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Determining the Observational Epoch of *Shi's Star Catalog* Using the Generalized Hough Transform Method

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Abstract

Ancient stellar observations are a valuable cultural heritage, profoundly influencing both cultural domains and modern astronomical research. *Shi's Star Catalog* (石氏星经), the oldest extant star catalog in China, faces controversy regarding its observational epoch. Determining this epoch via precession assumes accurate ancient coordinates and correspondence with contemporary stars, posing significant challenges. This study introduces a novel method using the Generalized Hough Transform to ascertain the catalog's observational epoch. This approach statistically accommodates errors in ancient coordinates and discrepancies between ancient and modern stars, addressing limitations in prior methods. Our findings date *Shi's Star Catalog* to the 4th century BCE, with 2nd-century CE adjustments. In comparison, the Western tradition's oldest known catalog, the Ptolemaic Star Catalog (2nd century CE), likely derives from the Hipparchus Star Catalog (2nd century BCE). Thus, *Shi's Star Catalog* is identified as the world's oldest known star catalog. Beyond establishing its observation period, this study aims to consolidate and digitize these cultural artifacts.

Key words: history and philosophy of astronomy – catalogs – methods: data analysis

1. Introduction

Throughout human history, the night sky has persistently captivated collective fascination, with stars functioning as both a wellspring of inspiration and a locus of intellectual exploration. Each culture has crafted its distinctive celestial landscape, and over millennia, individuals have meticulously documented their perceptions of the night sky. The constellations and the nomenclature of stars have transcended mere astronomical entities to become emblematic cultural symbols within diverse civilizations. Amidst these multifaceted observational endeavors, scientific inquiry has emerged, culminating in unique and richly detailed records of stellar observations within both Eastern and Western traditions.

In the Western tradition, Ptolemy's seminal astronomical work, Almagest, dating to the 2nd century CE, meticulously documented a star catalog that has endured to the present day. The epoch of this catalog is posited to be 137 CE (Verbunt & van Gent 2012). The Ptolemaic star catalog stands as the oldest extant star catalog in the Western world. Conversely, in China, the *Shi Shi Xing Jing* 石氏星经 (commonly referred to as Shi's Star Manual) was composed by the astronomer Shi Shen (石申) during the Zhanguo (Warring States) period, spanning the 5th to 3rd centuries BCE. This seminal work encompasses a star catalog known as *Shi's Star Catalog*. Subsequently, *Shi's Star Catalog* was referenced in the Tang Dynasty (7th to 10th century CE) compilation *Kaiyuan Zhanjing* (Kaiyuan Astrological Texts, 开元占经), from which modern scholars have excerpted *Shi's Star Catalog*.

Shi's Star Catalog meticulously records observational data for the coordinates of 120 stars. Over the past century, astronomers have primarily utilized retrograde precession to ascertain its observational epoch. This methodology entails cross-referencing the ancient catalog with contemporary star catalogs, followed by rigorous analytical procedures, ultimately leading to the definitive determination of Shi's observational epoch. Currently, four predominant theories prevail regarding the observational epoch of *Shi's Star Catalog* (Chen 2015):

(1) *The 4th Century BCE Period*. Based on the records of precession and retrograde precession, it is inferred that the observational epoch of *Shi's Star Catalog* approximately corresponds to the Zhanguo period, around 360 BCE (Shingō 1928).

(2) *Dual Epochs: 5th Century BCE and 2nd Century CE*. Two interpretations prevail regarding the observational epochs of *Shi's Star Catalog*. One posits that 44 stars were observed circa 360 BCE, while 46 stars were documented around 200 CE, as determined through graphical methods (Ueta 1930). Conversely, another perspective suggests that 52 stars were recorded circa 440 BCE, with an additional 37 stars observed around 160 CE, utilizing the conventional retrograde precession method (Pan 2009).

(3) *The 1st Century BCE Period*. This viewpoint garners substantial scholarly support, with many asserting that the observational timeframe likely spans from 100 BCE to 70 BCE. The methodologies predominantly employed in this

analysis include modern statistical methods and Fourier analysis (Qian 1937; Maeyama 1977; Yabuuchi & Kong 1984; Guo 1994; Sun 1994; Sun & Kistemaker 1997).

(4) *The 7th Century CE Period*. Some scholars also propose that the observations recorded in the *Shi's Star Catalog* might have taken place during the early Tang Dynasty. However, this analysis remains insufficiently comprehensive (Hu 1998).

Therefore, a multitude of perspectives exist regarding the observational timeframe of *Shi's Star Catalog*, with no definitive consensus reached. The authors of this study have previously employed the Generalized Hough Transform method to scrutinize star observation records from the Song and Yuan dynasties in China (He & Zhao 2024), effectively ascertaining the observation epochs of these star catalogs. This paper serves as a continuation of that endeavor, aiming to further analyze the data within *Shi's Star Catalog* to determine its genuine observational epoch.

2. Method

In ancient China, astronomers employed a traditional equatorial coordinate system, which consisted of two principal components: *ru xiu du* (RXD, the angular distance to the western boundary of a lunar mansion) and *qu ji du* (QJD, the angular distance from the North Celestial Pole). The Chinese constellation system segmented the celestial sphere into 28 lunar mansions, each demarcated by a principal star (ju xing) that served as a reference. RXD quantified the longitudinal separation between a star and its corresponding principal star, whereas QJD denoted the star's angular distance from the North Celestial Pole. In contrast, contemporary astronomy utilizes the equatorial coordinate system, characterized by R.A. (α) and decl. (δ).

$$\boldsymbol{s} = (\alpha, \delta)$$

The relationship between QJD (ω) and the decl. (δ) in the modern equatorial coordinate system is given by:

$$\delta = 90^\circ - \omega$$

The utilization of the Generalized Hough Transform method to ascertain the observational epochs of stars constitutes an innovative computational technique. This method merges a probabilistic model with the Monte Carlo algorithm, facilitating the calculation of parameters by leveraging the probability density within the parameter space. As a result, it accounts for potential inaccuracies in the precession values of ancient star catalogs and the ambiguities in the alignment between ancient and contemporary stars, provided that the predominant portion of the data remains valid, thus yielding dependable outcomes. Moreover, this method solely relies on QJD data for its analysis, distinguishing itself from other methodologies that require the conjunction of both QJD and RXD data.

