Chin. J. Astron. Astrophys. Vol. 3 (2003), No. 6, 569–575
(*http://www.chjaa.org* or *http://chjaa.bao.ac.cn*)

Chinese Journal of
Astronomy and
Astrophysics

A Check on the Variations of Earth's Rotation with an Ancient Solar Eclipse *

Yan-Ben Han and Qi-Yuan Qiao

National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012;
hyb@bao.ac.cn

Received 2003 May 13; accepted 2003 September 29

Abstract We address the relation between an ancient total eclipse, which occurred on A.D.1542 August 11 and the variation of Earth's rotation. The total eclipse was recorded in some ancient Chinese books, especially in local chronicles. Some of the documents include useful information for determining the location of the totality zone. The parameters of the eclipse are calculated by using the DE406 Ephemeris. A high-precision value of ΔT which expresses the variation of the Earth's rotation, of about $300 \sim 380$ s, is obtained.

Key words: solar eclipse — Earth rotation

1 INTRODUCTION

In the study of the secular variation of the Earth's rotation over historical times, observed un-timed records of ancient solar and lunar eclipses have a special significance. Analysis of such records may lead to an evaluation of ΔT, the clock error in Universal Time (UT) due to the variation of the Earth's rotation. Any trend and fluctuation in the rotation may be expected to be counterparted in the time series of ΔT.

However, the requirement of such a study on the observational records is demanding. For the records of central solar eclipses, (total, annular or total-annular), the date, place of observation and details of the eclipse should be clearly recorded. Now, it may happen that for some ancient records where some of the parameters are not recorded completely or clearly enough, we can resort to textual research. Quite a number of eclipses were observed and recorded in historical books but many of them cannot be used because of the lack of such data. Nevertheless some records have been made use of by different authors. A time series of ΔT values spanning the past 2000 years or more, has been obtained (Stephenson et al. 1984, 1992, 1997; Stephenson 1997; Wu et al. 1987; Pang et al. 1988; Han et al. 1984, 1996; Zhang 1994; Zhang et al. 1995, 1997). Of course, we want the number of the records to be used in the study to be as large as possible and the records be distributed in time as evenly as possible. So, we commend that every record be scrutinized carefully and meticulously. Stephenson et al. studied the Chinese

* Supported by the National Natural Science Foundation of China.

record of a total solar eclipse which occurred in A.D.1221, and obtained a significant result (Stephenson 1992).

In the study of ΔT using un-timed records of ancient solar eclipses, the inaccuracy of ΔT comes mainly from the width of totality zone and the precision of defining the observational place. According to Stephenson et al. (1997), for the variation of ΔT in the past 27 centuries, ΔT should be less than about 400s or 300s and more than about 100s from the beginning of 15th century to the end of 16th century. The relative errors of ΔT derived from observations in these two centuries are rather large. It is also difficult to obtain exact results from timed records of eclipses in the 16th and 17th centuries because the precision of clocks was not high enough, the error is about 7.5 minutes (Chen 1983). Eight solar eclipses that occurred in the years 1406, 1415, 1431, 1485, 1560, 1567, 1575 and 1601 have been used in the Stephenson book. The ΔT values obtained from the eclipses are about 170∼740s, –560∼670s, 10∼700s, –5500∼780s, –475∼205s, 145∼165s, –2150∼1390s, and –1460∼3170s, respectively (Stephenson 1997). Only the eclipse of 1567 Apr 9 gave a small error. Stephenson et al. (1997) studied the un-timed observations of the eclipse in Collegio Romano, Roma and obtained a result with high precision. This is an exceptional total-annular eclipse with a very narrow totality zone and the observational place was precisely recorded. This shows that a good result can be obtained if the record has good enough contents.

On 1542 August 11, a total solar eclipse occurred and its totality zone passed over China. The observed data were recorded in Chinese books and, in addition, some detailed descriptions were also recorded in many local chronicles. Because the totality zone of the eclipse was very wide, and the date of occurrence was so recent, the derived relative error of ΔT is quite large. Generally, such a large error makes the data of doubtful usefulness. However, we have found that some of the records include data that can be used for defining the totality zone and for calculating ΔT more precisely, so we consider this eclipse is still valuable and usable for the study.

