact may be deduced as 13.53 h for a value of ΔT of 11400 sec.

6 PRESENTATION OF RESULTS

The various results of the current investigation are summarised in four tables. In each table, years are given as negative integers, differing from one year by their BC equivalent; thus –685 is equivalent to 686 BC, and so on. This difference arises from the fact that there is no year zero on the BC/AD system. If more than one eclipse occurred in a year, tabular years are followed by a, b or c. The other parameters listed are, in order, computed eclipse magnitude (for reference only), measured time-interval in degrees, and derived ΔT result in seconds.

In Table 1, the investigation of 58 lunar first contact measurements relative to sunrise (SR) or sunset (SS) is summarised. For the eclipse of –554 October 6, both Sachs and Hunger (2006) and Huber and de Meis (2004) assume an error in the text; for "55 deg before sunrise" they read "55 deg after sunset"; this interpretation seems reasonable; adoption of the original reading would lead to an impossibly large value for ΔT of some 86000 sec! In several other instances, a text gives a clear measurement, but on account of partial damage it does not record whether the observation was made before sunrise or after sunset. However, similar reasoning to the above readily identifies the only viable alternative in each case.

Table 2 covers 17 measurements relative to the culmination of ziqpu stars. In most cases the text implies that the eclipse commenced at the time of culmination of the appropriate star or star group. However, in other examples the time interval before (indicated by a minus sign) or after (plus sign) culmination is specified in deg.

Table 3 deals with the four lunar observations in which the time interval between moonrise (MR) and fourth contact is estimated directly; first contact occurred when the Moon was still below the horizon.

Finally, Table 4 is restricted to solar first contact measurements, apart from a single preserved instance (in –280) where the time of end of the eclipse after sunrise is specified. There are ten observations in all. Unlike in the case of a lunar eclipse, the magnitude of a solar eclipse at a particular place is a function of the adopted value for ΔT. I have computed magnitudes using the approximate expression $\Delta T = 32t^2$, where t is in Julian centuries from the reference epoch AD 1820.

Table 1: ΔT results from lunar first contact timings measured relative to sunrise or sunset.

Year	Mag	Interval (deg)	ΔT (Sec)
–685	0.55	100 after SS	22500
–684	1.83	20 after SS	19100
–600	0.84	95 after SS	18000
–598	0.75	105 after SS	14400
–587	0.55	20 before SR	15700
–586	1.80	35 before SR	18900
–579	1.82	45 after SS	19100
–576	1.88	105 after SS	19200
–575	1.27	40 before SR	20000
–572	1.73	90 after SS	18000
–561	1.77	90 after SS	16000
–554	1.53	55 after SS	17800
–536	1.50	14 before SR	18800
–525	1.61	60 after SS	19300
–500	1.47	77 after SS	15000
–482	1.47	10 before SR	17300
–420	1.65	19 after SS	15400
–407	0.18	15 after SS	15200
–406	1.39	48 before SR	15000
–405	0.96	14 before SR	16500
–396	0.09	48 after SS	15500
–377	1.32	37 after SS	16000
–370a	0.78	66 after SS	12800
–370b	1.36	30 after SS	16100
–366	1.33	56 before SR	19500
–363b	0.33	40 before SR	16400
–363c	1.48	14 before SR	15300
–362	1.03	64 after SS	15500
–352	1.35	47 before SR	15900
–316a	0.37	10 after SS	15600
–316b	1.34	44 after SS	16600
–307	0.99	10 before SR	14100
–239	1.40	3 before SR	14200
–238	0.41	80 after SS	8800
–225	1.21	52 after SS	17600
–211a	0.62	20 before SR	11800
–211b	0.94	28 after SS	21300
–193	0.92	12 before SR	13600
–189	1.05	30 before SR	10800
–188	1.28	34 before SR	10800
–162	0.12	85 before SR	9500
–159	1.44	48 after SS	14000
–153	0.85	4 after SS	12700
–142	0.88	7 after SS	12600
–135	0.73	30 before SR	4000
–133a	0.25	9 before SR	11000
–133b	0.25	32 after SS	11600
–128	0.63	55 before SR	11900
–119	1.02	66 after SS	12500
–109	1.75	25 after SS	14600
–108	0.51	8 after SS	12100
–105a	1.61	66 after SS	10500
–105b	1.59	50 before SR	12900
–104	0.27	26 before SR	12000
– 95	0.71	57 after SS	13200
– 80	1.70	60 after SS	8900
– 79a	0.60	40 before SR	11500
– 79b	0.39	30 after SS	12100

Table 2. ΔT results from lunar first contact timings measured relative to the culmination of stars.