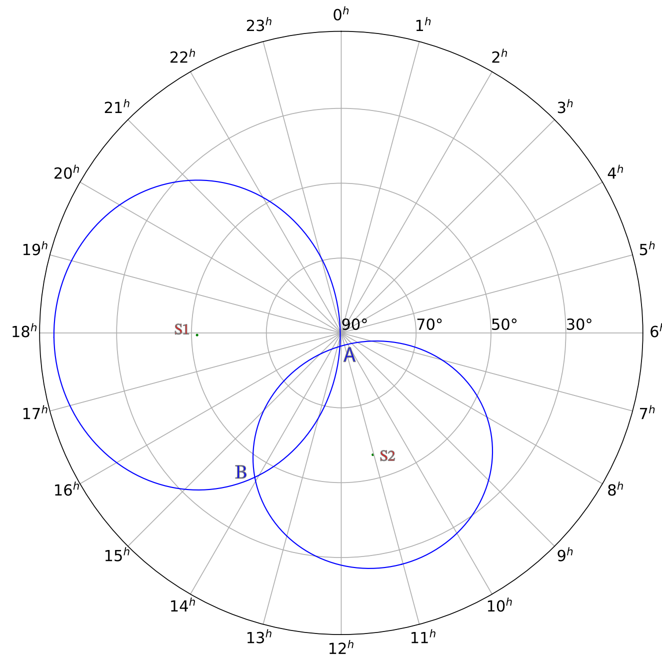

Figure 1. Simulation of the parameter space of the North Celestial Pole after generalized Hough transform.

The original dataset consists of rigorously validated stellar parameters, including essential attributes such as R.A., decl., proper motion, and QJD, all referenced to the J2000.0 celestial coordinate system. These parameters are obtained from The *Chinese Ancient Astronomy Fundamental Reference Star Catalog* (He 2024). The catalog's data is sourced from the relatively precise star data of the *Hipparchus Catalog* (ESA 1997; van Leeuwen 2007; Anderson & Francis 2012), supplemented with recent updates and additional stellar parameters such as magnitude, proper motion, parallax, and radial velocity.

In the computational process, the positional parameters of the North Celestial Pole (R.A. and decl.) are utilized as the primary focus for resolution within the parameter space. As a result, each star's representation within this space is depicted as a circle with its coordinates at the center and QJD as the radius. The selection of any two stars may yield intersections within the parameter space, which can be classified into three scenarios: no intersection, a single intersection, or two intersections.

Figure 1 serves as a visual representation, wherein the parameter space depicts the QJD of two stars, S_1 and S_2, as two concentric circles. Each circle's radius is proportional to the respective star's QJD value. The intersection of these circles at points A and B suggests that these coordinates could correspond to the North Celestial Pole for the epoch in question. When computing the parameters for any given pair of stars, the probability density for the actual North Celestial Pole is likely to be elevated at these intersection points. This intersection phenomenon underpins the core rationale of the Generalized Hough Transform algorithm.

However, the accurate determination of the true position is challenging due to observational errors, identification inaccuracies, and other variables. The use of Monte Carlo simulation provides a robust method for calculating these values. Utilizing the methodology of the Generalized Hough Transform, it is possible to determine the directional orientation of ancient instruments. However, this determined orientation does not entirely correspond to the actual direction of the North Celestial Pole. This discrepancy arises because the polar axes of ancient instruments typically fail to align precisely with the North Celestial Pole, resulting in observational data that often contain systematic errors. Nonetheless, by conducting a probabilistic analysis of the instrument's directional orientation, it is feasible to further infer the most probable location of the North Celestial Pole. Based on this inferred result, the specific observational epoch corresponding to the collected data can ultimately be ascertained.

The simulation method involves Gaussian sampling with a specified standard deviation (the standard deviation is measured in Chinese Degrees, where $1\quad \text{ChineseDegree} = \frac{360}{365.25}\quad \text{Degrees}$) for the QJD data of each star. In this study, random sampling was performed 10,000 times. A sufficiently large number of simulations allow Monte Carlo simulation to produce precise results and provide confidence intervals or measures of uncertainty. Therefore, Monte Carlo simulation calculations can effectively reduce the impact of errors.

For each pair of stars, 10,000 simulations are conducted. After processing all data, the results are represented in the parameter space as a two-dimensional Gaussian distribution. By calculating the centroid of this distribution, we can ascertain the position of the North Celestial Pole during the observations.

It is crucial to consider the proper motion of stars based on potential epochs during the calculation process. All results are consistent with the J2000.0 coordinate system framework.

The Earth's precession, characterized by a cycle of approximately 26,000 yr in which its axis of rotation shifts, allows us to employ state-of-the-art precession models (Vondrák et al. 2011) to compute the theoretical position of the North Celestial Pole for any specified year across millennia. Through comparison of this computed position with the documented theoretical positions of the North Celestial Pole in historical records, we can infer the precise observational epoch of the data.

In a previous study (He & Zhao 2024), the Generalized Hough Transform was utilized to analyze the star catalogs of the Song and Yuan dynasties. This approach exhibited a high degree of computational precision, effectively pinpointing the orientation of observational instruments for the respective eras and partially evaluating the observational inaccuracies of these instruments. For example, the observational error in the Song Dynasty star catalog was roughly 0.3 Chinese Degrees, while in the Yuan Dynasty, it was reduced to approximately 0.1 Chinese Degrees.

3. Data Analysis

Shi's Star Catalog documents 120 stars, with 118 entries possessing full positional data (refer to Table 1). The structuring of this data is grounded in pages 82–85 of the second edition of *History of Chinese Stellar Observations* (中国恒星观测史) (Pan 2009), drawing 114 stars from the *Kaiyuan Zhanjing*. To account for the six absent stars from the *Kaiyuan Zhanjing*, four were retrieved from a fragmentary manuscript of the *Tiandi Ruixiang Zhi* (天地瑞祥志), thereby compiling a comprehensive dataset of 118 stars.

