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STUDY ON SECULAR CHANGE OF THE EARTH'S ROTATION RATE BASED ON SOLAR ECLIPSE OBSERVATION RECORDS ON OCTOBER 13, 443 BC

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ABSTRACT. An observation of a solar eclipse that occurred on October 13, 443 BC during the reign of the Duke Ligong of Qin was recorded in the Twenty-Four Histories (China's dynastic histories from remote antiquity till the Ming Dynasty). With modern astronomical planetary ephemeris, the observation records were studied. The results showed that the eclipse probably occurred around sunset in Yongcheng, the capital of Qin, where the sunset time was exactly between the first contact stage (partial eclipse begins) and the fourth contact stage (partial eclipse ends) of the eclipse. Furthermore, secular change of the earth's rotation rate at that time is investigated in this work.

Keywords: solar eclipse observation, Earth's rotation, astronomical planetary ephemeris

1. INTRODUCTION

A solar eclipse is a special astronomical phenomenon in which the lunar shadow falls right on the surface of the earth as the moon crosses the line between the sun and the earth. In ancient China, special attention had been paid to the phenomenon. From the Spring and Autumn Period, the ancient Chinese made complete and continuous observation records of solar eclipse. The Annals of Chunqiu, an ancient China's chronicle, recorded 37 solar eclipses from 770 BC to 476 BC, 33 of which had been proved to be reliable (Liu & Ma, 2015). The Twenty-Four Histories is the general name for the 24 official histories written in ancient China. It starts from the time of the legendary Yellow Emperor (about 2550 BC) and goes down to the 17th year of Chongzhen in the Ming Dynasty (1644 AD). Its contents cover some ancient China's aspects including politics, economy, military, thought, culture, astronomy, and geography. The Twenty-Four Histories brings together a large number of solar eclipse observation records in ancient China. Some astronomical researchers checked these observations recorded in ancient China's historical books and revised erroneous records (Chu, 1934; Chen, 1984; BAO, 1988; Zhang, 1997; Liu & Ma, 2006; Liu, 2015).

There is an observation record of solar eclipse during the 34th year of the Duke Ligong of Qin (corresponding to 443 BC) in the Twenty-Four Histories. Some researchers studied this record. Chu (1934) believed that the observation record should be that of a total solar eclipse. Considering that there was no total solar eclipse visible in ancient China in 443 BC, he thought the record was from a total solar eclipse that occurred in 442 BC (the 35th year of the Duke Ligong of Qin). Chen (1984) also considered that this record corresponded to a total solar eclipse of 442 BC. Han et al. (1984) also agreed with the view and used the records to study secular change of the earth's rotation rate. Stephenson (1997) suggested that the records corresponded to an annular solar eclipse in 444 BC. Liu and Ma (2015) adopted the year 442 BC proposed by Chu (1934) during counting eclipse observation records from the Spring and Autumn Period to the Eastern Jin dynasty. After further examination, Liu (2015) thought that the recorded eclipse in the 34th year of the Duke Ligong of Qin occurred around sunset and could be seen in some places in China. According to Liu's opinions, the descriptions of "day became dim" and "stars were visible" in the records were wrong.

Modern astronomical planetary ephemeris has important applicable values for astronomy, Earth sciences, and some related disciplines. Now, the astronomical planetary ephemeris DE series released by the Jet Propulsion Laboratory (JPL) of the National Aeronautics and Space Administration (NASA) has been widely used in some fields including astrometry, deep space navigation, and interplanetary exploration. In this work, the DE ephemeris is used to analyze the solar eclipse observation made in 443 BC, with an emphasis on possible observations made at that time.

2. OBSERVATION RECORDS IN 443 BC

The Record of the Grand Historian, the first of the Twenty-Four Histories, was written by Sima Qian, a historian of the Western Han dynasty. It is the first biographical general history in ancient Chinese history. This book records more than 3000 years of China's history from ancient legend of the Yellow Emperor to the fourth year of Emperor Wu of the Han dynasty.

