EARTH'S RATE OF ROTATION BETWEEN 700 BC AND 1000 AD DERIVED FROM ANCIENT SOLAR ECLIPSES

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ABSTRACT. We analyzed 34 ancient solar eclipses between 700 BC and 1000 AD recorded in China and Japan. From the analysis we have found that the tidal acceleration of the Moon has been constant from 700 BC to the present, and that the TT − UT values had a semi-periodic variation with a period of several hundred years since 700 BC. The nontidal components of TT − UT should be due to the variation of the moment of inertia of the Earth.

1. INTRODUCTION

Stephenson (1997) obtained the values of $\Delta T = \mathrm{TT} - \mathrm{UT}$ from about 720 BC using mainly the ancient solar and lunar eclipses. According to the ΔT curve of his Fig. 14.4, the value of ΔT in the 7th century is between about 4000 and 4500 sec. In Journées 2002 we showed from the solar eclipse records in China and Japan that the ΔT value should have been about 3000 sec in the 7th century. In Sect. 2 we review the discussion about the values in the 7th century based on the solar eclipse records and we also give additional data supporting our ΔT value in the 7th century. In Sect. 3 we show that the tidal acceleration of the Moon obtained from the solar eclipse records from 700 BC to 1000 AD coincides with that derived from the recent lunar laser ranging data. In Sect. 4 we derive the ΔT values between 700 BC to 1000 AD from the same solar eclipse records and show that the ΔT values had a semi-periodic variation with a period of several hundred years since 700 BC.

2. ΔT VALUE IN THE SEVENTH CENTURY

The solar eclipse of 628 April 10 was recorded as "The sun was completely eclipsed" in the Nihongi (Japanese old history book). Nine years later, on 637 April 1, there was another solar eclipse observed in Japan. It was also recorded in the Nihongi, but only recorded as "The sun was eclipsed". If we assume that the ΔT value was 4500 sec at that time as given by Stephenson (1997), the magnitudes of the solar eclipses of the years 628 and 637 become 0.89 and 0.93, respectively, which contradicts the records. In China, solar eclipses of AD 616 and AD 702 were recorded. From these records we concluded that the ΔT value in the 7th century was about 3000 sec.

A lunar occultation of Mars on 681 November 3 was also recorded in the Nihongi as "Mars was occulted". Our calculations showed that actually Mars was not occulted at Asuka, the ancient capital of Japan, but the apparent distance of Mars' center from the lunar limb at the closest approach depends on the adopted ΔT value as follows:

ΔT	Distance
3000 sec	34″
4000 sec	71″

The Moon's age was 17.3 days and the Moon's phase (fraction of the area of the apparent disk that is illuminated by the Sun) was 95%, but Mars' altitude was 70° above the horizon and Mars' magnitude was -1.4 so that we thought that Mars was bright enough to be seen if it was separated from the bright lunar limb by more than the angular resolution of the naked eye (40″ or so), and thus we thought that the observation also showed ΔT should have been about 3000 sec instead of about 4000 sec at that time, but we lacked its definitive evidence.

This year on 2003 July 17 there was a grazing occultation of Mars in Florida, U.S.A., the condition of which was similar to that of the 681 occultation (Moon's age 17.6, Moon's phase 85%, Mars' altitude 50°, Mars' magnitude -1.9). Two people observed it with naked eye. Mars approached from the bright side of the Moon and they lost Mars a couple of minutes after Mars passed by the Moon's cusp. Their observation data were as follows:

Observer	UT	Long.	Lat.	Height	d_{limb}	d_{term}
	h m s	° ′ ″	° ′ ″	m	″	″
Christopher Stephan	08:22:00	81 03 11 W	27 17 55 N	10	28	35
Richard Coolick	08:20:07	81 49 08 W	26 43 43 N	3	30	38

UT is the time when the observer lost Mars, geodetic coordinates are on 1927 North American Datum and d_{limb} and d_{term} are the apparent distances of Mars' center from the lunar limb and the bright terminator, respectively. Mars' apparent semidiameter was 9″.8 and Moon's apparent semidiameter was 935″.3.

