Identification of stars in a J1744.0 star catalogue Yixiangkaocheng

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ABSTRACT
The stars in the Chinese star catalogue, Yixiangkaocheng, which were edited by the Jesuit astronomer Kôgl in AD 1744 and published in AD 1756, are identified with their counterparts in the Hipparcos catalogue. The equinox of the catalogue is confirmed to be J1744.0. By considering the precession of equinox, proper motions and nutation, the star closest to the location of each star in Yixiangkaocheng, having a proper magnitude, is selected as the corresponding identified star. I identified 2848 stars and 13 nebulosities out of 3083 objects in Yixiangkaocheng, and so the identification rate reached 92.80 per cent. I find that the magnitude classification system in Yixiangkaocheng agrees with the modern magnitude system. The catalogue includes dim stars, whose visual magnitudes are larger than 7, but most of these stars have Flamsteed designations. I find that the stars whose declination is lower than $-30^\circ$ have relatively larger offsets and different systematic behaviour from other stars. This indicates that there might be two different sources of stars in Yixiangkaocheng. In particular, I find that $\mu^1$ Sco and $\gamma^1$ Sgr approximately mark the boundary between two different source catalogues. The observer’s location, as estimated from these facts, agrees with the latitude of Greenwich where Flamsteed made his observations. The positional offsets between the Yixiangkaocheng stars and the Hipparcos stars are 0.6 arcmin, which implies that the source catalogue of stars with $\delta > -30^\circ$ must have come from telescopic observations. Nebulosities in Yixiangkaocheng are identified with a few double stars, $\omicron$ Cet (the variable star, Mira), the Andromeda galaxy, $\omega$ Cen and NGC6231. These entities are associated with listings in Halley’s Catalogue of the Southern Stars of AD 1679 as well as Flamsteed’s catalogue of AD 1690.

Key words: history and philosophy of astronomy – catalogues – astrometry.

1 INTRODUCTION
Humans have used their imagination to organize stars into small groups or asterisms. These asterisms are usually associated with culture, reflecting human life, customs, legends, social structure, etc. The Chinese developed their own system of asterisms in ancient times. According to the literature, the Shi, Gan and Wu schools of asterisms were established by the Han Dynasty (Sun & Kistemaker 1997). These schools designated 283 asterisms, which together consist of 1464 stars. Ancient Chinese astronomers first drew the asterisms by connecting dots with straight lines (Auerbach 2003).

The first measurements of the positions of stars in Chinese history were made during the former Han Dynasty. The positions of the determinative stars of the 28 lunar lodges were measured in 104 BC to reform the calendar system (Sun & Tian 1993). Yang Xiong (53–18 BC) in his book, Fa Yan (Comments on the Laws of Nature), reports that in 104 BC, Luoxia Hong made the equatorial armillary to measure the positions of stars and Geng Shouchang made the celestial globe based on Luoxia Hong’s measurements.

The observed positions were recorded in the book Shi Shi Xing Jing (Star Canon of Master Shi), but the book was lost and there remain only parts of the book cited in the Dunhuang manuscript P.2512 (AD 621), Kaiyuan Zhanjing (the Treatise on Astrology of the Kaiyuan Era) established in AD 718–726, Jiu-Tangshu (the Old Book of Tang) published in AD 940–945, Xin-Tangshu (the New Book of Tang) published in AD 1044–1060 and also Sanjia Buzan (Records and Eulogy for the Three Schools of Astronomy) originated from China and used by the Japanese astronomers of the Heian era in AD 794–1185 (Ahn 2010). The observational data were of only the 28 determinative stars. Additional stellar positions were mapped during the early Tang Dynasty, but the extensive star catalogue appeared during the Song Dynasty when an extensive sky survey was conducted (Sun & Kistemaker 1997; Pan 2009). The catalogue of Yang Weide also called the Jingyou Star Catalogue (epoch AD 1034), resulting from the measurements during the Jingyou reign period (AD 1034–1038), includes 341 stars. Another star catalogue made during the reign of the Song Dynasty was the star catalogue of Zhou Cong, also called the Huangyou Star Catalogue, resulting from the
measurements during the Huangyou reign period (AD 1078–1085); it consists of 360 stars. Further, during the 13th-century Yuan Dynasty, Guo Shoujing (AD 1231–1316) mapped the positions of 741 stars in a star catalogue. These catalogues consist of stars including almost all the reference stars for the 283 traditional Chinese asterisms.

Asterisms are usually shown either in star charts or on a celestial globe. The standard form of these star charts was first established during the Three-Kingdom era. The standard form is based on the star chart called Sanjia Xingtu (Star Charts of the Three Schools) made by Chen Zhuo, the third-century royal astronomer of the kingdom of Wu.

A number of Chinese ancient star charts remain to this day. For example, the Dunhuang chart, called S.3326, now held in the British Library, dates back to AD 649–684 (Bonnet-Bidaud, Praderie & Whitfield 2009). Other examples include the extent star chart shown in the Japanese mural painting called Kitora, which dates back to approximately AD 700, the Mercator-projected star charts in Xin Yixiang Fayao (Essentials of a New Method for Mechanizing an Armillary Sphere and a Celestial Globe) written by Su Song (AD 1020–1101) in AD 1084 and the Suzhou chart of AD 1247. However, the dots-and-lines system must have been developed in the earlier times because they appear on the stone engravings of the Han Dynasty.