The Chronicle of Qin from Volume V of the Record of the Grand Historian tells the history of the rise and development of the feudal state of Qin in the Spring and Autumn Periods and the Warring States Period. It describes the history before the state of Qin from rising to unification of the whole country by Ying Zheng, King of Qin. Among the chronicles, a solar eclipse observation during the reign of the Duke Ligong of Qin was simply recorded as follows: In the 34th year of the Duke Ligong of Qin, the sun was eclipsed.

The Chronology of the Six Kingdoms from Volume XV of The Records of the Grand Historian is a chronology of events that occurred in the six kingdoms destroyed by Qin among the Seven Kingdoms of the Warring States. There is a further description of the eclipse: In the 34th year of the Duke Ligong of Qin, the sun was eclipsed, the day became dim, and the stars were visible.

The 34th year of the Duke Ligong of Qin corresponds to 443 BC. Taking the above records together, this observation can be described as follows: In 443 BC, a solar eclipse phenomenon occurred, the day became dim, the stars were visible.

Purely from the written records of the phenomenon, the meaning of "day became dim" is quite broad, and it can be felt when the solar eclipse magnitude is above 0.85. Also, when the weather is good, even if there is no solar eclipse, several bright stars, such as Venus, can be visible (Liu et al., 1998). Therefore, it is impossible to conclude that a total solar eclipse was observed simply from the textual descriptions of "day became dim" and "stars were visible."

3. SOLAR ECLIPSE PATH ON OCTOBER 13, 443 BC

The astronomical planetary ephemeris DE series adopts a uniform time system from ideal Earth's rotation rate, which is called as the terrestrial dynamical time (TDT). Here, to further study the solar eclipse that occurred during the reign of the Duke Ligong of Qin, the DE ephemeris is used to calculate the position of the sun and the moon. The results show that a partial solar eclipse visible only in the Southern Hemisphere occurred on April 20 and a partial solar eclipse visible in the Northern Hemisphere occurred on October 13 during the whole 443 BC. Accordingly, it is preliminarily judged that the solar eclipse recorded in the 34th year of the Duke Ligong of Qin was the partial solar eclipse that occurred on October 13, 443 BC.

Furthermore, with positional relationship among the sun, the moon, and the earth, the observable situation of solar eclipse on the earth's surface can be obtained, which is called as solar eclipse path. Figure 1 shows the solar eclipse path of October 13, 443 BC under the TDT time system.

