Historical eclipses and Earth's rotation

F Richard Stephenson took a long view of Earth's rotation history in the 2002 Harold Jeffreys Lecture in October.

One of the many research interests of Sir Harold Jeffreys, FRS – who, incidentally, was my PhD external examiner – was tidal friction. In particular he made use of the results from ancient eclipses to estimate the rate of dissipation of the Earth's rotational energy. The theme of my lecture thus seems apt.

For more than three centuries – commencing with a paper by Edmond Halley in 1695 – the study of ancient and medieval observations of eclipses has provided valuable information about the Earth–Moon system. Today, early eclipse observations are the principal source of data for information on long-term variations in the Earth's rate of rotation. As well as the current geophysical importance of this interdisciplinary subject, its gradual development forms a fascinating chapter in the annals of the history of astronomy.

Abstract

The Earth, in its diurnal rotation, acts as a remarkably accurate timekeeper. However, small variations in the length of the day occur at the millisecond level. Historical eclipse observations, recorded by various ancient and medieval cultures, enable changes in the Earth's spin rate to be monitored with fair precision as far back as around 700 BC. Although lunar and solar tides are the main causes of long-term changes in the length of the day, the early observations reveal that non-tidal mechanisms are also important. In this paper I review both the historical development of this subject and recent advances.

Changes in the length of the day

Since remote antiquity, the Earth's rotation has provided a fundamental time-standard. Until the late 18th century, a basic unit of time was the *apparent* solar day: the interval between two successive transits of the Sun across the same meridian. However, because of the ellipticity of the Earth's orbit and the tilt of the terrestrial axis, the length of the apparent solar day can vary by about 30 seconds from the mean of 24 hours. The development of accurate pendulum clocks led to the introduction of Mean Time, based on the *mean* solar day (MSD) – with the variations due to the shape of the terrestrial orbit and axial tilt averaged out. Eventually Greenwich Mean Time was introduced as the world standard (in 1884), and this subsequently became known as Universal Time (UT). The MSD remains a fundamental standard for almost all practical purposes. Variations in the MSD are the subject of this lecture.

Following decades of speculation, Sir Harold Spencer Jones in 1939 conclusively demonstrated that even the MSD is not an ideal unit; the Earth in its diurnal rotation is a very good timekeeper but is by no means perfect. Astronomical observations reveal fluctuations in the length of the day (LOD) at the millisecond level; using historical observations these fluctuations can be traced back more than 2500 years.

1: The rusty red glow of the Moon in eclipse. (Sol Invictus hjp.arnold@btconnect.com)

Both external and internal mechanisms are responsible for variations in the Earth's rate of rotation. The most significant external causes are lunar and solar tides raised in the oceans and solid body of the Earth. Together with a further small solar contribution (the semi-diurnal atmospheric tide), these produce a steady increase in the LOD of about 2.3 milliseconds per century (ms/cy).

Internal mechanisms giving rise to changes in the LOD are more diverse. Short-term effects include changing wind patterns which produce seasonal and annual variations. On the decade to centennial timescale, the most significant cause of variations is probably electromagnetic coupling between the fluid core of the Earth and the lower mantle. There is a reasonable correlation between observed fluctuations in the LOD over the past 150 years and core angular momentum fluctuations (Hide *et al.* 2000). Global sea-level changes, associated with climatic variations, may also produce a significant effect on centennial and longer timescales. An additional long-term mechanism is post-glacial isostatic compensation; the ongoing rise of land that was glaciated during the last ice-age produces a slow diminution in the moment of inertia of the Earth, with consequent decrease in the LOD.

Seasonal and annual fluctuations have been mapped in detail only since the introduction of Atomic Time (AT) in 1955. Decadal variations in the LOD can be traced over the last four centuries or so (i.e. the telescopic period), mainly using occultations of stars by the Moon. However, any trend is difficult to detect over such a relatively short period. This is why rather crude observations made with the unaided eye in the ancient and medieval past have become so important. The substantial timescale they cover (extending back to around 700 BC) enables long-term trends to be determined with fair precision.

Early historical development of the problem

Not until the mid-18th century does there seem to have been any suggestion that the Earth's rate of rotation might be variable. Immanuel Kant in 1754 proposed that the effect of the lunar and solar tides on the terrestrial oceans would produce a drag on the Earth's spin. However, because of the complexity of oceanic tidal friction, it was not until the work of Jeffreys (1920) that a tolerable estimate of the rate of tidal dissipation could be made. Jeffreys' result of 1.1×10^{12} W was about one-third of the actual value.

Five years before Kant's investigation, Rev.