In Chinese history, whenever a star chart or a star catalogue was updated, the astronomers usually consulted the previous records. Unfortunately, the records were incomplete, because the positions of stars were usually described as sentences, not as coordinate values. Thus they had to identify the stars in the previous records with their real skies. Such identifications were carried out several times in Chinese history. In the 17th century, the Jesuit astronomers working in China made a whole-sky star catalogue that even included stars near the South Celestial Pole. In AD 1644, a Jesuit astronomer, Adam Schall (AD 1591–1666), compiled a star catalogue and drew star charts based on the star catalogue of Tycho Brahe. Tycho Brahe adopted the equatorial coordinate system, and so, the catalogue and charts of Adam Schall were made mainly in the equatorial coordinate system. However, the catalogue lists both the equatorial and the ecliptic coordinates of stars. The authors of the catalogue obtained the equatorial coordinates from the ecliptic coordinates after correcting for the precession of equinox. However, ecliptic coordinates were inconvenient for Chinese astronomers because they had long been using the equatorial system. Thus, another Jesuit astronomer, F. Verbiest (AD 1623–1688), revised the catalogue to publish Xinzhi Lingtai Yixiangzhi (An Explanation of the Newly Built Astronomical Instruments of the Imperial Observatory) in AD 1674. He designated the 261 traditional Chinese asterisms consisting of a total of 1210 stars. In addition to these stars, he added another 516 stars that had not been included previously in the Chinese asterisms. He also included 150 stars of the Southern hemisphere that made up 23 asterisms that had been included by Adam Schall. Hence, Verbiest’s catalogue contained 1876 stars (Pan 2009). Although Verbiest adopted the equatorial system instead of the ecliptic system, his identifications of asterisms were criticized because they had discrepancies when compared with the traditional Chinese asterisms. Thus, Kögl er (1680–1746), a German Jesuit missionary who succeeded the royal astronomer of the Qing Dynasty, proposed that Xinzhi Lingtai Yixiangzhi be revised (Pan 2009). He argued that the coordinates of stars had changed due to the precession of equinox and also that the obliquity had changed from 23°32′ to 23°29′. While compiling the catalogue, Kögl er died in the spring of AD 1746. He was succeeded by Hallerstein (AD 1703–1774), and A. Gogeisl (AD 1701–1771) was promoted as the vice chair. Finally, a star catalogue listing the coordinates of 3083 stars was completed in AD 1752; it was named to be Yixiangkaocheng (Compendium on Astronomical Instruments, hereafter abbreviated as YXKC). After the completion of the catalogue, the construction of a large armillary instrument was finished in AD 1754. This fact implies that the catalogue was not based on the data observed with the armillary. The complete catalogue was published in AD 1756.

The catalogue was partially analysed by Pan (1989). By assuming the equinox of the catalogue as J1744.0, he identified both the deterministic stars of the 28 lunar lodges and 26 stars (three stars in each Chinese zodiac sector) in the catalogue with modern counterparts. He found that the errors in the equatorial coordinates were smaller than those in the ecliptic coordinates. He ascribed the differences in errors to the errors during the coordinate transformation, and so he concluded that the source catalogue of YXKC must use the equatorial coordinate system. He also found that the positional error of the 28 deterministic stars in YXKC is 34 arcsec (26 arcsec when the deterministic star of the lunar lodge Wei(6) was excluded because it has a peculiarly large error). Thus, Pan (1989) concluded that the catalogue was based on another catalogue that recorded telescopic observations. It is known that Flamsteed’s catalogue was the first one that achieved subarcminute accuracy. Based on the above-mentioned facts, Pan (1989) concluded that Flamsteed’s catalogue of AD 1725 must be the reference catalogue of YXKC. Flamsteed’s catalogue has observational error of 10 arcsec, which was achieved by using a sextant with two telescopic sights from AD 1676 to 1690 (Hog 2010).

In this paper, we identify the entire stars in YXKC with their counterparts in the Hipparcos catalogue (Perryman et al. 1997). The median astrometric standard errors in position and annual proper motion of the Hipparcos catalogue are in the range of 0.7–0.9 mas for stars brighter than 9 mag at the catalogue epoch (J1991.25). This accuracy is quite sufficient for our investigation. Bright stars that can be seen with the naked eye are generally close to the Earth, and so their proper motions for the time-span of 250 yr are relatively large enough to affect the identification results. In many cases, the Yale Bright Star Catalogue was used to identify stars in historical star catalogues because it includes all the stars visible with the naked eye. However, it is known that YXKC is based on telescopic observations (Pan 1989, 2009), and that 200 stars designated by Flamsteed or approximately 8 per cent of the total are too faint to be contained in the Yale Bright Star Catalogue (Bidelman 1990; Wagman 1987). This means that the Yale Bright Star Catalogue is not sufficient for the identification of stars in YXKC, and thus, the Hipparcos catalogue is used in this study. Section 2 describes the basic characteristics of YXKC and the method of identification. Results are given in Section 3. Conclusions are provided in Section 4.

2 METHOD

2.1 YXKC star catalogue

In this study, I analysed the data in the YXKC books preserved in the Kyujanggak Library or the Royal Library of the Choson Dynasty (Seoul, Korea). The call number of these books is Kyujung 3539, where ‘jung’ means the Chinese books. Fig. 1 shows the first page of the equatorial catalogue in these books. Another edition can be found in Sikju Quanshu (Complete Library of the Four Treasures), which is basically the same as the original ones. YXKC in the Kyujanggak Library consists of 32 volumes bound into 12 books.
The books were published in AD 1756 in Beijing, and according to Sungjongwon-Ilg (Daily Records of Royal Secretariat of the Choson Dynasty), it was in AD 1788 a copy was first imported from Beijing to Seoul.

YXKC comprises six large parts. The first part explains the instrument used to measure the positions of stars. The next part describes the concepts related to stars and the changes in YXKC compared with previous star catalogues. There are three star charts at the end of this part. The first chart resembles the traditional Chinese star charts, and the other two are the star charts drawn with the stereographic projection. These charts are pictorial representations of only classical Chinese stars in the YXKC catalogue. The next two parts are star catalogues. Both catalogues present the ecliptic and equatorial coordinates of 3083 stars. The former lists stars in the increasing order of right ascension (hereafter RA). In this paper, a star in the equatorial table of YXKC is designated by Q and a star in the ecliptic table by C. That is, 'Q.100' refers the 100th star in the equatorial catalogue, and 'C.100' refers to the 100th star in the ecliptic catalogue. The next two parts of YXKC contain the coordinates of the boundaries of the Milky Way Galaxy and the coordinates of stars in the ecliptic belt, respectively.