In the initial determination of the epoch through the application of the Generalized Hough Transform, we utilized the identification data provided by Sun Xiaochun in the study *Research on the Shi Shi Constellations during the Han Dynasty* (Sun 1994; Sun & Kistemaker 1997), encompassing the identification outcomes for 116 stars. However, the star `Langwei` 郎位 is devoid of both RXD and QJD data. Consequently, the final dataset comprised 115 stars.

Drawing upon the research outcomes of seminal scholars (Section 1), the year 1 BCE was initially designated as the reference epoch for the computational analysis. The dataset was subjected to Monte Carlo simulation to facilitate the Generalized Hough Transform analysis, thereby allowing for a preliminary estimation of the epochs. Subsequent analyses were then performed, grounded in these preliminary results.

The computational results, as depicted in Figure 2, reveal two distinct epochs with notable outcomes. A prominent peak is observed around 130 CE, accompanied by a smaller peak circa 350 BCE. These peaks are significantly separated, both temporally by approximately 500 yr and spatially by about $2\overset{\circ}{.}8$. This indicates that the observational periods for the data within *Shi's Star Catalog* are clearly non-synchronous. The bulk of the observations are clustered around 130 CE, with an additional subset originating from approximately 350 BCE.

Within the dataset of these 118 stars (refer to Table 1), certain records exhibited substantial inaccuracies attributable to transcription errors in historical documentation. For instance, in Classical Chinese, the characters representing thirty (卅) and forty (卌) are visually similar, leading to potential errors during the copying of historical texts. Through meticulous calculations, analyses, and graphical comparisons, we have rectified these inaccuracies based on historical evidence. The rectified data encompasses:

1. `No. 31`, the QJD of `Genghe` (梗河) should be 48 instead of 38.
2. `No. 35`, the QJD of `Tianbang` (天棓) should be 42 instead of 32.

Table 1
Shi's Star Catalog Original Data

No.	Constellation	RXD		QJD	No.	Constellation	RXD		QJD
1	Jiao 角	Jiao 角	00.00	091.00	61	Tianda Jiangjun 天大将军	Kui 奎	15.50	060.33
2	Kang 亢	Kang 亢	00.00	089.00	62	Daling 大陵	Lou 娄	06.25	044.25
3	Di 氐	Di 氐	00.00	094.00	63	Tianchuan 天船	Lou 娄	09.00	043.50
4	Fang 房	Fang 房	00.00	108.00	64	Juanshe 卷舌	Wei 胃	10.25	056.00
5	Xin 心	Xin 心	00.00	108.50	65	Wuche 五车	Bi 毕	03.00	063.00
6	Wei 尾	Wei 尾	00.00	120.00	66	Tianguan 天关	Zi 觜	00.00	073.50
7	Ji 箕	Ji 箕	00.00	118.00	67	Nanhe 南河	Jing 井	17.25	080.00
8	Dou 南斗	Dou 斗	00.00	116.00	68	Wuzhuhou 五诸侯	Jing 井	02.00	057.00
9	Niu 牛	Niu 牛	00.00	110.00	69	Jishui 积水	Jing 井	13.00	055.00
10	Nü 女	Nü 女	00.00	106.00	70	Jixin 积薪	Jing 井	21.50	061.50
11	Xu 虚	Xu 虚	00.00	104.00	71	Shuiwei 水位	Jing 井	19.50	072.50
12	Wei 危	Wei 危	00.00	099.00	72	Xuanyuan 轩辕	Zhang 张	00.75	071.00
13	Shi 室	Shi 室	00.00	085.00	73	Shaowei 少微	Zhang 张	10.50	070.50
14	Bi 壁	Bi 壁	00.00	086.00	74	Taiweiyuan 太微垣	Yi 翼	09.00	076.50
15	Kui 奎	Kui 奎	00.00	077.00	75	Huangdizuo 黄帝座	Yi 翼	09.50	063.50
16	Lou 娄	Lou 娄	00.00	080.00	76	Sidizuo 四帝座	…	…	…
17	Wei 胃	Wei 胃	00.00	072.00	77	Ping 内屏	Yi 翼	07.00	072.50
18	Mao 昴	Mao 昴	00.00	074.00	78	Langwei 郎位	…	…	…
19	Bi 毕	Bi 毕	00.00	078.00	79	Langjiang 郎将	Zhen 轸	08.00	039.25
20	Zi 觜	Zi 觜	00.00	084.00	80	Changchen 常陈	Yi 翼	05.00	045.00
21	Shen 参	Shen 参	00.00	094.50	81	Santai 三台	Jing 井	30.75	030.25
22	Jing 井	Jing 井	00.00	070.00	82	Xiang 相	Yi 翼	05.00	031.50
23	Gui 鬼	Gui 鬼	00.00	068.00	83	Taiyangshou 太阳守	Zhang 张	13.25	035.50
24	Liu 柳	Liu 柳	00.00	079.00	84	Tianlao 天牢	Zhang 张	01.25	026.50
25	Xing 星	Xing 星	00.00	091.00	85	Wenchang 文昌	Jing 井	15.75	025.75
26	Zhang 张	Zhang 张	00.00	097.00	86	Beidou 北斗	Zhang 张	00.00	018.25
27	Yi 翼	Yi 翼	00.00	099.00	87	Ziweiyuan 紫微垣	Zhen 轸	10.00	009.50
28	Zhen 轸	Zhen 轸	00.00	099.00	88	Gouchen 钩陈	Bi 壁	08.75	011.50
29	Sheti 摄提	Jiao 角	08.25	059.50	89	Tianyi 天乙	Zhen 轸	10.00	010.50
30	Dajiao 大角	Kang 亢	02.50	058.00	90	Taiyi 太乙	Zhen 轸	10.00	010.00
31	Genghe 梗河	Kang 亢	08.00	048.00	91	Kulou 库楼	Zhen 轸	00.25	140.00
32	Zhaoyao 招摇	Di 氐	02.50	040.75	92	Nanmen 南门	Zhen 轸	14.00	130.00
33	Xuange 玄戈	Di 氐	01.00	032.50	93	Ping 平星	Zhen 轸	14.00	100.00
34	Tianqiang 天枪	Di 氐	00.75	028.75	94	Qiguan 骑官	Kang 亢	04.75	115.50
35	Tianbang 天棓	Ji 箕	08.50	042.00	95	Jizu 积卒	Di 氐	13.75	124.25
36	NüChuang 女牀	Ji 箕	01.00	050.00	96	Gui 龟	Wei 尾	12.00	131.00
37	Qigong 七公	Di 氐	04.50	039.25	97	Fuyue 傅说	Wei 尾	12.75	120.50
38	Guansuo 贯索	Wei 尾	00.50	059.25	98	Yu 鱼	Wei 尾	14.00	122.00
39	Tianji 天纪	Wei 尾	05.00	051.50	99	Chu 杵	Ji 箕	01.75	132.50
40	Zhinü 织女	Dou 斗	11.00	052.00	100	Bie 鳖	Dou 斗	01.00	129.50
41	Tianshiyuan 天市垣	Wei 尾	00.75	094.25	101	Jiukan 九坎	Dou 斗	14.50	136.00
42	Dizuo 帝座	Wei 尾	15.50	071.25	102	Baijiu 败臼	Nü 女	10.00	131.25
43	Hou 候	Ji 箕	02.50	073.75	103	Yulin 羽林军	Wei 危	04.75	120.75
44	Huanzhe 宦者	Wei 尾	12.00	072.50	104	Beiluoshimen 北落师门	Wei 危	09.00	130.75
45	Dou 斗	Wei 尾	10.25	072.00	105	Tusikong 土司空	Bi 壁	07.75	120.25
46	Zongzheng 宗正	Ji 箕	02.00	084.00	106	Tiancang 天仓	Kui 奎	04.75	120.00
47	Zongren 宗人	Ji 箕	07.50	085.00	107	Tianqun 天囷	Wei 胃	06.25	096.50
48	Zong 宗	Ji 箕	09.00	079.00	108	Tianlin 天廪	Wei 胃	11.25	090.00
49	Dongxian 东咸	Xin 心	02.00	103.00	109	Tianyuan 天苑	Bi 毕	02.75	114.00
50	Tianjiang 天江	Wei 尾	06.25	111.00	110	Shenqi 参旗	Bi 毕	09.50	093.00
51	Jian 建	Dou 斗	07.25	113.25	111	Yujing 玉井	Bi 毕	12.25	102.75
52	Tianbian 天弁	Dou 斗	06.75	090.75	112	Ping 屏	Zi 觜	00.75	118.00
53	Hegu 河鼓	Dou 斗	22.75	085.00	113	Ce 天厕	Shen 参	03.25	115.00
54	Lizhu 离珠	Nü 女	00.00	094.00	114	Shi 屎	Shen 参	07.00	123.00
55	Paogua 瓠瓜	Nü 女	00.25	081.50	115	Junshi 军市	Jing 井	03.25	110.00
56	Tianjin 天津	Dou 斗	02.00	049.00	116	Yeji 野鸡	Jing 井	08.00	111.00
57	Teshe 腾蛇	Shi 室	01.50	051.00	117	Lang 狼	Jing 井	13.00	106.75
58	Wangliang 王良	Bi 壁	00.50	042.50	118	Hushi 弧矢	Jing 井	16.00	122.75
59	Gedao 阁道	Kui 奎	05.00	043.25	119	Laoren 老人	Jing 井	19.00	143.50
60	Fulu 附路	Kui 奎	03.00	043.00	120	Ji 稷	Liu 柳	14.25	138.00

