Chin. J. Astron. Astrophys. Vol. 6 (2006), No. 5, 629–634
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

# Observational Accuracy of Sunrise and Sunset Times in the Sixth Century China

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Received 2005 December 22; accepted 2006 February 14

**Abstract** The Daye Calendar was compiled in AD 597 in the Sui Dynasty. We investigate the records of sunrise and sunset times on the 24 solar-term days in the calendar. By converting the ancient Chinese time units, Chen, Ke and Fen to hour, minute and second, and carrying out a comparison between the ancient records and values computed with modern astronomical theory, we find that the accuracy of solar measurements in the Sui period is remarkably high: for sunrise times, the average absolute deviation is 3.63 min (this value can be further reduced to 3.03 min when erroneous data are excluded), and for sunset times it is 3.48 min. We also find that the observed sunrise and sunset times are strictly symmetrically distributed with respect to both the Winter Solstice and the Summer Solstice, with their deviations showing a similar symmetrical distribution as well. We give a discussion on the date of observation, the feature of the data, and possible reasons of the deviation.

**Key words:** history of astronomy — astrometry — solar-terrestrial relations — methods: statistical

## 1 INTRODUCTION

Ancient Chinese annals contain a huge amount of astronomical material, such as observational records, calendars, theories and instruments (Zhonghua Book Company Editorial Office 1976). The works of some early western missionaries, and the works of Joseph Needham, whose well-known *Science and Civilisation in China* series, have presented introductions of Chinese ancient astronomical records to the world at large (Needham 1959).

Later many items of astronomical data recorded in different periods and different forms of historical records were surveyed, collected, or republished (Beijing Astronomical Observatory 1988). Such effort has even extended to the ancient literature of other East Asian countries (Xu et al. 2000). Current studies on ancient Chinese celestial records are not limited to eclipses (Liu 2002), comets (Strom 2002), calendars (Zhang 1990; Li et al. 1998) or secular variations of Earth's rotation (Han et al. 2003; Li et al. 1997), rather, they cover almost all aspects of ancient astronomy (The researching group for the history of Chinese astronomy 1981; Chen 2003). Pankenier (*http://spp.pinyin.info/abstracts/spp104_astrology.html*) has adduced evidence that from the early time the ancient Chinese were astute observers of celestial phenomena and that the observations were not results of careless star-gazing. Original records of regular astronomical observations ranging from the ordinary ones (sunrise and sunset, solstices, individual stars and planets) to the extraordinary ones (lunar and solar eclipses, sunspots, supernova, etc.) appeared as early as the writing itself in the Shang oracle bone inscriptions. In addition to determining the meridian and the 24 solar terms, these observations were regarded as most important for astrology (Li 1990).

After thousands of years of development and particularly with the use of the sundial, Chinese technology for solar observation gradually matured which includes measurements of the length of solar shadow, azimuth, altitude and time.

The earliest record of times of sunrise and sunset at the 24 solar term days was from the end of the 6th century. Since then systemic records have been preserved in the annals, for the purpose of calendar-making, and these can be compared with the values found in modern astronomical almanacs. In this paper we shall make a comparative study of the accuracy of solar observations in the 6th century.

## 2 MEASURING THE TIME OF SUNRISE AND SUNSET IN THE SUI DYNASTY (AD 581 – 618)

In the Sui Dynasty (AD 581–618), the capital was Daxin, the present Xi'an city (Long. =108 °55′ E; Lat.=34°15′ N). The Royal Astronomer at the time, Zhang Zhouxuan, composed a new calendar named Daye Li in AD 597 which, however, was not issued until 618. Here we analyze only those time records of sunrise and sunset when the sun was at the 24 particular positions, known as the 24 solar terms, measured for making the Daye calendar. All the data are taken from *Sui Shu*, the archives of Sui Dynasty (Zhonghua Book Company Editorial Office 1976).