The two catalogues in YXKC are basically identical except for the entry order of stars, and so, the coordinates in both catalogues can be cross-checked. After cross-checks between the two catalogues, only the equatorial catalogue is used for further analysis. Fig. 1 shows the first page of the equatorial catalogue in YXKC in which both the equatorial and ecliptic coordinates of stars are given. Recall that the first entry in Fig. 1 is read as 'Douxiu-Bei-Zeng-2', which means that this star is the second addendum star ('Zeng') located at the north ('Bei') of the lunar lodge of Dou(8). The addenda stars are not related to the classical Chinese asterisms, but they were added by the Jesuits in order to enlarge the catalogue. Here the classical Chinese stars are those which are identified based on the classical Chinese asterisms and classified as the Chinese traditional stars in the previous catalogues such as Chongzhenlishu (Calendrical Method of the Chongzhen Reign) and Xinzhi Lingtai Xiyangzi. I denote the name of the eighth lunar lodge by 'Dou(8)', where the number in the parenthesis is the sequence number.

YXKC contains 1319 stars of 277 Chinese asterisms, 1614 addenda stars and 150 stars of the 23 Southern asterisms. Thus, it has a total 300 asterisms with 3083 stars. Among the 150 stars in the Southern hemisphere, 130 stars were registered in the previous standard star chart or Xinzhi Lingtai Xiyangzi, while 20 stars were newly added to the catalogue. The catalogue contains 14 nebulosities called Qi. Among them are nine nebulosities that had already been listed in Xinzhi Lingtai Xiyangzi, while five nebulosities were new entries in YXKC.

The definition of declination in YXKC is exactly the same as the modern definition. The RA in YXKC is divided by 12 Gongs that resemble the 12 equatorial sectors in the traditional Chinese coordinate system. It is noticeable that the orientation of the Gongs is opposite to that of RA. That is, the Gong increases in the westward direction, while the RA increases in the eastward direction. In order to meet the origin of the traditional 12 sectors in Chinese astronomy, the 11th Gong is set to coincide with the origin of RA. This definition of RA is the same as that in the sequel of YXKC published in AD 1844 (Ahn, Park & Yu 1996). Thus, the RA of a star with the gth Gong, $d$ degree, $m$ minutes and $s$ second is $\alpha = 30(11 - g) + d + m/60 + s/3600$ in degree. Here $g$, $d$, $m$ and $s$ are all integers. If $g = 12$, then $\alpha' = \alpha + 360'$. 

2.2 Equinox of YXKC

The identification procedures are basically the same as those in Ahn et al. (1996). To begin with, the equinox of the catalogue is determined. It took approximately eight years to edit the catalogue, so I checked if the equinox of coordinates was spread over the eight years. The first magnitude stars and the determinative stars are important reference stars in Chinese astronomy. These stars can be easily and unambiguously identified with their counterparts in the Hipparcos catalogue. Thus, I determined the equinox of YXKC by analysing the coordinates of these stars. According to the official report in YXKC, the coordinates of stars in YXKC are represented with respect to the equinox of J1744 (Pan 2009, p. 638).

The precession-corrected RA and declination of a star in the Hipparcos catalogue at time $t$ are denoted by $\alpha(t)$ and $\delta(t)$, respectively. The RA and declination in YXKC are $\alpha$ and $\delta$, respectively; the offset or angular distance between the precession-corrected coordinate and the coordinate in YXKC is denoted by $\alpha - \alpha(t)$, here, the offsets are calculated by using the spherical geometry explained in Meeus (1998). I obtained the time $t_0$ when $\alpha(t_0) = \alpha$, and also the time $t_1$ when $\delta(t_1) = \delta$. I also obtained the time $t_2$ when $\alpha(t_2) = \alpha$, and $\delta(t_2) = \delta$. I minimized the function stars as a function of time. For most of the first-magnitude stars, the time of minimum separation, $t_0$, coincides with the equinox of the catalogue J1744.0. These $t_0$ values are given in Table 1, where the $t_0$ values for the three stars Shuiwei1 (\alpha Eri), Laoren (\alpha Car) and Nanmen2 (\alpha Cen) show particularly large deviations. In addition, Beiluoshimen (\alpha PsA) has a declination lower than $\delta < -30'$. These stars are not
visible at the latitude of Greenwich. These stars must have been inserted by Jesuits from other catalogues that contained stars of the Southern hemisphere. These four stars have large errors, and so, I exclude them from the statistics presented in the last three rows of Table 1. In addition, the $t_\alpha$ and $t_\delta$ values are shown in Table 1. These three values consistently indicate that the equinox of YXKC is J1744.0 with a typical uncertainty of 0.8–0.9 yr, which agrees with the official report in YXKC.

The 13th and 14th columns of Table 1 show the offset in RA, $\Delta \alpha$, and the offset in declination, $\Delta \delta$, between the positions of the stars in YXKC and the positions of the identified stars at the equinox J1744.0, respectively. The standard deviations of the offsets in RA and declination for the first magnitude stars are approximately from 0.6 arcmin or 40 arcsec. The positional error is definitely subarcminute. This can be thought to be the positional accuracy of stars in YXKC. The analysis will be continued in Section 3.2 in more detail.

Similar analyses are performed for the determinative stars of the 28 lunar lodges. The results are shown in Table 2. The last three rows are averages and standard deviations in RA ($\sigma_\alpha$) and declination ($\sigma_\delta$) between the coordinates in YXKC and the precessed-coordinates of the Hipparcos catalogue. The stars with low declination ($\delta < -30^\circ$), denoted with asterisks in Table 2, are excluded. As Pan (2009) has also pointed out, the determinative stars for the lunar lodges Weir(6) ($\mu_\alpha$ Sco) and Ji(7) ($\pm$ Sgr) have particularly large deviations, and so they are omitted in the statistics. Pan (2009) carried out a similar analysis as mine. I obtained $\Delta \alpha = 0.23 \pm 0.74$ arcmin, while he obtained $\Delta \alpha = 0.63 \pm 0.44$ arcmin. I also obtained the median value for the angular distances between the YXKC and Hipparcos stars to be 0.58 arcmin. Therefore, I conclude that the positional error of stars in YXKC is approximately 0.6 arcmin, which is in agreement with the suggestion that YXKC is originated from a catalogue with subarcminute accuracy. In Table 2, the $t_\alpha$, $t_\delta$, and $t_r$ values are all in agreement with $\Delta \alpha$ 1744, that is, the equinox mentioned in the official report of YXKC. Therefore, the equinox of the catalogue is fixed to be J1744.0.

