Chinese Mathematical Astronomy from ca. 4th Century to ca. 6th Century

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1. INTRODUCTION

Previously I wrote a paper "Formation of Chinese Classical Mathematical Astronomy" on the development up to the 3rd century, which was published in the *Gaṇita Bhāratī* (vol. 29, 2007, 101 – 115). I would like to discuss the further development from ca. 4th century to ca. 6th century in this paper. This is a revised version of the poster paper presented at the International Seminar on History of Mathematics in memory of Subash Handa, held at Ramjas College, University of Delhi (Delhi, 2007).

2. THE PERIOD FROM THE 4TH CENTURY TO THE 6TH CENTURY IN CHINESE HISTORY

The history of pre-modern China can roughly be summarized as follows:

(A) Xia dynasty (legendary)

(B) Shang (=Yin) dynasty (ca. 16th century BC ~ ca. 11th century BC)

(C) Western Zhou dynasty (ca. 11th century BC ~ 770 BC)

(D) Spring and autumn (''Chunqiu'') period (770 BC ~ 476 BC)

(E) Warring states (''Zhanguo'') period (475 BC ~ 221 BC)

(F) Qin dynasty (221 BC ~ 206 BC)

(G) Han dynasty (206 BC ~ 220 AD) (Western (Former) Han (206 BC ~ 23 AD) and Eastern (Later) Han (25 AD ~ 220 AD))

Gaṇita Bhāratī Vol. **30** (2008) No. 1, page 27-39

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(H) Three kingdoms (''Sanguo'') period (220 ~ 265) (Wei dynasty (220~265), Shu dynasty (221~263) and Wu dynasty (222~280))

(I) Jin dynasty (265 ~ 420) (Western Jin (265 ~ 316) and Eastern Jin (317 ~ 420))

(J) Sixteen states (''Shiliuguo'') period (304 ~ 439)

(K) Northern and southern dynasties (''Nanbeichao'') period (420 ~ 589) (Northern dynasties: Northern Wei, Eastern Wei, Western Wei, Northern Qi and Northern Zhou; and Southern dynasties: Song (Liu-Song), Qi, Liang and Chen)

(L) Sui dynasty (581 ~ 618)

(M) Tang dynasty (618 ~ 907)

(N) Five dynasties and ten states (''Wudai-shiguo'') period (907 ~ 979)

(O) Song dynasty (960 ~ 1279) (Northern Song (960 ~ 1127) and Southern Song (1127 ~ 1279))

(P) Liao dynasty (916 ~ 1125)

(Q) Jin dynasty (1115 ~ 1234)

(R) Yuan dynasty (1271 ~ 1368)

(S) Ming dynasty (1368 ~ 1644)

(T) Qing dynasty (1644 ~ 1911)

My previous paper roughly corresponds to the periods up to (H). In China, several astronomical ideas were produced in the "Spring and autumn" and "Warring states" periods, which were the periods of disturbances by war, but were also the periods of freedom of speech because absolute monarchy was not yet established. Then, the system of Chinese classical astronomy was basically established at the time of the Han dynasty. The Han dynasty was a kind of absolute monarchy, and the basis of Chinese science (and philosophy etc.) was well established during this dynasty.

The present paper roughly corresponds to the periods from (I) to (K). Although China was unified by the Western Jin dynasty for a certain period, China was again partitioned, and China was divided into the Northern dynasties and the Southern dynasties in the period (K), and this period of partition was a period to produce new ideas, some of which were free from conservatism.

After this period, China was again unified by the Sui dynasty. As regards the development of mathematical astronomy after this dynasty, I would like to discuss at another occasion.

3. YU XI'S DISCOVERY OF THE PRECESSION OF EQUINOXES

At the time of the Eastern Jin dynasty (317 ~ 420), YU Xi (YU is surname, 281 ~ 356) discovered the precession of equinoxes. The precession had already been discovered by a Greek astronomer Hipparchus (2nd century BC), but YU Xi's discovery must have been independent of Hipparchus.