Richard Dunthorne had obtained evidence of what was eventually recognized to be a closely related issue: an acceleration of the Moon's motion. From a study of six ancient and medieval eclipse observations ranging in date from 721 BC to AD 978, Dunthorne deduced the first numerical result for the lunar acceleration. Although long beforehand – in 1695 – Edmond Halley had suspected that the Moon might be accelerated, he does not appear to have made a quantitative determination. Dunthorne derived a value of +10 arcsec/cy^2 for the coefficient of t^2 in the lunar mean longitude (where t represents time in Julian centuries: in this case measured from Dunthorne's own era). Despite the low accuracy of the early observations that Dunthorne used, the key to the success of his method was the large values of t^2 (ranging from 60 to more than 600).

Pierre-Simon Laplace in 1787 gave what was to be a partial explanation of the lunar acceleration: a gradual diminution of the Earth's orbital eccentricity due to planetary action. Laplace derived a result for the coefficient of t^2 of +11.1 arcsec/cy^2, in reasonably good accord with observation. However, revised calculations by John C Adams in 1853 revealed that Laplace was in error; only about half the value obtained by Dunthorne could be explained in this way (the current result is +6.05 arcsec/cy^2). Subsequently, in 1865, both Charles-Eugene Delaunay and William Ferrel independently recognized that tidal retardation of the Earth's spin (as proposed by Kant) would produce an apparent lunar acceleration as a result of the corresponding increase in the adopted unit of time. At much the same time, Emmanuel Liais correctly proposed that there was both a real retardation of the lunar motion due to the tidal exchange of angular momentum in the Earth–Moon system and an apparent acceleration arising from the increase in the LOD. However, in general astronomers were slow to accept the importance of tidal effects.

In the late 19th century, Simon Newcomb and Friedrich Ginzel embarked on detailed investigations of historical eclipses in attempts to refine the value of the lunar acceleration. Ginzel mainly focused his attention on observations of total solar eclipses, having undertaken extensive searches of European historical sources: both ancient and medieval. By contrast, Newcomb was doubtful of the reliability of early allusions to total solar obscurations. He preferred instead to analyse timed measurements of eclipses of both Sun and Moon. In addition to ancient Greek observations, Newcomb investigated an important series of medieval timings of solar and lunar eclipses recorded by the Cairo astronomer Ibn Yunus.

No significant progress in the analysis of early eclipse observations was achieved until Philip H Cowell in 1905 announced his discovery of a solar acceleration in addition to a lunar acceleration. Although some of the observations on which Cowell's discovery was based were of dubious reliability, he had made a major breakthrough. Cowell suggested that the solar acceleration was purely apparent and arose from a gradual increase in the adopted unit of time: the mean solar day. He further noted that the observed ratio of the lunar and solar accelerations (2.7:1) was much less than the ratio of the mean motions (13.37:1). He correctly explained this discrepancy as due to the gradual retardation of the Moon's orbital motion arising from the reciprocal action of tides. However, the response to Cowell's work by Newcomb and others was far from encouraging.

2: A partial annular solar eclipse at sundown. (Sol Invictus hjp.arnold@btconnect.com)

Between about 1910 and 1920, John K Fotheringham made extensive efforts to determine both the solar and lunar accelerations from a wide variety of ancient observations, mainly from Europe. Fotheringham's final result for the coefficient of t^2 in the lunar and solar longitudes were respectively +10.6 and +1.5 arcsec/cy^2. Willhelm de Sitter in 1927 made a revision of Fotheringham's analysis, without incorporating any new data. His results for the lunar acceleration (c) – with the gravitational component of +6.05 arcsec/cy^2 removed – and the solar acceleration (c') were respectively:

$$c = +5.22 \pm 0.30 \text{ arcsec/cy}^2$$
$$c' = +1.80 \pm 0.16 \text{ arcsec/cy}^2.$$

The former value was to remain definitive for many years. In particular, de Sitter's result for c was used by Jones in 1939 in his far-reaching investigation of telescopically observed fluctuations in the motions of the Moon, Sun and inner planets. The explanation of these fluctuations had long been in doubt but Jones conclusively demonstrated that they were in the ratio of the mean motions. They were thus purely apparent and owed their origin to variations in the Earth's rotation. From the telescopic data which he analysed, Jones also deduced a value for c' of +1.23±0.04 arcsec/cy^2. This was substantially less than the result obtained by De Sitter (+1.80) from ancient observations and closer to Fotheringham's original value (+1.50).

One of the most important consequences of Jones's work was the introduction – for astronomical purposes – of a theoretically invariant time-system known as Ephemeris Time (ET). The standard LOD on this timescale was defined as the average LOD on the UT system between AD 1750 and 1890 (mean epoch 1820). On ET, the Sun has no acceleration, while the lunar acceleration is a linear combination of c and c'. Defining the lunar orbital acceleration ($\dot{n}$) on ET as twice the coefficient of T^2, where T is time in Julian centuries from the epoch 1900.0, and q is the ratio of the lunar and solar mean motions,

$$\dot{n} = 2(c - qc') \text{ arcsec/cy}^2.$$

Inserting $c = +5.22$, $q = 13.37$ and $c' = +1.23$ yields $\dot{n} = -22.44$ arcsec/cy^2.