2 OBSERVATIONS OF THE SOLAR ECLIPSE OF A.D.1542

As is well known, there are many records of solar and lunar eclipses in Chinese historical books. However, most of the records are too brief to be useful. Now, the dates of eclipses can generally be confirmed by the *ganzhi* dates (the ancient Chinese traditional sexagesimal system of day count) but the place of observation is often not so precisely known. Fortunately some detailed accounts of the total solar eclipse were recorded. The distribution of the observational places has itself included useful information, even when the records are not complete. Of the eclipse of A.D.1542 during *Jiajing* reign period (A.D.1522∼1566) of the *Ming* Dynasty, some observations were recorded in both the official dynastic annals and local chronicles, and some data on this eclipse are also found in local chronicles of the following dynasty, the *Qing* Dynasty. These records have been collected and published in recent year (Beijing Astron. Obs. 1988).

Two records in the official annals of the *Ming* Dynasty read:

Jiajing reign period, 21st year, seventh month, day*ji-you* (the 46th day in *Ganzhi* cycle), the 1st day of the lunar month: The Sun was eclipsed [*Ming Shi-Zong Shi-lu*, chap. 264, p1]; The Sun was eclipsed [*Ming history Shi-Zong 1*, chap. 17, p231]. According to the Gregorian calendar the date is 1542 August 11.

In A.D.1421, the capital of the *Ming* Dynasty was moved from Yingtian (Nanjing, today) to Beijing. The documents only said that the sun was eclipsed but did not specify whether the

eclipse was total or not. The official annals would be written in Beijing at the time, but the totality zone did not actually pass the Beijing region.

In later times, 10 other documents about the eclipse of A.D.1542, which give some details of the total or near total eclipse, were collected and published in a number of local chronicles. One was published in the *Lonqing* reign period (A.D.1567∼1572) of the *Ming* Dynasty, four in the *Wanli* reign period (A.D.1573∼1620) of the same dynasty, and another five in the annals of the *Qing* Dynasty (A.D.1644–1911). We note that four of the 10 records say that the sky became dark and stars were seen. These are from the chronicles of Luan, Lingshi, Yizhen (Yizheng at present) and Yixing counties. However, in these four records, the character *Ji* is absent, which is commonly used to describe a total solar eclipse. It is possible that this was a total or a near total eclipse depending on the place of observation. There is one record in *Shanxi Tongzhi*, the local chronicle of Shanxi Province, which includes two sentences, the first says, "the sun was eclipsed, *Ji,*", the second says "stars were seen, the sky was as night in Jiexiu, Xiaoyi, Changzhi, Pingshun, Lucheng, Jiang, Xie and Qinzhou counties" [*Shanxi Tongzhi*, chap. 153, p8]. It is known that these local chronicles collected reports on diverse events from different places in the province, and were written and published by a group of expert officials in the provincial capital. So *Shanxi Tonzhi* should be written and published in Taiyuan, the capital city of Shanxi province during the *Ming* Dynasty. As this solar eclipse did not take place in the remote past, it can be utilized to study the variation of the Earth's rotation rate only if its zone of totality has been determined with high precision.

We have special interest in five other records that contain the character *ji*. They are as follows:

The Sun was eclipsed, *Ji*, the sky became dark at noon, stars were seen, people very short distances apart cannot clearly see one another. [*Wuxiang Xianzhi* (Wuxiang County is in Shanxi Province. *Xianzhi* means the local chronicle of a county), chap. 2, p69];

The Sun was eclipsed, *Ji*. [*Kaifeng Xianzhi* (in Henan Province), chap. 2, p10];

The Sun was eclipsed, *Ji*, the sky became dark and stars were seen, birds flew into woods. [*Yifeng Xianzhi* (local chronicle of Yifeng County, an old county located in the east of Kaifeng, Henan Province), chap. 4, p41];

The Sun was eclipsed, *Ji*, all bright stars were seen. [*Shucheng Xianzhi* (in Anhui Province), chap. 10, p10];

The Sun was eclipsed, *Ji*, the sky became dark and stars were seen. [*Jiaxing Fuzhi* (in Zhejiang Province, *Fuzhi* means chronicle of a prefecture), chap. 2, p14].

