Solar Eclipses at Sunrise or Sunset in the Chunqiu Period

Kiyotaka Tanikawa, Tadato Yamamoto, and Mituru Sôma

Abstract In the Chinese chronicle 'Chunqiu' ('The Spring and Autumn Annals') which describes the history of the Chunqiu Period (771 BC–403 BC), there are 37 solar eclipse observations recorded, starting in 720 BC and ending in 481 BC. Among these, there are ten records which lack either the day of the 60-day cycle or the statement that the eclipse occurred at a 'new Moon' (shuo 朔) or both. A Japanese astronomer, Toshio Watanabe, conjectured that these eclipses may have been observed at sunrise or sunset. In the present paper, we intend to confirm Watanabe's conjecture, and after confirming it, we use these eclipses to accurately determine the range of ΔT in this period. Our results from five solar eclipses which were accompanied by near-contemporaneous eclipses are:

$20{,}153 < \Delta T < 21{,}094$ at around February 2, 720 BC,
$18{,}526 < \Delta T < 20{,}686$ at around April 15, 676 BC,
$19{,}409 < \Delta T < 20{,}402$ at around April 6, 648 BC, if the site is Paros
$18{,}353 < \Delta T < 19{,}235$ at around April 6, 648 BC, if the site is Thasos
$19{,}172 < \Delta T < 20{,}910$ at around March 6, 598 BC,
$16{,}134 < \Delta T < 19{,}101$ at around May 31, 558 BC.

Finally, we discuss the meaning of the lack of information. Our tentative conclusion is that most (seven out of nine) eclipses without the statement of the first day of the month took place at sunrise or sunset.

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1 Introduction

Knowledge of variations of the Earth's rotational velocity in the pre-telescopic past is important not only for astronomy and geophysics but also for history. It is well known that ancient solar and lunar eclipses are essential for determining the Earth's rotation period. Conversely, we have basically two unknown parameters by which the place and time of eclipses are determined. These are ΔT and the lunar tidal acceleration (LTA) along its orbit.

Let us first introduce ΔT. Homogeneously-flowing time is denoted by TT, the abbreviation for Terrestrial Time. The time measured by the rotation of the Earth is denoted by UT (Universal Time). Then, we denote the difference of these two as

$$\Delta T = TT - UT. \tag{1}$$

ΔT represents the delay of the Earth's clock compared to a correct clock.

We know that ΔT was roughly 3 h 2,000 years ago. The Moon is receding from the Earth by 3.8 cm/year at present (Chapront et al. 2002). This corresponds to a LTA of $-25.83''/\mathrm{cy}^2$ where the minus sign means that the Moon actually decelerates due to the tidal interaction with the Earth. In the past, the decrease rate might have been different. We expect that our research may more accurately determine the values of these two parameters. The results can also be used for the study of ancient history.

The number of historical astronomical records before the fifth century BC is extremely small. So the eclipse records of the Chunqiu (the original manuscript and its copies have been lost) are very valuable. Stephenson (1997) expressed the long-term variations of ΔT by a fitted spline curve assuming the present value of the LTA. There, the dispersion of the data around the spline curve is so large that we suspect that the spline fitting may conceal large amplitude variations of shorter periods.

Now, we turn our attention to the eclipses in the Chunqiu Period. The study of the eclipses in the 'Chunqiu' (The Spring and Autumn Annals) has a long history. The first study already appeared in the Zhanguo Period (Warring States Period: BC 403–221). Three explanatory books, the *Zuoshi-zhuan* (左氏伝, 1981), *Guliang-zhuan* (穀梁伝, 1993) and *Gongyang-zhuan* (公羊伝, 1993), edited in the Zhanguo Period or in the early Han Dynasty, have different interpretations concerning eclipse records which fail to mention either the day of the 60-day cycle ('ganzhi') or the first day of the month ('shuo' 朔), or both. The *Zuoshi-zhuan* simply says that Royal Astronomers forgot to record these data. The *Guliang-zhuan* says that these eclipses were observed on the last day of the month or in the evening. The *Gongyang-zhuan* says that they were mainly observed on the second day of the month. A famous astronomer of the Han Dynasty, Liuxin, argued along the same lines as the *Gongyang-zhuan*. These discussions are related to the problem of establishing the precise calendar system in the Chunqiu Period. The controversy continues to this day.

In more recent times, Shinzo Shinjo (1928) published the *Long Calendar of Chunqiu*, in which he lists many earlier Chinese authors who studied the Chunqiu calendar. Shinjo reconstructed the calendar of the Chunqiu Period based on the periodicity of ganzhi of eclipse records with the aid of dates (which he determined) of 33 reliable solar eclipse records. On the basis of astronomical calculations, Watanabe (1984) found sunrise and sunset eclipses and mentioned them in his *Canon of the Solar and Lunar Eclipses*. However, the theory used in his calculation was from the 1920s, so his conclusions may contain systematic errors.

In order to better determine the value of ΔT, total eclipses observed from known sites are the most useful. However, records of this type are rare. Instead, we are particularly interested in eclipse records which lack either ganzhi or mention of the first day of the month, or both, among 37 solar eclipses recorded during the Chunqiu Period. These are our ‘target eclipses’, and they are listed in Table 1. From the beginning (during the Han Dynasty), they were suspected to have occurred at sunrise or sunset (Hanshu 1962).

The purpose of the present paper is to actually show that these were eclipses at sunrise or sunset, and by way of this to obtain limits to the range of ΔT. We also discuss the reasons for the lack of descriptions of some of these eclipses.

The values of ΔT obtained from the same eclipse or contemporaneous eclipses should be identical or nearly identical. Fortunately, in some cases, there are records of total eclipses observed close to the years of the target eclipses. We will show that by considering multiple eclipses at one time we can obtain a narrower range of ΔT. We will also point out the utility of non-total eclipses.

2 Target Eclipses and Auxiliary Eclipses

2.1 Previous Studies

In Chinese history, eclipse records were fundamental for determining future calendars. In particular, solar eclipses should take place on the first day of the month. Astronomers Royal had a duty to record the serial number of the day in the month, in addition to the day in the 60-day cycle, which is called the ganzhi cycle. The latter tradition goes back to much earlier times. Some Chunqiu eclipse records lack the serial day number in the month or the day in the ganzhi cycle, or both. These facts were already the subject of discussion in the following books edited during the Zhanguo Period: *Zuoshi-zhuan*, *Gongyang-zhuan*, and *Guliang-zhuan*. In fact, Wuxing-chi (Volume 7) says as follows:

(01) Duke Yin, 3rd year, 2nd month, day jisi [6], the sun was eclipsed.

The Guliang-zhuan says that here the ganzhi day is recorded but ‘shuo’ (the first day of the month) is not mentioned, so the eclipse took place on the last day of the month. The Gongyang-zhuan says that the eclipse was on the second day of the month.

The Shiji generally considered that when a (solar) eclipse took place, in some cases, ‘shuo’ is written but the day is not ‘shuo’, in other cases, ‘shuo’ is not written but the day is ‘shuo’, in yet other cases, both ‘shuo’ and ganzhi were not written; all these mean that the astronomers lost the data.

(03) Duke Huan, 17th year, 10th month, 1st day, the sun was eclipsed.