Yixing (683 ~ 727), a celebrated monk astronomer of the Tang dynasty, described the discovery of YU Xi as follows in his discourse *Dayan-liyi* (Discourse on the *Dayan* calendar) (article 7) (recorded in the *Xin-Tangshu* (New official history of the Tang dynasty), *Lizhi* (Chapter of calendar) (III-1)). I would like to note one thing before translating the discourse that one "Chinese degree" was the angular distance (on the celestial sphere) which was traversed by the (mean) sun in one day, and "[the degrees of] the circumference of the celestial sphere" in the following quotation is the same as the number of days in a sidereal year. Therefore, one Chinese degree is slightly smaller than one modern degree. Yixing wrote:

> "In the old calendars, [the movement of] the sun was uniform, and [the degrees of] the circumference of the celestial sphere was the same as the length of a [tropical] year. Therefore, the positions of the stars were fixed to the divisions of season. This theory looks true but is not so actually, and errors increase in a long-term. YU Xi noticed this fact, and differentiated the circumference of the celestial sphere and the [tropical] year. He investigated the difference and traced its effect, and concluded that [the position of the sun at certain season] retrogrades 1 degree (Chinese degree) in 50 years." (Translated by me from the *Xin-Tangshu, Lizhi* (III-1)).

According to the above quotation, it is clear that YU Xi understood the precession of equinoxes and the difference between the sidereal year and the tropical year correctly. The exact value of the precession is 1° per about 71.6 years, and the value of YU Xi was slightly larger.

At the time of YU Xi, Greek influence is not found in Chinese astronomy, and the discovery of YU Xi must be independent of Hipparchus (2nd century BC).

4. HE CHENGTIAN'S CALENDAR REFORM

4.1 Introduction

In the Song (Liu-Song) dynasty (420-479), the first dynasty of the Southern dynasties, an astronomer HE Chengtian (HE is surname, 370-447) made an excellent calendar called *Yuanjia* calendar. The *Yuanjia* calendar is recorded in the *Lizhi* (chapter of calendar) (III) in the *Song-shu* (Official history of the Song dynasty).

4.2 Chinese luni-solar calendar

The Chinese traditional calendar is a luni-solar calendar. A calendrical day begins from midnight, a (synodic) month begins from the day in which new moon occurs. The number of a calendrical day in a month is numbered serially (from 1 to 29 or 30). A (tropical) year (from winter solstice to winter solstice) is divided by 24 "*jieqi*", and 12 "*zhong-qi*" among them (selected alternately) are used to denominate the month which contains one of them. For example, the month which contains the winter solstice is the 11th month. The number of a month is numbered serially (from 1 to 12), and a month which does not contain any "*zhong-qi*" becomes an intercalary month.

A Chinese traditional calendar was also an astronomical ephemeris, and, besides the calendar for daily use, treated the prediction of eclipses, the movement of five planets etc. As a calendar was considered to be a symbol of the authority of empire, the astronomers of each dynasty tried to make more accurate calendars. So, the astronomers made astronomical observation constantly to check the accuracy of the calendar. When a calendar was found to be inaccurate, astronomers tried to make a new more accurate calendar and substitute it for the old calendar.

4.3 HE Chengtian's *Yuanjia* calendar

Before the *Yuanjia* calendar of HE Chengtian, all Chinese calendars assumed that the length of a calendrical synodic month is constant, although the inequality corresponding to the equation of centre of the moon had been discovered in the 1st century AD in the Later Han dynasty. HE Chengtian tried to adjust the first day of a calendrical synodic month to the true conjunction of the moon corrected by the lunar inequality, and proposed a new calendar in 443 AD.

4.4 HE Chengtian's statement

The following is my English translation of an extract from HE Chengtian's statement (AD 443) (recorded in the *Song-shu*, *Lizhi* (II)).

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The *Yaodian* (a section of a Confucianist classics) reads: "When the daytime is longest (at the time of the summer solstice), the [culminating] star [in the evening] is *Huo* (It is supposed to be a star or stars around α Sco.). By this, mid-summer is ascertained." At present, the star *Huo* culminate in late summer. The *Yaodian* reads: "When the nighttime is middle (at the time of the autumnal equinox), the [culminating] star [in the evening] is *Xu* (It is supposed to be a star or stars around β Aqr). By this, mid-autumn is ascertained". At present, the star *Xu* culminates in late autumn. (Translator's note: The *Yaodian* (Book of the King Yao) is a section of the *Shujing*, a Confucianist classic. The date of its actual composition is controversial. In China, one year is divided into 4 seasons, each of which consists of 3 months. For example, mid-summer includes the summer solstice, and late summer is one month later than mid-summer.)