The two observers were able to follow Mars until its apparent distance from the bright terminator became less than 40″, which is almost equal to the angular resolution of naked eye. Thus, the observations confirmed our supposition and they strengthen our result that ΔT was about 3000 sec in the 7th century.

3. TIDAL ACCELERATION OF THE MOON

In order to investigate further the Earth's rate of rotation and the tidal acceleration of the Moon's longitude from the ancient times we have found 34 records of ancient solar eclipses between 700 BC and 1000 AD with descriptions of one of the words of "total", "complete", or "stars were seen" in Chinese and Japanese books. Among these 34 records 4 were found to be the predicted eclipses that cannot be used for our analysis. Remaining 30 records were used in our analysis.

On the tidal acceleration of the Moon versus ΔT plane, we plot an area of the parameters which gives the recorded total/annular eclipses in the capital of the dynasty. Since the tidal acceleration and the ΔT value do not change significantly within a short period of time, we can expect substantially the same values of these parameters for two successive eclipses occurring within a period of, say, 60 years. Fig. 1 shows one of such examples.

The three solar eclipses were recorded in China and it is assumed that these eclipses were observed in Ch'ang-an. The BC 198 Aug 7 eclipse (shown by the bold lines in the figure) was

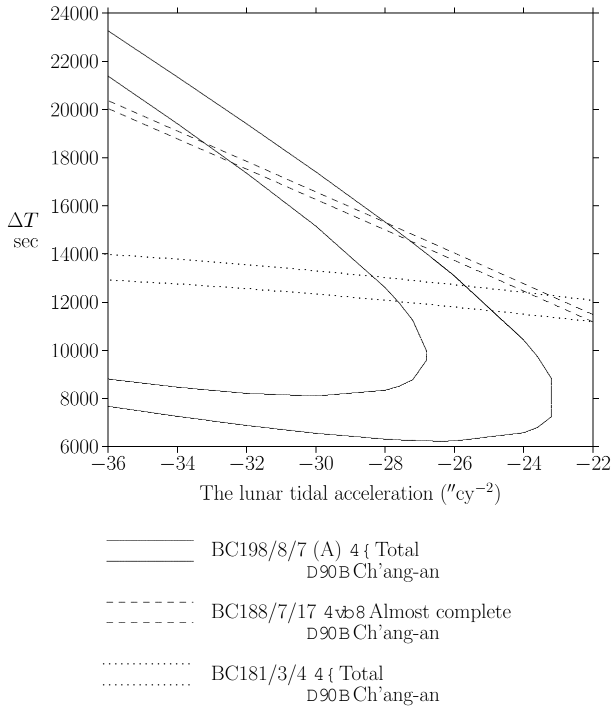


Figure 1: Solar eclipses of 198 BC, 188 BC, and 181 BC The solid lines show the area of the annular phase of the 198 BC eclipse, the broken lines the total phase of the 188 BC eclipse, and the dotted lines the total phase of the 181 BC eclipse.

recorded as "chin". "Chin" usually means total but it was also used for annular eclipses, and in this case the observed eclipse was annular. The BC 188 July 17 eclipse (the broken lines) was recorded as "almost complete". The BC 181 Mar 4 eclipse (the dotted lines) was recorded as "total". Therefore the values of the parameters should be in the common area surrounded by the bold lines and dotted lines and should also be outside the area shown by the broken lines. Hence the tidal acceleration of the Moon can be determined from these eclipse records to be $-(26 \pm 1)''/\mathrm{cy}^2$.

The pair of the solar eclipses of AD 516 and 522 and the pair of those of 616, 628 and 702 also give the result that the tidal acceleration has been $-26''/\mathrm{cy}^2$. The pair of the solar eclipses of 709 BC, 601 BC and 549 BC gives a wider range for the tidal acceleration (see Fig. 2), but it is also consistent with the value of $-26''/\mathrm{cy}^2$ for the tidal acceleration of the Moon. The places and the recorded discriptions for the solar eclipses appearing in the present analysis for the tidal acceleration are given in Table 1.