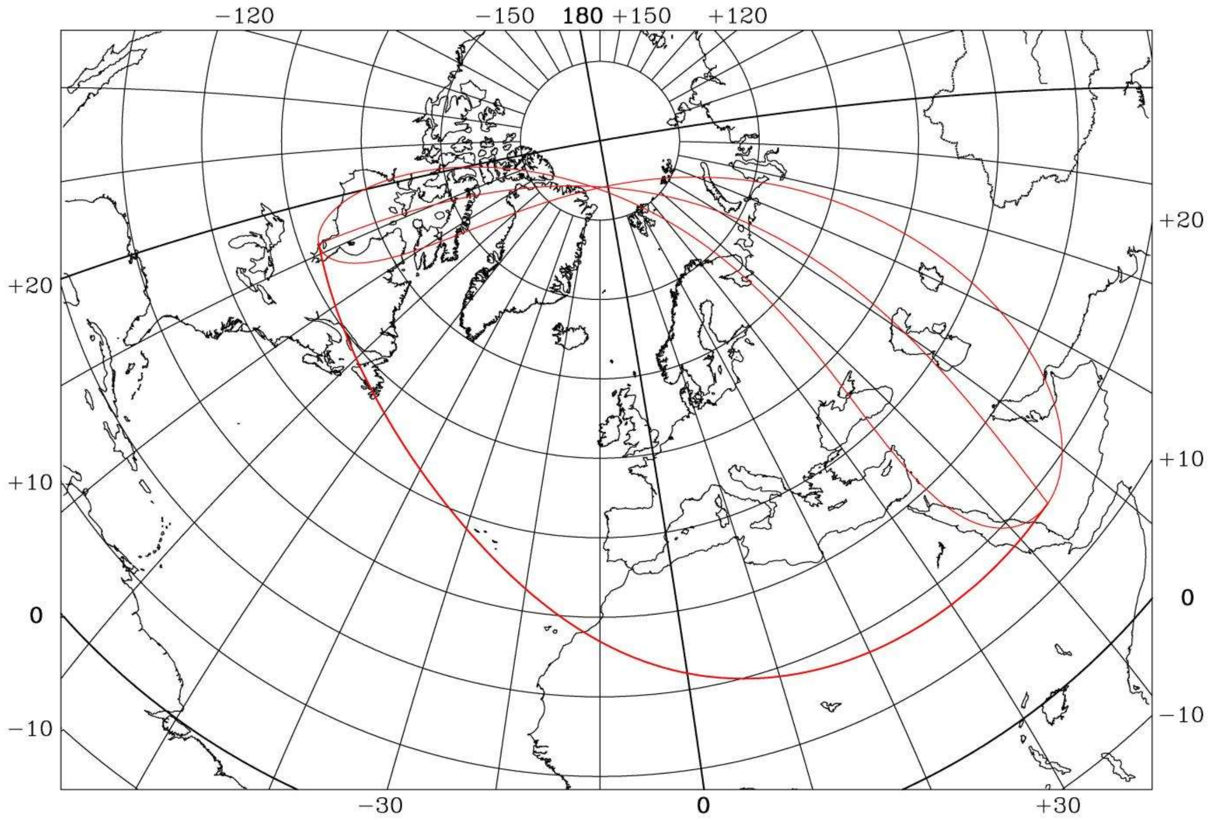

Figure 1. Solar eclipse path of October 13, 443 BC (under the TDT time system). The lower curve gives the southern boundary of visible partial solar eclipse. The approximate circles on the left and right sides give areas where the eclipse is visible at sunrise and sunset, respectively. The left and right halves of every circle correspond to the boundaries where the first contact stage (partial eclipse begins) and the fourth contact stage (partial eclipse ends) can be observed, respectively.

Actually, secular change existing in the earth's rotation rate causes a time difference between TDT and the universal time (UT), which is called as the UT correction (expressed as ΔT). The time difference results in an overall east–west translation of solar eclipse path along the direction parallel to the equator. With local observations of solar eclipse phenomena, the secular change of the earth's rotation rate can be studied (Han et al., 1984; Wu & Liu, 1987; Pang et al., 1995; Zhang, 1994; Liu, 1994). Of course, it is also possible to study observable situation of ancient people about the astronomical phenomena at that time in conjunction with the secular change of the earth's rotation rate (Espenak & Meeus, 2006; Ma et al., 2021, 2022).

Based on the above solar eclipse path, it is confirmed that the solar eclipse is a partial eclipse phenomenon. Considering the secular change of the rotation rate of the earth, this solar eclipse path could be observed in the capital city of Qin at that time after moving the eclipse path as a whole to a certain extent. However, this partial solar eclipse does not cause the phenomena of “day became dim” and “stars were visible”.

4. SECULAR CHANGE OF THE EARTH’S ROTATION RATE ON OCTOBER 13, 443 BC

It is well known that bright stars appear in the sky after sunset, when the daylight is dim. The descriptions of “day becomes dim” and “stars are visible” are also astronomical phenomena that just occur after sunset. If a solar eclipse happens to occur before sunset, it enters sunset when the eclipse is not completely over. People observe this phenomenon and record it as it happens. Theoretically, the phenomena including “day became dim” and “stars were visible” were regarded as the phenomena caused by the solar eclipse and recorded.

4.1. ΔT value from solar eclipse path

During the period of the Duke Ligong of Qin, the capital city of Qin was Yongcheng (34°28′22″N, 107°22′08″E), located in Fengxiang district of Baoji city, northwest China’s Shaanxi Province. According to the solar eclipse path, for a terrestrial place in the same latitude as Yongcheng, the capital of Qin, after considering secular change of the earth’s rotation rate, the place (34°28′22″N, 59°35′10″E) could see the first contact stage of the solar eclipse at sunset and the place (34°28′22″N, 35°23′47″E) could see the fourth contact stage of the eclipse at sunset.

