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Causes and cures of the $O-C$ diagram
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Historical Eclipses

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Abstract. Analysis of ancient and medieval observations of solar and lunar eclipses from between 700 BC and AD 1600 provides an intriguing illustration of long-term $O-C$ investigation. These measurements are from several different eras and cultures: principally ancient Babylon; ancient and medieval China; medieval Europe; and the medieval Arab world. Such diverse observations have proved of great value in studying long-term changes in the Earth's rate of rotation – as produced by tides and other mechanisms.

1. Introduction

More than 300 unaided-eye measurements of eclipse times by astronomers are preserved from between 700 BC and AD 1600. These measurements are from several different eras and cultures: principally ancient Babylon; ancient and medieval China; medieval Europe; and the medieval Arab world. Such diverse observations have proved of great value in studying long-term changes in the Earth's rate of rotation – as produced by tides and other mechanisms. Before discussing the analysis of these observations, it is appropriate to begin with some background information, particularly in relation to time systems.

2. Time Systems

For the purposes of the present paper, we need to consider three separate time-systems: Local Apparent Time, Universal Time, and Terrestrial Time.

2.1. Local Apparent Time

Since antiquity the diurnal rotation of the Earth has provided the time standard for everyday practical purposes. Throughout the period covered by the eclipse observations under discussion, the length of the *apparent solar day* (the interval between two successive transits of the Sun across an observer's meridian) was regarded as uniform. This definition, of course, applied whether the Earth was considered to be stationary (with the Sun and celestial vault imagined to be revolving around it), or whether – following Copernicus – the Earth itself was recognised as rotating. The length of the apparent solar day can be up to 30 sec longer or shorter than the standard of 86400 SI sec. This does not represent an actual change in the speed of the Earth's axial rotation, but an apparent change in the frame of reference resulting from the ellipticity of the Earth's orbit and the tilt of the terrestrial equatorial plane to the plane of the orbit. Although around AD 150 Ptolemy estimated the cumulative effect of these discrepancies (known as the equation of time), changes in the length of the apparent solar day remained undetectable until the late 17th century.

All of the eclipse measurements made by naked-eye astronomers were expressed in some form of local apparent time. Babylonian astronomers recorded time intervals in 'time-degrees' (each equal to 4 min) relative to sunrise or sunset; whereas their Chinese counterparts centred the first of twelve equal double hours on local midnight. Medieval Arab and European astronomers both measured time indirectly by determining the altitude of the Sun, Moon or a selected bright star. These various measurements can be readily reduced to a standardised Local Apparent Time (LT) – a 24 hour system in which the Sun is due south precisely at 12 noon.

2.2. Universal Time

During the 18th century improvements in the design and accuracy of mechanical clocks led to the gradual introduction of *mean* solar time. On this system, the effects of variations in the length of the apparent solar day were averaged out. Mean solar time was disseminated over much of the inhabited area of the terrestrial globe during the 19th century. Initially, a variety of reference meridians were utilised. However, in 1884 the meridian of Greenwich was adopted as the international standard, and with it Greenwich Mean Time (GMT). GMT was subsequently replaced – without significant change in definition – by Universal Time (UT). Although astronomers now adopt three separate forms of UT (UT0, UT1 and UTC), they differ from one another by no more than about 1 sec. Early measurements quoted in LT can be converted directly to UT by adjusting for geographic longitude and the equation of time.

2.3. Terrestrial Time

During the 19th and early 20th centuries, the question of whether the Earth's rate of spin relative to a fixed frame of reference was variable was often considered. Convincing evidence was not obtained until 1939 when Harold Spencer Jones was able to demonstrate that fluctuations which had been observed over the previous two or three centuries in the motions of the Sun, Moon and planets were accurately in the ratio of the mean angular speeds of these celestial bodies. The observed fluctuations were thus purely apparent and owed their origin to variations in the Earth's rate of rotation and its time-frame, UT. It was now clearly recognised that UT was not an ideal time frame (despite its obvious practical advantages).

The concept of a theoretically uniform time-system based on the celestial motion of the Sun, Moon and planets, rather than the terrestrial spin, was considered in detail by Gerald Clemence in 1948. Only four years later, the new time system, named Ephemeris Time (ET), was formally adopted at a meeting of the International Astronomical Union. More recently, ET has been redefined as Terrestrial Time (TT).

Although ET was defined in terms of the celestial motion of the Sun, in practice time on this system was measured by the motion of the Moon. The Moon is relatively easy to observe and its angular speed is much more rapid than that of the Sun. Hence from the investigation by Spencer Jones (1939), Clemence (1948) developed the necessary relationships to enable ET to be measured directly from lunar observations. Although ET – and its modern equivalent TT – is a theoretically uniform time-system, the motion of the Moon is far from regular – largely due to its elliptical orbit around the Earth and the strong perturbations of the Moon's motion by the Sun.

Even the *mean* lunar motion, with the irregularities averaged out, is not uniform. The reciprocal action of the tides which the Moon raises on the Earth causes a gradual acceleration (negative) of the lunar motion. When ET was first introduced in 1952, the value for this acceleration (denoted by $\dot{n}$) was taken as -22.44 arcsec $\mathrm{c}^{-1}\mathrm{y}^{-2}$ (arcsec per century squared), following the investigation by Spencer Jones. However, recent measurements based on lunar laser ranging (Williams et al., 2003; Chapront et al., 2002) yield results for $\dot{n}$ very close to -26.0 arcsec $\mathrm{c}^{-1}\mathrm{y}^{-2}$. Using this value for $\dot{n}$, TT can be projected into the past or into the future with considerable confidence. On the TT system, the standard length of day is 86400 SI seconds, which for historical reasons is the average length of the mean solar day over the period from AD 1750 to 1892 (mean epoch close to 1820).

3. The $C - O$ Parameter, ΔT

It is now known that several separate mechanisms produce changes in the Earth's spin. These operate on a wide variety of time-scales. Annual and seasonal fluctuations in the spin are largely caused by changing trade wind patterns. Decade variations – of typical length some 30 years – are probably mainly due to magnetic interaction between the fluid core of the Earth and the lower mantle. The main cause of long-term changes in the spin (on the centennial to millennial time-scale) is lunar and solar tidal friction. However, the ongoing rise of land which suffered temporary glacial loading during the last ice-age has also a significant effect.

Actual changes in the spin, even over the entire historical period, amount to only a small fraction of a second. The *cumulative* effect of these variations – the Earth's rotational clock error – is termed ΔT. At any selected epoch, ΔT can be deduced by comparing observed astronomical events such as eclipses, measured in UT, with the corresponding value of TT calculated from orbital theory. Although since AD 1600 ΔT has not exceeded 100 sec, in ancient times it was very large, amounting to several hours. Anticipating the results of Table 1, in AD 1000 ΔT was some 1600 sec (0.44 h), but in 700 BC it was as much as 21000 sec (5.8 hours). These figures clearly illustrate why even fairly primitive measurements of eclipse times can still prove important.

Since 1955, ΔT has been determined with very high precision (small fractions of a second). In that year, the first atomic (caesium) clock was introduced. This device had a remarkable stability: 1 part in 10^{13}. Its development led to the introduction of a further time-system: International Atomic Time (TAI).

Since 1955, ΔT has been derived by direct comparison between TAI and UT1 (a measure of UT freed from polar motion).

The main concern of this paper is to discuss the determination of ΔT on the decade to millennial time-scales. In order to derive ΔT prior to 1955, it is necessary to make use of astronomical observations: occultations of stars by the Moon are by far the best source of data in the telescopic period, whereas in more ancient times eclipses prove to be of most value.