Use of the above result, which was adopted as an international standard, enabled ET to be determined by monitoring the lunar motion. The difference ET–UT, a measure of the Earth's rotational clock error, became known as ΔT. In recent years, ET has been formally replaced by Terrestrial Time (TT), without significant change.

Principal investigations of historical eclipses in recent decades

After the work of Fotheringham, there was little interest in the direct study of ancient and medieval eclipses for about half a century; it seemed that all of the available records had been thoroughly worked over. Newton (1970, 1972) made an exhaustive investigation of ancient and medieval observations (mainly eclipses) from both Europe and the Arab world, although he added little original data. Newton's main innovation was the use of ET rather than UT in his analyses. He attempted to solve for both $\dot{n}$ and the rotational acceleration of the Earth ($\dot{\omega}$).

Unfortunately, Newton's investigations suffered from two fundamental defects. The two parameters he sought to determine were highly correlated; and he also adopted a somewhat arbitrary weighting scheme in analysing suspected observations of total solar eclipses. Many of the observations he investigated were of doubtful reliability. Hence, despite the low weight he assigned them, they had a disproportionate effect on his solutions. In particular, Newton obtained discordant values for $\dot{n}$ of around –40 arcsec/cy^2. More reliable investigations of ancient eclipses had to await the independent determination of $\dot{n}$.

Improved values for $\dot{n}$ began to be obtained from the mid-1970s. Morrison and Ward (1975), from a discussion of observations of transits of Mercury, determined $\dot{n} = -26 \pm 2$ arcsec/cy^2. Subsequent results were obtained using both lunar laser ranging and studies of the orbits of artificial satellites. Current results from these two methods are in good accord. Using artificial satellite observations, Christodoulidis *et al.* (1988) obtained $\dot{n} = -25.27 \pm 0.61$ arcsec/cy^2, while Williams and Dickey (2003) have lately deduced –25.7 arcsec/cy^2 from lunar laser ranging. On the basis of conservation of angular momentum in the Earth–Moon system, it may be calculated from these results that the rate of increase in the LOD due to tides alone is close to 2.3 ms/cy.

In analysing ancient observations, it has become accepted practice to assume that $\dot{n}$ is accurately known and to solve only for changes in the Earth's spin rate by enumerating the variation in ΔT. Since global sea-level changes have been minimal over the historical period, there are good reasons for assuming that tidal friction – and hence $\dot{n}$ – has remained sensibly constant during that time.

Assuming a fixed value for $\dot{n}$ of –26.0 arcsec/cy^2, Stephenson and Morrison (1984, 1995) investigated a wide variety of eclipse observations. Their data set included many previously well-known reports, especially from medieval Europe. However, numerous hitherto unused observations were also introduced: mainly from ancient Babylon, ancient and medieval China and the medieval Arab world. Stephenson and Morrison's value for the mean rate of increase in the LOD is 1.7 ms/cy – significantly lower than the tidal figure. These authors have also demonstrated the existence of quasi-periodic variations of non-tidal origin with amplitude some 3 ms and periodicity 1500 years or so. Converting to UT, the observed mean rate of increase in the LOD (1.7 ms/cy) is equivalent to a solar acceleration (c') of 1.3 arcsec/cy^2; this is fairly close to Fotheringham's result (1.5 arcsec/cy^2), suggesting that the reanalysis of his data by de Sitter may have contained errors.

Much of the remainder of this lecture is based on the work of Stephenson and Morrison (1995), as enlarged in the monograph by Stephenson (1997).

Historical observations and the determination of ΔT

Experience has shown that of the various types of pre-telescopic observation, only eclipses are of real value in determining variations in the Earth's spin rate. Although occultations of stars by the Moon are extremely important in the telescopic period (i.e. after about AD 1600), few timings of similar events are preserved from the ancient and medieval world. By contrast, many valuable observations of eclipses – both timed and untimed – are extant in the history of certain early cultures: almost exclusively Babylon, China, Europe and the Arab dominions. Ancient and medieval astronomers were in the habit of timing the various phases of eclipses to improve the accuracy of future prediction. Often astrology provided the ultimate impetus, although medieval Arab astronomers sometimes timed lunar eclipses to determine geographic longitude. Historians and annalists (especially in Europe) usually noted eclipses because of their spectacular nature.