Figure 2. Temporal variations of separations between YXKC stars and its counterparts in the Hipparcos catalogue for the first magnitude stars. The time of minimal separation corresponds to the equinox of the YXKC catalogue. The three stars below the horizon of the Northern hemisphere such as $\alpha$ Eri, $\alpha$ Car and $\alpha^1$ Cen show larger deviations.

Table 1. First magnitude stars in YXKC identified with the stars in the Hipparcos catalogue. The first column is the sequence number of a star in the equatorial catalogue. The second column represents the names of stars. Columns 3–8 are the RA and declination for each star as they are written in YXKC. Column 9 is the Hipparcos number. F (column 10) refers to the Flamsteed number and column 11 is the Bayer denomination. $\mu_\alpha$ is the magnitude of the identified star in the Hipparcos catalogue (column 12). The offset of a star in YXKC from its counterpart in the Hipparcos catalogue has a component in RA, $\Delta \alpha$, and in declination, $\Delta \delta$ (columns 13 and 14) and angular separation $r$ (column 15). The probable equinoxes $t_\alpha$, $t_\delta$, and $t_r$ are determined for each star (columns 16–18). See the text for details.

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<th>RA</th>
<th>Declination</th>
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<th>Bayer</th>
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<th>$\Delta \alpha$</th>
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2.3 Identification method

In order to identify each star in YXKC with its counterpart in the Hipparcos catalogue, I first transform the equatorial coordinates of stars in the Hipparcos catalogue (equinox J2000.0) to the coordinates of equinox J1744.0 (or 12\textsuperscript{th} 1744 Jan 1 in terrestrial time). It is obvious that the transformation should include the precession of equinox and the proper motions. The YXKC catalogue is known to be based on Flamsteed’s catalogue (Pan 1989), which is thought to list the apparent positions of stars. Therefore, in principle, the transformation should include the precession of the stars for approximately 250 yr are less than 1’’. However, YXKC (and also Flamsteed’s catalogue) match to a star in YXKC is already be included in the transformation. However, there is no information on observation time of stars in YXKC, and so only nutation is considered in this study. The obliquity of J1744.0 was calculated by using the precise method of Meeus (1998), and I obtained ε = 23° 28’’. However, YXKC (and also Flamsteed’s catalogue) adopted ε = 23° 29’. In this paper, only linear proper motions are applied separately to RA and declination, and the curvature effect in the spherical coordinate is ignored. Since proper motions for most of the stars for approximately 250 yr are less than 1°, the linear corrections are sufficient. In calculating the precession, it is noticeable that the Hipparcos coordinates are for the equinox 2000.0. The method for calculating precession is given in Meeus (1998).

After coordinate transformation, candidate stars in the Hipparcos catalogue are selected based on the criterion that their angular distances with respect to the corresponding YXKC stars are less than 20 arcmin. Then, the nearest match among the candidates is determined to be the identified star, with the magnitudes also being taken into account. If the candidates are too dim or V ≥ 7.0, then only stars with Flamsteed designations are chosen.

The identification method can be more self-consistent if these procedures are performed iteratively by applying the standard deviations in angular distances and magnitudes of identified stars obtained above as new selection criteria. However, in practice, most stars can be identified without these iterations, and a majority of stars in YXKC have a positional error of σr ≤ 2 arcmin. In a majority of cases, the nearest Hipparcos match to a star in YXKC is easily determined because there would be no other stars nearby. This feature can be seen in Fig. 3, which shows the Orion region.

In order to check for the typographical errors in coordinates, I compared star charts such as those in Fig. 3 with the star charts in YXKC, shown in Fig. 4. I found a number of typographical errors. One example is Q.1462 or the fourth star in the asterisms 29 and 30 of Fig. 3, which shows the Orion region.
Figure 3. Star chart showing the Orion region. Here, the black open dots are the Hipparcos stars. The red solid dots represent the genuine Chinese stars in YXKC, and the red open dots are the addendum stars in YXKC. The sizes of the dots indicate the apparent magnitude. The numbers represent the entry order of stars in YXKC.

of Yujing, shown in Fig. 3 as an arrow. The erroneous position written in YXKC is drawn by a blue open dot at the end part of the arrow, while the corrected position is shown by a red solid dot in front of the arrow. In other words, by adding one degree to the RA value in YXKC, we can find a star with the proper magnitude and in the proper location in the star chart in YXKC. However, only traditional stars are depicted in the star charts in YXKC and there are no addenda stars. The validity of the identification of the addenda stars can be checked using their names. The addenda stars are named after their relative positions with respect to the traditional asterisms. For example, the name of the Q.1 star in the YXKC equatorial catalogue is titled ‘Douxiu-bei-zeng 2’. This means that this addendum (‘zeng’) star is located to the north of the traditional asterism Douxiu. In fact, the star is very close to and north of Q.3081 Douxiu 3, a star in a traditional asterism. Q.281 is a nebulosity or Qi. Its name is ‘Niuixiu-nan-zeng 8’, where ‘nan’ means south and so the nebulosity is located south of the traditional asterism called Niuixiu. In fact, the location of the star is in agreement with its name. However, the object has a different name in the ecliptic catalogue: ‘Niuixiu-xi-zeng 8’, where ‘xi’ means the west, which does not agree with the real locations of the stars. Thus, I conclude that ‘nan’ is correct.

It is also useful that the stars are given in the increasing order of RA. For example, the number for the arcminute of Q.1735 in RA is 28, but it should be 38 in order for its RA to be between those of Q.1734 and Q.1736. Its ecliptic coordinate, when converted into equatorial coordinate, also coincides with 38 arcmin. There is a counter-example. The RA of the Q.1023 star is 40 arcmin, but its ecliptic coordinate indicates that it should be 4 arcmin. If it is 40 arcmin, the star cannot have a modern counterpart near its location. On the other hand, if it is 4 arcmin, it does have a counterpart. However, if it is 4 arcmin, it disobeys the ordering rule in RA. Possibly there must have been an error in sorting the stars in the increasing order of RA. The list of the typographical errors in the catalogue entries is shown in Appendix B.