There is a difference in longitude between the two places with Yongcheng. This difference originates from the secular change of the earth’s rotation rate. Therefore, the lower and upper limits of ΔT value are 11,436 and 17,226 s, respectively. Here, another expression can be given as 14,331 ± 2895 s.

4.2. Sunset time from different twilight conditions

The time of sunset is the time when the sun is below the horizon. It can be judged by the value of solar altitude angle (or zenith angle). In the solar eclipse path, the sunset is judged by setting the altitude angle to zero degree. In astronomy, the sunset is classified into civil twilight (with a solar altitude angle of −6°), nautical twilight (with a solar altitude angle of −12°), and astronomical twilight (with a solar altitude angle of −18°) (NAO, 1990). Generally, civil twilight should be closer to people’s visual perception. Therefore, there is an error in calculating the sunset boundary by choosing a solar altitude angle of zero degree in the solar eclipse path. In the following, the sunset time is calculated by using −6° of solar altitude as the judgment condition of the sunset.

Considering the secular change of the earth’s rotation rate, the sunset time of a certain place can be calculated only after the ΔT value is determined. Here, the ΔT value obtained in the previous section is used to calculate the sunset time, and the results are presented in Table 1. The local time (LT) is obtained by adding the local longitude/15 to the UT time. It can be seen that the sunset time is delayed by 1752 s after modifying twilight conditions.

Table 1. Sunset time from two twilight conditions

ΔT (s)	Twilight with a solar altitude angle of 0°		Civil twilight		Difference (s)
	TDT (h:min:s)	LT (h:min:s)	TDT (h:min:s)	LT (h:min:s)	
11,436	13:34:44	17:33:05	14:03:56	18:02:17	1752
17,226	15:11:25	17:33:00	15:40:37	18:02:12	1752

4.3. Comprehensive ΔT value

During the solar eclipse of October 13, 443 BC, if the sun set over the capital city of Qin, the solar eclipse was followed by the sunset, which caused "day became dim" and "stars were visible." The historians at that time could not distinguish whether the phenomena of "day became dim" and "stars were visible" were caused by the eclipse or by the sunset, and could only make a continuous record of these phenomena.

Thus, the actual situation of the solar eclipse observation in the 34th year of the Duke Ligong of Qin is that the solar eclipse was observed before the sunset (solar eclipse entering the first contact stage), and the sun set in the local area before the end of the eclipse (solar eclipse entering the fourth contact stage). That is, the local sunset occurred between the first contact and the fourth contact stage of the solar eclipse. After further considering the sunset condition, the range of ΔT value with 16,083 ± 2895 s is obtained.

5. SUMMARY

Considering the historical records of the solar eclipse on October 13, 443 BC, modern astronomical planetary ephemeris is used to study the observation. It is concluded that the solar eclipse occurred around the sunset in Yongcheng, the capital of Qin. The local sunset was between the first contact stage (partial eclipse begins) and the fourth contact stage (partial eclipse ends) of the solar eclipse. The secular change of the earth's rotation rate is obtained by using civil twilight as the sunset condition.

6. DISCUSSION

Because of the complexity of Earth's variable rotation, there was no strict formula for calculating the ΔT value in the past. Researchers update the ΔT value by uncovering more ancient astronomical observation records. Morrison and Stephenson (2004) combined astronomical observations from ancient China, ancient Babylon, ancient India, and Europe and gave a formula for estimating the ΔT value in the form of a step function. According to the formula, the ΔT value on October 13, 443 BC can be calculated as 16,111 ± 409 s. The results are within the ΔT range obtained in this work and their central values are also very close. This confirms each other's accuracy to a certain extent.

Furthermore, using the Stellarium software, it can be found that several bright stars including Venus, Mercury, Arcturus, Vega, and Altair appeared in the sky after sunset on October 13, 443 BC at Yongcheng, the capital city of Qin at that time. If the weather conditions permitted, the ancient people could observe the phenomena of "day became dim" and "stars were visible" caused by the sunset. The method in this work can also be extended to other similar solar eclipse observation records.

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