4. Determination of ΔT between AD 1620 and 1955

Beginning around AD 1620, astronomers frequently timed occultations of stars by the Moon. Modern studies of these observations have compared the measured timings, reduced to UT, with their computed equivalents on the TT system. Each individual estimate of the difference Terrestrial Time *minus* Universal Time represents a determination of $TT - UT = C - O$. Over the interval from AD 1860 to 1955, some 40,000 individual occultation timings are available (Morrison et al., 1981). Throughout this period, ΔT is known to better than 1 sec (Jordi et al., 1994).

For a detailed investigation of the data from AD 1620 to 1860, see Stephenson & Morrison (1984). Between AD 1680 and 1860 around 1200 occultation observations are preserved. Combining these various measurements enables ΔT to be derived throughout this interval with a standard error (σ) of between 1 and 5 sec. Unfortunately very few occultation measurements are preserved in the earliest telescopic period – that is, before AD 1680. In order to make reasonable solutions for ΔT during the interval from AD 1620 to 1680, it is necessary to supplement the occultation observations with solar-eclipse timings. Stellar occultations are effectively instantaneous events, but resolution of solar eclipse contacts with a primitive telescope would be rather poor. As a result of these difficulties, and the low accuracy of early clocks, the uncertainity in ΔT at this period is relatively large: between 10 and 20 sec.

The scatter of individual estimates of ΔT between AD 1620 and 1860 is shown in Figs. 1a and 1b, which are taken from Figs. 2a and 2b of Stephenson & Morrison (1984). The scale of Fig. 1b is enlarged to reveal the fluctuations after about AD 1800 in more detail.

In Fig. 2 is depicted the measured ΔT curve since AD 1620 (solid line), together with a parabola representing the long-term mean as derived from ancient and medieval eclipse observations. This diagram is taken from Morrison & Stephenson (2004). The parabola has the equation $\Delta T = -20 + 32t^2$ sec, where t is time in Julian centuries measured from the reference epoch AD 1820. Clearly the actual ΔT curve shows considerable departures from a parabola, implying marked variations in the Earth's rate of spin on the decade time-scale. The principal cause of these variations is almost certainly core-mantle coupling. Figure 2 also shows the limits on ΔT in the year AD 1567, as deduced from a remarkable observation of a marginally total solar eclipse in that year by the Jesuit astronomer Christopher Clavius. This single untimed observation enables the ΔT curve to be traced back fairly confidently to around AD 1500 (Stephenson et al., 1997).

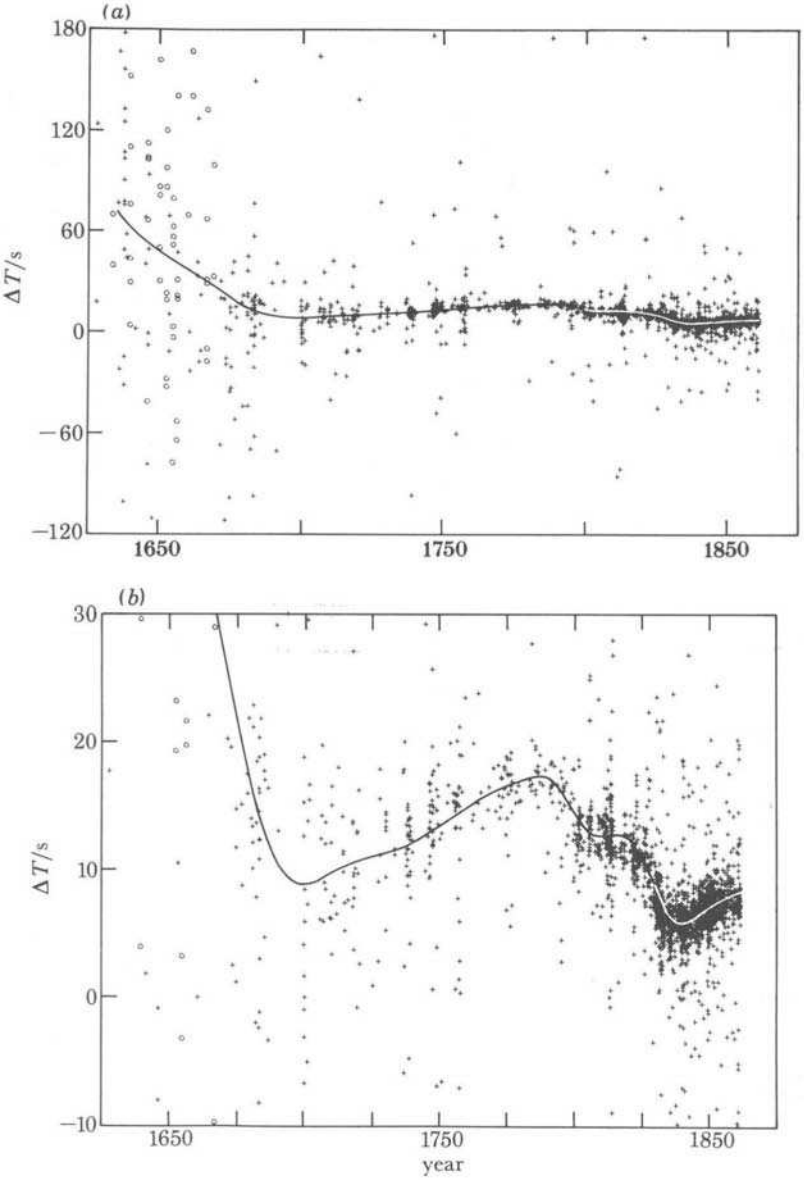

Figure 1. Values of ΔT as derived from individual timings of occultations of stars by the Moon (crosses) and solar eclipse contacts (open circles). Fig. 1(b). As in (a) but on an enlarged scale.

5. Determination of ΔT in the Ancient and Medieval Period using Timed Measurements

In the pre-telescopic era, there are scarcely any viable timings of occultations of stars by the Moon. Hence in order to investigate ΔT at this remote period, it is necessary to concentrate on reports of solar and lunar eclipses. Because of their spectacular nature, eclipses were extensively observed in much of the ancient

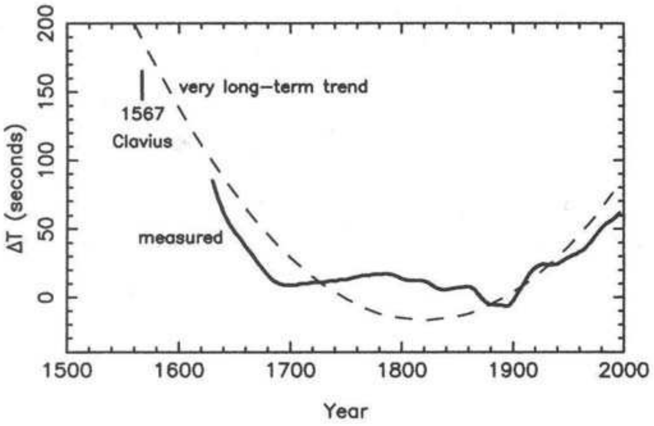

Figure 2. ΔT curve as derived from telescopic measurements after AD 1600. The narrow ΔT range obtained from an unusual solar eclipse observation by Clavius in AD 1567 is also depicted. The very long-term trend is obtained from ancient and medieval eclipse observations.