Table 1 List of solar eclipses that occurred during the Chunqiu period[a]

		Julian date			Chunqiu period									
No	Oppol. no.	Year	Month	Day	Duke	Year	Month	Day	Shuo?	*Z-z*	*Go-z*	*Gu-z*	Liuxin	Watanabe
01	1,147	–719	02	22	Yin	03	02	Jisi[6]	–	Lost	2nd	Last	2nd	Sunrise
02	1,176	–708	07	17	Huang	03	07	Renchen[29]	Shuo.T					Total
03	1,211	–694	10	10		17	10	–	Shuo	Lost		2nd		
04	1,257	–675	04	15	Zhuang	18	03	–	–	Lost	Last	Last	Last	
05	1,275	–668	05	27		25	06	Xinwei[8]	Shuo				2nd	
06	1,278	–667	11	10		26	12	Guihai[60]	Shuo				2nd	
07	1,288	–663	08	28		30	09	Gengwu[7]	Shuo					
08	1,311	–654	08	19	Xi	05	09	Wushen[45]	Shuo					
09	1,328	–647	04	06		12	03	Gengwu[7]	–	Lost	2nd	Last		Sunset
10	–	–644				15	05	–	–	Lost	Last	Night	Shuo	Non-eclipse
11	1,383	–625	02	03	Wen	01	02	Guihai[60]	–	Lost	2nd	Last	Shuo	
12	1,419	–611	04	28		15	06	Xinchou[38]	Shuo				2nd	
13	1,449	–600	09	20	Xuan	08	07	Jiazi[1]	–.T	Lost	2nd	Last	2nd	
14	1,452	–598	03	06		10	04	Bingchen[53]	–	Lost	2nd	Last		Sunrise
15	–					17	06	Guimao[40]	–	Lost	2nd	Last	last	Non-eclipse
16	1,516	–574	05	09	Cheng		06	Bingyin[3]	Shuo				2nd	
17	1,519	–573	10	22		17	12	Dingsi[54]	Shuo					
18	1,555	–558	01	14	Xiang	14	02	Yiwei[32]	Shuo				2nd	
19	1,559	–557	05	31		15	08	Dingsi[54]	–	Lost	2nd	Last	2nd	Sunrise
20	1,572	–552	08	31		20	10	Bingchen[53]	Shuo					
21	1,574	–551	08	20		21	09	Gengxu[47]	Shuo					
22	–					21	10	Gengchen[17]	Shuo					Error
23	1,579	–549	01	05		23	02	Guiyou[10]	Shuo				2nd	
24	1,582	–548	06	19		24	07	Jiazi[1]	Shuo.T					Total
25	–					24	08	Guisi[30]	Shuo					Error
26	1,590	–545	10	13		27	12	Yihai[12]	Shuo					

27	1,616	–534	03	18	Zhao	07	04	Jiachen[41]	Shuo	
28	1,636	–526	04	18		15	06	Dingsi[54]	Shuo	
29	1,642	–524	08	21		17	06	Jiaxu[11]	Shuo	2nd
30	1,652	–520	06	10		21	07	Renwu[19]	Shuo	2nd
31	1,655	–519	11	23		22	12	Guiyou[10]	Shuo	
32	1,659	–517	04	09		24	05	Yiwei[32]	Shuo	2nd
33	1,678	–510	11	14		31	12	Xinhai[48]	Shuo	2nd
34	1,690	–504	02	16	Ding	05	03	Xinhai[48]	Shuo	2nd
35	1,709	–497	09	22		12	11	Bingyin[3]	Shuo	2nd
36	1,717	–494	07	22		15	08	Gengchen[17]	Shuo	
37	1,751	–480	04	19		14	05	Gengshen[57]	Shuo	2nd

[a]The first column is the serial number; the second shows the Oppolzer number; the third is the Julian year, month, and day; the fourth is the Chinese Duke, year, month and day of the Chunqiu Period; the fifth lists when shou is mentioned, and T = total; the sixth, seventh and eighth columns represent the understanding of the target eclipses according to the *Zuoshi-zhuan*, *Gongyang-Zhuan*, and *Guliang-zhuan*; the ninth column shows the interpretation according to Liuxin; and the tenth column shows Watanabe's interpretation

> The Guliang-zhuan says that the record talks of ‘shuo’, but it does not mention the ganzhi day, hence the eclipse took place on the second day of the month.
>
> (04) Duke Yan, 18th year, 3rd month. The sun was eclipsed.
>
> The Guliang-zhuan says that the record does not give the ganzhi day, and does not give ‘shuo’, hence it took place in the evening. The present historian (historian of the Hanshu) guesses that the conjunction of the Sun and Moon was on the night of the first day of the month, and the next morning, the Sun rose being eclipsed by the Moon, and after sunrise, the eclipse was over. The Gongyang-zhuan says that the eclipse was on the last day of the month. (Hanshu 1962: Volume 27).

In the above, (01), (03) and (04) denote the serial number of data in Table 1. Duke Yan in (04) is also called Duke Zhuang.

Now at this point we summarize what three Zhuans thought of the target eclipses. From (01), if the ganzhi day is mentioned and shuo is lacking, the eclipse was taken to be one which occurred on the last day of the month in the *Guliang-zhuan*, whereas in the *Gongyang-zhuan* it was taken to be on the second day of the month.

From (03), if shuo is mentioned and the ganzhi day is not, the eclipse was taken to be one which occurred on the second day of the month in the *Guliang-zhuan*. From (04), it was taken to be on the last day of the month in the *Gongyang-zhuan*.

In the case of the *Guliang-zhuan*, an eclipse with neither shuo nor the cyclic day number mentioned was considered to be a night eclipse. In the *Guliang-zhuan*, it was taken to be an eclipse on the last day of the month. These interpretations are listed in the seventh and eighth columns of Table 1.

In the case of the *Zuoshi-zhuan*, there is a comment only on the data of (01). The *zhuan* says that data with shuo but without a ganzhi day result from the fact that Royal Astronomers forgot to record them.

The Hanshu (1962) summarizes Chunqiu eclipses as follows:

> There were 12 Dukes in the Chunqiu Period, and the Period continued for 242 years, during which there were 36 solar eclipses. The *Guliang-zhuan* calculates that there were 26 eclipses on the first day of the month, 7 eclipses on the last day, 2 were night-time eclipses and one was on the second day. The *Gongyang-zhuan* calculates that there were 27 eclipses on the first day of the month, 7 eclipses on the second day, and 2 were on the last day. The *Zuoshi-zhuan* calculates that there were 16 eclipses on the first day of the month, 18 eclipses on the second day, one was on the last day, and 2 were without cyclic day number. [Our English translation is from the Japanese translation by Kotake (1997).]

It seems that the number of eclipses on the first day in the *Zuoshi-zhuan* is too small. The problem posed by the above summary is related to the calendar system of the Chunqiu Period. The *Gongyang-zhuan* and *Guliang-zhuan* followed a definite rule for second-day eclipses, last-day eclipses, and night-time eclipses. Our purpose is to obtain a clear-cut conclusion on the astronomical logic behind this rule (Figure 1).

Churyo Noda and Kiyoshi Yabuuti (1947) introduced the public to the calculation of Liuxin in the Hanshu, and we list it in the eighth column in Table 1. Toshio Watanabe (1958) calculated the time of the day of the Chunqiu eclipses based upon the theory of Schoch (1927). From this calculation, he concluded that eclipses (01), (14), and (19) were at sunrise, while eclipse (09) was at sunset. Eclipse (04) was

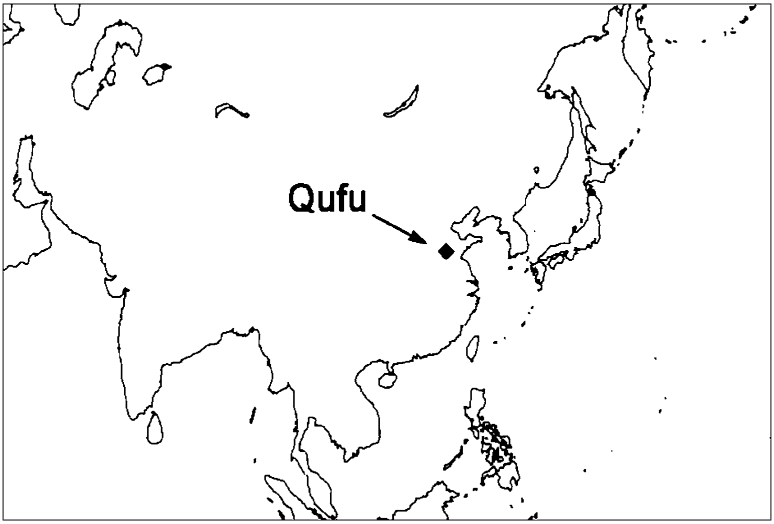

Fig. 1 The position of Qufu.

almost at sunset according to the same calculation. However, Watanabe does not say anything about this eclipse. Later, Kuniji Saito and Kenji Ozawa (1992) added eclipse (04) to the list of eclipses at sunset. In addition, they added eclipse (22) to the same list by changing the date from Duke Xiang, 21st year, 10th month, day gengchen [17], shuo to Duke Xiang, 26th year, 10th month, day gengchen [17], the last day of the month. Stephenson and Yau (1992) introduced the Chunqiu to an English-speaking audience. They compared the ΔT of the Chunqiu eclipses with the parabolic curve of long-term variations in ΔT obtained from Babylonian-timed lunar eclipses, and confirmed the results of the previous authors as to the reliability of eclipse records.