Thus, the 10 records contain descriptions on a total or near total eclipse, mentioning some 17 places of observation. The coordinates of these places are listed in Table 1.

3 ACTUAL POSITION OF THE TOTALITY ZONE OF THE ECLIPSE

In our calculation of the parameters of solar eclipses, the positions of the sun and the moon were based on the Planetary and Lunar Ephemerides, DE406, and the uniform time system, Terrestrial Time (TT). We calculated the Bessel elements and the eclipse parameters. DE406 is produced by the Jet Propulsion Laboratory (JPL) of NASA with high precision. For example, the precision of lunar position derived by using DE406 is about 1 m. The results of our calculation of the 1542 eclipse are: time of conjunction of the sun and moon—$4^{\rm h}33^{\rm m}.6$, maximum eclipse magnitude—1.027, beginning and end of total eclipse—$3^{\rm h}12^{\rm m}.8$ and $6^{\rm h}29^{\rm m}.5$ TT. The width of the totality zone was nearly 180 km in Shanxi Province and nearly 190 km

in Zhejiang Province. Through an initial analysis we found that the places of observation were distributed in a band parallel, and similar in width, to the calculated totality zone. Only one of the places, Xie Zhou recorded in *Shanxi Tongzhi*, is far from the other places.

Table 1 Coordinates of Observational Places and Magnitude of the Solar Eclipse of A.D.1542

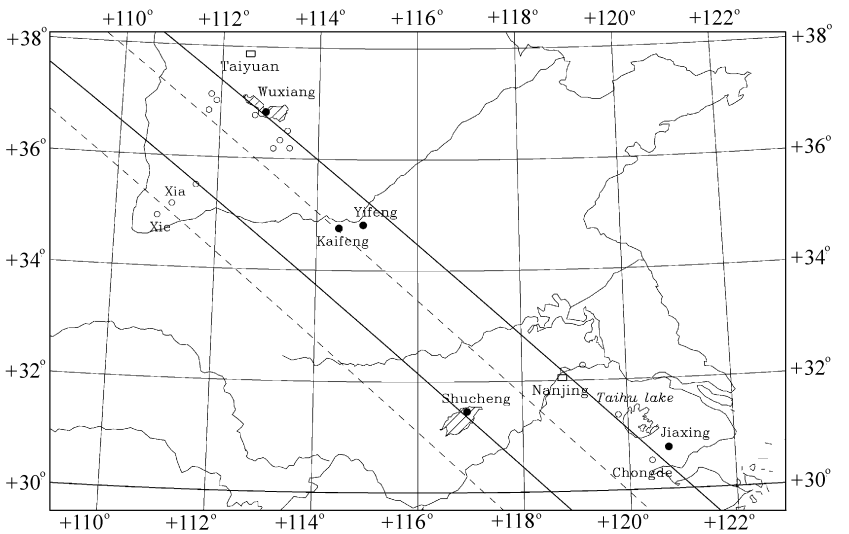
City	Latitude	Longitude	Magnitude for $\Delta T =$		
	(°)	(°)	300s	340s	380s
Beijing	39.90	116.38	0.869	0.872	0.874
Taiyuan	37.87	112.56	0.979	0.982	0.985
Xiaoyi	37.13	111.80	1.010	1.012	1.015
Jiexiu	37.02	111.91	1.010	1.013	1.016
Lingshi	36.84	111.76	1.017	1.020	1.023
Luan	36.18	113.09	1.011	1.014	1.017
Licheng	36.50	113.37	0.999	1.001	1.004
Pingshun	36.19	113.42	1.005	1.008	1.011
Lucheng	36.33	113.22	1.005	1.008	1.011
Qinzhou	36.77	112.70	1.003	1.006	1.009
Wuxiang*	36.83	112.92	0.998	1.001	1.004
Jiang	35.49	111.57	0.999	0.996	0.993
Xie	34.92	110.83	0.972	0.970	0.967
Xia	35.14	111.11	0.983	0.980	0.977
Kaifeng*	34.76	114.44	1.021	1.024	1.026
Yifeng*	34.82	114.92	1.011	1.014	1.017
Shucheng*	31.46	116.94	1.002	0.999	0.996
Yizheng	32.27	119.17	0.990	0.994	0.997
Yixing	31.36	119.82	0.998	1.001	1.004
Jiaxing*	30.75	120.75	0.993	0.996	0.999
Chongde(*)	30.52	120.43	1.004	1.007	1.011

Where is the actual totality zone when the eclipse occurred? The value of ΔT leads to a relative displacement between the actual and calculated totality zone. For a uniform time system, the value of ΔT is obtained when the actual location of the totality zone of a solar eclipse is known. Of course, the actual location will be defined when ΔT is known.