Year	Mag	Interval (deg)	ΔT (sec)
–225	1.19	0	15500
–214	1.37	0	14200
–193	0.92	0	14000
–177	1.11	0	13300
–162	1.53	–3	10400
–149	1.11	+4	11400
–142	0.88	–5	12900
–135	0.73	0	11800
–134	1.57	0	11900
–122	0.15	–5	14000
–119	1.02	–5	11900
–104	0.27	–7	12000
– 95	0.71	+5	11600
– 93	0.25	0	9800
– 90	0.55	0	10600
– 86	0.41	0	12000
– 79a	0.60	+5	11300

Table 3. ΔT results from lunar last contact timings measured relative to sunrise or sunset.

Year	Mag	Interval (deg)	ΔT (sec)
–562	0.35	6 after MR	19200
–464	1.47	21 after MR	15700
–363a	0.21	10 after MR	14100
– 66	0.81	23 after MR	10100

Table 4. ΔT results from solar first contact timings (all measured relative to sunrise or sunset).

Year	Mag	Interval (deg)	ΔT (sec)
–356	0.90	76 before SS	15600
–321	0.17	3 before SS	14200
–280	0.20	20 after SR	12900
–253	0.26	56 before SS	11500
–248	0.80	90 after SR	13900
–189	0.77	30 after SR	12900
–169	0.44	20 before SS	12300
–135	1.05	24 after SR	12600
–132	0.87	51 before SS	11200
– 88	0.36	45 after SR	9100

In addition to the results listed in Table 4, precise limits to ΔT at the epoch –135 (= 136 BC) are set by the total solar eclipse of 15 April in that year. This is the only solar eclipse recorded in Late Babylonian history which is definitely recorded as total. Visibility of four planets—Mercury, Venus, Mars and Jupiter—as well as several stars is noted during the total phase. Only values of ΔT somewhere between 11200 and 12150 sec would yield totality at Babylon.

7 DISCUSSION OF RESULTS

The individual ΔT results (89 in all) listed in column 4 of each table are shown diagrammatically in Figure 1. Here three separate symbols are used: for lunar eclipses timed relative to sunrise, sunset or moonrise; for lunar eclipses timed relative to the culmination of ziqpu stars; and for solar eclipses. Only a single ΔT result is off the scale covered by Figure 1; a value of 4000 sec derived from the lunar eclipse of –135 (= 136 BC). This is presumably the result of a scribal error.

There is clearly a considerable scatter among the results displayed in Figure 1; scribal errors may well be partly responsible for this feature. The scatter is especially notable among the lunar eclipse timings measured relative to sunrise or sunset. However, these have the advantage over the other types of data of extending over a much longer time-scale (more than 600 years). Although after about the year 550 BC the Babylonian astronomers consistently estimated time-intervals to the nearest UŜ—and thus 240 seconds—they clearly did not achieve anything like this precision. Furthermore, there is little evidence of improvement in the accuracy of timing down the centuries. Evidently, the accuracy which the astronomers did achieve was adequate for their purposes.

Two curves are shown in Figure 1. The upper curve, representing the effect of lunar and solar tides, has the equation $\Delta T = 42t^2$, where t is measured in centuries from the standard reference epoch AD 1820. As is evident from the diagram, with a single exception the various ΔT results lie systematically below the tidal curve. Hence there is clear evidence of a marked non-tidal component tending to increase the Earth's spin rate in opposition to the main tidal term. The lower curve is the best fitting parabola through the set of ΔT values shown in Figure 1; this has the following equation:

$$\Delta T = (31.7 \pm 0.3)t^2 \qquad (1)$$

In deriving this latter curve I have rejected six data points (all lunar timings relative to sunrise or sunset) in the years –598, –366, –238, –225, –211 and –135. These lay more than 2.5 sigma from the mean curve, and may well be attributed to scribal errors. As shown in Figure 1, the mean parabola also intersects the limits fixed by the observation that the solar eclipse in –135 was total in Babylon; only coefficients of t^2 between 29.3 and 31.8 would satisfy this critical observation.