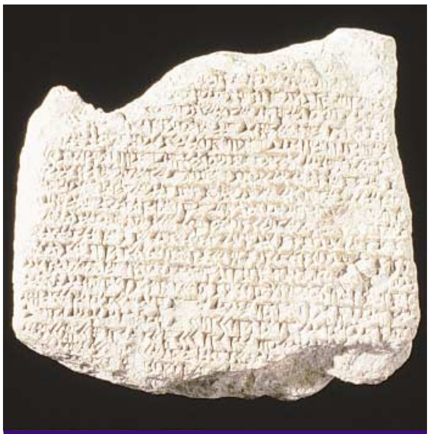
The various early eclipse observations that are preserved form two independent data sets: timed measurements of limb contacts between the Moon and Sun; and untimed descriptions of total and near-total solar eclipses. A further alternative may be provided by untimed observations where the Sun or Moon set while eclipsed. However, these are of relatively low precision; a level horizon is required and the observations may be affected by anomalous refraction. All of the timed observations were made by astronomers. Unfortunately, very few astronomers were favoured with the opportunity to witness a total or near-total eclipse of the Sun. Hence nearly all reports of these events are by chroniclers and these accounts tend to be qualitative rather than quantitative. Nevertheless, the total phase is so well-defined that even a simple description of the complete disappearance of the Sun is usually adequate.

Timings of the various phases of solar or lunar eclipses enable specific values of the parameter ΔT to be determined. Untimed accounts of solar eclipses in which the Sun was either said to disappear completely or was reduced to a slender crescent are also important. Observations of totality provide sharp limits within which the value of ΔT must lie. However, when an eclipse fell a little short of totality a range of ΔT is excluded.

I shall now briefly discuss the various historical sources and the types of observation available. In each case I shall give an example to illustrate the determination of ΔT.

Babylon

A few Babylonian eclipse reports – in edited form – are preserved by Ptolemy in his *Almagest*. These range in date from 721 to 381 BC. However, the main source of astronomical records from this part of the world is the Late Babylonian astronomical texts. These clay tablets, inscribed with a cuneiform syllabic script, contain the records of the official astronomers who observed from the city of Babylon. Dates range mainly from about 700 BC to 50 BC. Of the roughly 2000 surviving texts, many of which are very fragmentary, nearly all are now in the British Museum. Translations of most of the datable texts have been published recently by Abraham J Sachs and Hermann Hunger.

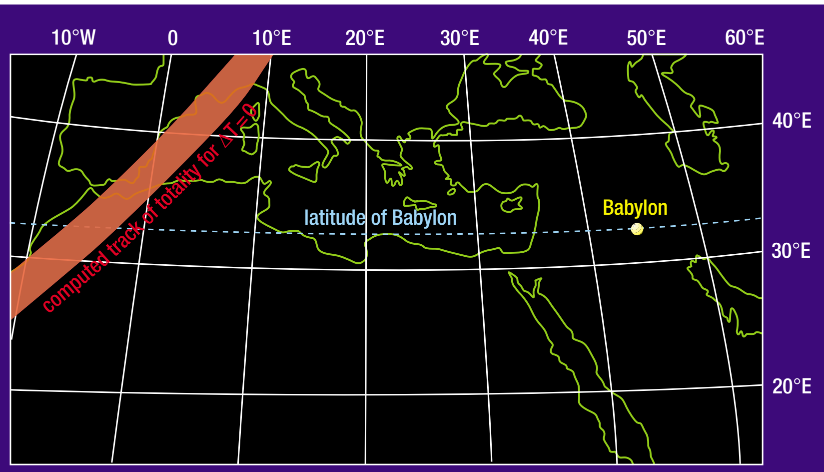


3: Late Babylonian astronomical tablet containing a record of the total solar eclipse of 15 April in 136 BC. See text for translation. (Courtesy: British Museum)

The Babylonian astronomers kept a regular watch for celestial events and both lunar and solar eclipses were frequently recorded. Times of the various phases were usually expressed to the nearest US ("time degree"), a unit equal to 4 minutes. These measurements were probably made with the aid of a clepsydra (water clock). The Babylonians employed a luni-solar calendar, the rules of which are well understood. Convenient tables for converting dates to the Julian calendar have been published. Dates of astronomical events on the Late Babylonian astronomical texts prove to be highly accurate and this is true for the eclipse observations.

Babylonian observations of a solar eclipse in 136 BC are without parallel over the whole of the pre-telescopic period. Not only did the astronomers time its various phases, they also noted that the eclipse was total. Two damaged texts in the British Museum collection provide overlapping details (figure 3). A composite translation is as follows:

"(Year) 175, month XII$_2$. The 29th (day), at 24 time-deg after sunrise, solar eclipse; when it began on the south-west side, in 18 time-deg of daytime it was entirely total; Venus, Mercury and the Normal Stars were visible; Jupiter and Mars, which were in their period of invisibility, were visible in that eclipse. It threw off (the



4: Computed track of totality for the eclipse of 15 April in 136 BC, assuming a fixed length of day ($\Delta T = 0$). This track lies more than 50° to the west of Babylon, where totality was actually observed.

shadow) from south-west to north-east; 35 time-deg (duration) of onset, maximal phase and clearing," (trans. H Hunger).