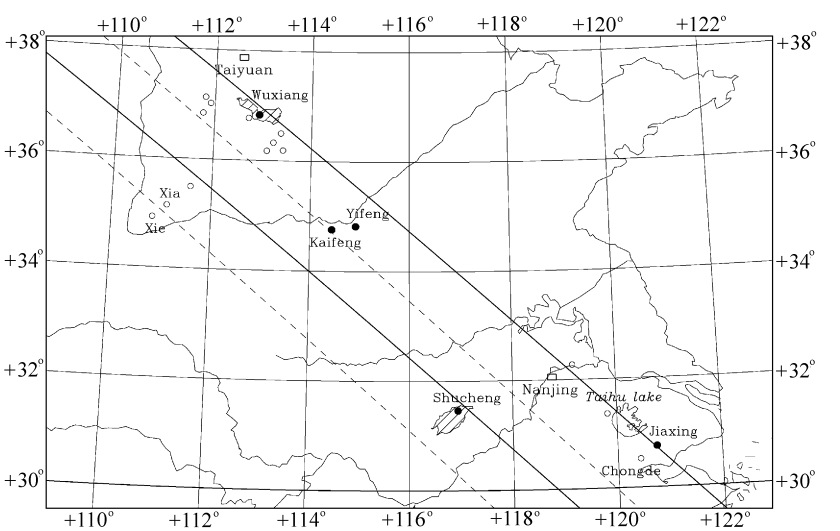
We consider that the five records with the character *Ji* should be taken as the main basis for defining the actual position of the zone of eclipse totality. The five observational places are Wuxiang, Kaifeng, Yifeng, Shucheng counties and Jiaxing prefecture. Of course, we shall also refer to other records not containing the character *Ji*. Generally, the actual totality zone of the eclipse is obtained by a least-squares fitting of the observational places. However, we note that the distribution of the places of the eclipse is not uniform. Some close-by places will have a large weight and this may lead to the fitted zone possibly deviating from the actual position. So we define the totality zone by changing the ΔT. There is an interesting phenomenon. When the totality zone is moved along the west-east direction, we find that the totality zone can be moved so as to include almost all the observational places except two, Shucheng and Jiaxing.

It seems that there is a contradiction because the records say that the total eclipse was seen at these two places. However, we think that *Xianzhi* might include events not only in the county city itself but also in all places belonging to the county, and so the whole of the two counties should be considered. The two counties are shown in Fig. 1. When ΔT is about

300s, it is found that the totality zone can pass the western parts of both Wuxiang County and Jiaxing Prefecture. The totality zone and the observational places are drawn in the Fig. 1(a).



(a) $\Delta T = 300$ s



(b) $\Delta T = 380$ s

Fig. 1 Totality zone of the total solar eclipse of A.D.1542. Dotted lines are the southern and northern boundaries of the calculated totality zone in TT system. Solid lines are the boundaries of the actual totality zone. The angle between the totality zone and latitude line is about 41°. The filled circles mark the places with records containing the Chinese character *Ji*, and the circles mark the other places. The slanting lines delineate Wuxiang County and Shucheng County.

The filled circles mark the places where the records contain the character *Ji*, and the circles, the other places. We can also find that the city included in the zone is not Jiaxing but Chongde, which is near Jiaxing City. Actually, Chongde was one of counties in Jiaxing Prefecture in that period. When ΔT is about 380s, the zone can pass the east part of Shucheng County (see Fig. 1(b)). For both values of ΔT (300s and 380s), the two cities, Kaifeng and Yifeng, are always included in the totality zone. We also find that 14 of 15 other observational places without *Ji* are inside the zone or very close to it, and so a total or near total eclipse would be seen in these places. However, it would be still difficult to see a near total eclipse in Xie Zhou city when ΔT is about 300s. The near total eclipse, however, should have been seen in the east of Xie Zhou Prefecture since the magnitude is more than 0.98 in Xia County which is in an area under the jurisdiction of Xie Zhou. The Xia County is marked by a circle in Fig. 1.