For both stars in a binary or stars in crowded regions, I checked the identified results carefully by referring to detailed star charts. For example, the equatorial coordinates of the Q.2889 and Q.2890 stars are very close to each other. In such a case, a unique identification cannot be made. In fact, the stars being discussed are 36 Her...
and 37 Her, respectively. These stars comprise a binary system. In such cases, I identified the star manually in the modern star chart by considering the relative position and the similarity of magnitude. If the candidate stars belong to a close binary system, we choose the primary star, which is brighter. Multiple identification was avoided in this study. In Section 3.4, I will present a couple of such examples that have significant implication with respect to the source catalogue of the YXKC catalogue. It is noteworthy that some of the identified stars, whose offsets are larger than 20 arcmin and which have no Flamsteed designations, were chosen by manual identification. Finally, there are 14 nebulosities listed in YXKC called Qi. These were identified individually by inspecting modern star charts.

3 RESULTS

3.1 Magnitudes

In total, 2848 stars were identified with stars in the *Hipparcos* catalogue and 13 nebulosities were also identified with modern observations. Since there are 3083 entries in YXKC, the identification rate reaches 92.80 percent. Fig. 5 shows the magnitude distributions of the stars in YXKC that are identified with those in the *Hipparcos* catalogue. In the figure, the horizontal axis represents the Johnson visual magnitudes and the vertical dashed line in each panel represents the mean magnitudes. It is worth noting that the magnitudes of stars in YXKC correspond to a classification rather than a measurement (Verbunt & van Gent 2010). We see in Fig. 5 and Table 3 that the classification in YXKC correlates well with the modern magnitude system. However, a number of faint stars with magnitude 6 in YXKC are identified with faint stars whose visual magnitudes $V > 7$. Although these faint stars are beyond the limit of naked-eye observations, a majority of them have numbers designated by Flamsteed. This fact indicates that the YXKC stars were based on the telescopic observations made by John Flamsteed.

### Table 3. Visual magnitudes of stars in YXKC.

<table>
<thead>
<tr>
<th>$V_{\text{HH}}$</th>
<th>$N$</th>
<th>$V_{\text{hip}}$</th>
<th>$\sigma$</th>
</tr>
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<tbody>
<tr>
<td>1.0</td>
<td>17</td>
<td>0.70</td>
<td>0.49</td>
</tr>
<tr>
<td>2.0</td>
<td>68</td>
<td>2.18</td>
<td>0.56</td>
</tr>
<tr>
<td>3.0</td>
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<tr>
<td>4.0</td>
<td>453</td>
<td>4.24</td>
<td>0.61</td>
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<td>5.0</td>
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<td>4.94</td>
<td>0.66</td>
</tr>
<tr>
<td>6.0</td>
<td>1395</td>
<td>5.74</td>
<td>0.71</td>
</tr>
</tbody>
</table>

3.2 Positions

The offsets in RA and declination of stars in YXKC with respect to the precession-corrected positions of the identified stars in the *Hipparcos* catalogue are shown in Figs 6 and 7. Here, the offset in RA is weighted by $\cos \delta$ to avoid the projection effects. Here, only stars within the range of $-30^\circ < \delta < 60^\circ$ are shown because the circumpolar stars show relatively large offsets, as can be seen in Fig. 11. Figs 6 and 7 show that there are no conspicuous systematic variations in the offsets of RA.

Verbunt & van Gent (2010) found that the error in ecliptic latitude ($\Delta \beta$) for the stars in the catalogue of Tycho Brahe depends on the RA ($\alpha$). They attributed this dependence to the error in obliquity ($\epsilon$). The equinox of the Flamsteed catalogue is known to be J1690.0 (Verbunt & van Gent 2010), and the obliquity of the ecliptic used in the Flamsteed catalogue is $\epsilon' = 23^\circ 29' 00''$ (Kollerstrom & Allop 1995). I have shown that the equinox of the star catalogue in YXKC is J1744.0. It is known that YXKC was published to meet the newly adopted obliquity of the ecliptic, $\epsilon' = 23^\circ 29' 00''$. This obliquity is the same value as that measured by Flamsteed himself. However, the obliquity of J1744.0 calculated by using the precise method in Meeus (1998) is $\epsilon = \epsilon_0 + \Delta \epsilon = 23^\circ 28' 28''$. Here the mean obliquity of the ecliptic $\epsilon_0$ is given by equation 3.531-2 in Seidelmann (1992) or equivalently equation 22.2 in Meeus (1998), and the nutation in...
obliquity $\Delta \epsilon$ is also given in chapter 22 of Meeus (1998). There is a difference in obliquity, $\Delta \epsilon = \epsilon' - \epsilon = 32$ arcsec. I confirmed that the effects of using a wrong obliquity on the offset are at most 1 arcsec that is negligible.

Fig. 8 shows the distribution of the angular distances between YXKC stars and Hipparcos stars for each YXKC magnitude. Here, stars in perpetual invisibility are excluded. The dashed vertical lines represent medians. The median angular distance between the YXKC stars and their counterparts in the Hipparcos catalogue is $r \simeq 0.6$ arcmin, which contains both the errors arising from measuring the positions of stars by Flamsteed and the errors from calculating the precessions by the Jesuits. It is known that the subarcminute accuracy can be achieved by using telescopes. It is noticeable that the mode values are $r \simeq 0.4$ arcmin.

Figs 9, 10 and 11 show the deviations in RA ($\Delta \alpha \cos \delta$), the deviations in declination ($\Delta \delta$) and the angular offsets ($r$) as a function of declination, respectively. It is shown in the figures that the stars near the South Celestial Pole ($\delta < -30^\circ$) have deviations much larger than those in the visible sky ($\delta > -30^\circ$). Their boundary is approximately $\delta(1744) = -30^\circ$. In addition to this, Table 2 shows
Identification of stars in Yixiangkaocheng

The same as Fig. 9, but for the offsets in declination. The stars whose declination is less than $\delta < -30^\circ$ show relatively larger offsets. In addition, the circumpolar stars also have relatively large deviations. It is noteworthy that there exists the systematic behaviour.