In ancient China, the day was usually divided into 12 equal time parts called the 12 Chen. Each Chen has two hours, so there is a correspondence to the present local time. The 12 Chen are: Zi, from 23:00 (of previous day) to 1:00; Chou, 1:00–3:00; Yin, 3:00–5:00; Mao, 5:00–7:00; Chen, 7:00–9:00; Si, 9:00–11:00; Wu, 11:00–13:00; Wei, 13:00–15:00; Shen, 15:00–17:00; You, 17:00–19:00; Xu, 19:00–21:00 and Hai, 21:00–23:00. In a similar fashion to our modern hours, minutes and seconds, the units of time then were Chen, Ke and Fen in the Daye calendar. The exact correlations between the units are 1 day (24 hours) = 100 Ke, and 1 Ke = 60 Fen. So 1 Ke = 14.4 minutes and 1 Fen = 14.4 s.

Since the ancient time data exactly represent apparent local solar time, they can be converted to modern time system of hour, minute and second. Table 1 lists the observed time of sunrise (OTR) in columns 4 and 5, and the observed time of sunset (OTS) in columns 6 and 7. Although all the data have been revised by ancient compilers, it is still clear that the order of Qizhe and Yushui should be reversed. In this table we have made the necessary correction. And the total measuring times are also displayed in Figure 1 more intuitively.

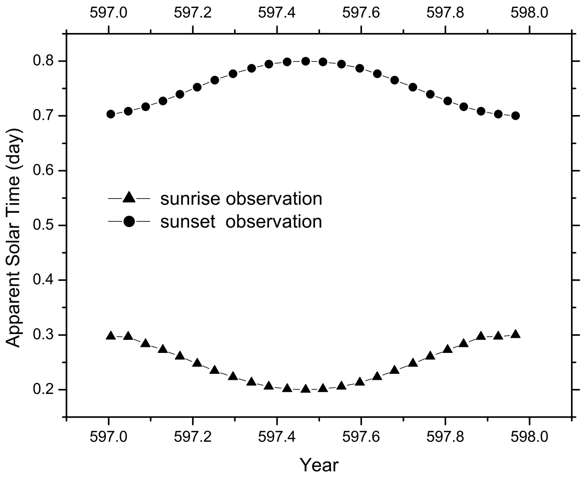

**Fig. 1** Measured apparent solar times of sunrise and sunset on the days of the 24 solar terms in AD 597 given in *Sui Shu*.

## 3 ANALYSIS AND ACCURACY

For evaluating the accuracy of ancient time-records of sunrises and sunsets we first convert all the observation dates to the system of Gregorian calendar. We are fortunate in being able to adopt our latest work on "Date Recover System" devised especially for ancient China to obtain the modern dates, not the 24 solar