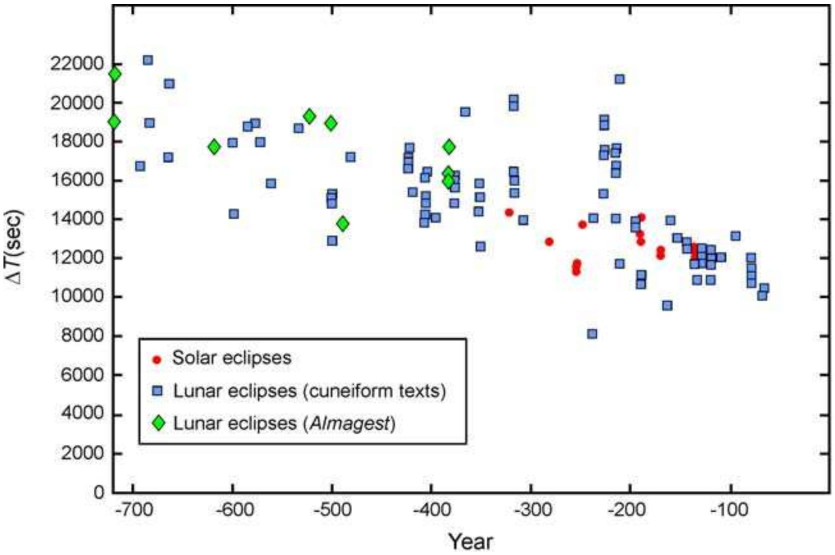

Figure 3. ΔT values between about 700 and 100 BC obtained from timed Babylonian observations of solar and lunar eclipses – mainly from cuneiform texts, but with additional lunar eclipses from the *Almagest.*

and medieval world. Useful eclipse observations fall into two main categories: timings of the various phases of both solar and lunar eclipses by astronomers (the subject of this Section) and untimed reports of total or near-total solar eclipses by historians, chroniclers, etc (to be discussed briefly in Section 6). The investigation of the whole suite of timed observations (some 300 in all) is a fascinating illustration of $C - O$ determination over more than 2,000 years. For fuller details, see Stephenson (1997).

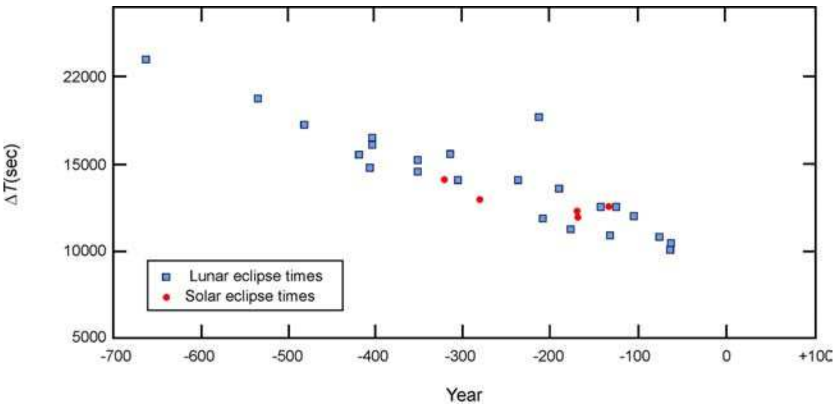

Figure 4. ΔT values derived from a restricted set of Babylonian eclipse timings for which the measured interval was short (less than 100 min).

For both timed and untimed eclipses, the earliest reliable observations date from around 700 BC. Before discussing the analysis of this material, the constancy of the lunar acceleration $\dot{n}$ down the intervening centuries needs to be considered. Global studies indicate that mean sea-level has not changed significantly over the past three millennia (see papers in Sabadini et al. 1991). Hence it may be reasonably inferred that lunar and solar tidal friction has remained sensibly constant during this interval. Computations based on a fixed value for $\dot{n}$ of -26.0 arcsec $\mathrm{c}^{-1}\mathrm{y}^{-2}$ thus enable TT to be accurately defined over the entire historical period.

In the following subsections, examples will be given of the derivation of $\Delta T = C - O$ at selected epochs by comparing the results of observation and computation. Eclipse timings measured by a variety of early astronomers will first be converted to UT and then compared with the computed value of TT.

5.1. Late Babylonian Astronomical Texts

The oldest set of preserved timings of both solar and lunar eclipses is from Babylon. These measurements are recorded, along with many other astronomical observations, on clay tablets which are now largely in the British Museum. This huge archive contains around 3,000 texts, nearly all of which, unfortunately, are in a fragmentary condition. It is estimated that less than 10 per cent of the original material is preserved today. The extant tablets, which are inscribed with a cuneiform script, came to light during the 1870s and 1880s when the site of Babylon was being pillaged by local inhabitants for re-usable bricks; very few texts were ever purposely excavated. The recorded observations range in date from about 700 BC to 50 BC. For a detailed translation of these Late Babylonian Astronomical Texts (LBAT), see Sachs & Hunger (1988, 1999, 1996, 2001, 2004).

By chance, many more lunar eclipses are recorded on the extant LBAT than their solar counterparts. The date range for viable Babylonian lunar eclipse observations is from 695 to 47 BC, compared with 369 to 89 BC for solar obscurations. Presumably the earlier reports of solar eclipses are all lost without trace. Ptolemy in his *Almagest* records a few additional eclipses of the Moon

– ranging in date from 721 to 381 BC. However, he makes no mention of any Babylonian solar eclipse reports.

Over the long interval covered by the preserved texts, the Babylonian astronomers systematically measured the times of the various phases of both solar and lunar eclipses. Probably a water-clock was used, although the surviving LBAT give no information on the timing device. The fundamental unit of time was the *us*, best translated as 'time-degree', but usually abbreviated simply to degree. This time unit is precisely equal to 4 minutes, as was confirmed by Stephenson & Fatoohi (1993) from an investigation of the recorded durations of lunar eclipses recorded on the LBAT. The very earliest measurements were largely expressed to only the nearest 5 or even 10 *us*, but after about 550 BC all eclipse timings were estimated to the nearest *us*.

The time of onset of an eclipse was systematically measured relative to sunrise or sunset – depending on which was nearer. In addition, the durations of the various phases (e.g. totality) were usually quoted. The site of Babylon (32.33 deg N, 44.42 deg E) lies in a remarkably level plain. Hence it is a straightforward matter for us to derive the local time of sunrise or sunset on any selected date and thus reduce the various measured times to UT. We give below two examples showing the analysis of Babylonian eclipse observations in order to deduce ΔT: one for a lunar eclipse in 215 BC and the other for a solar eclipse in 136 BC. Translations are based on Sachs & Hunger (1996, 2004), with minor variations. For the first of these events, the sign for the day of the lunar month is damaged. However, restoration can be made with considerable confidence since on the Babylonian calendar eclipses of the Moon invariably occurred on either the 13th, 14th or (rarely) 15th day of the month.

> Year 97 (Seleucid), month IX, night of the 1[3th](?)... lunar eclipse, on the east side; when it began, in 21 deg of night all of it became covered; 16 deg of night (duration) of totality; when it began to clear, it cleared in 19 deg of night from east and north to west(?); 56 deg onset, totality [and clear]ing; it began at one-half *beru* (i.e. 15 deg) after sunset...

The Babylonians adopted a luni-solar calendar, the operational rules of which are well understood for dates as far back as around 650 BC. Most years had only twelve lunar months (totalling about 354 days), but every two or three years a 13th month was intercalated in order to keep the calendar roughly in step with the seasons. Intercalary months followed either the 6th or 12th regular months. Years were numbered either from the start of a king's reign, or (from 311 BC) the Seleucid Era. For some of the texts, as above, the date is at least partially preserved. Many other dates can be derived indirectly. For instance, several major tablets list series of lunar eclipse reports at 18-year intervals; although these texts are extensively damaged, the names of kings are occasionally mentioned, allowing the whole chronological scheme to be inferred (see Huber & De Meis, 2004).