The year is expressed relative to the Seleucid era (312 BC). The equivalent Julian date – 15 Apr in 136 BC – is precisely correct. Computing the local time of sunrise at Babylon and converting to UT gives 2.53 h. Since 1 time-deg was equal to 4 minutes, the observed UT of the three contacts may be deduced as 4.19 h, 5.39 h and 6.52 h. For comparison, the computed TT of these same phases (obtained using an iterative procedure) are respectively 7.69 h, 8.76 h and 9.93 h. Differencing the appropriate TT and UT values, the corresponding results for ΔT are: 12 600 s (3.50 h), 12 100 s (3.37 h) and 12 250 s (3.41 h).

This eclipse was specifically described as total. However, computations based on the TT timescale indicate only a small partial obscuration of the Sun at Babylon, with the track of totality passing far to the west (see figure 4). Only for ΔT values between 11 200 s (3.11 h) and 12 150 s (3.38 h) would the eclipse be fully total at Babylon. Both the individual values of ΔT and the limits derived from this eclipse are thus remarkably self-consistent. Numerous further timings of both lunar and solar eclipses from Babylon enable the variation of ΔT to be traced with tolerable accuracy between about 700 BC and 50 BC.

China

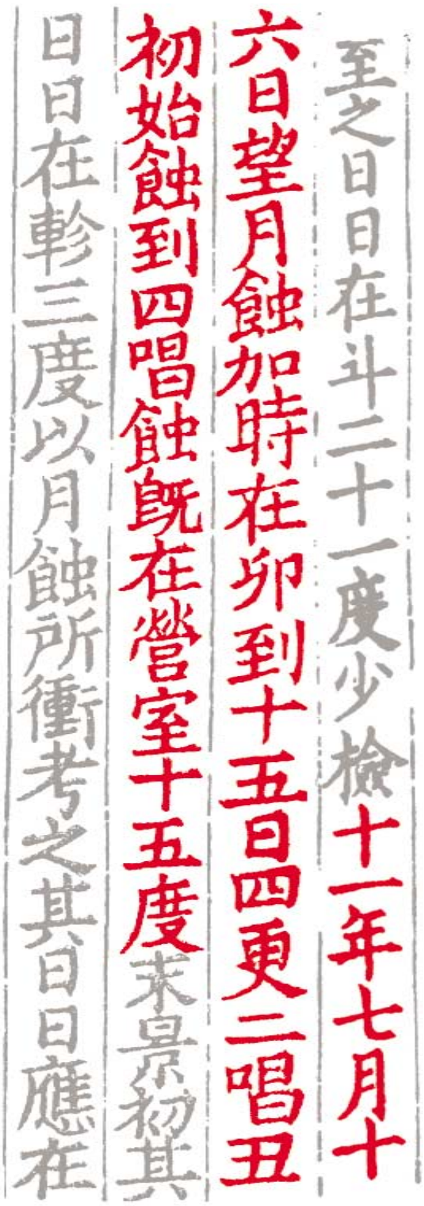
Official astronomers made frequent observations of a wide variety of celestial events, including eclipses, from the Chinese capital. The most prolific sources of astronomical records are the standard histories, most of which contain a special astronomical treatise. A few additional historical sources are also important. Several allusions to eclipses have been found on the oracle bone fragments from the latter half of the second millennium BC. However, dating of these damaged texts is fraught with difficulties; in no case is the year cited, while only a single report even specifies the lunar month. The earliest reliable observations (all of solar eclipses) date from between 720 and 480 BC, although systematic records are only available after about 200 BC. Unlike solar eclipses, little interest in lunar eclipses was shown by Chinese astronomers until the fifth century AD. However, from then on lunar eclipses were noted with a frequency comparable to their solar counterparts.

Careful eclipse timings are only preserved from the fifth century AD onwards. Times, measured with a water clock, were usually quoted to the nearest *ke* ("mark"), equal to 0.24 hours. However, some early lunar eclipse times (from the fifth and sixth centuries) were expressed in terms of the the five *geng* or night watches instead. Each watch was subdivided into five equal parts. Several total solar eclipse reports are also preserved, the earliest in 709 BC; in a few later instances the appearance of stars, darkness, etc is described. The Chinese calendar was luni-solar. A separate 60-day cycle was frequently employed, which greatly simplifies date conversion to the Julian or Gregorian calendar. A variety of conversion tables has been published. The dates of eclipses and other celestial phenomena are recorded with consistently high precision.

The calendar treatise of the *Songshu*, the official history of the former Song dynasty in China, records a lunar eclipse on the night of AD 434 Sep 4/5 (see figure 5). This observation was made by the official astronomers at the capital of Jiankang (i.e.Nanjing):

"Yuanjia reign period, 11th year, 7th month, 16th day, full Moon... The Moon began to be eclipsed at the second call of the 4th watch... The eclipse was total at the fourth call..."