The data are probably not of sufficient accuracy to indicate significant short-term fluctuations about the mean parabola; most of the scatter results from the inaccuracy of the observations. No obvious trends on the centennial time-scale are evident. The data divide fairly well into two groups: before and after 350 BC. For the earlier group, of average date close to 460 BC, the mean deviation from the parabola $\Delta T = 31.7t^2$ is +170 ± 220 sec. For the later group, of average date close to 140 BC, the corresponding mean deviation is –110 ± 190 sec, a difference which is barely statistically significant.

Comparison between equation (1) and the cubic spline fit by Morrison and Stephenson (2004)—based on timings of a variety of eclipse phases—reveals discrepancies of no more than 170 sec between 500 and 100 BC. Before the former date, discrepancies are much larger (500 sec at 600 BC and nearly 900 sec at 700 BC. However (as evident from Figure 1), there are scarcely any useful observations prior to 600 BC, while —as noted in Section 2 above—all measurements before 550 BC are rounded to the nearest 5 or even 10 UŜ. Hence at these earlier dates spline fitting ceases to be a viable option; see also Morrison and Stephenson (2005).

The average increase in the length of the day (LOD) as derived from equation (1) is 1.74 ± 0.03 milliseconds per century (ms/cy). The difference of about 0.55 ms/cy between this result and the tidal figure of 2.3 ms/cy can probably be largely explained by the effect of post-glacial isostatic compensation: the continuing rise of land which was glaciated during the last ice-age. This leads to a gradual diminution in the terrestrial oblateness, with consequent decrease in the LOD. Artificial satellite measurements yield a decrease in the LOD of approximately 0.45 ms/cy (e.g. Cheng et al, 1989), in reasonable accord with the non-tidal result deduced from the historical observations. However, the relatively short period (6 centuries) covered by the Babylonian data is insufficient to enable the rate of change in the Earth's zonal harmonic, J_2, to be estimated. This would require the use of more archaic data, little of which is accessible.

8 CONCLUSION

In summary, equation (1) provides an excellent fit to an extensive set of independent data. In addition to the geophysical implications of this investigation, it is hoped that the ΔT parabola will prove of value in investigation other ancient eclipses of similar date, e.g. as recorded in Greek and Latin writings.

The question of extrapolation into the more remote past almost inevitably arises. For this purpose I recommend cautious use of Equation (1) back to around 1000 BC. However, so few archaic observations are preserved that the earlier history of ΔT may well remain indeterminate.

I would very much welcome unaided eye observation of the contacts of the following future total lunar eclipses: 3 March 2007 and 28 August 2007.

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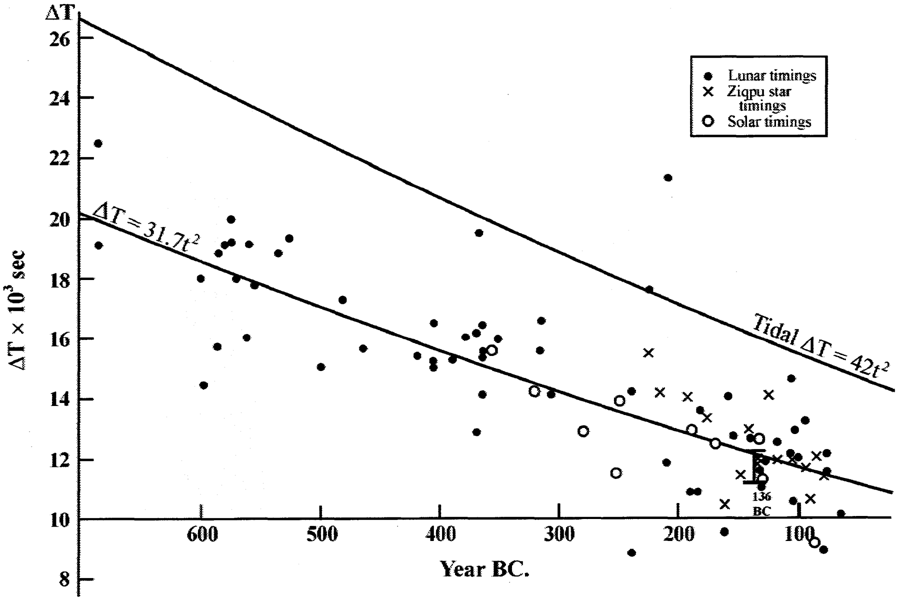

Figure 1: ΔT values and limits derived from late Babylonian eclipse observations.