For three values of ΔT, 300s, 340s, and 380s, the calculated eclipse magnitudes in all the observational places are calculated and listed in Table 1. The places where the records contain *Ji* are marked by *, Chongde city is marked by (*).

4 RESULT AND DISCUSSION

As stated above, in the study of the variation of the Earth rotation using un-timed observations of central solar eclipses, the precision of ΔT mainly depends on the precision of defining the observational place and the width of the totality zone. The error from the inaccuracy of the observational place can be large if the place cannot be determined exactly and the totality zone is wide. The inaccuracy limit of ΔT from the totality zone width in the west-east direction, W, will be about $+W/2$ when the place is close to the northern boundary of the totality zone and about $-W/2$ when close to the southern boundary. If W_0 is the vertical distance between southern and northern boundaries of the zone, and α is the angle between latitude line and the zone, then $W = W_0/\sin\alpha$. So, the smaller the angle α, the larger the error. The problem is especially important for the more recent eclipses.

For the total solar eclipse of A.D.1542, the calculations show that the width of the totality zone in the middle part of China is $W_0 \approx 1.9^\circ$ and the angle between the latitude line and the totality zone is about 41°, hence $W \approx 2.9^\circ$. Therefore, if the eclipse was seen and recorded in only one place, the inaccuracy of the ΔT will be about $\pm 1.45^\circ$, or about $\pm$350s. For a solar eclipse in the 16th century, such a larger inaccuracy would mean the ΔT is useless for the study of the Earth rotation. Fortunately, as mentioned above, the observations of this eclipse recorded in the local chronicles of Shucheng, Jiaxing and Wuxiang include useful information for determining its actual totality zone. In addition, observations of other places also give support for the determination of the zone. Therefore the ΔT value, 300$\sim$380s, or 340$\pm$40s, derived for the total solar eclipse of A.D.1542, is a usable value for the study. Of course, its inaccuracy is larger than the result derived from the special eclipse of A.D.1567 by Stephenson et al., but it is still obviously better than the results obtained from the other eclipses in A.D.1406, 1415, 1431, 1485, 1560, 1575 and 1601, as reported in the first section of the paper.

Acknowledgements This research was supported by the National Natural Science Foundation of China under No. 19973011).

References

Beijing Astronomical Observatory, 1988, A Compilation of Chinese Records of Ancient Astronomical Phenomena, Nanjing: Jiangsu Science and Technology Press
Chen Jiujin, 1983, Studies in the History of Natural Sciences, 2(4), 303
Han Yanben, Li Zhisen, Lin Bosen et al., 1984, Acta Astrophys. Sinica, 4, 2, 107
Han Yanben, Zhang Peiyu, 1996, Journal of Korean Astronomical Society, 29, S439
Li Yong, Zhang Peiyu, Xu Bangxin, 1995, Journal of Nanjing University, 31, 2, 228
Pang K. D., Kevin Yau, Hung-hsiang Chou et al., 1988, Vistas in Astronomy, 31, 833
Pang K. D., Yau K. K. C., 1992, Eos Trans. AGU, 73, 43, Fall Meeting Suppl., 62
Stephenson F. R., Jones J. E., Morrison L. V., 1984, Geophys. J. R. Astron. Soc., 77, 1, 324
Stephenson F. R., Said S. S., 1989, A&A, 215, 1, 181
Stephenson F. R., Yau K. K. C., 1992, A&A, 260, 485
Stephenson F. R., 1997, Historical eclipses and Earth's rotation, Cambridge: Cambridge University Press
Stephenson F. R., Jones J. E., Morrison L. V., 1997, A&A, 322, 347
Wu Shouxian, Liu Ciyuan, 1987, Progress in Astronomy, 5, 2, 147
Zhang Peiyu, 1994, Publications of Purple Mountain Observatory, 13, 1, 23
Zhang Peiyu, Han Yanben, 1995, Acta Astronomica Sinica, 36, 3, 314
Zhang Peiyu, Han Yanben, 2000, Chinese Science Bulletin, 45, 11, 988