The recorded date, when converted to the Julian calendar, is exactly correct. At this time of year, each night watch was of duration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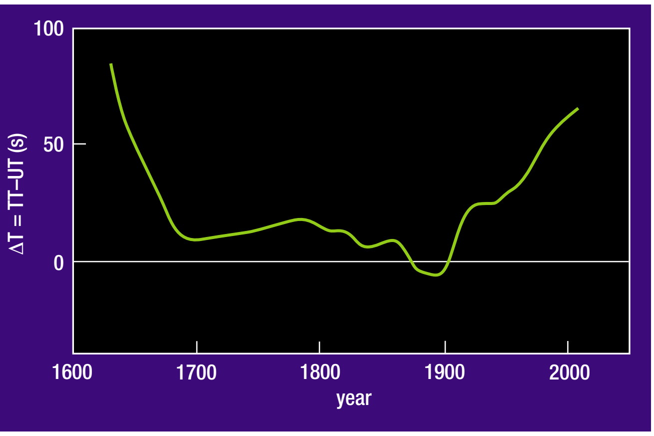
5: Record of the total lunar eclipse of 4/5 September AD 434 (shown highlighted) in the calendar treatise of the *Songshu* – the official history of the Song dynasty.

2.01 h. Hence each of the five "calls", into which a watch was subdivided, was of length 0.40 h. The observed UT values of first and second contact for the eclipse may be deduced as 17.65 h and 18.42 h. Comparing with the computed TT values of respectively 18.14 h and 19.20 h yields results for ΔT of 1750 s (0.49 h) and 2800 s (0.78 h). Because of the relatively low precision of measurement, the accord between these two results may be considered adequate. Chinese eclipse timings from this fairly early period are unfortunately rather rare. However, between about AD 1000 and 1300 they are especially numerous.

Europe

The *Almagest* cites several Greek timings of lunar eclipses between 200 BC and AD 136.



6: The Earth's rotational clock error (ΔT) since around AD 1600, derived mainly from telescopic observations of occultations of stars by the Moon.

These times were typically estimated to the nearest third of an hour. There are also several ancient Greek and Roman allusions to very large solar eclipses (all untimed), but most of these are of dubious reliability. It is usually difficult to establish a reliable date, while the place of observation is often uncertain. Furthermore, in most cases it is not clear whether the Sun was completely obscured. Later, especially between AD 800 and 1500, many European chronicles give vivid descriptions (untimed) of total solar eclipses, frequently describing the complete disappearance of the Sun. Often the precise date on the Julian calendar (relative to the Kalends, Nones or Ides) is cited. Numerous medieval European chronicles have been published in their original language, usually Latin.

Few chronicles give careful descriptions of very large partial solar eclipses. However, under the year AD 1330, the annals of the monastery of Aula Regia (at Zbraslav near Prague) describes such an event in adequate detail. The recorded date (equivalent to 15 July) is one day in error; the actual date was 16 July.

"1330. In this same year on the Ides of July at the 8th hour of the day, the Sun was so greatly obscured that of its great body only a small extremity like a three-night-old Moon was seen."

Although the estimated time is too imprecise to be of value, the fact that this eclipse, which was generally total, was observed to be only partial sets firm limits on the value of ΔT at this date. For the zone of totality to pass either to the west or east of Aula Regia, either $\Delta T < 890$ s or > 1210 s. Intermediate values – which would render the eclipse total at this site – are excluded by the observation.

The Arab world

Many solar and lunar eclipse timings measured by Arab astronomers between about AD 830 and 1020 are accessible. Most of these are to be found in a single manuscript: a treatise by Ibn Yunus, who died in AD 1008. This treatise, entitled *al-Zij al-Kabir al-Hakimi*, is preserved in the library of Leiden University. Times of the various eclipse phases were usually obtained indirectly: by determining the altitude of the Sun, Moon or a selected bright star – usually to the nearest degree – with an astrolabe and afterwards reducing the measurement to local time. Several medieval Arab chroniclers also record total solar eclipses in considerable detail, although without accurate times.

The Islamic calendar is lunar; every year contains 12 lunar months so that the start of the year regresses through the seasons in a period of some 33 years. Precise date conversion is assisted by the frequent use of weekdays. Conversion tables are available, although a simple algorithm can be used instead. Eclipse dates in both astronomical treatises and chronicles are usually accurate.

As an example, I have selected a timed observation recorded by Ibn Yunus at Cairo on a date equivalent to AD 979 Nov 6/7:

"This lunar eclipse was in the month of Rabi 'al-Akhir in the year 369, on the night when the morning was Friday the 13th of the month... A group of scholars gathered to observe this eclipse... The altitude of the Moon when they perceived the eclipse was 64 $^1/_2$ deg in the east. The altitude when its clearance completed was 65 deg in the west."