Using the detailed calendar conversion Tables of Parker & Dubberstein (1956), the Seleucid year 97 is equivalent to 215 – 214 BC. Reading the 13th day of the lunar month in the above text, the Julian date of the eclipse is equivalent to the night of Dec 25/26 in 215 BC. This is in precise accord with the computed date of the eclipse. On this occasion, sunset would have occurred at a local apparent time of 16.99 h; adjusting for the longitude of Babylon and the equation of time, the UT of sunset may be readily deduced as 14.10 h. The eclipse began at 15 deg (= 60 min) after sunset and became total 21 deg (= 84 min) later; totality ended after a further 19 deg (= 76 min), and the eclipse ended 56 deg (= 224 min) after it began. Hence from the various observations, the UT of first contact, start of totality, end of totality and last contact occurred respectively at 15.10 h, 16.50 h, 17.57 h, and 18.83 h. Comparing with the corresponding computed TT values of 20.04 h, 21.09 h, 22.47 h and 23.52 h, leads to individual results for ΔT of 17750 sec (4.93 h), 16500 sec (4.58 h), 17650 sec (4.90 h) and 16850 sec (4.68 h). These results are in fair, but not good accord, bearing in mind that the various times were all quoted to the nearest 4 min (= 0.07 h).

Two separate Babylonian texts record observations of a total eclipse of the Sun occurring in 136 BC. These records may be translated as follows:

> (i) Year 175 (Seleucid), month XII_2, (day) 29, solar eclipse. When it began on the SW side, in 18 deg of day in the morning it became completely total (?). (It began) at 24 deg after sunrise.
>
> (ii) Year 175 (Seleucid), [King] Arsaces [month XII_2], (day) 29, at 24 deg after sunrise, solar eclipse. When it began on the SW side [Ven]us, Mercury, and the Normal Stars were visible; Jupiter and Mars, which were in their period of invisibility, were visible in its eclipse... 35 deg onset, maximal phase and clearing...

In the above translations, month XII_2 identifies the intercalary month in that year. The date of this eclipse corresponds to Apr 15 in 136 BC (Julian calendar) – a date which agrees precisely with modern computation. The eclipse was observed to begin 24 deg (= 96 min) after sunrise, reaching totality 18 deg (= 72 min) later and ending 35 deg (= 140 min) after it began. On this occasion, sunrise would have occurred at a local apparent time of 5.56 h (UT = 2.59 h). Hence the UT of first contact, totality and last contact were respectively at 4.19 h, 5.39 h and 6.52 h. Deducting these from the computed TT values for these phases of 7.69 h, 8.76 h and 9.93 h leads to separate results for ΔT of 12600 sec (3.50 h), 12100 sec (3.36 h) and 12250 sec (3.40 h). All three results are mutually self-consistent.

Figure 3 displays the various ΔT results obtained from about 100 Babylonian timings of both solar and lunar eclipses (including both 215 BC and 136 BC). (N.B. Figs. 3–6 and Fig. 8 are based on diagrams by Stephenson, 1997). We estimate the standard deviation (s.d.) to be about 30 min, which compares unfavourably with the typical unit of measurement of 4 min. Presumably the main source of error lay in the operation of the clocks, which were used to measure time intervals of up to about 6 hours, relative to sunrise or sunset. It seems likely that using primitive timing devices, clock drift would be substantial over even a few hours. Supporting evidence for this conclusion comes from our selection of a restricted set of data: eclipses which occurred within 25 deg (100 min) of sunrise or sunset: see Fig. 4. In this case the s.d. is reduced to 13 min.

5.2. Chinese Histories

Prior to about AD 1600, virtually all of the original Chinese manuscripts recording eclipses and other celestial phenomena have been lost. In general, only summaries now exist, often with the loss of key information. The bulk of the *extant* material is to be found in the astronomical and calendrical treatises of the official Chinese dynastic histories. These have been reprinted many times. A further important source of data is the *Wenxian Tongkao*, an historical compendium dating from around AD 1300.

Before AD 400, preserved Chinese eclipse timings are rare and very crude. However, beginning with a lunar eclipse observation in AD 434, the precision of extant measurements reaches a tolerable level of accuracy. These early observations were timed to the nearest fifth of a night watch. Between dusk and dawn there were five equal watches (*geng*) and each watch was divided into five 'calls' (*chang*), named after the periodic calls of the night watchmen. The average length of a *chang* was thus rather less than half an hour.

Commencing in AD 585, we find the first reasonably precise solar eclipse timings from China. These are quoted to the nearest 'mark' (*ke*), a unit equal to 1/100 of a full day and night and thus 14.4 min. Preserved lunar and solar eclipse timings are fairly infrequent until around AD 750 and almost non-existent between this date and AD 1050. However, from then until AD 1280 they are fairly numerous. At this later period, both lunar and solar eclipses were timed to the nearest *ke*; the night watches were only occasionally used. After AD 1280, no further Chinese eclipse timings are preserved until as late as AD 1572. Analysis of these measurements (made between 1572 and 1617) reveals a very large scatter, with a s.d. approaching one hour (Steele, 2000). These relatively recent observations are thus valueless for the determination of ΔT, which is known to much better accuracy from European observations (see Fig. 2).

Below we cite two examples of Chinese records, both from dynastic histories: a lunar eclipse seen in AD 434 and a solar eclipse in AD 1068. We begin with the observation in AD 434:

> Yuanjia reign period, 11th year, month VII, day 16, full Moon. The Moon was eclipsed. The calculated time was the (double) hour of *mao* (i.e. 5 – 7 a.m.). The Moon (actually) began to be observed at the second call of the fourth watch, in the initial half of the hour of *chou* (i.e. 1 – 2 a.m.). The eclipse was total at the fourth call.

Almost throughout their recorded history, the Chinese numbered years from the start of each reign or subdivision of a reign. As in the case of the Babylonians, most years contained twelve months; occasional intercalation of a 13th month ensured that the calendar kept pace with the seasons. Conversion of Chinese dates to the western calendar presents few problems; chronological tables are readily available (e.g. Hsueh & Ou-yang, 1956).

The above observation was in all probability made by the court astronomers at the then capital city of Jiankang, currently known as Nanjing (32.03 deg N, 118.78 deg E). Comparing the astronomers' predicted and observed times, it is evident that their eclipse predictions – based by fitting numerical cycles to series of past observations – was at a low level. (Not until much later, around AD 1000, were substantial improvements made in the prediction of eclipses). From the recorded times expressed relative to the night watches in the above example, the apparent local time of the start of the eclipse may be deduced as 1.65 h on Sep 5; this is equivalent to a UT of 17.65 h on Sep 4. Totality was observed to begin 0.77 h later, or at 18.42 h UT. The corresponding computed TT values were respectively 18.14 h and 19.20 h, leading to results for ΔT of 1750 and 2800 sec. Such a marked disparity between the two separate results is not unexpected since the times were only quoted to the nearest half hour or so. The report of the solar eclipse of AD 1068 may be translated as follows:

> Xining reign period, first year, month I, day *jiaxi* [11], the first day of the month. The Sun was eclipsed. According to the astronomers, on this day at 8 marks in the hour of *si*, the Sun was seen to diminish; the loss began on the south-west side. After 5 marks in the hour of *wu*, the eclipse reached six divisions (*fen*). Not until 3 marks in the hour of *wei* was it restored to roundness.

The date corresponds to AD 1068 Feb 6. In addition to the day of the lunar month, the above record quotes the day of the sexagenary cycle: *jiaxi* was the 11th day of this cycle. Probably introduced during the Shang dynasty (ca 1500 to 1050 BC), this cycle – independent of any astronomical parameter – has run continuously until modern times.

