Astronomy in Focus - XXX
Proceedings IAU Symposium No. XXX, 2018
M. T. Lago, ed.

doi:10.1017/S1743921319003971

Eclipses and the Earth's Rotation

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Abstract. Analysis of historical records of eclipses of the Sun and Moon between 720 BC and AD 1600 gives a measure of the time difference, $\mathrm{TT} - \mathrm{UT} = \Delta\mathrm{T}$. The first derivative in time along a smooth curve fitted to the values of ΔT measures the changes in the length of the day (*lod*). The average rate of change of the *lod* is found to be significantly less than that expected on the basis of tidal friction. Fluctuations on a time-scale of centuries to millennia are mainly attributed to the effects of post-glacial uplift and core-mantle coupling.

Keywords. Eclipse, length of day

1. Introduction

Historical records of eclipses of the Sun and Moon between 720 BC–AD 1600 provide vital information on the rotation of the Earth. From several hundred records we derive an estimate of the difference, $\mathrm{TT} - \mathrm{UT} = \Delta\mathrm{T}$, which measures the cumulative discrepancy in UT due to fluctuations in the Earth's rate of rotation. The fluctuations are derived from the slope on a smooth curve fitted to ΔT, which are conveniently measured by changes in the length of the mean solar day (*lod*).

2. Historical Sources of Eclipses Observations

The extant records come from the ancient civilizations of Babylonia, China, and Greece, together with the medieval Arab Dominions and medieval Europe, and their provenance is described in Stephenson (1997). The calculated values of ΔT are listed in Stephenson *et al.* (2016), with a few additions in Morrison *et al.* (2019).

3. Observations

The eclipse observations are subdivided into two main categories: untimed and timed. These in turn are subdivided into solar and lunar.

Untimed solar -708 to $+1567$ (61 observations): The accuracy of the ΔT results from untimed observations depends on the width of the paths of totality parallel to the equator at the places of observation. We have used only observations where the place, date and description of the eclipse are unambiguous. In most cases, the observation gives a clear statement that the eclipse was total or that the Sun completely disappeared, along with details such as 'day turned to night' and/or 'stars appeared'. This gives a solution space for ΔT with sharp upper and lower bounds. We have also used a few observations of large solar eclipses where a description such as 'not total, like a hook' is given. This defines a solution space of ΔT outside the range of totality. Generally this is wide, but in some cases the observations give a useful boundary condition.

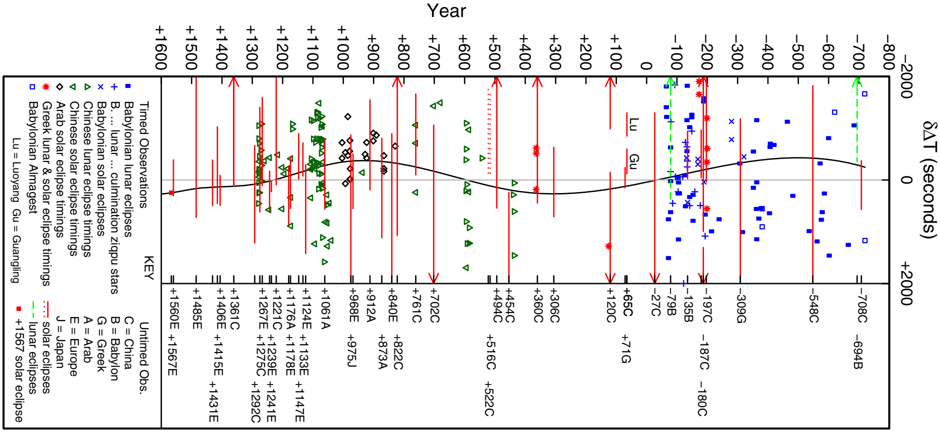

Figure 1. Residuals $\delta\Delta$T and spline plotted with respect to the parabola (Eqn. 4.1).

Untimed lunar −719 to −79 (14): Useful limits on ΔT can also be obtained from Babylonian untimed observations of lunar eclipses, where the Moon rose or set eclipsed, or the degree of obscuration at rising or setting is given.