**Table 1** Time-Records for Sunrise and Sunset of the 24 Solar Terms in AD 597 in *Sui Shu*

| No | Names of 24 Solar Terms | Solar Longitude | Observed Time of Sunrise | | Observed Time of Sunset | |
|---|---|---|---|---|---|---|
| | | (°) | Chen:Ke:Fen | h: m: s | Chen:Ke:Fen | h: m: s |
| 1 | Dongzhi (Winter Solstice) | 270.0 | Chen:0:50 | 7:12:0 | Shen:7:30 | 16:48:0 |
| 2 | Xiaohan (Lesser Cold) | 285.0 | Chen:0:32 | 7:7:41 | Shen:7:48 | 16:52:19 |
| 3 | Dahan (Greater Cold) | 300.0 | Mao:8:49 | 7:6:58 | You:0:1 | 17:0:14 |
| 4 | Lichun (Beginning of Spring) | 315.0 | Mao:7:28 | 6:47:31 | You:0:52 | 17:12:29 |
| 5 | Yushui (Rain Water) | 330.0 | Mao:6:25 | 6:32:24 | You:1:55 | 17:27:36 |
| 6 | Qizhe (Awakening from Hibernation) | 345.0 | Mao:5:13 | 6:15:7 | You:3:7 | 17:44:53 |
| 7 | Chunfen (Spring Equinox) | 0.0 | Mao:3:55 | 5:56:24 | You:4:25 | 18:3:36 |
| 8 | Qingming (Fresh Green) | 15.0 | Mao:2:37 | 5:37:41 | You:5:43 | 18:22:19 |
| 9 | Guyu (Grain Rain) | 30.0 | Mao:1:28 | 5:21:7 | You:6:52 | 18:38:53 |
| 10 | Lixia (Beginning of Summer) | 45.0 | Mao:0:28 | 5:6:43 | You:7:52 | 18:53:17 |
| 11 | Xiaoman (Lesser Fullness) | 60.0 | Yin:8:3 | 4:55:55 | Xu:0:17 | 19:4:5 |
| 12 | Mangzhong (Grain in Ear) | 75.0 | Yin:7:36 | 4:49:26 | Xu:0:44 | 19:10:34 |
| 13 | Xiazhi (Summer Solstice) | 90.0 | Yin:7:30 | 4:48:0 | Xu:0:50 | 19:12:0 |
| 14 | Xiaoshu (Lesser Heat) | 105.0 | Yin:7:36 | 4:49:26 | Xu:0:44 | 19:10:34 |
| 15 | Dashu (Greater Heat) | 120.0 | Yin:8:3 | 4:55:55 | Xu:0:17 | 19:4:5 |
| 16 | Liqiu (Beginning of Autumn) | 135.0 | Mao:0:28 | 5:6:43 | You:7:52 | 18:53:17 |
| 17 | Chushu (End of Heat) | 150.0 | Mao:1:28 | 5:21:7 | You:6:52 | 18:38:53 |
| 18 | Bailu (White Dew) | 165.0 | Mao:2:37 | 5:37:41 | You:5:43 | 18:22:19 |
| 19 | Qiufen (Autumnal Equinox) | 180.0 | Mao:3:55 | 5:56:24 | You:4:25 | 18:3:36 |
| 20 | Hanlu (Cold Dew) | 195.0 | Mao:5:13 | 6:15:7 | You:3:7 | 17:44:53 |
| 21 | Shuangjiang (First Frost) | 210.0 | Mao:6:25 | 6:32:24 | You:1:55 | 17:27:36 |
| 22 | Lidong (Beginning of Winter) | 225.0 | Mao:7:28 | 6:47:31 | You:0:52 | 17:12:29 |
| 23 | Xiaoxue (Light Snow) | 240.0 | Mao:8:49 | 7:6:58 | You:0:1 | 17:0:14 |
| 24 | Daxue (Heavy Snow) | 255.0 | Chen:0:32 | 7:7:41 | Shen:7:48 | 16:52:19 |

terms only. The results are listed in Table 2 (column 2) along with other parameters. The serial numbers are used for the solar terms in Tables 1 and 2.

In Table 2, column 3 denotes equation of time ($\eta$ apparent solar time minus mean solar time), and column 4 is $\Delta T$ = ET–UT (ephemeris time minus universal time). With the calculated time of sunrise (CTR) and calculated time of sunset (CTS) computed by modern method for the given position in Beijing zone time (=UT+8 hours), the accuracy of the sunrise observation (AR) in column 7 is:

$$\mathrm{AR} = \mathrm{CTR} - (\mathrm{OTR} - \eta + (120.0^\circ - L_{\mathrm{Xi'an}})/360.0^\circ)\,, \tag{1}$$

where $L_{\mathrm{Xi'an}} = 108^\circ 55' = 108.92^\circ$ is the longitude of Xi'an, and the accuracy of the sunset observation (AS) in column 8 is:

$$\mathrm{AS} = \mathrm{CTS} - (\mathrm{OTS} - \eta + (120.0^\circ - L_{\mathrm{Xi'an}})/360.0^\circ)\,. \tag{2}$$

In both equations a consistent set of the units are used for the parameters. The average value of AR is $-2.18$ minutes and that of AS is 2.00. The computed mean of the absolute values of AR is 3.63 minutes and, that of AS is 3.48. The results are listed in Table 2.