Since then, more than 2700 years have passed, and the examination of culminating stars shows the difference of 27~28 degrees (Chinese degrees). At the time of the King Yao, the sun at the winter solstice located at the position of about 10 degrees in the lunar mansion *Nü* (right ascensionally measured from ε Aqr). According to the *Taichu* calendar of the [Former] Han dynasty, the point [of the sun at the time] of the winter solstice was at the beginning of the lunar mansion *Niu* (measured from β Cap). According to the *Sifen* calendar of the Later Han dynasty and the *Jingchu* calendar of the Wei dynasty (of the Three kingdoms period), it was at the position of 21 degrees of the lunar mansion *Dou* (measured from φ Sgr). Your servant (I, He Chengtian) examined it through the observation of lunar eclipses, and concluded that the present point of the sun at the winter solstice according to the *Jingchu* calendar should be at the position of 17 degrees in the lunar mansion *Dou*. (Translator's note: The above description shows the observational evidence of the precession of equinoxes. The "winter solstice according to the *Jingchu* calendar" is the calendrical winter solstice, and is different from the actual observational winter solstice. The *Jingchu* calendar (officially used since 237 AD) of Yang Wei had been used just before the *Yuanjia* calendar was accepted.)

And also, the court historian(s) (and astronomer(s)), by royal order, observed the solstices by measuring the gnomon-shadow, and the difference [with calendrical prediction] was more than 3 days. (Translator's note: The length of a year in the *Jingchu* calendar is about 365 + 455/1843 days or 365.2469 days, and is slightly larger than the exact value. Therefore, its error increases gradually. The difference of "more than 3 days" means that the actual observational winter solstice was more than 3 days earlier than the calendrical winter solstice.)

Till now, for several years, including reports from Jiaozhou (in south China), the changes have been observed, and were checked each other. The result is that the present [calendrical] solstices are not the heavenly (actual observational) solstices. At the heavenly southernmost movement (i.e. actual winter solstice), the sun is at the position of 13~14 degrees in the lunar mansion *Dou*. This is due to the 19-year cycle, during which 7 intercalary months are inserted, in which numbers are minute but still several errors are produced. To change the method and calendrical cycle, its required calculation is quite complicated. Revisions should be made time to time, so that adjustment [between calendar and observational data] is made. (Translator's note: The 19-year cycle of intercalation was used since the Warring states period or so in China. This Chinese cycle must be independent of the Greek Metonic cycle.)

According to the *Houhan-zhi* (treatises of the Official history of the Later Han dynasty), the daytime at the vernal equinox is long, the daytime at the autumnal equinox is short, and the difference exceeds a half *ke* (one *ke* = 1/100 day). Considering that the equinoxes are at the middle of the solstices, and they are long and short, we know that the vernal equinox is close to the summer solstice, and is long, and that the autumnal equinox is close to the winter solstice, and is short. (Translator's note: According to the *Sifen* calendar recorded in the *Houhan-zhi*, the length of daytime at the vernal equinox is 55.8 ke, and that at the autumnal equinox is 55.2 *ke*, so the difference was more than a half ke. These figures were succeeded by the *Jingchu* calendar of YANG Wei. At that time, the solar movement was considered to be constant, and HE Chengtian proposed to make them symmetrical as the theory at that time required. The interpretation of HE Chengtian that "the [calendrical] vernal equinox is close to the summer solstice" etc. suggests that the irregularity is a kind of systematic error due to the inaccuracy of the date of the solstices and equinoxes, and he was probably right. At that time, solstices and equinoxes were punctually equally divided on the basis of the time of the winter solstice. So, if the time of the winter solstice was inaccurate, systematic error should have appeared.)

YANG Wei (compiler of the *Jingchu* calendar) did not notice this matter, used it, and, presenting his calendar, said: "From ancient time till this time, all calendrical works are not comparable to the skill of my work." How ignorant he is, what else can be said!

By this reason, your servant (I, HE Chengtian) newly compiled the *Yuanjia* calendar, made 608 [years] be one *"ji"* (a calendrical cycle), made its half (304) be *"dufa"* (a calendrical constant used as a denominator), made 75 be *"shifen"* (numerator of a fraction concerning the lunar mansion *Shi*), made the month of tiger (month which includes a *jieqi "yushui"*) be the beginning of a year, made *"yushui"* (point of time which is 1/6 year after the winter solstice) be the beginning of *"qi"* (24 divisions *"jieqi"* of a tropical year), and made the year when the fraction of several figures including the fraction of intercalation is standardized be the beginning of *"zhang"* (19-year cycle)· (Translator's note: One *ji* (608 years) is a multiple of a *zhang* (19 years). Although HE Chengtian must have been aware of the inaccuracy of the 19-year cycle, he still maintained this cycle. It may be noted here that the 19-year cycle had already been abolished by ZHAO Fei in his *Xuanshi* calendar (officially used since 412 AD). Later, ZU Chongzhi also abolished the 19-year cycle. In the *Yuanjia* calendar, one year is 365 + 75/304 days, where the fraction is *"shifen/dufa"*.)