Since the tidal acceleration $-26''/\mathrm{cy}^2$ of the Moon we obtained agrees with the value obtained from the recent LLR (lunar laser ranging) measurements (Chapront et al. 2002; the value they obtained is -25.858 ± 0.003 ($''/\mathrm{cy}^2$)). It is also consistent with the value -26 ± 2 ($''/\mathrm{cy}^2$) derived from the comparison of the observations of transits of Mercury and lunar occultations of stars covering the period from 1677 to 1973. These facts indicate that the tidal acceleration of the Moon has been constant since 700 BC.

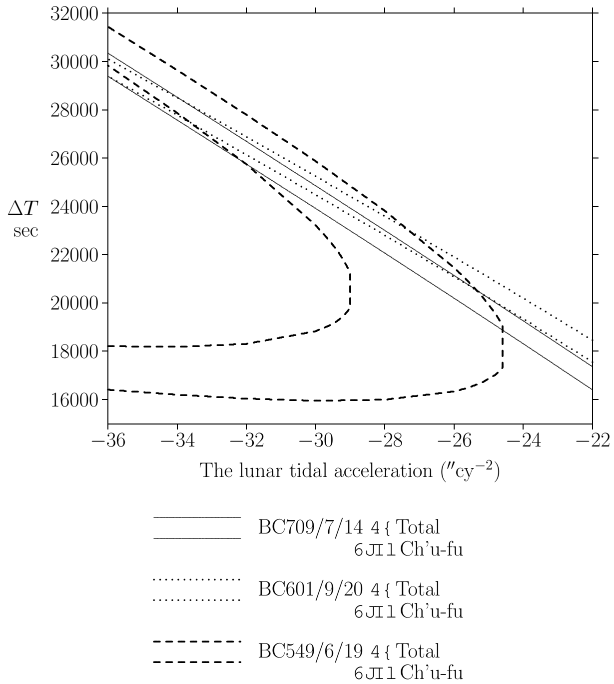


Figure 2: Solar eclipses of 709 BC, 601 BC, and 549 BC. The solid lines show the area of the total phase of the 709 BC eclipse, the dotted lines the total phase of the 601 BC eclipse, and the broken lines the total phase of the 549 BC eclipse.

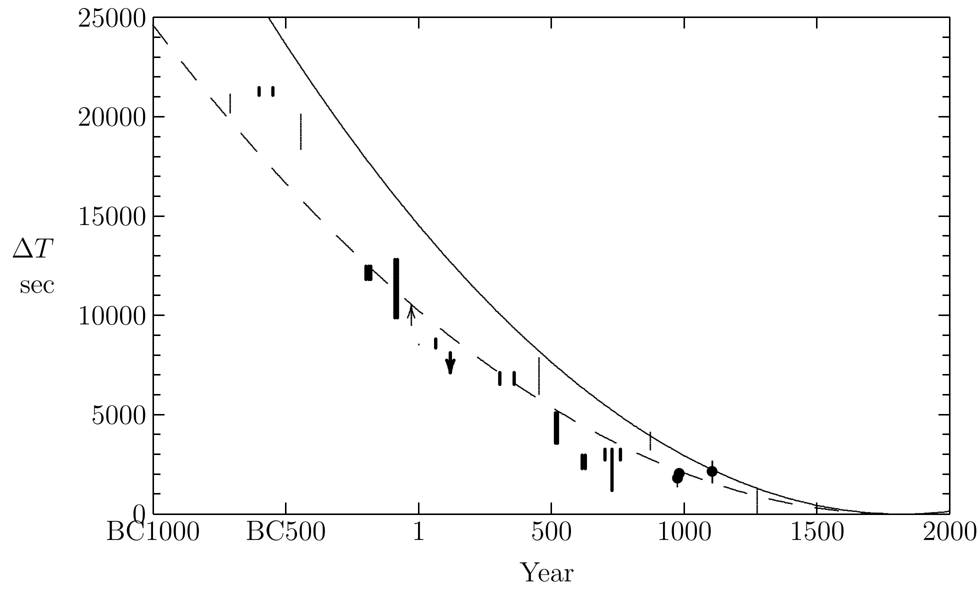
Table 1. Eclipses used for the tidal acceleration determination.