It may be calculated that at Cairo the Moon would reach an altitude of 64.5° in the east at a UT of 20.08 h; this was the observed time of first contact. Similarly, fourth contact was observed at a UT of 23.30 h. Comparing these times with the computed TT values of respectively 20.61 h and 23.67 h gives results for ΔT of 1900 s and 1300 s. Since the altitude of the Moon would change by 1° in about 300 s, these two results are in adequate accord.

ΔT variation

Figure 6 shows the marked variations in ΔT that have occurred since soon after AD 1600. Telescopic occultations of stars by the Moon provide the data for most of this period. Over the whole of the *pre-telescopic* period, the precision of observation is quite insufficient to reveal any short-term variations, such as those displayed in figure 6. Instead, the eclipse data provide important evidence of long-term trends over more than two millennia.

Figure 7 is a plot of the individual ΔT values obtained from timed eclipse observations for the interval from 700 BC to AD 1600. AD and BC dates are denoted by positive and negative numbers respectively. In the case of BC years, the slight discrepancy introduced by the absence of a year zero is ignored (by retrospective convention, 1 BC was followed by AD 1).

Figure 8 shows the ΔT limits defined by each of the untimed solar eclipse data (total and near-total) over the same period as covered by figure 7. Only results from the most reliable observations are displayed. A single vertical bar denotes the ΔT range defined by an observation of a total eclipse; the actual value of ΔT at that date has an equal probability of lying anywhere within this range. In the case of an observation for which totality is expressly denied, there are two possible solutions, separated by an exclusion zone; these are denoted by a pair of vertical lines with arrowheads. Redundant arrows are not shown in figure 8.

Two curves are delineated on both figures 7 and 8. The dotted curve (shown in blue) represents the mean tidal parabola of equation:

$$\Delta T = 42\tau^2$$

Here τ is measured in Julian centuries from AD 1820, an epoch determined by the definition of ET. The solid curve (shown in green) represents a cubic spline fit to the data. This curve satisfies *all* of the constraints imposed by the untimed observations. By comparison, the equation of the parabola of best fit (not shown) is $31\tau^2$. However, this parabola fails to satisfy several key observations. On the scale of the diagrams the ΔT variations during the telescopic period would be of negligible amplitude.

Changes in the length of the day

Observed variations in the LOD from 700 BC to the present are displayed in figure 9. These are expressed relative to the standard LOD of 86 400 SI seconds. In this diagram, the dashed straight line (shown in blue) denotes the tidal component: a steady increase in the LOD of approximately 2.3 ms/cy. The dotted line (shown in orange) indicates the actual long-term trend over the historical period: an average increase in the LOD of 1.7 ms/cy. Hence in opposition to the main tidal retardation of the Earth's spin there is a small but significant non-tidal component causing a secular decrease in the LOD at a mean rate of 0.6 ms/cy. This diminution in the LOD may be largely due to post-glacial isostatic compensation; observation of near-Earth satellites imply a decrease in the LOD due to this mechanism of about 0.45 ms/cy (Cheng *et al.* 1989).

However, the non-tidal history of the Earth's rotation may be more complex. For the pre-telescopic period, the solid curve in figure 9 (shown in green) is derived by taking the first derivative along the cubic splines shown in figures 7 and 8. The decade fluctuations observed since soon after the introduction of the telescope are also shown for comparison. These largely owe their origin to core–mantle coupling. Fluctuations on a similar scale have probably occurred throughout the pre-telescopic period, but no more than the envelope can be detected. Although the precise form of the long-term variations as revealed by ancient and medieval observations is somewhat uncertain, the evidence suggests oscillations about the mean of amplitude up to 5 ms. In addition to core–mantle coupling, small global changes in sea-level linked with minor climatic variations may be significant; however, it would be a complex task to quantify the effect of such changes.

Conclusion

Studies in the Earth's rotation over the millennial timescale have made considerable progress in recent years. However, in order to trace long-term variations in the length of the day with greater accuracy, more historical observations are needed. Reliable data would be particularly valuable in the most ancient period – before 700 BC – and also for a few centuries on either side of AD 500. The prospects of obtaining such observations are difficult to assess; the cooperation of historians would be much appreciated! From the geophysical point of view, although the early observations clearly reveal long-term variations in the Earth's spin rate which are of non-tidal origin, the relative contributions from individual mechanisms are still not well-determined. In particular, the effect of global sea-level changes of climatic origin may well be significant and further studies would be welcomed. ●