The time of the winter solstice is advanced for 3 days 5 *shi* (one *shi* is 1/12 day). The position of the sun [at the winter solstice] is shifted for 4 degrees.

And also, the movement of the moon is sometimes slow and sometimes fast, and the time of a conjunction or lunar eclipse is not necessarily in the [previous calendrical] new and full moon. This is not the proper way of a calendar.

Therefore the *Yuanjia* calendar determines the time [of the lunar conjunction etc.] applying the [lunar] inequality, and using this result determines the date of the new and full moon.

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4.5 Adaptation of the *Yuanjia* calendar

The accuracy of the *Yuanjia* calendar was attested by QIAN Yuezhi (QIAN is surname; the first Chinese character of his given name "Yuezhi" has two pronunciations, and there is also a possibility that his name was pronounced as QIAN Lezhi.), the then director of the Institute of chronology (and astronomy), and YAN Can, the deputy director. However, its use of the true conjunction for the first day of a calendrical synodic month was opposed by Qian Yuezhi and Yan Can that the calendar becomes too complicated. HE Chengtian modified his calendar, and made the length of a calendrical synodic month constant. In 445 AD, HE Chengtian's *Yuanjia* calendar was finally accepted as an official calendar.

4.6 Science and society

I think that both HE Chengtian and QIAN Yuezhi etc. are fair and understandable. This controversy shows that there can be several opinions regarding the distance between the mathematical astronomy as pure science and the civil calendar as applied technology.

From a purely scientific point of view, more accurate calendar is better, and the first day of a calendrical month should be adjusted to the true conjunction of the moon. Then, for example, a solar eclipse certainly occurs in the first day of the month.

On the contrary, from technological point of view, too much accurate calendar may be too complicated and inconvenient for daily use.

If the mean conjunction of the moon is used to determine of the first day of the month, a small month (29 days) and a large month (30 days) are distributed almost alternately, and sometimes two successive large months appear. This is easy to understand. If the true conjunction is used, the distribution of small months and large months is very complicated. After stating the accuracy of the celestial position and the date of the winter solstices in the *Yuanjia* calendar had been attested by observations, QIAN Yuezhi and YAN Can reported as follows:

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> And also, using the method of Chengtian, the date and time of the new moon, full moon, and half-moons of every month are determined. Although the prediction of the time of conjunction is accurate, the correction of inequality (equation of centre of the moon) is applied there, and there occur three successive large months or two successive small months. This is quite different from the old method. In days of old, solar eclipses were not necessarily in the first day of the month. They could be in the last day of the previous month or in the second day. This is what *Gongyang-zhuan* (a classical commentary on the *Chunqiu*, a Confucianist classics) says "Sometimes errors towards the time before are made, and sometimes errors towards the time after are made". I say that as regards this matter the old method should be followed." (Translated by me from the *Song-shu*, *Lizhi* (II).)

In the *Yuanjla* calendar, the use of true conjunction of the moon for the determination of calendrical month was abolished. Later, the true conjunction of the moon began to be used at the time of the Tang dynasty.

Both the scientific point of view and the technological point of view are understandable, and difficult to say which is better. It may depend on the requirement of society.