In this present paper, we treat eclipses (01), (04), (09), (14) and (19) using the method we developed, and decide whether these were eclipses at sunrise or sunset, and with these results, obtain better ranges for ΔT. In Sect. 5, we discuss the remaining target eclipses and the meaning of our results.

2.2 Target Eclipses and Observing Sites

There are ten 'target eclipses' in Table 1, and we list them anew in Table 2.

In what follows we do not treat all of these eclipses. Our actual targets are eclipses (01), (04), (09), (14) and (19). We will explain in Sect. 5 why we do not consider eclipses (03), (10), (11), (13) and (15).

Table 2 List of target eclipses[a]

No.	Oppol. number	Julian date Year	Month	Day	Chunqiu period Duke	Year	Month	Day	Shuo?	Watanabe & Wangtao
01	1,147	–719	02	22	Yin	03	02	Jisi[6]	–	Sunrise
03	1,211	–694	10	10	Huang	17	10	–	Shuo	
04	1,257	–675	04	15	Zhuang	18	03	–	–	Sunset
09	1,328	–647	04	06	Xi	12	03	Gengwu[7]	–	Sunset
10		–644			Xi	15	05	–	–	Non-eclipse
11	1,383	–625	02	03	Wen	01	02	Guihai[60]	–	
13	1,449	–600	09	20	Xuan	08	07	Jiazi[1]	–.T	Mag. 0.87
14	1,452	–598	03	06	Xuan	10	04	Bingchen[53]	–	Sunrise
15					Xuan	17	06	Guimao[40]	–	Non-eclipse
19	1,559	–557	05	31	Xiang	15	08	Dingsi[54]	–	Sunrise

[a] The first column is the Chunqiu serial number; the second shows the Oppolzer number; the third is the Julian year, month, and date; the fourth is the Chinese Duke, year, month, day of the Chunqiu Period; the fifth lists when shuo is mentioned, and T = total; and sixth column lists the interpretations of Watanabe (1958) and Wangtao (see Shinjo 1928)

3 Preparations

In Sect. 4 we make our calculations for the individual eclipses and obtain the ranges of ΔT. Here we prepare for that calculation. We assume that all eclipse observations were made at Qufu, the capital of Lu. Watanabe (1958: 351) suggests that eclipse (13) (Duke Xuan reign period, 8th year, 7th month) might have been observed at a place other than Qufu because the magnitude was 0.87 according to his calculation, based on Schoch's theory. This might be possible. However, if we admit variable observing sites, then one more free parameter is added. We do not consider this possibility, and for the purpose of this investigation fix on Qufu as the observing site.

We now introduce the Sôma Diagram. We take as the abscissa the value of the LTA or its correction to the present value (unit: arcsec/century^2), and take as the ordinate the value of ΔT (unit: sec). We plot on this plane the curves of the boundary of total eclipse(s) observed at sites of known positions. It is cumbersome to give this figure a name based on its properties so we simply call it the 'Sôma Diagram'. The positions on the Earth's surface of the total eclipse band of an eclipse depend on these parameters. The present value of the lunar tidal acceleration is –25.83″ cy^{-2}. The utility of the Sôma Diagram is that contemporaneous eclipses can be expressed in the same figure and the possible ranges of LTA and ΔT are obtained as the intersections of multiple bands.

According to Sôma, Tanikawa and Kawabata (2004) the present value of the LTA may be consistently extended to the past 2,000 years. Basically, in the present work we adopt the present value. Nevertheless, our analysis shows that there is uncertainty of 1″/cy^2. So, we keep in mind that the value of the LTA is still uncertain within this error, and always use the Sôma Diagram for confirmation.

The method adopted in the present paper has been developed in Tanikawa and Sôma (2002, 2004a, b), and in Sôma, Tanikawa and Kawabata (2004). In this method, multiple phenomena are used to simultaneously determine the range of ΔT for the year or years of observation. In the present paper, the eclipses which will be the object of analysis are called *target eclipses*, and the other contemporaneous eclipses will be called *auxiliary eclipses*. Auxiliary eclipses do not necessarily exist in close temporal proximity to the target eclipse. Here we estimate the errors due to the difference in years of observation. We use as a reference the curves proposed by Stephenson (1997):

$$\Delta T = 31 \times ((\text{year} - 1820)/100)^2 - 20\text{s}. \quad (2)$$

According to this formula, ΔT decreases by 15 s/year on average from 700 to 500 BC. We adopt this value to estimate the errors in the ΔT obtained. It is to be noted that if we use an auxiliary eclipse observed n years earlier or later, then the errors are $n \times 15$ s.

An intuitive explanation of the effect of ΔT is that if ΔT increases the eclipse band shifts to the east, while if ΔT decreases the eclipse band shifts to the west. On the other hand, the effect of the difference in LTA is difficult to explain intuitively. However, basically the eclipse band moves to the west if the correction to the adopted acceleration is positive, and to the east otherwise.

We explain what the *eclipse at sunrise* and the *eclipse at sunset* at Qufu is by using Figure 2. If the observation site lies in the region bounded by curve ADCE in the figure, the Sun rises eclipsed. If, in addition, the site is to the right of arc ABC, the maximum obscuration is observable, whereas if the site is to the left, the maximum obscuration takes place below the horizon. If the observation site is in the region bounded by curve HKJL, the Sun sets while eclipsed. If, in addition, the site is to the left of arc HIJ, the maximum phase of eclipse can be observed, whereas if the site is to the right of the arc, the maximum obscuration takes place below the horizon.

In determining the range of ΔT using the supposed sunrise eclipses or sunset eclipses, we have some remarks to make. In the case of an eclipse at sunrise, the upper limit to ΔT is rather strictly fixed because for a larger ΔT the eclipse ends when the Sun is fully risen. The lower limit of ΔT is not so clear cut. In the case of a sunset eclipse, the situation is reversed.

If the eclipse takes place in the arctic region, either arc AFH or arc CGJ degenerate into a point (see the lower panel of Figure 2). In these cases, some subtlety is present, but we will not go into the details.

Since all of the target eclipses were surely observed, the cases in which the Sun rises after the eclipse or the eclipse starts after sunset will not be considered further here.

4 Individual Eclipses

In this section we carry out an analysis of the individual eclipses, in chronological order. There are two eclipse records which are not from China (see Table 3), and these represent very useful independent observations. In Table 4 we list the observation sites, together with their latitudes and longitudes.