The Chinese capital at this period was Bian, the present Kaifeng (lat = 34.78 deg N, 144.33 deg E). The local apparent times of beginning, maximum and end may be deduced as 10.96 h, 12.44 h and 13.84 h. Allowing for for the longitude of Bian and the equation of time, the equivalent UT values are: 3.60 h, 5.07 h and 6.48 h. Subtracting these from the computed TT figures of 4.05 h, 5.40 h and 6.71 h leads to results for ΔT of respectively 1600, 1200 and 850 sec. The mutual accord is quite good, bearing in mind that the unit of time was equal to about 900 sec.

In Figs. 5 and 6 are shown the individual ΔT results obtained from more than 100 Chinese timings of both solar and lunar eclipses (including the observations made in AD 434 and 1068). Figure 5 covers the period from AD 400 to 750, and Fig. 6 from AD 1000 to 1300. The scatter among the few results in the earlier period is very large. However, during the later interval errors are much smaller (s.d. = 13 min).

5.3. Ancient Greek Records

Claudius Ptolemy of Alexandria, in his *Mathematike Syntaxis* or *Almagest*, records a number of lunar eclipse timings made by Greek astronomers between 201 BC and AD 145. In addition, a single Greek report, containing the measured times of a solar eclipse in AD 364 has survived. Theon of Alexandria made some remarkably self-consistent timings of the solar eclipse which occurred in that year. Furthermore, Theon's description followed Ptolemy's style in quoting both the date and the times of the various phases:

> The exact ecliptic conjunction... took place according to the Egyptian calendar in the 1112th year from the reign of Nabonassar... on the 22nd of (the month) Payni... We observed with the greatest certainty the time of the beginning of contact, reckoned by civil and apparent time, as $2\frac{5}{6}$ equinoctial hours after midday, and the time of the middle of the eclipse as $3\frac{4}{5}$ hours, and the time of complete restoration as $4\frac{1}{2}$ hours after the said midday.

On the Julian calendar, the recorded date is equivalent to AD 364 Jun 16. The latitude and longitude of Alexandria are respectively 31.22 deg N, 29.92 deg E. Reducing Theon's measured times gives UT values of 12.79 h, 13.76 h and 14.46 h for the observed beginning, maximal phase and end of the eclipse. Deducting from the computed TT figures of 15.09 h, 16.01 h and 16.79 h yields results for ΔT of 8100 sec (2.25 h), 8300 sec (2.31 h) and 8400 sec (2.33 h). The very close accord between these figures is intriguing, bearing in mind that the individual timings were only quoted to the nearest 600 or 700 sec. However, there do not seem to be any grounds for questioning their authenticity.

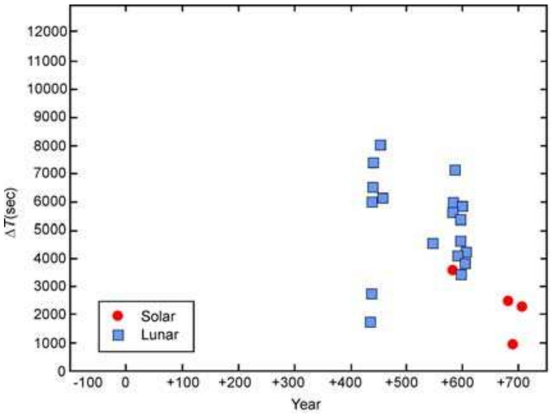

Figure 5. ΔT results obtained from Chinese timings of solar and lunar eclipses between AD 400 and 750. (N.B. only crude measurements are extant before AD 400).

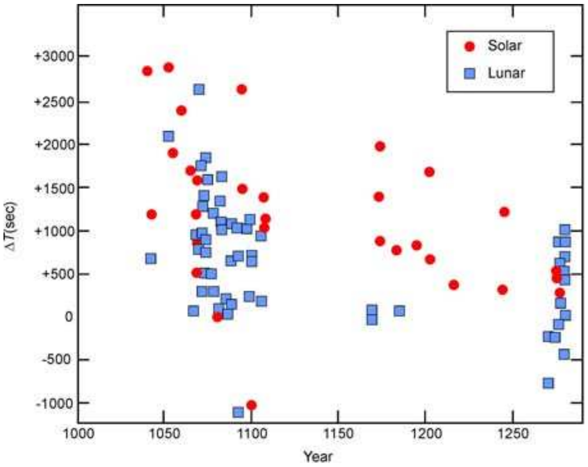

Figure 6. ΔT results obtained from Chinese timings of solar and lunar eclipses between AD 1000 and 1300.

The number of ΔT results derived from ancient Greek eclipse timings is too few to justify diagrammatic representation. The observations are of most utility when combined with other data – e.g. from Babylon and China.

5.4. Medieval European Records

Astronomers in medieval Europe who measured eclipse times include Isaac ben Sid, Levi ben Gerson, Jean de Murs, Johannes Muller (= Regiomontanus), Georg Peurbach, Bernard Walther, Nicholas Copernicus and Tycho Brahe. These observations extended from AD 1265 to 1600 (Steele, 2000). Presumably doubting the accuracy of their clocks, most observers measured time by determining the altitude of the Sun, Moon or a selected bright star. This technique had already been adopted by Arab astronomers around AD 800 (see Section 5.5). The following observation in AD 1460 is fairly typical.

> In the same year (= AD 1460), there was a total eclipse of the Moon... (on) the 27th day of December, in which by observation at the start of the eclipse the star which is called *Alramech* (α Boo) had an altitude in the east of 7 deg. At the beginning of totality the altitude was 17 deg and at the end of totality the altitude was 28 deg... The observers were Georg Peurbach and Johannes Regiomontanus in the town of Vienna.

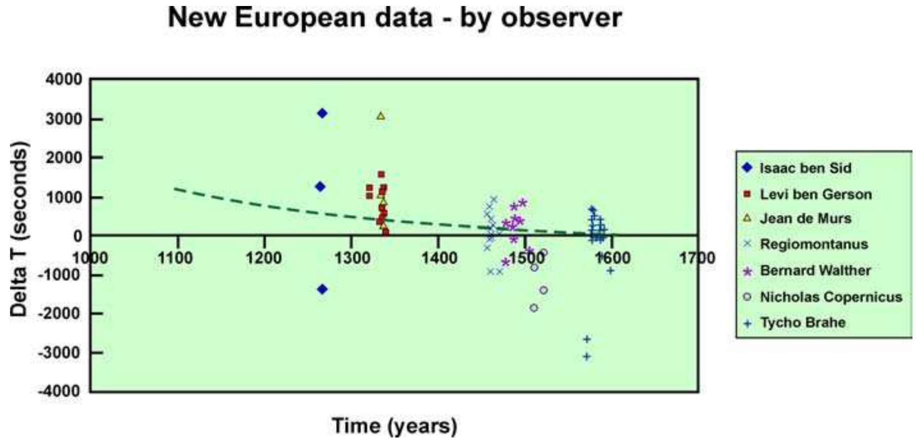

Figure 7. ΔT values derived from European measurements of eclipse times from AD 1250 to 1600 (after Lee, 1999).