5. ZU CHONGZHI —— GREAT ASTRONOMER AND MATHEMATICIAN

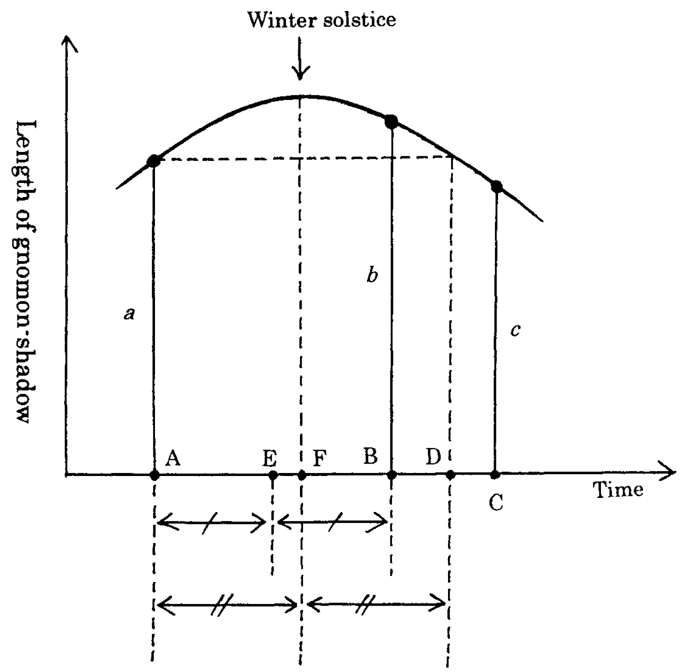
5.1 Introduction

ZU Chongzhi (ZU is surname) is a Chinese mathematician and astronomer in the Southern dynasties in the Northern and Southern dynasties period.

ZU Chongzhi was born in 429, and died in 500 AD. The domicile of origin of his family was Fanyang (now in Hebei province in North China), but his ancestors moved to South China. ZU Chongzhi worked as a government officer of Song (Liu-Song) dynasty and Southern Qi dynasty. He made a new calendar entitled *Daming* calendar, and requested to use it officially in 462 AD, but was severely opposed, and the calendar was not accepted.

ZU Chongzhi's son ZU Gengzhi (or ZU Geng) was also a mathematician and astronomer. Thanks to ZU Gengzhi's effort, the *Daming* calendar was officially used since 510 AD.

The *Daming* calendar of ZU Chongzhi is recorded in the *Lizhi* (chapter of calendar) (III) in the *Song-shu* (Official history of the Song dynasty).



5.2 ZU Chongzhi's observational astronomy

ZU Chongzhi devised a method to determine the exact time of winter solstice from the observations of the midday gnomon-shadow. ZU Chongzhi's explanation is recorded in the *Song-shu, Lizhi* (III).

For the determination, three observations (A, B, and C in the figure) of the midday gnomon-shadow (a, b, and c) are used. Here, $b>a>c$ and the period BC is one day. In ancient China, one day was divided into 100 "*ke*". Let an imaginary gnomon-length at D (between B and C) be equal to a. The point E is the midpoint of AB, and F the midpoint of AD, that is the time of winter solstice. Then, EF is a half of BD. Now, by linear interpolation,

$$\mathrm{BD} = \frac{100\times(b-a)}{b-c}\ ke.$$

Therefore,

$$\mathrm{EF} = \frac{100\times(b-a)}{2\times(b-c)}\ ke.$$

As the time E is already known, the time F of winter solstice is obtained from this equation.

5.3 ZU Chongzhi's theoretical astronomy

Most of all Chinese calendars before ZU Chongzhi used the cycle of 19 years for intercalation, during which 7 intercalary months are added. This cycle is called *zhang*, and was already used by the end of the "Warring states" period (475-221 BC). Although this cycle is the same as the Greek Metonic cycle, Chinese and Greek cycles must be independent. The earliest Chinese calendar which abandoned the 19-year cycle is the *Xuanshi* calendar (412 AD) of ZHAO Fei of the Northern Liang dynasty (which is one of the 16 states existed almost simultaneously at the time of the Eastern Jin dynasty), who used 600-year cycle during which 221 intercalary months are added.

The *Daming* calendar (462 AD) of ZU Chongzhi is the second calendar to abandon the 19-year cycle, and used 391-year cycle during which 144 intercalary months are added.

Another important significance of the *Daming* calendar of ZU Chongzhi is that it took account of the precession of the equinoxes. The precession had already been discovered by YU Xi, but ZU Chongzhi was the first to take it into account in an official calendar. Accordingly, the tropical year and the sidereal year were differentiated, and their length used there is $365\frac{9589}{39491}$ (=365.2428148…) days and $365\frac{10449}{39491}$ (=365.2645919…) days respectively.

The *Daming* calendar also used the length of a nodical month $\frac{717777}{26377}$ (= 27.212230…) days, which is quite accurate. The nodical month is used for the prediction of eclipses (See my previous paper in the *Gaṇita Bhāratī* (vol.29, 2007, 101 – 115, particularly pp.106~107).).

The *Daming* calendar was severely opposed by a conservative DAI Faxing. Although ZU Chongzhi objected him, the calendar could not be used officially during the lifetime of ZU Chongzhi. The calendar was officially used since 510 AD by the effort of ZU Gengzhi, a son of ZU Chongzhi.