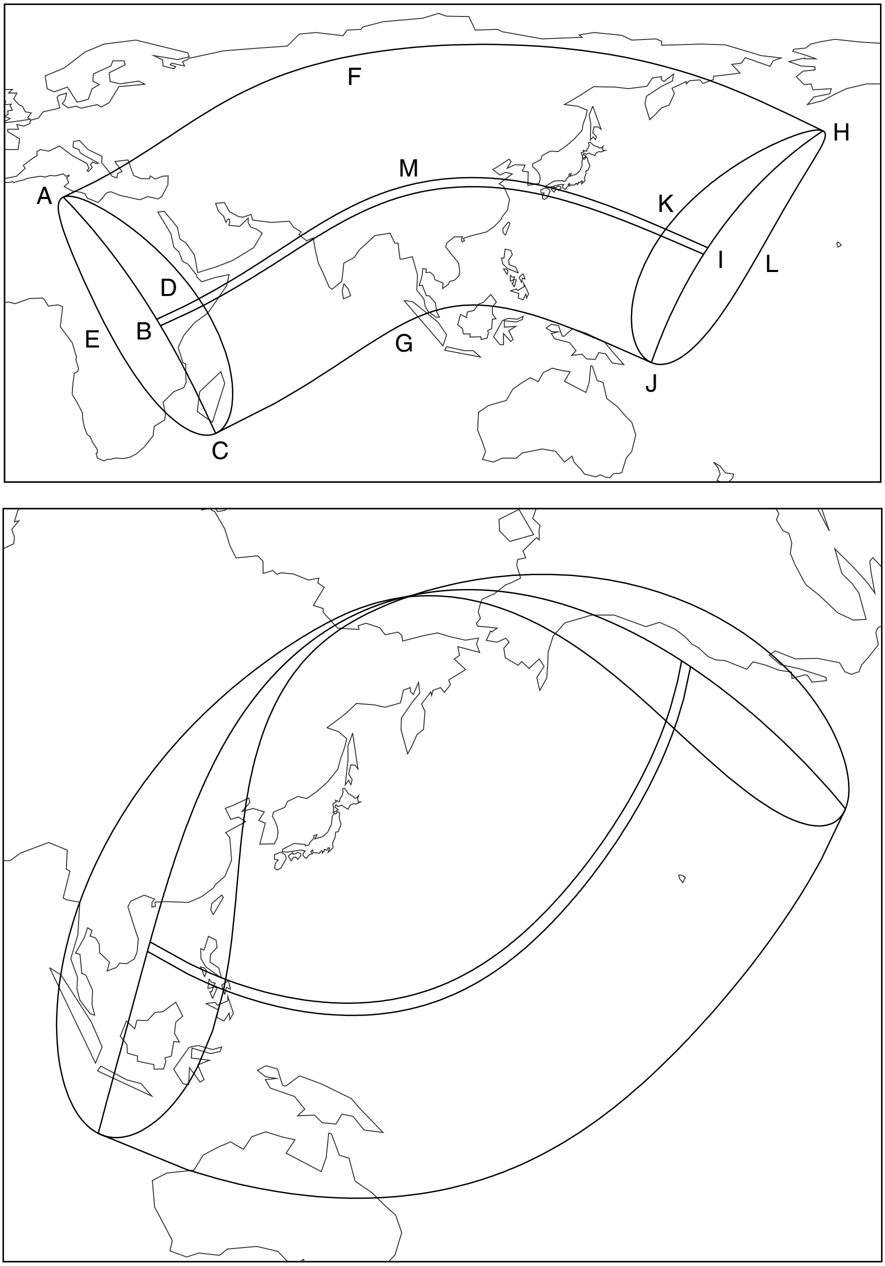

Fig. 2 Shadow of the Moon. The *upper panel* shows the eclipse band for a general eclipse at low latitude, while the *lower panel* shows a general eclipse at high latitude. The eclipse takes place at sunrise if the observation site is in a region bounded by curve ADCE, whereas the eclipse takes place at sunset if the observation site is in a region bounded by curve HKJL. The band BDMKI shows the sites for a total eclipse.

Table 3 Auxiliary eclipses observed at places other than China

	Julian date			
Opp. no.	Year	Month	Day	Remarks
1,328	–647	4	6	Total either at Paros or Thasos. Eclipse (09)
1,489	–584	5	28	Total at Pteria

Table 4 Observation sites

Place	East Longitude (°)	North latitude (°)	Remarks
Qufu	117.02	35.53	Capital of Lu
Paros	25.10	37.07	Island in the Aegean sea
Thasos	24.70	40.77	Island in the Aegean sea
Pteria	34.23	39.77	Asia Minor

Table 5 Target and auxiliary eclipses for 22 February –719

		Julian date			Chunqiu period					
No.	Category	Year	Month	Day	Duke	Year	Month	Day	Shuo?	Comment
01	Target	–719	02	22	Yin	03	02	Jisi[6]		
02	Auxiliary	–708	07	17	Huan	03	07	Renchen[29]	Shuo	Total eclipse

4.1 The Sunrise Eclipse of 22 February –719

As shown in Table 5, the record of the target eclipse lacks any mention of shuo. The auxiliary eclipse is considered to be total at Qufu. The two eclipses were observed 11 years apart, so the errors of our estimates amount to 165 s.

The range of ΔT is given as a function of the LTA. We could provide a table of the data. However, we are afraid that our paper may then become too long, so we omit the table and only show the range in the figures.

Figure 3 shows how to determine the ranges of ΔT and the LTA (or its correction to the present value). As we pointed out above, the two eclipses are 11 years apart, so errors of ±165 s should be taken into account. The band for the target eclipse covers the band for the total eclipse over a wide range of LTA. In particular, it is true if the absolute value of the correction to the LTA is less than $1''/\mathrm{cy}^2$. This means that as long as the auxiliary eclipse was total, the target eclipse was an eclipse at sunrise. We adopt the range of ΔT for the present value of the LTA (in Figure 3, this corresponds to zero for the abscissa value), so the range is

$$20{,}153\ \mathrm{s} < \Delta T < 21{,}094\ \mathrm{s}.$$

In addition, the range is below the central dotted curve, which means that the maximum obscuration was observed after sunrise.

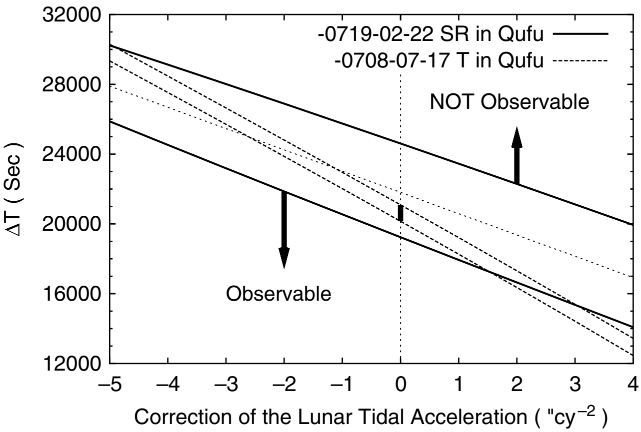

Fig. 3 The Sôma Diagram for the target eclipse of 22 February –719. The *band with solid curves* is for the sunrise eclipse on 22 February –719, and the *band with dotted curves* is for the total eclipse on 17 July –708. The *vertical thick line* indicates the candidate range of ΔT.

4.2 The Sunset Eclipse of 15 April –675

As seen in Table 6, we have four auxiliary eclipses within 20 years of the observed date of the target eclipse. The four eclipses were all partial because the word 'total' is missing. So, in the Sôma Diagram, candidate areas are out of the bands for a total eclipse. The resulting Sôma Diagram is shown in Figure 4.

The candidate areas are between thick parallel lines and out of several parallel curves. Adopting the present value of the LTA, we have two separate ranges of ΔT as shown by the two thick lines in Figure 4.

$$15{,}810\ \text{s} < \Delta T < 17{,}193\ \text{s or } 18{,}526\ \text{s} < \Delta T < 20{,}686\ \text{s}$$

Let us check which of these ranges is appropriate. We obtain the range of ΔT for year –708 of $20{,}153\ \text{s} < \Delta T < 21{,}094$ s. The time difference is 30 years. Thus the difference in ΔT may be at most 500 s. Then the second range is preferable since otherwise we need to consider a 4,000 s jump over 30 years.