Figure 10. The same as Fig. 9, but for the offsets in declination. The stars whose declination is less than $\delta < -30^\circ$ show relatively larger offsets. In addition, the circumpolar stars also have relatively large deviations. It is noteworthy that there exists the systematic behaviour.

Figure 11. The same as Fig. 9, but for the angular separations of YXKC stars from the precession-corrected Hipparcos stars as a function of declination. The stars with $\delta < -30^\circ$ also clearly show larger offsets. The circumpolar stars also have larger offsets.

that the determinative star of the lunar lodge Wei(6), $\mu^1$ Sco, and also the determinative star of the lunar lodge Ji(7), $\gamma^1$ Sgr, have peculiarly large offsets. They each have commonly low declination $\delta < -30^\circ$. Pan (1989) too reported this fact. These large deviations indicate that these stars are possibly located below the perpetual invisibility boundary. The declination of $\mu^1$ Sco at J1744.0 was $\delta(1744) = -37.6$ and that of $\gamma^1$ Sgr was $\delta(1744) = -30.4$. The existence of this boundary declination means that the YXKC catalogue consists of two kinds of data originating from different sources. The lowest limit of declinations is given by $\delta(1744) > \phi - 90^\circ + \Delta$. Here, $\Delta$ is the practical limit of astrometrical observation possible under severe atmospheric extinction. I adopt $\Delta \simeq 5^\circ$, where the atmospheric extinction in magnitude reaches approximately the third magnitude (Green 1992). Thus, the observer’s latitude should be $\phi < \delta(1744) - \Delta + 90^\circ = 55^\circ$.

The latitude of the Greenwich Observatory, where John Flamsteed measured the positions of stars, is $\phi = 51.3$, and the latitude of the Beijing Ancient Observatory is $\phi = 42.6$. The latitude of Uraniborg Observatory, where Tycho Brahe observed stars, is $\phi = 54.9$. Thus, it is improbable that the visible stars in YXKC might have originated from the measurements at the latitude of Beijing. These facts support an idea that that YXKC was based on Flamsteed’s catalogue.

Figs 9 and 10 show that the systematic behaviour in offsets exists in both RA and declination. This behaviour might be possibly due to the misalignment of the quadrant used by Flamsteed as well as due to a manufacturing error of the quadrant itself. However, these assumptions should be tested by studying the Flamsteed catalogue.

It is also noticeable that the positional errors of the stars with $\delta < -30^\circ$ in Fig. 11 have a random error of $3$ arcmin as well as systematic behaviour. According to Verbunt & van Gent (2011), four catalogues were published in the 17th century, by Tycho Brahe (1601), De Houtman (1603), Kepler (1627) and Halley (1679), and all catalogues except for Halley’s have large positional errors, much larger than $30$ arcmin. The stars in Halley’s catalogue have positional errors of $\sigma \sim 3$ arcmin. These facts also suggest that the positions of the southern stars in YXKC catalogue may have been taken from Halley’s catalogue. It will be elaborated in Section 3.4.

Fig. 12 shows the correlation between $\Delta \alpha$ and $\Delta \delta$ for stars whose declinations are $-30^\circ < \delta < 60^\circ$. I confirmed that both $\Delta \alpha$ and $\Delta \delta$ have normal distributions. I obtained $\sigma_{\Delta \alpha \cos \delta} = 0.045 \pm 0.085$ arcmin and $\sigma_{\Delta \delta} = 0.0065 \pm 0.32$ arcmin.

It is noticeable that the deviation in RA ($\Delta \alpha$) is statistically larger than that in declination by a factor of 0.8.
3.3 Stars in crowded regions

The stars in crowded regions were inspected very closely. Two examples of such regions are the Orion’s dagger region, corresponding to the Orion nebula and the Trapezium cluster. Fig. 13 shows the Orion’s dagger region. The black open circles are stars in the Hipparcos catalogue, two-digit numbers are Flamsteed numbers, and Greek letters are Bayer’s designations. The red dots represent the stars in YXKC. In this figure, it is obvious that the YXKC catalogue has only those stars that have Flamsteed designations. Another finding is that all the YXKC stars seem to have a systematic shift in RA by about 1 arcmin. This shift corresponds to precession during one year. The cause of this shift must be further elaborated. Fig. 14 is the zoomed star chart of the Beehive cluster (M44). The figure also shows that only the stars having Flamsteed designations are cast in the YXKC catalogue. This part of the sky in the YXKC catalogue has no shift in RA.

3.4 Nebulosities

YXKC has coordinates of 14 nebulosities called Qi. Table 4 lists these identified nebulous objects. All but one object, whose entry number is Q.214, have been identified with their modern counterparts. According to Wagman (1987), Flamsteed cited 11 nebulous objects in his catalogue: 33 And (Andromeda galaxy), 55 And, 39 Cnc, 41 Cnc, 15 Com, 39 Ori, 4 Sgr, 5 Sgr, 7 Sgr, 32 Sgr and 35 Sgr. Flamsteed’s nebulous objects are denoted in the 14th column as asterisks. One example is 55 And that is, although not nebulous, a double and perhaps Flamsteed mistook its double image in his telescope for a patch of nebulosity (Wagman 1987). It is noticeable that 55 And is an addendum star that is thought to have originated from Flamstead’s catalogue. I will classify nebulous objects as being of a few kinds and discuss their historical meaning.

The four stars belonging to the constellation Capricorn in Table 4 are similar to 55 And. Each of these four stars belongs to a double system. 12 Cap is a binary consisting of o1 Cap (V = +5.94) and o2 Cap (V = +6.74) that are separated by 21.9 arcsec. 10 Cap or CCDM J20273–1813AB is a triple star consisting of a spectroscopic binary π Cap A (V = +5.08) and a star π Cap B (V = +8) separated by 3 arcsec. The spectroscopic binary π Cap A consists of two stars separated by 0.1 arcsec. 11 Cap is also a double star consisting of ρ Cap A (V = +4.77) and ρ Cap B (V = +8) separated by 1.013 arcsec. 7 Cap is also a star in a double system called CCDM J20194–1908A. However, all but 7 Cap was inherited from the previous catalogue Xinzhi Lingtai Yixiangzhi. That is, 7 Cap is an addendum star.