The geographic co-ordinates of Vienna are 48.20 deg N, long = 16.37 deg E. From the measured altitudes of α Boo, the local apparent times of first contact, beginning of totality and end of totality may be deduced as 23.71 h (on Dec 27), and 0.78 h and 1.89 h (on Dec 28). Comparing the corresponding UT values of 22.74 h, 23.80 h and 0.91 h with their computed TT equivalents of 22.57 h, 23.63 h and 0.85 h leads to results for ΔT of -600 s, -625 s and -225 s (all negative). By contrast, roughly contemporary eclipse observations by these same two astronomers indicate values of ΔT ranging from 0 to around $+1000$ sec. Figure 7 shows results derived from more than 50 medieval eclipse timings, as derived by Lee (1999). Clearly the accuracy of unaided eye timings at this relatively recent epoch is much too low to yield meaningful values for ΔT. Instead, it is necessary to rely on roughly contemporaneous untimed sightings of total solar eclipses (see Section 6).

5.5. Medieval Arab Reports

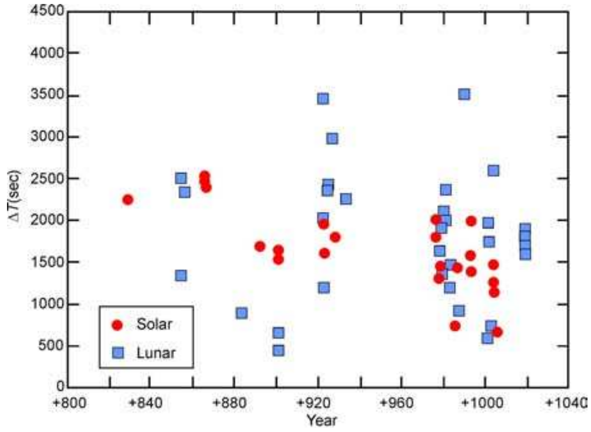

Figure 8. ΔT values derived from medieval Arab timings of solar and lunar eclipses between AD 800 and 1040.

There is no direct record of Arab astronomers timing eclipses until AD 829. Over the next 100 years, Baghdad skywatchers made many such measurements. Later, from AD 979 to 1004, Cairo astronomers – notably Ibn Yunus – made many similar measurements. Both sets of observations were published by Ibn Yunus in a treatise, of which only a single manuscript copy exists today (in Leiden). A few additional observations by al-Battani (between AD 883 and 901) and by al-Biruni (AD 1003 – 1019) are preserved in their own writings.

When observing an eclipse, the usual practice of medieval Arab astronomers was to determine the times of the various phases indirectly. The altitude of the Sun, Moon or a selected bright star at that moment was first noted. This measurement was then reduced to local time with the aid of an astrolabe.

One of the motivations for these observations was to test the accuracy of current eclipse tables. In addition, the astronomers sometimes used lunar eclipse observations made at two widely spaced locations to determine the difference in longitude between the two stations. This method was still in vogue – especially in Europe – during the 18th and 19th centuries.

Of the many Arab observations, we have selected the following example: a lunar eclipse observed by Ibn Yunus and others at Cairo (30.05 deg N, 31.25 deg E) in AD 979.

> This lunar eclipse was in the month of Rabi 'al-Akhir in the year 369 (of *al-Hijrah*) on the night whose morning was Friday the 13th day of the month... A group of scholars gathered together to observe this eclipse. They estimated that what was eclipsed of the Moon's circular surface was 10 digits (= 10 twelfths). The altitude of the

> Moon when they perceived the eclipse was 64 $\frac{1}{2}$ deg in the east. The altitude when its clearance completed was 65 deg in the west...

The date corresponds to the night of Nov 6/7 in AD 979. The Muslim calendar has twelve lunar months in each year; each month contains either 29 or 30 days. Hence a year contains only about 354 days – some 11 days shorter of the tropical year. As a result, the start of the year retrogrades through the seasons every 33 years. Conversion of dates to the Julian calendar may be effected using a simple algorithm, especially if – as above – the weekday is specified. However, it should be noted that the Islamic day begins at sunset.

For the above eclipse, the altitude measurements at first and last contact correspond to local times of 22.40 h (Nov 6) and 1.62 h (Nov 7). Correcting for the longitude of Cairo and the equation of time, the UTs of the two contacts are respectively 20.08 and 23.30 h (both on Nov 6). Subtracting these two results from the computed TTs of 20.61 and 23.67 h yields reasonably mutually-consistent values for ΔT of 1900 and 1300 sec.

In Fig. 8 are plotted the individual ΔT results obtained from the analysis of all the available medieval Arab eclipse timings (more than 50 individual measurements). The s.d. is only 9 min. For the subset of solar eclipses the s.d. is as small as 6 min. The lunar observations (s.d. = 15 min) were significantly less accurate than their solar counterparts, perhaps due to the difficulty of reading a scale at night and the poorer definition of lunar eclipse contacts.

6. ΔT as Determined from Untimed Observations of Total Solar Eclipses

This Section is not as closely relevant to the theme of the conference as the timed data and we shall give only a brief outline here.

Many early observers recorded qualitative accounts of total solar eclipses largely because of their spectacular nature. In general, these records make little or no mention of times, but they often carefully describe the complete disappearance of the Sun. A total solar eclipse typically lasts only about 4 min and the duration never exceeds 8 min. The edge of the solar photosphere is extremely sharp so that even an inexperienced observer may clearly identify the total phase. Provided the date and place of observation are known and a report specifically notes the disappearence of the Sun, firm limits can be set to the value of ΔT at that date.

Unlike timed observations, the accuracy with which ΔT can be defined by a report of totality shows no improvement down the centuries until after the introduction of the telescope. For a particular unaided-eye observation, much depends instead on the angle which the path of totality makes with parallel of latitude through the place of observation. If this angle is steep, quite narrow limits on ΔT may be set, but if the path of totality runs almost parallel to the equator, a wide range of possible values of ΔT may be indicated. From the many ancient and medieval reports of total solar eclipses, in what follows, we give two examples: observations made at Babylon in 136 BC and in Siena, Italy in AD 1239. At the former date a narrow range of ΔT is indicated, whereas the geographical circumstances on the latter date do not enable meaningful limits to be set.

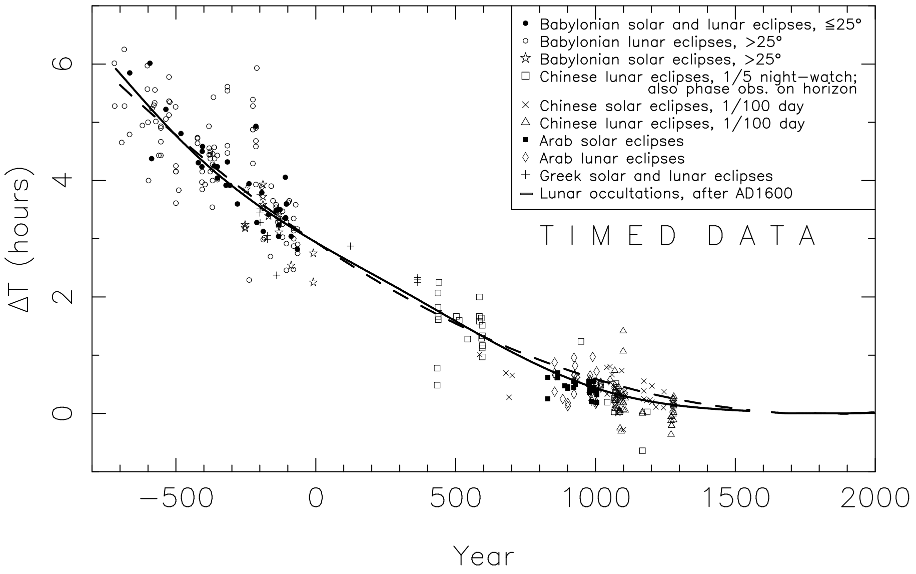

Figure 9. Assembled results for ΔT obtained from timed eclipse observations (see Section 5), together with a cubic spline fit (full line) and the best fitting parabola (broken line).