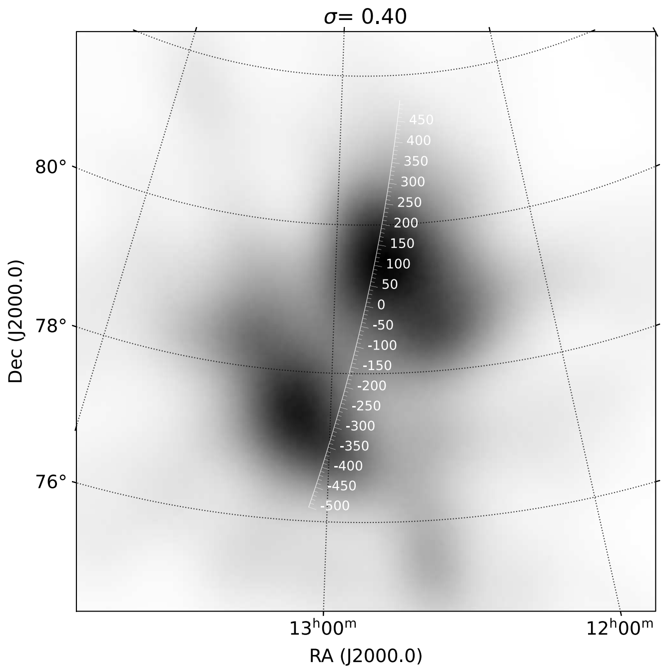

Figure 2. The calculation results using 1 BCE as the reference epoch.

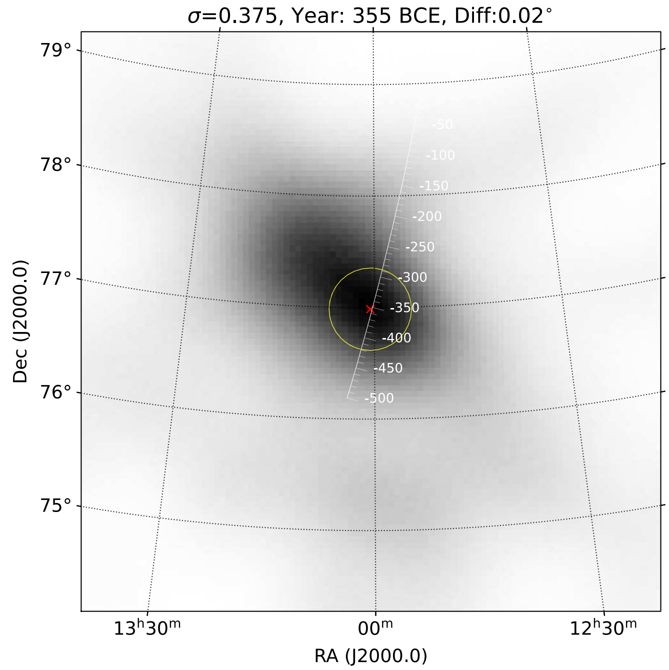

Figure 3. The epoch corresponding to the orientation of the first North Celestial Pole. (355 BCE).