Date	Place	Description
BC 709 July 14	Ch'u-fu, China	Total
BC 601 Sept 20	Ch'u-fu, China	Total
BC 549 June 19	Ch'u-fu, China	Total
BC 198 Aug 7	Ch'ang-an, China	Total (actually annular)
BC 188 July 17	Ch'ang-an, China	Almost complete
BC 181 Mar 4	Ch'ang-an, China	Total
AD 516 Apr 18	Chien-k'ang, China	Total (actually annular)
522 June 10	Chien-k'ang, China	Total
616 May 21	Lo-yang, China	Total (actually annular)
628 Apr 10	Asuka, Japan	Total
702 Sept 26	Ch'ang-an, China	Almost total

4. PERIODIC VARIATION OF THE EARTH'S ROTAION RATE

Now that we know that the tidal acceleration of the Moon has been $-26''/\mathrm{cy}^2$, we can determine the ΔT values at the times of the recorded solar eclipses using this value for the lunar tidal acceleration. Table 2 shows the solar eclipses we used and the resulting ΔT values.

The obtained ΔT values are shown in Fig. 3. The thick lines indicate that the range was obtained from multiple eclipses and the thin line from single eclipses.



Solid line: tidal effect. Dashed line: parabolic fitting (Stephenson 1997).
•: timed data.

Figure 3: Obtained ΔT values.

The figure clearly shows that the ΔT value had a semi-periodic variation with a period of several hundred years since 700 BC. The nontidal components of ΔT should be due to the variation of the moment of inertia of the Earth.

Suppose that glaciers in polar regions melt and the sea level on the Earth's surface rises by 1 m over 1000 years in a constant rate. Then due to the increase of the Earth's moment of inertia ΔT increases by about 30 minutes. The variation of the sea level due to the variation of atmospheric temperature in the polar regions is a probable cause of the variation of the Earth's rate of rotation in hundreds of years or in a millennium.

5. CONCLUSION

We showed from the ancient solar eclipse records that the tidal acceleration of the Moon has been constant from 700 BC and the ΔT values had a semi-periodic variation with a period of several hundred years since 700 BC. The variation of the sea level due to the variation of atmospheric temperature in the polar regions is a probable cause of the non-tidal components of the variation of the ΔT value.

Table 2. Used Eclipses and Derived ΔT Values.

Date	Description	ΔT/sec		
Single events				
BC 709 July 17	Total	20201	–	21143
BC 444 Oct 24	Stars seen	18375	–	20119
BC 28 June 19	Not complete; Like a hook	9512	$<$	
AD 2 Nov 23	Total	8510	–	8542
65 Dec 16	Total	8362	–	8810
120 Jan 18	Almost complete		$<$	8117
454 Aug 10	Total	6027	–	7858
873 July 28	Dark; Total	3237	–	4106
975 Aug 10	Total; Inky darkness	1167	–	4452
Multiple events				
BC 601 Sept 20	Total	21093	–	21466
BC 549 June 19	Total			
BC 198 Aug 07	Total			
BC 188 July 17	Almost complete	11816	–	12471
BC 181 Mar 04	Total			
BC 89 Sept 29	Almost complete; Like a hook	9880	–	12820
BC 80 Sept 20	Almost complete			
AD 306 July 27	Total	6529	–	7120
360 Aug 28	Not complete; Like a hook			
516 Apr 18	Total			
522 July 10	Total	3567	–	5085
523 Nov 23	Venus seen			
616 May 21	Total	2278	–	2959
628 Apr 10	Complete			
702 Sept 26	Almost total; Like a hook			
729 Oct 27	Not complete; Like a hook	2728	–	3254
761 Aug 05	Total; Stars seen			

6. REFERENCES

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