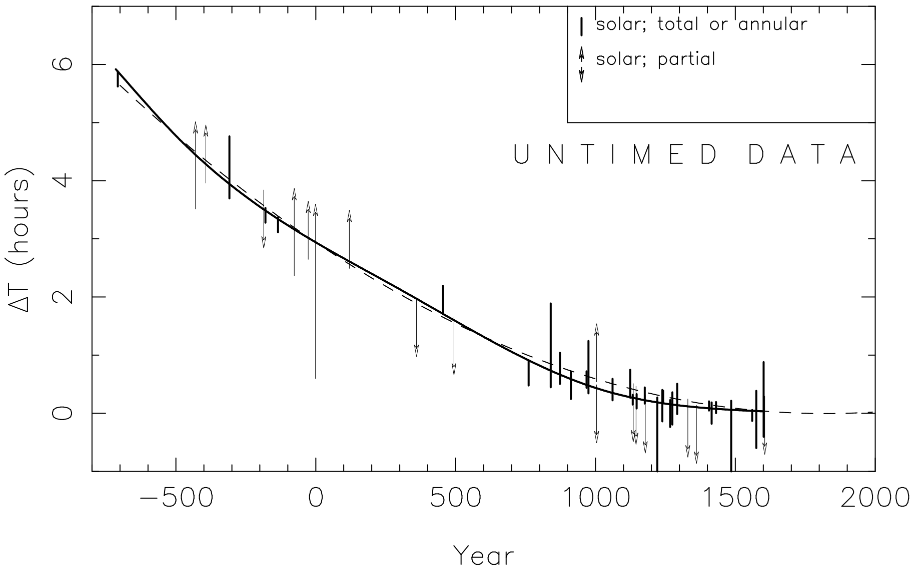

Figure 10. ΔT limits derived from untimed eclipse observations discussed (see Section 6), together with the cubic spline fit and best fitting parabola as in Fig. 9.

The observation of totality at Babylon on Apr 15 in 136 BC has already been discussed in Section 5.1. The date and place of observation are precisely known and it is clear from the two separate accounts which are preserved that the total phase was witnessed at Babylon. We compute that only for values of ΔT

between 11200 sec (3.11 h) and 12150 sec (3.38 h) would the path of totality cross the city of Babylon. For ΔT less than 11200 sec, the eclipse would only be total to the west of Babylon, while for ΔT greater than 12150 sec the path of totality would pass to the east of the city. The indicated range of ΔT is fairly narrow, largely because the path of totality was steeply inclined to the parallel of latitude at Babylon. Reference to Section 5.1 shows that the timed measurements closely support the above limits at this date.

On Jun 3 in AD 1239, the Moon's umbral shadow crossed southern Europe. Totality was recorded at several places in Portugal, France, Italy and Croatia. In Italy, the path of totality ran closely parallel to the equator, and although some splendid accounts of the total phase are preserved, these provide very little information about ΔT. The following record is from Siena:

> 1239, on Friday at the 6th hour, the Sun began to be obscured as if by a veil and was covered in a clear sky. At the ninth hour it was totally obscured, whence it gave no light; as if a dark night arose with the result that a starry sky was seen, as on a clear night. People lit lamps in houses and shops. After some space of time it gradually became uncovered and restored to Earth, with the result that before the evening hour it was restored to its brilliance.

The precise date is not specified, but there was only one total solar eclipse in AD 1239, on Jun 3, and this indeed occurred on a Friday. Although the above account from Siena (43.32 deg N, 11.33 deg E) gives only a rough indication of time, the description of the complete disappearance of the Sun is very clear. Computation reveals that this eclipse would have been total at Siena for any value of ΔT between -4700 sec (-1.31 h) and $+3600$ sec (1.00 h): a huge range at such a relatively recent epoch. Fortunately, a total eclipse visible in central Europe only two years later (AD 1241 Oct 6), at which the geographical circumstances are much more favourable, enables ΔT to be fixed within reasonably narrow limits around this date: between 630 sec and 1400 sec.

If a solar eclipse report clearly asserts that the phase was only partial, it may still prove of value. In this case, a range of ΔT is excluded by the observation. A good example is from China in AD 120.

> Yuanqi reign period, 6th year, month XII, day *wuwu* [55], the first day of the month. The Sun was eclipsed. It was almost complete; on Earth it became like evening...

There follows an astrological commentary associating the eclipse with the death of the Empress Dowager. The above date corresponds to AD 120 Jan 18. The eclipse would only be partial at the Chinese capital of Luoyang (34.75 deg N, 112.47 deg E) for values of ΔT either less than 8150 sec (2.26 h) or greater than 8950 sec (2.49 h). Intermediate values would lead to a total obscuration of the Sun, thus contravening observation.

Many other untimed observations of total or very large partial solar eclipses from China, Europe and the Arab dominions allow the variation in ΔT between 700 BC and AD 1600 to be studied independently of the timed data – see also Section 7.

7. Discussion

Assembling the results from the various timed eclipse observations considered in Section 5, we obtain the plot shown in Fig. 9. This diagram covers the period from 700 BC to the present day. Figure 10 exhibits the limits set by untimed observations of total and very large partial solar eclipses – examples of which are given in Section 6. Both Figs 9 and 10 (which are taken from Morrison & Stephenson, 2004) also display two curves: the best fitting parabola to the timed data ($\Delta T = -20 + 32\,t^2$), and a spline fit. Both curves are derived from unaided-eye and telescopic observations; in deriving the spline fit, several untimed solar eclipse observations were used to impose limits on ΔT at certain discrete dates (see Stephenson & Morrison, 1995).

Table 1. Values of ΔT taken from the curve shown in Figs. 2 and 3. The standard errors σ(s) are estimated as follows: −1000 to +1200 $\sigma = 0.8[(Year - 1820)/100]^2$, +1300 to +1600 $\sigma = 20$. After +1600, from the scatter of the points in Fig. 1(b). $^*\Delta T$ by parabolic extrapolation using $+32[(\mathrm{Year} - 1820)/100]^2$.

Year	ΔT(s)	σ(s)	Year	ΔT(s)	σ(s)	Year	ΔT(s)	σ(s)
−1000	+25400*	640	+1000	+1570	55	+1830	+ 8	<1
−900	23700*	590	1100	1090	40	1840	6	
−800	22000*	550	1200	740	30	1850	7	
−700	21000	500	1300	490	20	1860	8	
−600	19040	460	1400	320	20	1870	+2	
−500	17190	430	1500	200	20	1880	−5	
−400	15530	390	1600	120	20	1890	−6	
−300	14080	360	1700	9	5	1900	−3	
−200	12790	330	1710	10	3	1910	+10	
−100	11640	290	1720	11	3	1920	21	
0	10580	260	1730	11	3	1930	24	
+100	9600	240	1740	12	2	1940	24	
+200	8640	210	1750	13	2	1950	29	
+300	7680	180	1760	15	2	1960	33	
+400	6700	160	1770	16	2	1970	40	
+500	5710	140	1780	17	1	1980	51	
+600	4740	120	1790	17	1	1990	57	
+700	3810	100	1800	14	1	+2000	+65	
+800	2960	80	1810	13	1			
+900	+2200	70	+1820	+12	1			

Table 1 lists the derived values of ΔT at century intervals from 1000 BC to AD 1700 and at 10-year intervals since the latter date (see also Morrison & Stephenson, 2004). Estimated uncertainties at each date are also given in the table. From AD 1700 to the present, ΔT results are taken from the well-defined curve derived from telescopic observations (see Fig. 2). Values of ΔT from 700 BC to AD 1600 are from the spline curve described above. Owing to the complete lack of suitable observational material before about 700 BC, for the three dates listed before 700 BC, we have extrapolated using the parabola

$\Delta T = +32\,t^2$. We have felt it inadvisable to even consider the history of ΔT before 1000 BC.