3. `No. 55`, the QJD of `Paogua` (瓠瓜) should be 81.5 instead of 71.5.
4. `No. 111`, the QJD of `Yujing` (玉井) should be 102.75 instead of 120.75.
5. `No. 119`, the QJD of `Laoren` (老人) should be 143.5 instead of 133.5.
6. `No. 120`, the QJD of `Ji` (稷) should be 138 instead of 148.

Additionally, we rectified the identification data that exhibited significant deviations. Beyond the initial 115 stars, we successfully identified three previously unclassified stars (`Yu` 鱼, `Gui` 龟, and `Chu` 杵) utilizing RXD and QJD data. Consequently, we compiled a comprehensive dataset of 118 stars with validated observational data.

Subsequent to these adjustments, calculations were conducted to assess the discrepancy between the theoretical and observed precession values at the two identified temporal points. This led to the selection of two distinct data sets, each correlated with one of the time periods: the first dataset included 59 stars with observations closer to the North Celestial Pole around 350 BCE, and the second dataset consisted of 59 stars with observations nearer to the North Celestial Pole around 130 CE. Each star was recalibrated according to its proper motion corresponding to the respective epoch.

3.1. The First Epoch

An analysis of the 59-star candidate dataset from before 350 BCE, as depicted in Figure 3, involved Gaussian random sampling of each star 10,000 times with a standard deviation of $\sigma = 0.375$ Chinese Degrees, yielding an estimated epoch of approximately 355 BCE. The calculated centroid is roughly 0.02 Chinese Degrees from the North Celestial Pole's position in 355 BCE. The comprehensive dataset is presented in Table 2.

From the 59-star dataset, after excluding six stars with substantial errors, the remaining 53 stars exhibit an average discrepancy of 0.59 Chinese Degrees between the observed and theoretical declinations. The observed minimum deviation is 0.01 Chinese Degrees, and the maximum discrepancy reaches 2.14 Chinese Degrees. The results of the error analysis are provided in Figure 4.

3.2. The Second Epoch

The analysis of the 59-star candidate dataset from the year 125 CE, as illustrated in Figure 5, involved Gaussian random sampling with a standard deviation of $\sigma = 0.375$ Chinese Degrees for each star, conducted 10,000 times. This yielded a calculated observation epoch of approximately 125 CE. At this time, the computed centroid is roughly 0.16 Chinese Degrees distant from the North Celestial Pole's position in 125 CE. The full dataset is presented in Table 3.

Within the dataset of 59 stars, following the removal of two stars exhibiting significant deviations, the remaining 57 stars display an average discrepancy of 0.45 Chinese Degrees between the observed and theoretical declinations. The smallest recorded deviation is 0.001 Chinese Degrees, and

Table 2
Shi's Star Catalog (355BCE)