Figure 2 shows the two runs of errors in opposite phases. The data in the middle part of the runs are of higher accuracy, particularly at Spring Equinox and Autumnal Equinox, but those in January, February, November and December are with bigger fluctuations. Obviously there is an open problem: why did the accuracy of sunrise time at Greater Cold and Light Snow drop abruptly to less than $-12$ min?

## 4 DISCUSSION

### 4.1 Date of Observation

When was the calendar made? In fact there are two possible dates, one is the 17th year of Reign-period Kaihuang (AD 597), the other is the 4th year of Reign-period Daye (AD 608). Even so, the annal does not

**Table 2** Accuracy of Time Observations of Sunrise and Sunset on the Days of the 24 Solar Terms in AD 597

| No | Date | Equation of Time (m) | $\Delta T$ (s) | CTR (h: m: s) | CTS (h:m:s) | AR (m) | AS (m) |
|---|---|---|---|---|---|---|---|
| 1 | Dec. 19 | −0.95 | 4609.19 | 7:50:45 | 17:41:34 | −6.52 | 8.30 |
| 2 | Jan. 2 | −7.93 | 4616.47 | 7:54:59 | 17:51:18 | −4.95 | 6.73 |
| 3 | Jan. 17 | −13.60 | 4616.16 | 7:52:28 | 18:04:50 | −12.42 | 6.68 |
| 4 | Feb. 1 | −16.42 | 4615.85 | 7:43:09 | 18:19:18 | −5.10 | 6.08 |
| 5 | Feb. 16 | −16.03 | 4615.54 | 7:28:16 | 18:32:57 | −4.49 | 5.00 |
| 6 | Mar. 3 | −13.02 | 4615.23 | 7:09:34 | 18:45:16 | −2.89 | 3.05 |
| 7 | Mar. 18 | −8.25 | 4614.92 | 6:48:45 | 18:56:23 | −0.22 | 0.21 |
| 8 | Apr. 2 | −2.93 | 4614.61 | 6:27:31 | 19:06:59 | 2.58 | −2.59 |
| 9 | Apr. 18 | 2.15 | 4614.27 | 6:06:11 | 19:18:22 | 2.90 | −2.69 |
| 10 | May 4 | 5.47 | 4613.94 | 5:48:08 | 19:30:08 | 2.56 | −2.00 |
| 11 | May 19 | 6.37 | 4613.63 | 5:35:47 | 19:41:00 | 1.91 | −1.04 |
| 12 | Jun. 4 | 4.93 | 4613.30 | 5:28:54 | 19:50:56 | 0.08 | 0.98 |
| 13 | Jun. 20 | 1.85 | 4612.97 | 5:29:01 | 19:56:56 | −1.45 | 2.46 |
| 14 | Jul. 5 | −1.28 | 4612.66 | 5:34:44 | 19:57:10 | −0.30 | 1.00 |
| 15 | Jul. 21 | −3.43 | 4612.32 | 5:44:57 | 19:50:48 | 1.28 | −1.04 |
| 16 | Aug. 6 | −3.40 | 4611.99 | 5:57:08 | 19:38:01 | 2.70 | −2.99 |
| 17 | Aug. 21 | −1.22 | 4611.68 | 6:08:55 | 19:21:29 | 2.26 | −2.94 |
| 18 | Sep. 5 | 2.62 | 4611.37 | 6:20:27 | 19:02:02 | 1.06 | −1.99 |
| 19 | Sep. 21 | 7.52 | 4611.04 | 6:32:44 | 18:39:57 | −0.47 | −0.45 |
| 20 | Oct. 6 | 11.72 | 4610.73 | 6:44:48 | 18:19:40 | −2.92 | 2.18 |
| 21 | Oct. 21 | 14.38 | 4610.41 | 6:58:01 | 18:01:33 | −4.32 | 4.01 |
| 22 | Nov. 4 | 14.62 | 4610.12 | 7:11:30 | 17:48:08 | −5.72 | 5.95 |
| 23 | Nov. 19 | 11.93 | 4609.81 | 7:26:33 | 17:39:08 | −12.80 | 6.51 |
| 24 | Dec. 4 | 6.38 | 4609.50 | 7:40:28 | 17:36:51 | −5.15 | 6.60 |
|  |  |  |  |  | Average Value | −2.18 | 2.00 |
|  |  |  |  |  | Mean of Absolute Value | 3.63 | 3.48 |