The auxiliary eclipse in –654 gives almost the same condition for ΔT as the eclipse in –668 for the zero correction to the LTA. Then we can dispense with the eclipse in –654. In this case, the maximum time difference becomes 12 years and the results become more reliable.

As a conclusion, we obtain as the candidate range of ΔT:

$$18{,}526\ \text{s} < \Delta T < 20{,}686\ \text{s}.$$

This range is consistent with ranges obtained from other target eclipses. This means that the probability that the eclipse was at sunset is very high.

Table 6 Target and auxiliary eclipses for15 April –675

		Julian date			Chunqiu period				
No.	Category	Year	Month	Day	Duke	Year	Month	Day	Shuo?
04	Target	–675	04	15	Zhuang	18	03		
05	Auxiliary	–668	05	17	Zhuang	25	06	Xinwei[8]	Shuo
06	Auxiliary	–667	11	10	Zhuang	26	12	Guihai[60]	Shuo
07	Auxiliary	–663	08	28	Zhuang	30	09	Gengwu[7]	Shuo
08	Auxiliary	–654	08	19	Xi	05	09	Wushen[45]	Shuo

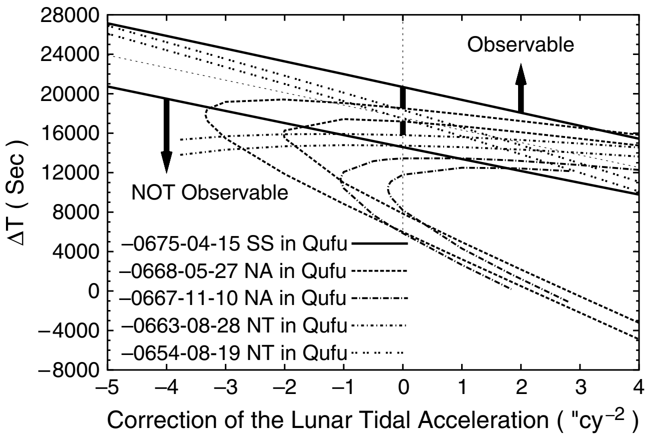

Fig. 4 The Sôma Diagram for the target eclipse 15 April –675. The *band with solid curves* is for the sunrise eclipse on 15 April –675, and the *band with dotted curves* is for the total eclipse on 17 July –708. The *vertical thick line* indicates the candidate range of ΔT. *Dashed lines* are for the annular eclipse of 27 May –668, *dot-long dash lines* are for the annular eclipse of 10 November –667, *dot-short dash lines* are for the total eclipse of 28 August –663, and *dotted lines* are for the total eclipse of 18 August 654. The *thick vertical intervals* are the candidate ranges of ΔT.

4.3 The Sunset Eclipse of 6 April –647

Table 7 lists two auxiliary eclipses. Eclipse (08) was already used in the preceding subsection. The other one is the record of an eclipse observed either in Paros or Thasos (see Figure 5). Both are cities on islands in the Aegean Sea. The most interesting feature of the eclipse is that it was observed in both China and Greece.

The eclipse was recorded in an undated poem of Archilochus. We need to identify this eclipse with the one in Oppolzer's canon. Fortunately, according to Fotheringham (1920), the poet was known to have been in Paros or Thasos on the day of eclipse. Newton (1970) and Stephenson (1997) listed several eclipses as candidates, and Stephenson (ibid.) calculated ΔT for them. He had no definite criterion to choose one above the others. He concluded that in either Paros or Thasos, a total solar eclipse took place, and selected the eclipse of 6 April –647 as the most probable candidate. Our conclusion is more definite.

The corresponding Sôma Diagram is shown in Figure 6. It is apparent that we could not have had a total eclipse at both Paros and Thasos. At zero correction to the

Table 7 Target and auxiliary eclipses for 6 April –647

		Julian date			Chunqiu period					
No.	Category	Year	Month	Day	Duke	Year	Month	Day	Shuo?	Comment
09	Target	–647	04	06	Xi	12	03	Gengwu[7]		
	Auxiliary	–647	04	06						Total at Paros or Thasos
08	Auxiliary	–654	08	19	Xi	05	09	Wushen[45]	Shuo	

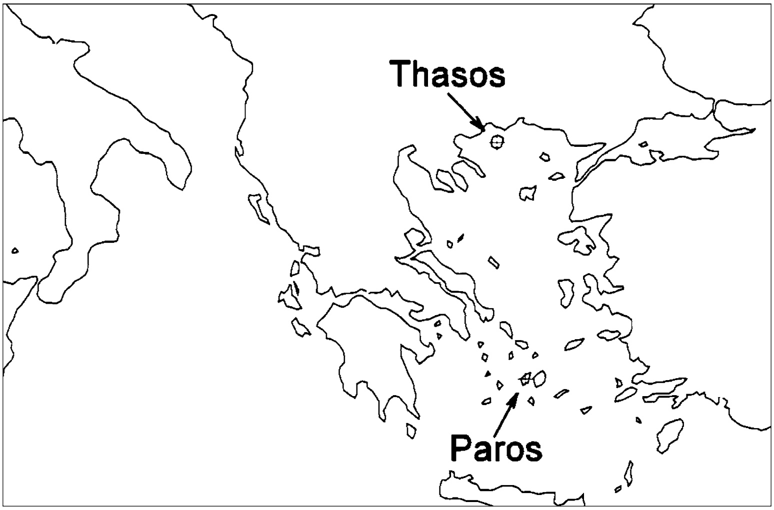

Fig. 5 The positions of Paros and Thasos.

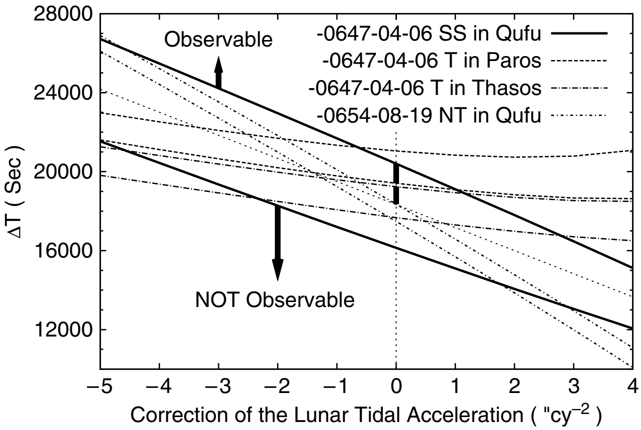

Fig. 6 The Sôma Diagram for the target eclipse 6 April –647. The *band with solid lines* is for the eclipse on 6 April –647 at Qufu. The *dashed band* is for Paros, the *dot-dash line* is for Thasos, and the *band with dot-short dash* is for the eclipse on 19 August –654 at Qufu. The *vertical thick lines* show the candidate ranges of ΔT.

present LTA, we have two separate ranges of ΔT. If we adopt Thasos, then we can impose an additional restriction on the range of ΔT for an eclipse that was not total at Qufu in –654. The two ranges are

$$19{,}409 \text{ s} < \Delta T < 20{,}402 \text{ s for Paros}$$
$$18{,}353 \text{ s} < \Delta T < 19{,}235 \text{ s for Thasos}$$

In either case, the target eclipse satisfies the sunset condition. In addition, both cases are plausible. We cannot say which is a better candidate.

4.4 The Sunrise Eclipse of 6 March –598

As shown in Table 8, we have two auxiliary eclipses within 16 years. The record says that eclipse (13) was total, but Watanabe (1958) says that it was not. The total eclipse in –584 at Asia Minor was a famous eclipse which was said to have been predicted by Thales. Although Stephenson (1997) does not specify the observation site, Özel, and Kacar (2007) say that it was Pteria (see Figure 7), and we adopt this idea.