There are also four stars belonging to the Beehive cluster (M44). Contrary to the Capricorni stars, all but 40 Cnc is addenda stars originating from Flamstead’s catalogue. I have already shown their
Identification of stars in Yixiangkaocheng 923

Table 4. Nebulosities in YXKC identified with their modern counterparts. The objects with asterisks in their Flamsteed designations belong to Flamsteed's 11 nebulous objects. The third column denoted by G represents the number of Gong. The 13th column denoted by a represents the classical Chinese star (0) or the addenda stars (1).

<table>
<thead>
<tr>
<th>No.</th>
<th>Chinese name</th>
<th>G</th>
<th>RA arcm</th>
<th>arsec</th>
<th>RA m s</th>
<th>Declination arcm</th>
<th>arsec</th>
<th>A</th>
<th>Flamsteed</th>
<th>HIP/name</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q.214</td>
<td>Zaosi North 9</td>
<td>2</td>
<td>24</td>
<td>40</td>
<td>26</td>
<td>19</td>
<td>38</td>
<td>41.7</td>
<td>26</td>
<td>48</td>
<td>49</td>
</tr>
<tr>
<td>Q.281</td>
<td>Nixiu South 8</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>23</td>
<td>20</td>
<td>4</td>
<td>37.5</td>
<td>−19</td>
<td>53</td>
<td>35</td>
</tr>
<tr>
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<td>Nixiu 4</td>
<td>1</td>
<td>3</td>
<td>10</td>
<td>2</td>
<td>20</td>
<td>12</td>
<td>40.1</td>
<td>−19</td>
<td>1</td>
<td>39</td>
</tr>
<tr>
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<td>Nixiu 6</td>
<td>1</td>
<td>3</td>
<td>33</td>
<td>52</td>
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<td>15.5</td>
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<td>7</td>
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<td>31</td>
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<td>1</td>
<td>38</td>
<td>5.1</td>
<td>39</td>
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<td>57</td>
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<td>Chugao North 2</td>
<td>10</td>
<td>1</td>
<td>36</td>
<td>6</td>
<td>2</td>
<td>6</td>
<td>24.4</td>
<td>−4</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>Q.1896</td>
<td>Jishi</td>
<td>7</td>
<td>6</td>
<td>20</td>
<td>15</td>
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<td>25</td>
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<td>20</td>
<td>51</td>
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<td>Q.1898</td>
<td>Jishi South 3</td>
<td>7</td>
<td>6</td>
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<td>Q.1899</td>
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<td>8</td>
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<td>17</td>
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<td>16.8</td>
<td>−46</td>
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<td>Q.2912</td>
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<td>8</td>
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<td>−41</td>
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</tr>
</tbody>
</table>

coincidence with the stars designated by Flamsteed in Fig. 14. It should be noted that the two stars, 39 Cnc and 41 Cnc, are listed as nebulosities in Flamsteed's catalogue (Wagman 1987). In fact, 39 Cnc and 40 Cnc are stars in double systems. 41 Cnc is a spectroscopic binary.

The other star in Table 4 is ω Ceti, designated by Johann Bayer in AD 1603. The variability of ω Ceti was first observed by David Fabricius (AD 1564–1617) in AD 1596 (Hoffleit 1997). In 1638, Johann Holwarda (AD 1618–1651) determined its period as 11 months. Johannes Hevelius of Danzig (AD 1618–1651) observed it in AD 1639 and in AD 1642 and named it Mira in AD 1662. The star is also listed in Flamsteed's catalogue. It is listed in YXKC as an addendum object, which means that it must have originated from a new catalogue such as Flamsteed's.

There are non-stellar objects in Table 4. First, YXKC includes the Andromeda galaxy. The galaxy was catalogued as M 31 by Charles Messier in AD 1764. Flamsteed listed the galaxy in his catalogue and designated 33 And. Since it is listed as an addendum object in YXKC that was published in AD 1756, it might have possibly originated from Flamsteed’s catalogue.

Another non-stellar object in Table 4 is NGC 5139 or ω Cen, which is a globular cluster. It was recorded as a star by Ptolemy and designated as ω Cen by Bayer in AD 1603. It was classified as a nebula by Edmond Halley in AD 1677. It was the English astronomer John William Herschell who recognized this object as a globular cluster in the 1830s. Because ω Centauri is below the horizon of Greenwich, it could not be cast in Flamsteed’s catalogue. However, this object was observed by Edmond Halley during his journey to St. Hellena (Ashworth 1981, De Cheseaux in AD 1745–1746 and by Abbé Lacaille in AD 1751–1752. Considering the history of observing NGC 6231, this object is thought to originate from Halley’s observation.

NGC 6231 is designated as Shengong, which is a traditional object listed in Xinzhi Lingtai Xiyangzhi. However, Shengong is not defined to be a nebulosity in Xinzhi Lingtai Xiyangzhi. Therefore, the nebulosity Shengong in YXKC is certainly adopted from a new source. Halley’s catalogue has four entries that cannot be identified with the Hipparcos catalogue (Verbunt & van Gent 2011), including objects such as NGC 6231, M7, κ Car and ω Cen. The object called Q.2201 in YXKC is identified as η Car; it is also classified as a traditional object or an object included in Xinzhi Lingtai Xiyangzhi. Therefore, three among four non-stellar objects listed in Halley’s catalogue are listed in YXKC. Thus, it is probable that the observations of Edmond Halley in AD 1678 were transferred to China in some way. Further investigation is required to understand how this was possible.