tell us the year when the measurements were made. Here we take the earlier date as the presumptive date in our analysis. On the other hand, we should notice the differences between the solar terms of the Daye calendar and those of modern astronomy. In the Daye calendar they were the so-called Ping Qi (mean solar terms), with the date of Winter Solstice of the previous year being determined by observation, and the dates of the other solar terms being obtained by counting equal number of days, thought to be 1/24 of the tropical year, the value = 15 + (9315 + 1/8)/42640 = 15.2185 days, so the length of tropical year was taken to be 365.2430 days, which is only 1.2 min larger than modern value of 365.2422 days. Later, however, a more exact system, Ding Qi (real solar term), replaced Ping Qi, which divides the ecliptic into 24 equal parts, and the solar terms were determined by the sun being at those particular positions. The concept of Ding Qi is very close to the modern concept, except that the positions were apparent longitudes of the sun. The difference between the two is less than one day. The dates in Table 2 are obtained by means of modern astronomy.

## 4.2 Features of Data

For most of the solar terms investigated here, OTR + OTS = 1 applies strictly, except for Greater Cold and Light Snow when the largest error in the the sunrise time happened ($< -12$ min) as shown in Table 2 and Figure 2. However, the problem might be that the original data were given like that the sunrise is at “8 Ke and 49 Fen in Mao Chen”. So, we deem this record is incorrect, according to

$$\mathrm{OTR} = 1 - \mathrm{OTS},$$

we change it to “8 Ke and 19 Fen in Mao Chen”. We need to delete only one Chinese character Si (four) in the original record to get it right. In addition to this possible copying error, the ancient compilers found that Heavy Snow had been missing in the original list and they adjusted the sequence of the solar terms accordingly.

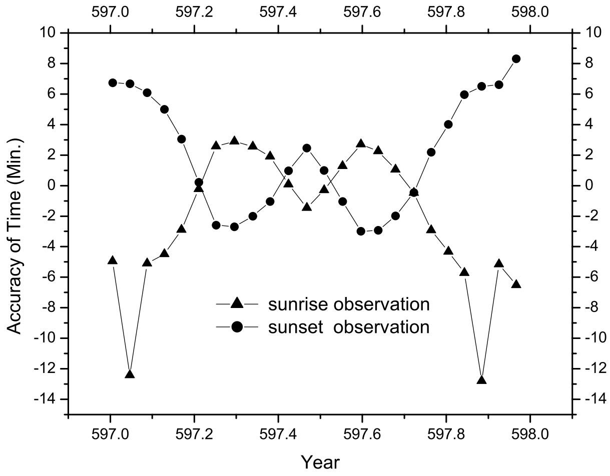

**Fig. 2** Accuracies of the times of sunrise and sunset on the days of the 24 solar-terms in AD 597 given in *Sui Shu*.

After this modification, the calculated accuracy is improved a great deal. For Greater Cold the error decreased from $-12.42$ to $-5.22$ min and for Light Snow, from –12.80 to –5.60 min. The average value of accuracy is improved from $-2.18$ to $-1.58$ min, and the mean of the absolute value of error falls from 3.63 to 3.03 min.