Timed solar −356 to +1004 (100): The Babylonians timed the beginning or end of solar eclipses by measuring the time elapsed from sunrise or sunset to the nearest 4 minutes. The Chinese measured time as a fraction of the day length, typically to the nearest 1/100th (14 minutes). The Greek observations are given to a precision in the range 1/3rd to 1/6th hour (20-10 minutes). The Arab timings were made by astrolabe measurement of the Sun's altitude, giving a precision of 4 min.

Timed lunar −720 to +1277 (≈250): The Babylonian lunar observations were timed using the same method as the solar observations, and after the mid-6th century BC, with the same resolution (4 minutes). The precision of the Chinese observations ranged from 0.5 hours prior to +1050, to 14 minutes afterwards. The Greek observations were recorded with a precision of 1/3 h, typically. The Arab precision is similar to the solar observations (4 minutes), using astrolabe altitudes of the Moon or reference stars.

4. Analysis of ΔT −720 to +1600

The behaviour of ΔT over time is predominantly parabolic as a result of the deceleration in the Earth's rate of rotation caused by the action of tidal friction due to the Moon, and, to a lesser extent, the Sun. In our paper Stephenson *et al.* (2016), we find the average parabola fitted to ΔT to be

$$\Delta\text{T(parabola)} = -320.0 + (32.5 \pm 0.6)((\text{year} - 1825)/100)^2 \text{ s.} \tag{4.1}$$

This parabola is subtracted from the values of ΔT to obtain the residuals $\delta\Delta$T, which are plotted in Figure 1 together with the subset of critical observations.

There are clearly fluctuations of $\delta\Delta$T around this parabola. We weighted the data, both discrete points (mainly due to timing) and extended solutions (untimed), and fitted a smooth curve using cubic splines. That is plotted in Figure 1. Particular care was taken over the reliability of the critical limits of the untimed eclipses of −708C, −694B, −135B, +454C, +761C, +1239E, +1361C and +1567E. They are discussed in Stephenson *et al.* (2016), Morrison *et al.* (2019), and Stephenson *et al.* (2018).

https://doi.org/10.1017/S1743921319003971 Published online by Cambridge University Press

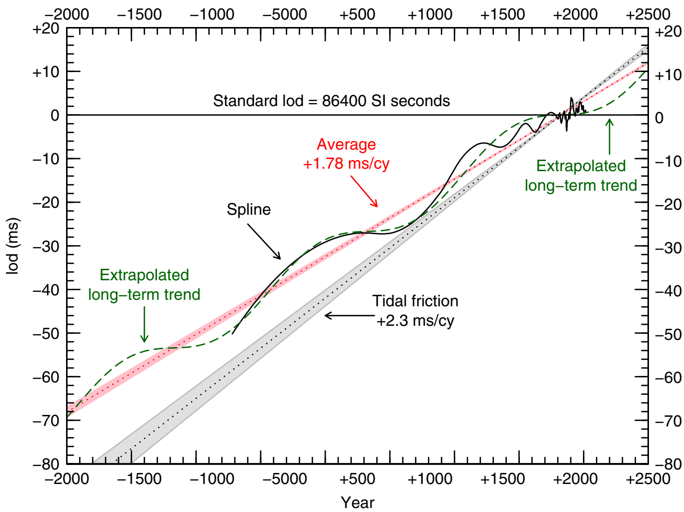

Figure 2. Change in the *lod* derived from the slope of the spline fitted to ΔT.

5. Change in *lod*: −720 to +1600

The slope along the spline curve in Figure 1 gives the change in *lod* plotted in Figure 2. The average long-term increase in the *lod* is found to be +1.78 milliseconds per century (ms/cy), which is significantly less than the increase of +2.3 ms/cy expected on the basis of tidal friction. This implies an accelerative component decreasing the *lod* by −0.5 ms/cy since 720 BC, which is mainly attributed to the effects of post-glacial uplift and core-mantle coupling. The decadal fluctuations resolved after +1600 are derived from timings of lunar occultations (Stephenson *et al.* 2016), which are not discussed here.

6. Acknowledgements

The authors acknowledge support by HM Nautical Almanac Office and the IAU's Standards for Fundamental Astronomy WG of Division A.

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