4 CONCLUSIONS

In this study, I identified stars in the catalogue of YXKC with those in the Hipparcos catalogue. There are 3083 stars in the YXKC catalogue, including 1319 stars inherited from the previous star catalogue Xinzhi Lingtai Xiyangzhi, 1614 addenda stars, and 150 stars of perpetual invisibility in China. There are 14 nebulosities listed in the YXKC catalogue. I first calculated the equinox of the YXKC catalogue presented in the literature or J1744.0. Subsequently, considering the precession of equinox, proper motions and nutation, the identification were conducted. The magnitude information of each star was also considered in the identifications. Finally, our results are compared with the star chart presented in YXKC. A total of 2848 stars and 13 nebulosities were identified, with the
identification rate reaching 92.80 per cent. The results were analysed and it was found that the magnitude classification system adopted in the YXKC catalogue agrees well with the modern magnitude system. I found that the stars in the YXKC catalogue had an error of 0.6 arcmin. Here, the error can be attributed to both observational errors and coordinate transformation errors. The error is certainly subarcminute, which means that the catalogue was based on telescopic observations. I also found that the YXKC catalogue originated from a source catalogue that was observed at the latitude $52^\circ \leq \phi \leq 55^\circ$. By analysing the stars in crowded regions such as the Orion's dagger region and the Beehive cluster (M44), I found that only the stars designated by Flamsteed were catalogued in YXKC. While going through the stars in the whole catalogue, I found that although some stars are too dim to be observed with the naked eye (or $V < 7$), they were catalogued only if they had corresponding Flamsteed’s designations. All these facts indicate that the source of the YXKC catalogue is Flamsteed’s catalogue. I found that the deviations in RA are statistically larger than those in declination by a factor of 0.8. One possible explanation for this fact is that the determination of RA for a star requires two measurements while the declination need one. However, the precession calculation method used in YXKC can also have intrinsic errors. Further study is needed to solve this problem.

In addition, the 13 nebulosities listed in the YXKC catalogue were identified. It turned out that the catalogue contained the Andromeda galaxy, the variable star Mira ($\alpha$ Ceti), $\omega$ Centauri, NGC 6231, four stars in the Beehive cluster (M44) and four stars in the Capricorni region. Nearly all the addenda nebulosities were found to be listed as nebulae in Flamsteed’s catalogue. Both $\omega$ Centauri and NGC 6231 were first classified as nebulae by Edmond Halley in his Catalogue of the Southern Stars published in $1679$, but they were not designated by Flamsteed because of their low declination. Thus, it would be interesting to find out if Halley’s discoveries affected the compilation of YXKC. Further investigation is required to understand the history.

The precession of equinox was thought to be calculated in the ecliptic coordinate system by the Jesuit astronomers. Since Flamsteed adopted the equatorial coordinate system in his catalogue, they have first transformed the equatorial coordinate to the ecliptic coordinate and then added $51$ arcsec yr$^{-1}$ to the ecliptic longitude. Following this, they must have performed an inverse coordinate transformation. This would have been a convenient and labour-saving method for the 18th-century scientists. However, there are specific explanations for both coordinate transformation and precession corrections in volume one of YXKC. Hence, we will need to further investigate these methods in the future.

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**APPENDIX A: THE MACHINE-READABLE CATALOGUE**

The machine-readable table of the YXKC catalogue is available at the CDS via http://samtay.kasi.re.kr/yixiangkaocheng.txt. It contains the following information. The first column gives the entry number of the stars in the equatorial catalogue where stars are arrayed in the increasing order of the RA. The second column gives the Gong, and the third, fourth and fifth columns give the degree, minute and second of the RA, respectively. The sixth, seventh and eighth columns give the degree, minute and second of the declination, respectively, where the positive (negative) degree value means that the stars are located in the Northern (Southern) celestial sphere. The ninth column is the magnitude, and the tenth column gives whether the star belongs to the traditional star or the addendum star. Here 0 means the traditional star, which is listed in the Xinzhi Lingtai Yixiangzhi catalogue, and 1 means the addendum star. 3 and 4 mean that the star is either a traditional star (3) or an addendum star (4) that are located in the perpetual invisibility or the Southern hemisphere. 7 means that the object is classified as a nebulosity.

The 11th column is the Johnson visual magnitude of the counterpart star in the *Hipparcos* catalogue. The 12th, 13th and 14th columns give the offset in RA (12th), declination (13th) and angular distance (14th). The 15th, 16th and 17th columns give the HIP number, the HD number and the HR number of the counterpart star in the *Hipparcos* catalogue, respectively. The 18th, 19th and 20th columns give the Flamsteed number, Bayer’s designation and the constellation name, respectively. The final 21st column gives the name of the star that had been used in history.

**APPENDIX B: TYPOGRAPHICAL ERRORS IN THE YXKC CATALOGUE**

The following entries in YXKC have typographical and other errors.

**Q.309**: It is the first addendum star in Baigua. Its declination should be corrected by $-10^\circ$.

**Q.894**: This star disobeyes the ordering rule. However, the ecliptic coordinate transformed from its equatorial coordinate coincides with the YXKC values. I conclude that an error was introduced during editing.
Q.1023: It is the fifth star in Tiancang. Its RA value should be 4 arcmin rather than 40 arcmin. I checked this emendation by comparing the coordinate value with its ecliptic coordinate transformed into an equatorial coordinate.

Q.1057: It is an addendum star in the north of Louxiu. Its RA should be 17 arcmin rather than 27 arcmin.

Q.1110: It is the first star in Chugao. Its declination should be corrected by $-1^\circ$.

Q.1387: It is the second star in Jiuyou. Its declination should be corrected by $-1^\circ$.

Q.1425: It is the sixth star in Bagu. Its declination should be corrected to be $51^\circ$ rather than $50^\circ$. Also, the star is identified to be 63 Eri, but its position coincides with that of Q.1426. Q.1426 is an addendum star, while Q.1425 is a traditional Chinese star. Thus, I determine that Q.1425 is 31 Eri and Q.1426 cannot be identified.

Q.1462: It is the fourth star in Yujing. Its RA value is corrected by an amount of $+1^\circ$.

Q.1500: A letter of the degree unit of the declination is not clearly read, but it should be 23.

Q.1532: This star is possibly uniquely determined to be 30 Cam, but its RA has an offset of 20 arcmin, and so its RA value should be 51 arcmin rather than 31 arcmin. The error must be a typographical error due to the similarity between the Chinese letters for three and five.

Q.1735: Its RA should be 38 arcmin. I checked this emendation by comparing the coordinate value with its ecliptic coordinate transformed into an equatorial coordinate. In addition, its positional offset becomes smaller if it is 38 arcmin rather than 28 arcmin.

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