8. Conclusion

It is our hope that the data in Table 1 should prove of lasting value. In recent years, several further Babylonian eclipse timings have come to light − not as the result of discovery of further texts but by closer examination of the extant material. These observations should enable ΔT to be defined with slightly improved precision in the period from 700 BC to 100 BC. However, progress in the study of ΔT over more recent centuries is likely to be very slow, especially where timed data are concerned. Prospects for the discovery of further Chinese or Arab observations seem far from promising. The discovery of additional reports of medieval total solar eclipses may prove to be a more attractive prospect. In this regard, the assistance of local historians at a variety of European centres could prove invaluable. The help of anyone who is in contact with such scholars is earnestly solicited.

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Barrera: Do you have any knowledge about eclipses observed by the Mayas?

Stephenson: Although the Mayas were very interested in eclipse prediction, there do not appear to be extant eclipse observations. Many Mayan codices were destroyed by the Conquistadores.

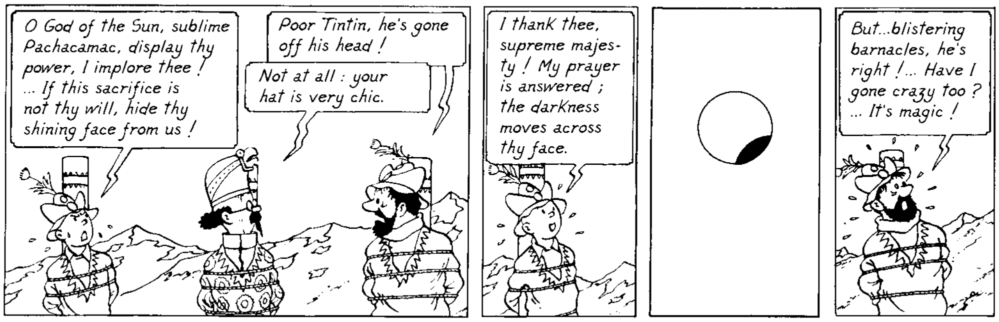
Zavala: Why are there no eclipse timing records before 200 BC? Are there any Egyptian records?

Stephenson: Detailed Chinese history, containing specially compiled astronomical treatises, only commences around 200 BC. Before then, references to eclipses and other astronomical events are very brief and spasmodic. There may be earlier Chinese archives which we are at present unaware of yet, either still in the ground or in some of the more obscure museums. But I am not hopeful of finding anything.

Very few allusions to eclipses survive from any part of the world before 700 B.C. Chinese oracle bone records list a earlier eclipses, but we do not have a direct indication of the date of any of these events. It is necessary to make an assumption about which eclipse an oracle bone refers to, and that seems a dangerous thing to do. For the Babylonian records, a Greek historian (Diodorus) reported that eclipse records prior to about 700 BC were destroyed by King Nabonassar, but I do not know how true that story is. Nevertheless, scarcely any Babylonian records of eclipses survive before 700 BC.

Unfortunately there are no known ancient Egyptian records of eclipses, perhaps because they were recorded on papyrus, and so were unlikely to survive. Tomb excavations may still yield useful records, but we can only speculate on this possibility.

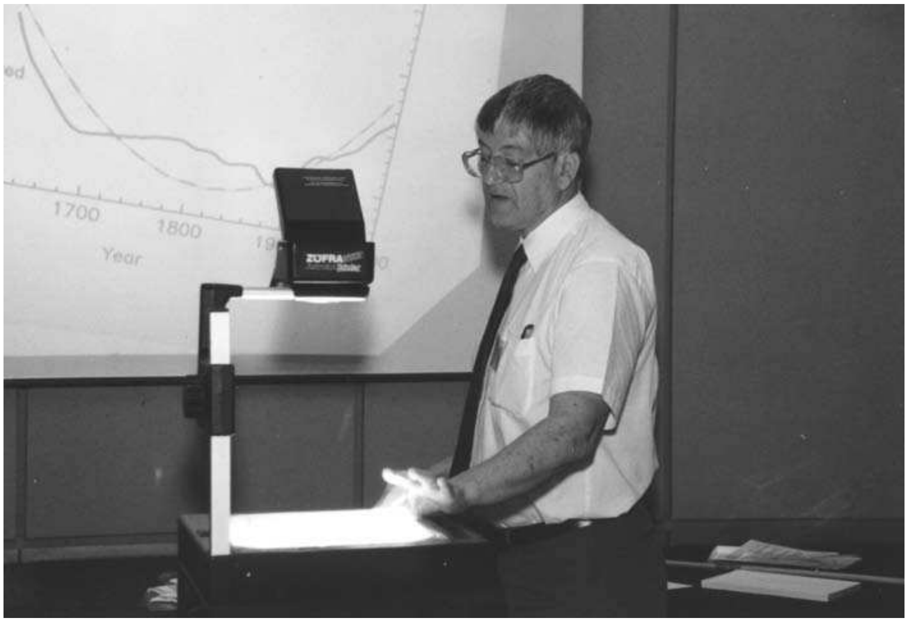
Sterken: Since the meeting of today takes place at the *Belgian Centre of Comic Strip Art* in Brussels, I wish to point out a very nice illustration of the use of $O-C$ in arts, specifically in comic-strip art. Hergé, in his 1949 album *Prisoners of the Sun*, invokes the occurrence of a predicted total solar eclipse to convince the locals to free their captives (see illustration below). It is widely known that Hergé researched his topics very well, and I have been trying to find the source of his inspiration. One possibility is the occurrence of a partial solar eclipse on January 16, 1665 near Beijing, China. It so happened that the Belgian Jesuit Ferdinand



Reproduction after Hergé *"Prisoners of the Sun"* ©Hergé/Moulinsart 2005

Verbiest[1] (1623–1688), together with his Jesuit colleagues Johann Adam Schall von Bell, Ludovicus Buglio and Domingo Jose Goncalves de Magalhaens, was taken prisoner and was accused of diffusing incorrect scientific doctrines[2]. They had predicted a solar eclipse to occur at 03:26 p.m. on 16 January 1665, whereas the calculation by the local astronomers Wu Ming-Xuan and Yang Guang-Xian predicted the beginning of the eclipse 35–45 min earlier. The eclipse occurred as predicted by the missionaries, they received congratulations but were not released. In fact, their $O-C$ was about 5 minutes ($0^{\mathrm{d}}.003$), and this discrepancy was not noticeable because the accuracy of the chronographs was worse, still the difference was less than 10% of the $0^{\mathrm{d}}.03$ achieved by their hosts.

It is not impossible that Hergé took his inspiration from this event, although the stage of the happening is very different (Peru instead of China), and the outcome definitely has a happier end. The most striking aspect, however, is that the captors of Tintin seemed not to be aware of an impending eclipse, a most unlikely situation indeed to remind us that we are dealing with fiction.



F. Richard Stephenson at the *Belgian Centre of Comic Strip Art*

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[1] Verbiest, whose chinese name was Nan Huai-Ren, was a missionary, scientist and diplomat who contributed significantly to the growth of Christianity in China and to Sino-Western cultural exchange.

[2] Blondeau, R.A. 1970, "Mandarijn en astronoom", Desclée De Brouwer, Brugge-Utrecht p. 238.

Unidentified comic hero

Sergei Shugarov and Drahomir Chochol discussing