Figure 1 shows remarkably the symmetrical runs of the sunrise and sunset times, not only strictly for the original data, but also roughly for the accuracies (see Fig. 2). Moreover, regarding the measured data, only one group of the data for sunrises and sunsets was independent, but we are sure that only half of them are derived from real observations. Even for each group, between Winter Solstice and Summer Solstice, the data are symmetrical because of the same reason. Actually within one year there are only 13 data from independent measurements for each group. Moreover, between Winter Solstice and Summer Solstice, there are other 11 sets of data. Now for all the 48 sets of data although perhaps no more than 13 of them are from independent measurements, we can still hardly distinguish derivations from real observations. This does not affect our analysis of the time accuracy of solar observations. Our results show the 3.03–3.48 min level of precision (mean of absolute errors) in the 6th century, which is remarkably high and even approaches the solar meridian observations made in the 13th century, where the accuracy was 2.64 min (Li 2005).

## 4.3 Other Sources of Deviations

In this paper, although the deviations of ancient observation of sunrise and sunset times are mainly from errors in the measurements, the calculations are also affected by other factors, such as atmospheric refraction, equation of time ($\eta$), $\Delta T$ value as well as the geographical position (longitude and latitude) and dates of observations, etc.

Now a clue for how to obtain these parameters accurately has been found, because some related parameters may be found by iteration. For example, when we use these observational data of the 24 solar terms in an iterative calculation, the secular variation of Earth's rotation value $\Delta T$ may be calculated as long as the iteration accommodates different combinations of both the times of sunrise and sunset in order to reduce errors. In the case discussed in this paper, for Mar. 18, 597 (Spring Equinox), when sunrise time plus sunset time is taken as the iterative value, then $\Delta T = 4400$ s is obtained; and for Sep. 21, 597 (Autumnal Equinox), if we use the value of sunset time minus sunrise time for iteration, we have the result $\Delta T = 4800$ s. The average value of $\Delta T$ is 4600 s, which is reasonable, being close to 4609–4616 s, the approximate value adopted in this paper. So it is advisable to design some programs to recover these parameters in future studies.

**Acknowledgements** The author thanks Prof. Peiyu Zhang and the referee, for their significant suggestions. This work was supported by the Tianyuan Foundation of China (Grant No. A0324673).

## References

Beijing Astronomical Observatory, 1988, Zhongguo Gudai Tianxiang Jilu Zongji (A Compilation of Chinese Records for Ancient Celestial phenomena), Nanjing: Jiangsu Science and Technology Press

Chen M. D., 2003, Zhongguo Kexue Jishu Shi Tianwenxue Juan (Volume Astronomy in Chinese History of Science and Technology), Beijing: Science Press

Han Y. B., Qiao Q. Y., 2003, Chin. J. Astron. Astrophys., (ChJAA), 3, 569

Li Y., Zhang C. Z., 1997, Earth, Moon and Planets, 76, 11

Li Y., Zhang C. Z., 1998, A&A, 333, L13

Li Y., 1990, Exploration of Nature, 9, 119

Li Y., 2005, Progress in Astronomy, 23, 70

Liu C. Y., 2002, Chin. J. Astron. Astrophys. (ChJAA), 2, 391

Needham J., 1959, Science and civilisation in China (Vol. 3), Cambridge: Cambridge Univ. Press

Strom R., 2002, A&A, 387, L17

The researching group for the history of Chinese astronomy, 1981, Zhongguo Tianwenxue Shi (History of Chinese astronomy), Beijing: Science Press

Xu Zhentao, Pankenier David W., Jiang Yaotiao, 2000, East Asian Archaeoastronomy: Historical Records of Astronomical Observations of China, Japan and Korea, Amsterdam: Gordon and Breach Science

Zhang P. Y., 1990, Sanqian Wubai Nian Liri Tianxiang (Ancient Date and Celestial phenomena within 3500 Years), Zhengzhou: Henan Education Press

Zhonghua Book Company Editorial Office, 1976, Lidai Tianwen Lulidengzhi Huibian (Compilation on ancient Chinese astronomy), Beijing: Zhonghua Book Company