No.	Xingguan	HIP	Star	R.A. (355BCE)	Decl. (355BCE)	QJD	QJD_err	Pos_err
2	Kang 亢	69427	κ Vir	12 11 20.37	+02 01 45.58	89.00	0.25	0.25
3	Di 氐	72622	α Lib	12 46 30.54	−04 23 45.09	94.00	1.77	1.75
4	Fang 房	78265	π Sco	13 44 37.80	−16 31 41.62	108.00	0.08	0.08
5	Xin 心	80112	σ Sco	14 05 40.31	−16 53 19.26	108.50	−0.05	0.05
6	Wei 尾	82514	μ Sco	14 22 38.94	−30 23 16.10	120.00	2.14	2.11
7	Ji 箕	88635	γ Sgr	15 38 33.48	−26 28 28.58	118.00	0.17	0.17
8	Dou 南斗	92041	ϕ Sgr	16 19 34.17	−25 24 42.69	116.00	1.09	1.08
23	Gui 鬼	41822	θ Cnc	06 13 08.61	+22 43 33.46	68.00	0.26	0.25
24	Liu 柳	42313	δ Hya	06 30 27.72	+10 54 59.95	79.00	1.24	1.22
25	Xing 星	46390	α Hya	07 30 42.63	−00 46 38.73	91.00	1.10	1.09
26	Zhang 张	48356	υ Hya	07 57 58.32	−05 49 24.29	97.00	0.22	0.22
27	Yi 翼	53740	α Crt	09 06 25.45	−06 59 31.94	99.00	−0.59	0.58
29	Sheti 摄提	69727	η Boo	12 15 58.39	+05 42 19.20	59.50	26.02	26.03
30	Dajiao 大角	69673	α Boo	12 27 37.16	+32 40 42.91	58.00	0.16	1.36
31	Genghe 梗河	71053	ρ Boo	12 47 56.39	+42 07 07.92	48.00	0.58	1.09
32	Zhaoyao 招摇	71075	γ Boo	12 54 08.51	+49 57 47.47	40.75	−0.13	0.38
33	Xuange 玄戈	69732	λ Boo	12 42 14.06	+58 03 24.51	32.50	−0.09	1.09
35	Tianbang 天棓	86414	ι Her	16 34 53.30	+49 01 36.14	42.00	−0.43	3.78
37	Qigong 七公	73555	β Boo	13 32 00.46	+51 13 13.61	39.25	0.10	4.34
39	Tianji 天纪	80181	ξ CrB	14 51 22.80	+38 29 08.01	51.50	0.77	1.91
40	Zhinü 织女	91262	α Lyr	17 17 52.12	+38 46 44.83	52.00	−0.03	2.91
41	Tianshiyuan 天市垣	81377	ζ Oph	14 31 48.55	−02 49 25.16	94.25	−0.07	1.55
42	Dizuo 帝座	84345	α Her	15 28 57.30	+19 48 17.09	71.25	−0.03	1.22
43	Hou 候	86032	α Oph	15 47 23.94	+17 08 16.46	73.75	0.17	0.30
44	Huanzhe 宦者	83613	60 Her	15 17 59.88	+18 42 57.62	72.50	−0.18	1.91
45	Dou 斗	83000	κ Oph	15 08 15.86	+15 45 47.30	72.00	3.32	3.50
46	Zongzheng 宗正	87108	γ Oph	15 51 43.32	+06 42 37.52	84.00	0.50	1.40
47	Zongren 宗人	88290	68 Oph	16 03 57.54	+04 33 27.33	85.00	1.69	1.96
48	Zong 宗	88765	71 Oph	16 16 01.62	+11 28 01.12	79.00	0.68	0.83
49	Dongxian 东咸	80343	ψ Oph	14 12 34.12	−11 31 45.93	103.00	0.01	0.24
50	Tianjiang 天江	84970	θ Oph	15 02 48.07	−19 03 14.90	111.00	−0.36	3.68
52	Tianbian 天弁	92117	5 Aql	16 45 33.79	−00 08 01.16	90.75	0.70	0.71
57	Teshe 腾蛇	111169	α Lac	20 59 20.20	+39 24 41.01	51.00	0.33	2.90
61	Tianda Jiangjun 天大将军	9640	γ And	23 53 45.72	+29 45 12.43	60.33	0.80	1.25
69	Jishui 积水	37265	o Gem	05 02 02.88	+35 49 38.95	55.00	−0.04	1.68
73	Shaowei 少微	52911	53 Leo	08 40 33.78	+21 23 51.55	70.50	−0.90	0.93
74	Taiweiyuan 太微垣	57757	β Vir	09 46 03.44	+14 19 16.72	76.50	0.28	1.04
75	Huangdizuo 黄帝座	57632	β Leo	09 43 47.79	+27 01 16.19	63.50	0.40	0.39
79	Langjiang 郎将	63125	α CVn	10 55 31.65	+51 18 24.43	39.25	0.01	0.96
80	Changchen 常陈	56997	61 UMa	09 24 02.54	+46 32 58.83	45.00	−0.92	0.97
81	Santai 三台	44127	ι UMa	06 01 23.28	+53 16 34.39	30.25	7.01	6.92
82	Xiang 相	57399	χ UMa	09 19 39.87	+59 53 02.25	31.50	−0.94	1.24
83	Taiyangshou 太阳守	54539	ϕ UMa	08 36 35.96	+55 38 04.88	35.50	−0.63	2.03
86	Beidou 北斗	54061	α UMa	07 47 00.35	+72 06 43.36	18.25	−0.10	0.85
89	Tianyi 天乙	62423	7 Dra	10 31 27.72	+79 46 24.90	10.50	−0.12	1.16
90	Taiyi 太乙	63076	8 Dra	10 49 50.45	+78 28 39.32	10.00	1.69	1.70
92	Nanmen 南门	64004	ξ^2 Cen	11 05 22.20	−36 52 37.45	130.00	−1.27	1.97
93	Ping 平星	64962	γ Hya	11 17 09.37	−10 09 25.22	100.00	1.62	1.89
94	Qiguan 骑官	72010	c1 Cen	12 31 28.20	−23 10 44.55	115.50	−0.67	0.73
96	Gui 龟	85792	α Ara	14 42 33.85	−43 36 44.46	131.00	4.56	6.82
97	Fushuo 傅说	87261	G Sco	15 15 47.45	−32 10 44.70	120.50	3.46	3.47
98	Yu 鱼	87569	M7	15 21 42.77	−30 15 55.16	122.00	0.02	0.84
99	Chu 杵	90422	α Tel	15 37 11.07	−42 37 50.44	132.50	2.06	2.56
100	Bie 鳖	92226	μ CrA	16 04 41.66	−38 26 55.04	129.50	0.82	3.79
106	Tiancang 天仓	5364	η Cet	23 08 11.18	−23 06 35.16	120.00	−5.24	5.17
109	Tianyuan 天苑	18543	γ Eri	02 09 41.90	−22 31 32.32	114.00	0.17	4.21
111	Yujing 玉井	23875	β Eri	03 14 16.14	−11 01 32.64	102.75	−0.25	2.20
116	Yeji 野鸡	30324	β CMa	04 40 00.12	−19 36 02.80	111.00	0.20	1.41
120	Ji 稷	42913	δ Vel	07 38 45.66	−47 30 06.24	138.00	1.51	2.55

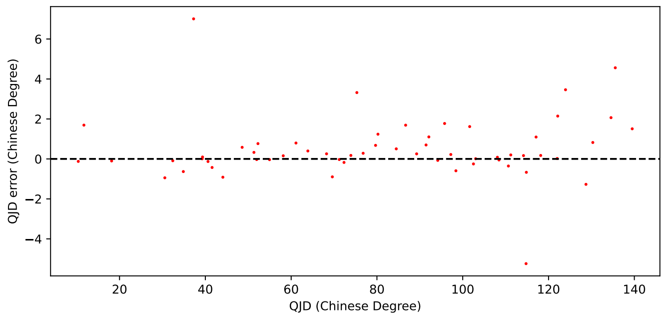

Figure 4. QJD errors in 355 BCE.

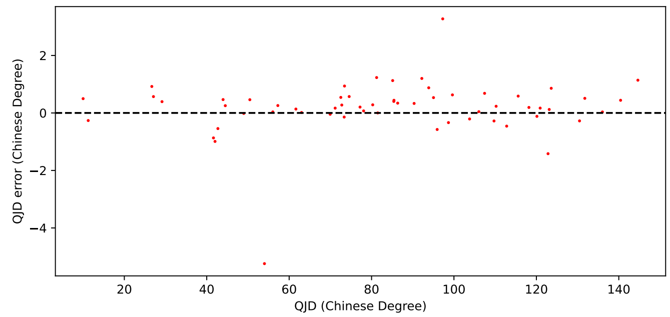

Figure 6. QJD errors in 125 CE.