Table 8 Target and auxiliary eclipses for 6 March –598

		Julian date			Chunqiu period					
No.	Category	Year	Month	Day	Duke	Year	Month	Day	Shuo?	Comment
14	Target	–598	03	06	Xuan	10	04	Bingchen[53]		
13	Auxiliary	–600	09	20	Xuan	08	07	Jiazi[1]	Shuo	
	Auxiliary	–584	05	28						Total at Pteria in Asia minor

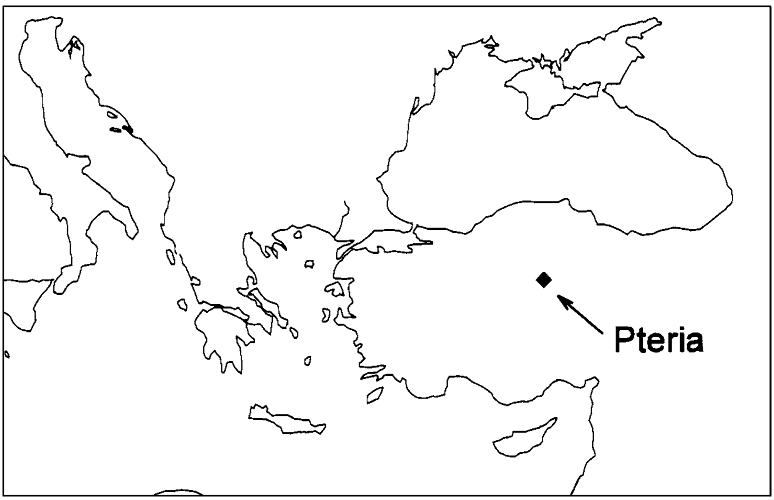

Fig. 7 The position of Pteria.

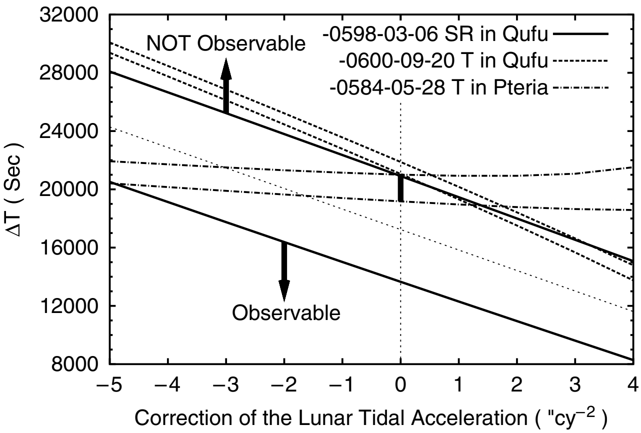

Fig. 8 The Sôma Diagram for the target eclipse 15 April –598. The *band with solid lines* shows the sunrise eclipse of 6 March –598 at Qufu. The *band with dashed lines* is for the total eclipse on 20 September –600 at Qufu. The *band with dot-long dash lines* is for 28 May –584 at Pteria. The *vertical interval* is the candidate range of ΔT.

We give the corresponding Sôma Diagram in Figure 8. As seen in the figure, the range for the target eclipse and the range for eclipse (13) do not overlap for zero correction to the LTA. This means if the eclipse was total in –600, then the eclipse in –598 could not have been observed since the eclipse took place just below the horizon. Conversely, if the eclipse in –598 was observable at sunrise, then the eclipse in –600 was not total at Qufu but almost total. The eclipse in –598 was surely observed. So we consider that the eclipse in –600 was not total but almost total. This idea is strengthened if we add the eclipse observed at Pteria to the figure. In fact, the total eclipse band of this eclipse at Pteria overlaps the sunrise condition for the eclipse in –598. The errors are about 250 s due to the time difference of 16 years.

Let us consider the possibility that three eclipses were observed as the records tell us. In order for this to happen, the bands for –598 and –600 must overlap. If we move to the right in Figure 8, that is, if we take the correction to larger LTA, this can be realized. However, the eclipse band for (24) superimposed in Figure 9 indicates that the correction should be less than $1''/\mathrm{cy}^2$ in order for this eclipse to have been total at Qufu. The overlap is negligibly small. The correction to the LTA has little effect in this case.

The eclipse in –647 satisfies the condition of zero correction to the LTA. This also strengthens our conclusion. Another possibility is that the observation site may have been different. We do not have any information on this, so we ignore this case. We may conclude that the eclipse in –600 was not total in Qufu.

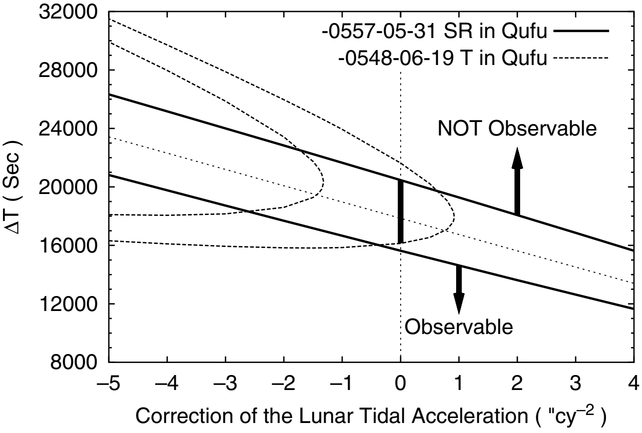

Fig. 9 The Sôma Diagram for the target eclipse 15 April –598. For reference, the total eclipse band for the eclipse of 18 June –548 is added (a folded band in the figure) to Figure 8.

Table 9 The maximum magnitude of the eclipse on 20 September –600 at Qufu

ΔT	Maximum magnitude
20,910	0.99156
19,172	0.90211

If the correction to the LTA is zero, the eclipse in –600 was almost total, and the eclipse in –584 was total at Pteria, then the range of ΔT is given by

$$19{,}172\ \mathrm{s} < \Delta T < 20{,}910\ \mathrm{s}$$

The maximum magnitude of the eclipse of 20 September –600 at Qufu is given in Table 9. The eclipse at Pteria can be considered total. This is consistent with the sunrise eclipse of Qufu.

4.5 The Sunrise Eclipse of 31 May –557

As shown in Table 10, there were two auxiliary eclipses within 9 years. According to the records, eclipse (24) was total, whereas eclipse (23) was partial. The corresponding Sôma Diagram is shown in Figure 10.

According to Figure 10, the intersection of the eclipse bands of the target eclipse and total eclipse is rather large due to the form of the eclipse band of eclipse (24).

Table 10 Target and auxiliary eclipses for 31 May –557

		Julian date		Chunqiu period						
No.	Category	Year	Month	Day	Duke	Year	Month	Day	Shuo?	Comment
19	Target	–557	05	31	Xiang	15	08	Dingsi[54]		
23	Auxiliary	–668	05	17	Xiang	23	Spring	Guiyou[10]	Shuo	
24	Auxiliary	–667	11	10	Xiang	24	07	Jiazu[1]	Shuo	Total eclipse

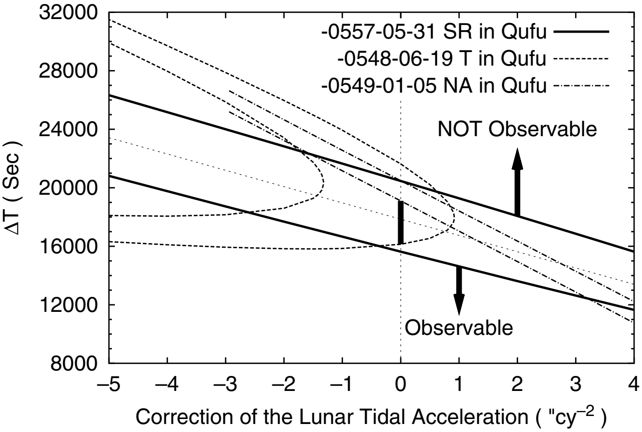

Fig. 10 The Sôma Diagram for the target eclipse 31 May –557. The *band with solid lines* shows the sunrise eclipse of 31 May –557 at Qufu. The *band with dashed lines* is for a total eclipse on 19 June –548 at Qufu. The *band with dot-long dash lines* is for 5 January –549 at Qufu. The *vertical interval* is the candidate range of ΔT.