ZU Chongzhi was also a great mathematician. He calculated that the value of π lies between 3.1415926 and 3.1415927. He is said to have composed a high-grade mathematical work *Zhuishu*, which is not extant by now.

6. ZHANG ZIXIN'S DISCOVERY OF THE EQUATION OF CENTRE OF THE SUN

ZHANG Zixin (ZHANG is surname) discovered the inequality corresponding to the equation of centre of the sun in the 6th century AD at the time of the Northern dynasties.

According to the *Suishu* (Official history of the Sui dynasty), *Tianwenzhi* (Chapter of astronomy) (III), ZHANG Zixin renounced the world and observed heavenly bodies for about 30 years, and found that the movement of the sun is slow after the vernal equinox, and is fast after the autumnal equinox.

As the direction of the solar perigee is near the first point of Capricorn (direction of the sun at the winter solstice), it can roughly be said that the movement of the sun is fast from the autumnal equinox to the vernal equinox, and is slow from the vernal equinox to the autumnal equinox. Therefore, ZHANG Zixin was basically right. (Actually, the solar perigee is moving slowly. This fact was not noticed by Chinese astronomers before Western influence, and the point corresponding to the modern perigee was assumed to be at the direction of the sun at the winter solstice in the Chinese classical astronomy after ZHANG Zixin.)

By this time, the equation of centre of the sun was already known in the ancient Mediterranean world and also in India. Although certain information of Indian astronomy was already known in China, it was basically the information of Vedāṅga astronomy. The Hindu classical astronomy (including the equation of centre etc.) was not yet known. Therefore, ZHANG Zixin's discovery must be independent of the ancient Mediterranean and Indian astronomies.

7. CONCLUSION

We have seen that several new astronomical discoveries were made, and several new ideas were produced during this period.

Chinese astronomy was further developed by great astronomers like Yixing (683 ~ 727) of the Tang dynasty, GUO Shoujing (1231 ~ 1316) of the Yuan dynasty etc. I would like to discuss the contribution of these astronomers at another occasion.

BIBLIOGRAPHICAL NOTE

1 General works

The followings are general works written in English.

For Chinese mathematics and astronomy in general, the following work may still be consulted.

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For the history of Chinese mathematics in general, the following works may be consulted.

LI Yan and DU Shiran (translated by John N. Crossley and Anthony W.C. Lun): *Chinese Mathematics, A concise history*, Clarendon Press, Oxford, 1987.

Martzloff, Jean-Claude : *A History of Chinese Mathematics*, (originally published in French in 1987), Springer, Berlin, 1997.

For the mathematical astronomy in China, the following article may be consulted.

Martzloff, Jean-Claude : "Chinese Mathematical Astronomy", in Selin, Helaine (Ed.): *Mathematics Across Cultures*, Kluwer Academic Publishers, Dordrecht, 2000, pp.373–407.

The followings are some detailed histories of Chinese astronomy written in Chinese.

CHEN Zungui : *Zhongguo tianwenxue-shi* (History of Chinese astronomy, in Chinese), 4 vols., Shanghai renmin chubanshe, Shanghai, 1980-1989.

CHEN Meidong : *Zhongguo kexue-jishu-shi, Tianwenxue-juan* (A History of Science and Technology in China, Astronomy Volume, in Chinese), Kexue chubanshe, Beijing, 2003.

2 Original sources

Most of the original sources are recorded in the official histories of Chinese dynasties, which are quite popular in East Asia. There are several editions. Astronomical and calendrical chapters in them were separately published in the following collection. This collection is very convenient, and is usually used by East Asian historians of astronomy.

Lidai tianwen-lüli-deng-zhi huibian (Collection of the Astronomical, Acoustical and Calendrical Chapters in the Official Dynastical Chronicles, in Classical Chinese), 10 vols., Zhonghua shuju, Beijing, 1975~1976.

3 Biographies of ZU Chongzhi

The following biography in English is written from mathematical point of view.

Kobori, Akira : "Tsu Ch'ung-chih", in Charles Coulston Gillispie (ed.): *Dictionary of Scientific Biography*, Vol.13, Charles Scribner's Sons, New York, 1976, pp.484-485.

The following is a biography written in Chinese.

LI Di : *ZU Chongzhi* (in Chinese), Shanghai renmin chubanshe, Shanghai, 1977.

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