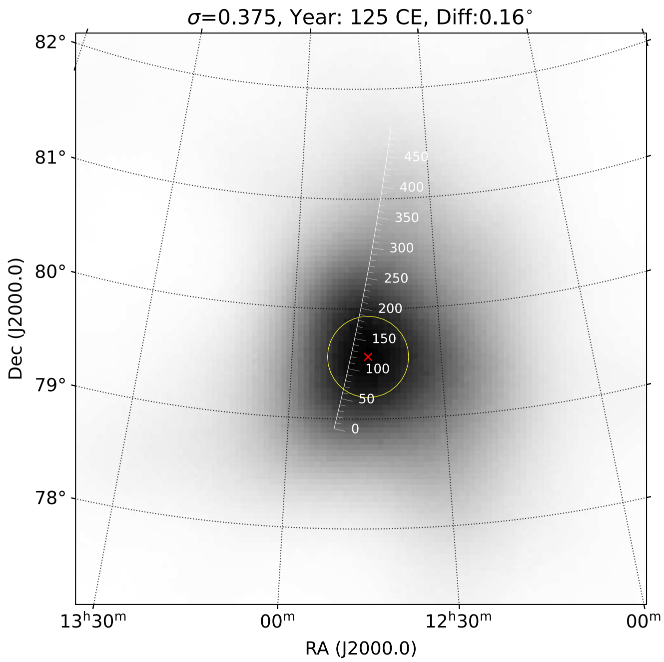

Figure 5. The epoch corresponding to the orientation of the second North Celestial Pole. (125 CE).

the largest deviation extends to 1.42 Chinese Degrees. The outcomes of the error analysis are presented in Figure 6.

4. Discussion and Conclusion

The Generalized Hough Transform represents an advancement over prior methodologies by integrating a probabilistic computation model with the Monte Carlo algorithm for sampling. During the computation process, the model exclusively considers the QJD, while the RXD is excluded. This strategy effectively reduces the influence of various errors on the calculation outcomes, thereby significantly improving the accuracy of epoch estimation for observational data.

The application of the Generalized Hough Transform to *Shi's Star Catalog* data reveals that the catalog encompasses observations from two separate epochs. It is inferred that *Shi's Star Catalog* was originally compiled around 355 BCE, establishing a constellation system of 120 constellations and recording astronomical observations. Later, around 125 CE, an additional observation session was conducted, updating the data for 59 stars, which were then incorporated into *Shi's Star Catalog*, ensuring its preservation to the present day.

The illustrious Eastern Han astronomer Zhang Heng (张衡) assumed the exalted office of Grand Astrologer (Taishi Ling, 太史令), a role entails the supervision of astronomical matters, on two separate occasions spanning the intervals of 115-120 CE and 126-132 CE. During his incumbency, he conceptualized and fabricated an armillary sphere (Hunyi, 浑仪), which he employed to undertake methodical astronomical observations. Scholarly inquiry indicates that segments of *Shi's Star Catalog* may have been either revised or originally derived from the observational data amassed by Zhang Heng. Nevertheless, in the process of textual transmission across subsequent historical epochs, some data have preserved their original records dating back to the Zhanguo period, whereas others presumably embody observations conducted during Zhang Heng's own era. This dual provenance of the data-integrating antecedent records with contemporary observations-plausibly accounts for the coexistence of two discrete observational time frames within *Shi's Star Catalog*.

Our research indicates that the earliest recorded observations in *Shi's Star Catalog* date to approximately 355 BCE. In contrast, Japanese scholar Yasukatsu Motohashi has analyzed several ancient Western star catalogs (Maeyama 1984). The Timocharis catalog is from approximately 300 BCE to 250 BCE, the Aristyllus catalog is from around 260 BCE, the Hipparchus catalog is believed to have originated around 130 BCE, and the Ptolemy catalog is dated to around 130 CE. Among these, Ptolemy's catalog is considered the most reliable and its epoch is relatively precise, indicating observations around 130 CE.

In summary, the computational method of the Generalized Hough Transform effectively mitigates the error issues encountered in previous methodologies, thus reliably resolving the challenge of determining the observation epochs of ancient Chinese stars. Consequently, the issue of observation epochs within *Shi's Star Catalog* is successfully addressed. In

Table 3
Shi's Star Catalog (125CE)