As before, the zero correction to the LTA is included in the area. That the correction should be less than $1''/\text{cy}^2$ was already mentioned before. The non-totality of eclipse (23) gives an additional restriction to the range of ΔT. We, as before, adopt the range of ΔT for zero correction to the LTA as

$$16{,}134\ \text{s} < \Delta T < 19{,}101\ \text{s}.$$

4.6 The ΔT Curve

Let us compare our ranges of ΔT with those found by Stephenson (1997) and in Equation (2) in Sect. 3. Figure 11 shows that the two results almost coincide. However, it is apparent that the change of ΔT is not along a parabolic curve. We already pointed out in several places that there can be variations of shorter period in the ΔT curve. The enlargement in the lower panel in Figure 11 shows that if we adopt Thasos, ΔT approaches Stephenson's value, whereas if we adopt Paros the value deviates from his value.

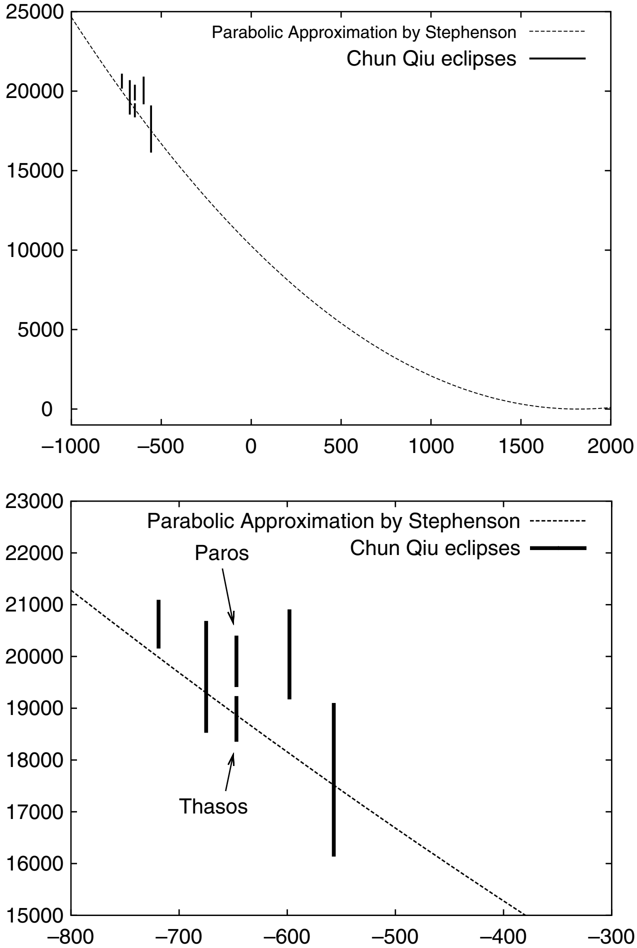

Fig. 11 Long-term variations of ΔT. The present results and Stephenson's curve. The *lower panel* shows an enlargement.

5 Discussion

5.1 Other Eclipses Which Lack Some Information

There are five remaining eclipses which lack information on the date or shuo. These are eclipses (03), (10), (11), (13) and (15) in Tables 1 and 2. Let us examine these eclipses one by one.

Eclipse (03) took place on 10 October –694. Watanabe (1958) considers that the cyclic day number was simply missed. According to our calculation, this eclipse occurred at sunset for ΔT = 17,000 s. This value is inconsistent with the ranges of ΔT given by eclipses on 22 February –719 and on 15 April –675, though they were close to the sunset eclipse.

Eclipse (10) is judged to be a non-eclipse by Watanabe because no corresponding Oppolzer eclipse exists. Saito and Ozawa (1992) changed the date to 7 June –650, and suggested that this eclipse was at sunset. We confirm this with the range of ΔT similar to that for eclipse (09).

Eclipse (11) took place on 3 February –625. The record has shuo in the *Gongyang-zhuan*. Our calculation says that this eclipse was neither at sunrise nor at sunset. According to Shinjo (1928: 250), an old version of the *Gongyang-zhuan* has no shuo for this eclipse. If so, it would be very interesting to know why shuo was added to the record in later years.

Eclipse (15) does not have a corresponding Oppolzer eclipse. According to Shinjo (1928: 284; our translation), Wangtao of the late Qing Dynasty considered that the record should read "Duke Xuan reign period, 7th year, 6th month, guimao [40], shuo" instead of "Duke Xuan reign period, 17th year, 6th month, guimao [40]":

> Wangtao says that the record is the mis-location of the eclipse of the Duke Xuan reign period, 7th year, 6th month, guimao [40], shuo (May 8, –601). According to calculation, there was an eclipse on that day in China, but I do not like to revise the record by changing the year of the record.

Shinjo was not sympathetic to this alteration. Let us examine whether this eclipse was either at sunrise or sunset. Figure 12 shows the result. The figure is almost the

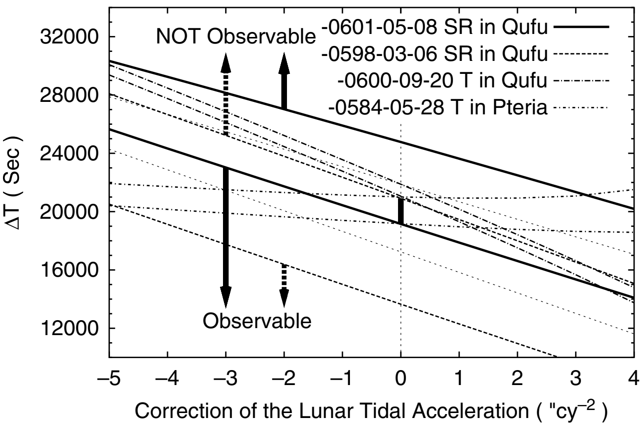

Fig. 12 The Sôma diagram for the target eclipse 8 May –601. The *band with solid lines* shows the sunrise eclipse of 6 March –598 at Qufu. The *band with dashed lines* is for total eclipse on 20 September –600 at Qufu. The *band with dot-long dash lines* is for 28 May –584 at Pteria. The *vertical interval* is the candidate range of ΔT.

same as the figure in Sect. 4.4 for eclipse (14). The figure strongly suggests that the eclipse was at sunrise. Therefore, Wangtao's alteration is justifiable.

As a tentative conclusion, we may say that eclipses without the word shuo were eclipses at sunrise or sunset. There are only two exceptions among nine: eclipse (11) and (13). Eclipse (13) was described as total.

5.2 Paros or Thasos

Stephenson (1997: 341) found several candidates for the eclipse versified by Archilochus taking into account previous research. Apart from the eclipse on 6 April –647, he listed eclipses on 28 July –690, 15 April –656, 8 September –645, and 29 August –636 which were seen as total at Paros or Thasos, and gave the range of ΔT.

These four additional eclipses give quite different ranges of ΔT. So we conclude that these were not the eclipse Archilochus saw. Newton (1970) listed eclipses on 11 January –688, 12 January –661, 27 January –660, and 15 April –656. Among them, the eclipse on 11 January, –688 gives us a wide range of ΔT. Stephenson (1997) omitted this eclipse because it was annular. The remaining eclipses do not give appropriate ranges of ΔT. Thus, the eclipse on 6 April –647 is the unique candidate for the eclipse of Archilochus.