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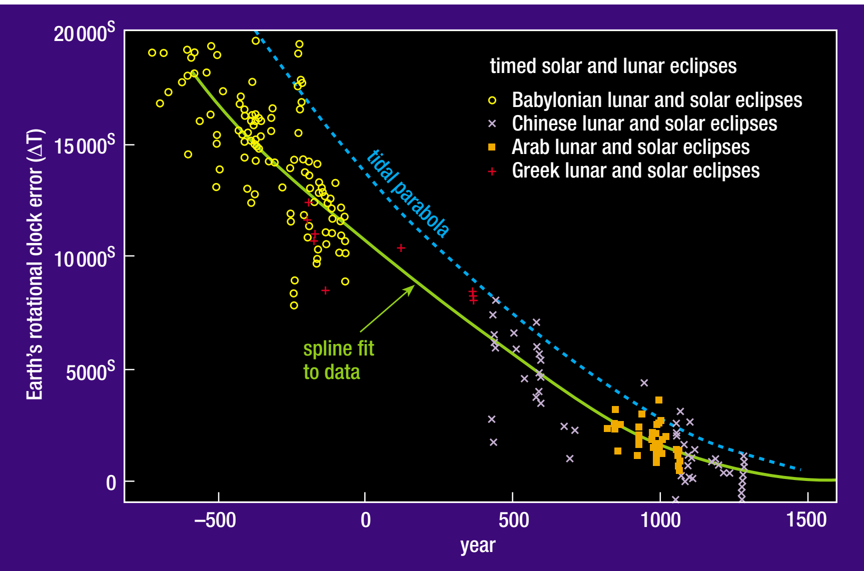
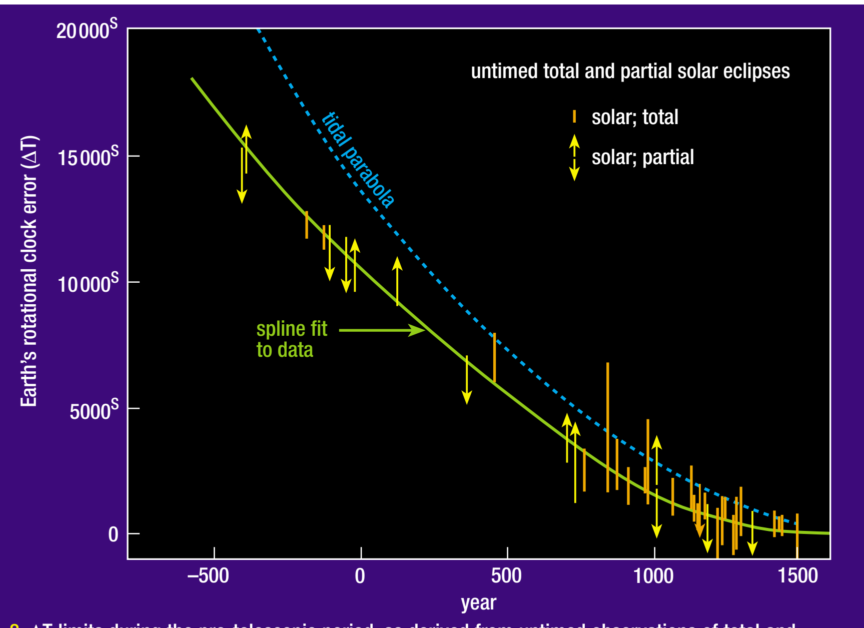
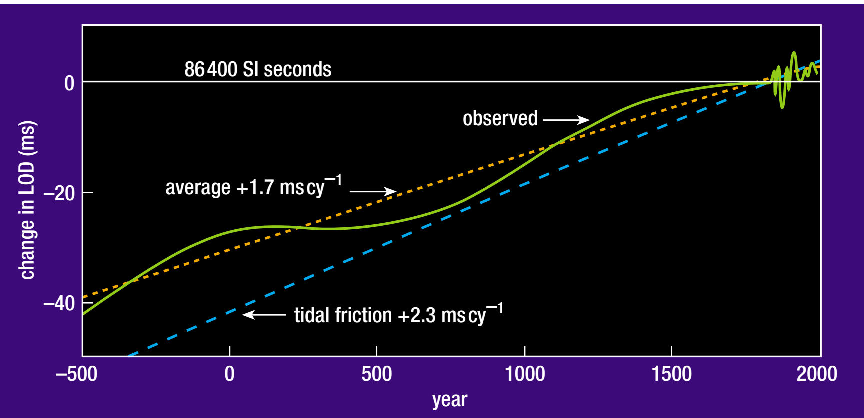


7: ΔT values during the pre-telescopic period, as derived from timings of lunar and solar eclipses. Also shown are the tidal parabola and the cubic spline fit to the data, as constrained by untimed observations (see figure 8).



8: ΔT limits during the pre-telescopic period, as derived from untimed observations of total and near-total solar eclipses. Also shown are the tidal parabola and the cubic spline fit (see also figure 7).



9: Observed fluctuations in the length of day since 700 BC with the long-term mean and tidal term for comparison. Fluctuations of similar amplitude and periodicity to those during the telescopic period probably took place throughout ancient and medieval times, but only the envelope is detectable.