5.3 Relations Between Lack of Data and Sunrise or Sunset

Starting from the fact that there was almost no lack of data in the latter half of the Chunqiu records, Shinjo (1928) discusses the setting up of the Chinese calendar system in this era. According to our calculation, however, eclipses of the latter half of the Chunqiu Period happened at neither sunrise nor sunset. This may mean that the lack of information was not related to the setting up of the calendar system.

The *Gongyang-zhuan* and *Guliang-zhuan* recorded our eclipses at sunrise or sunset as eclipses on the last day of the month or on the second day of the month. This may be important for reconstructing the calendar system of the Chunqiu Period. The problem is whether dusk or dawn belongs to today, tomorrow or yesterday. In Volume 7, Wuxing-zhi, Volume 27 of the Hanshu (1962), there is a record: Duke Yan reign period, 18th year, 3rd month, eclipse (eclipse (04) in Table 1). It is written: "The historian guesses that the conjunction was at night. The next day, the Sun rose eclipsed, and the eclipse finished after sunrise. This is said to be a night eclipse." The historian of the Hanshu interpreted the night eclipse in the *Guliang-zhuan* as an eclipse at sunrise. The historian did not consider the possibility that the eclipse was at sunset. In fact, this was a sunset eclipse.

The terms 'eclipse at sunrise' and 'eclipse at sunset' appeared in the *Xin-Wudaishi*. However, it is clear that the notion already existed during the Hanshu Period. Even the *Guliang-zhu*an might have called an 'eclipse at sunrise' or 'eclipse at sunset' a night eclipse. In that case, modern usage of ‘night eclipse’ meaning an eclipse which takes place on the night side of the Earth may be different from the historical usage.

6 Conclusions

In the present paper we have taken solar eclipse records with no mention of shuo or the day of the 60-day cycle, or both, calculated the ranges of ΔT given by these eclipses, and checked whether Watanabe’s supposition that these were eclipses at sunrise or sunset is true, and obtained narrower ranges of ΔT compared with previous studies.

We have several results.

1. The following eclipses were eclipses at sunrise or sunset at Qufu, the capital of Lu:

   Sunrise
   –719 02 22
   –598 03 06
   –557 05 31

   Sunset
   –675 04 15
   –647 04 06

2. We obtain narrower ranges of ΔT by incorporating near-contemporaneous eclipses. We give here the following ranges of ΔT assuming the present value for the lunar tidal acceleration:

   –719: $20{,}153\ \text{s} < \Delta T < 21{,}094\ \text{s}$
   –675: $18{,}526\ \text{s} < \Delta T < 20{,}686\ \text{s}$
   –647: $19{,}409\ \text{s} < \Delta T < 20{,}402\ \text{s}$ for Paros
   $18{,}353\ \text{s} < \Delta T < 19{,}235\ \text{s}$ for Thasos
   –598: $19{,}172\ \text{s} < \Delta T < 20{,}910\ \text{s}$
   –557: $16{,}134\ \text{s} < \Delta T < 19{,}101\ \text{s}$

   Note that there are two different candidate ranges of ΔT for the year –647.
3. In the present paper, we use auxiliary eclipses to narrow the candidate range of ΔT. There is no doubt that total eclipses are most useful. However, data such as ‘non-total’, ‘at sunrise’, and ‘at sunset’ turn out to be useful in some cases.
4. We have again confirmed that the correction to the LTA is less than $\pm 1''/\text{cy}^2$ in Figure 10.
5. The lack of data in the records of eclipses turns out to have an important meaning. In particular, the lack of shuo corresponds to eclipses at sunrise or sunset, but the lack of the ganzhi is not important. As a result, the change from “Duke Xuan, 17th year, 6th month, day guimao[40]” to “Duke Xuan, 7th year, 6th month, day guimao[40]” seems plausible.

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References

Chapront, J., Chapront-Touzè, M., and Francou, G., 2002. A new determination of lunar orbital parameters, precession constant and tidal acceleration from LLR measurements. *Astronomy and Astrophysics*, 387, 700–709.

Fotheringham, J.K., 1920. A solution of ancient eclipses of the Sun. *Monthly Notices of the Royal Astronomical Society*, 81, 104–126.

Gongyang-zhuan (公羊伝), 1993. Tokyo, Tsurumoto Publishing Company (1993) (in Chinese).

Guliang-zhuan (穀梁伝), 1993. Tokyo, Tsurumoto Publishing Company (1993) (in Chinese).

Hanshu. Beijing, Zhonghua Publishing Company (edited by Bangu, 1962, originally around AD 82) (in Chinese).

Kotake, Takeo (translation), 1997. *Hanshu*. Tokyo, Chikuma-shobo (in Japanese).

Newton, R., 1970, *Ancient Astronomical Observations and the Accelerations of the Earth and Moon*. Baltimore. The Johns Hopkins University Press.

Noda, Churyo, and Yabuuti, Kiyoshi, 1947. *Study of Lizhi of Hanshu*. Osaka, Zenkok-Shobo (in Japanese).

Özel, Mehmet E. and Kacar, Yasemin 2007. Eclipses in Human History: 585 BC Event. In Demiran, O., Selam, S.O., and Albayrak, B. (eds.). *Solar and Stellar Physics Through Eclipses*. San Francisco, Astronomical Society of the Pacific (Conference Series, Volume 370). Pp. 319–323.

Saito, Kuniji, and Ozawa, Kenji, 1992. *Checking Chinese Ancient Astronomical Records*. Tokyo, Yusankaku (in Japanese).

Schoch, K., 1927. *Planeten-tafeln fur jedermann zur berechnung der geozentrischen orter der grossen planeten (und des mondes) fur den zeitraum von 3400 v. Chr. bis 2600 n. Chr. ohne anwendung der logarithmen und trigonometrischen funktionen bis auf ein zehntel grad unter besonderer berucksichtigung der Babylonischen astronomie*. Berlin-Pankow, Linser-verlag g.m.b.h. (in German).

Shinjo, Shinzo, 1928. *Study of the History of Astronomy of East Asia*. Toyo Tenmongaku-shi Kenkyu, Kobundo (in Japanese).

Sôma, M., Tanikawa, K., and Kawabata, K., 2004. Earth's rate of rotation between 700 BC and 1000 AD derived from ancient solar eclipses. In Finbelstein, A., and Capitaine, N. (eds). *Journés 2003: Astrometry, Geodynamics and Solar System Dynamics: from Milliarcseconds to Microarcseconds*. St. Pertersburg, IAA of the Russian Academy of Science. Pp. 122–127.

Stephenson, F.R., 1997. *Historical Eclipses and Earth's Rotation*. Cambridge, Cambridge University Press.

Stephenson, F.R., and Yau, K.K.C., 1992. Astronomical records in the Ch'un-Ch'iu chronicle. *Journal for the History of Astronomy*, 23, 31–51.

Tanikawa, K., and Sôma, M., 2002. Reliability of the totality of the eclipse in AD 628 in Nihongi. *Astronomical Herald*, 95(1), 27–37 (in Japanese).

Tanikawa, K., and Sôma, M., 2004a. On the totality of the eclipse in AD 628 in the Nihongi. *Publications of the Astronomical Society of Japan*, 56, 215–224.

Tanikawa, K., and Sôma, M., 2004b. Delta T and tidal acceleration of the lunar motion from eclipses observed at plural sites. *Publications of the Astronomical Society of Japan*, 56, 879–885.

Watanabe, Toshio, 1958. Eclipses in Chunqiu. In Hitotuyanagi, Juichi (ed.). *Selected Papers for Tosima Araki's 60 years-old Anniversary*. Tokyo, Kouseisha Publishing (in Japanese).

Watanabe, Toshio, 1984. *Canon of Eclipses in Japan, Korea, and China*. Tokyo, Yusankaku Publishing (in Japanese).

Zuoshi-zhuan (左氏伝), 1981. Tokyo, Meiji Shoin Publishing Company, (1981) (in Chinese).

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