No.	Constellation	HIP	Star	R.A. (355BCE)	Decl. (355BCE)	QJD	QJD_err	Pos_err
1	Jiao 角	65474	α Vir	11 48 46.00	−00 52 29.73	91.00	1.20	1.18
9	Niu 牛	100345	β Cap	18 33 27.96	−18 38 52.80	110.00	0.23	0.23
10	Nü 女	102618	ϵ Aqr	19 04 01.71	−14 31 10.88	106.00	0.04	0.04
11	Xu 虚	106278	β Aqr	19 50 42.00	−12 17 56.34	104.00	−0.21	0.21
12	Wei 危	109074	α Aqr	20 27 54.19	−08 11 47.01	99.00	0.63	0.62
13	Shi 室	113963	α Peg	21 32 08.96	+05 49 35.51	85.00	0.40	0.40
14	Bi 壁	1067	γ Peg	22 38 31.23	+04 53 59.41	86.00	0.34	0.34
15	Kui 奎	3693	ζ And	23 11 47.24	+13 54 20.45	77.00	0.20	0.20
16	Lou 娄	8903	β Ari	00 15 18.16	+10 52 15.75	80.00	0.28	0.28
17	Wei 胃	12719	35 Ari	00 59 18.86	+18 30 07.33	72.00	0.54	0.53
18	Mao 昴	17499	17 Tau	01 58 30.00	+16 30 05.52	74.00	0.57	0.56
19	Bi 毕	20889	ϵ Tau	02 42 49.45	+13 03 04.10	78.00	0.07	0.07
20	Zi 觜	26176	ϕ Ori	03 53 36.37	+06 05 51.57	84.00	1.13	1.11
21	Can 参	25930	δ Ori	03 57 33.63	−03 40 01.59	94.50	0.53	0.53
22	Jing 井	30343	μ Gem	04 30 29.67	+21 03 04.10	70.00	−0.05	0.04
28	Zhen 轸	59803	γ CrV	10 41 35.32	−07 14 43.51	99.00	−0.34	0.33
34	Tianqiang 天枪	69483	κ Boo	13 03 45.31	+61 16 33.08	28.75	0.39	1.28
36	NüChuang 女牀	84380	π Her	16 10 41.88	+40 15 53.03	50.00	0.46	0.48
38	Guansuo 贯索	75695	β CrB	14 10 38.52	+36 46 08.66	59.25	−5.24	10.17
51	Jian 建	93085	ξ Sgr	17 05 42.35	−21 10 12.03	113.25	−0.46	2.75
53	Hegu 河鼓	97649	α Aql	18 18 56.35	+05 47 15.63	85.00	0.44	0.45
54	Lizhu 离珠	101847	1 Aqr	19 00 13.72	−05 52 32.28	94.00	3.27	3.36
55	Paogua 瓠瓜	101769	6 Del	19 09 24.38	+09 40 13.20	81.50	0.00	1.08
56	Tianjin 天津	97165	δ Cyg	18 46 26.10	+41 43 14.43	49.00	−0.02	20.40
58	Wangliang 王良	746	β Cas	22 40 21.81	+48 58 00.64	42.50	−0.87	0.86
59	Gedao 阁道	6242	ϕ Cas	23 37 22.02	+47 54 27.18	43.25	−0.54	1.12
60	Fulu 附路	4292	υ Cas	23 17 45.25	+48 35 42.04	43.00	−0.99	1.38
62	Daling 大陵	11060	9 Per	00 27 52.43	+46 08 13.19	44.25	0.25	2.10
63	Tianchuan 天船	13268	η Per	00 50 40.13	+46 40 01.16	43.50	0.46	0.46
64	Juanshe 卷舌	17529	ν Per	01 47 16.39	+34 46 10.27	56.00	0.04	1.55
65	Wuche 五车	23015	ι Aur	02 59 56.48	+27 53 28.13	63.00	0.01	1.17
66	Tianguan 天关	26451	ζ Tau	03 47 56.42	+17 41 50.75	73.50	−0.14	1.36
67	Nanhe 南河	36188	β CMi	05 44 49.67	+09 56 11.71	80.00	1.23	1.97
68	Wuzhuhou 五诸侯	33018	θ Gem	04 49 04.52	+33 33 56.63	57.00	0.26	2.24
70	Jixin 积薪	38538	ϕ Gem	05 56 10.67	+29 15 01.26	61.50	0.14	0.24
71	Shuiwei 水位	36760	68 Gem	05 45 29.30	+17 37 08.78	72.50	0.94	1.03
72	Xuanyuan 轩辕	49669	α Leo	08 25 19.38	+19 51 18.92	71.00	0.17	0.31
77	Ping 内屏	57328	ξ Vir	10 06 37.30	+18 16 15.12	72.50	0.28	2.28
84	Tianlao 天牢	53261	44 UMa	08 39 51.89	+63 19 13.92	26.50	0.57	1.62
85	Wenchang 文昌	41704	o UMa	05 38 29.66	+63 42 44.95	25.75	0.92	1.11
87	Ziweiyuan 紫微垣	61281	k Dra	10 43 28.30	+80 08 47.15	9.50	0.50	1.64
88	Gouchen 钩陈	11767	α UMi	23 18 27.50	+78 55 32.26	11.50	−0.26	0.37
91	Kulou 库楼	59747	δ Cru	10 46 39.54	−48 25 18.98	140.00	0.44	0.81
95	Jizu 积卒	78384	η Lup	14 03 44.11	−31 04 00.74	124.25	−1.42	1.43
101	Jiukan 九坎	98032	ι Sgr	17 41 17.89	−44 04 45.06	136.00	0.03	0.83
102	Baijiu 败臼	107380	ι PsA	19 45 54.99	−39 51 51.59	131.25	0.51	0.69
103	Yulin 羽林军	111449	υ Aqr	20 47 18.96	−29 10 51.17	120.75	0.17	0.22
104	Beiluoshimen 北落师门	113368	α PsA	21 07 08.12	−38 35 53.63	130.75	−0.28	0.78
105	Tusikong 土司空	3419	β Cet	23 06 51.79	−28 24 16.79	120.25	−0.12	0.50
107	Tianqun 天囷	14135	α Cet	01 26 34.52	−04 32 44.35	96.50	−0.58	0.86
108	Tianlin 天廪	15900	o Tau	01 46 50.28	+00 58 03.91	90.00	0.33	0.86
110	Shenqi 参旗	22797	π^5 Ori	03 18 27.94	−02 31 34.67	93.00	0.88	0.97
112	Ping 屏	23685	ϵ Lep	03 46 58.61	−26 29 32.34	118.00	0.19	2.15
113	Ce 天厕	25606	β Lep	04 08 44.95	−23 55 28.17	115.00	0.59	0.69
114	Shi 屎	26460	ν^2 Col	04 25 22.32	−31 21 03.66	123.00	0.12	0.13
115	Junshi 军市	28816	17 Lep	04 42 01.80	−18 08 37.21	110.00	−0.28	0.41
117	Lang 狼	32349	α CMa	05 22 28.13	−15 53 16.98	106.75	0.68	0.69
118	Hushi 弧矢	32759	κ CMa	05 40 15.53	−31 49 51.77	122.75	0.86	1.66
119	Laoren 老人	30438	α Car	05 42 50.70	−52 33 37.52	143.50	1.14	1.19

comparison to the observation epochs of other ancient star catalogs worldwide, *Shi's Star Catalog* predates even the oldest Western star catalogs, affirming its status as the oldest star catalog in the world.

In future studies, we will build upon the findings of this study to progressively reconstruct the complete dataset of *Shi's Star Catalog*, implement data visualization, and further advance related academic research.

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References

Anderson, E., & Francis, C. 2012, AstL, 38, 331
Chen, M. D. 2015, History of Science and Technology in China: Astronomy (Beijing: Science Press), (in Chinese)
ESA 1997, The HIPPARCOS and TYCHO catalogues.Catalogues. Astrometric and photometric star catalogues derivedPhotometric Star Catalogues Derived from the ESA HIPPARCOS Space Astrometry Mission, in ESA Special Publication, 1200 (Noordwijk: ESA Publications Division)
Guo, S. C. 1994, Studies in the History of Natural Sciences, 13, 18, (in Chinese)
He, B. L. 2024, The Chinese Ancient Astronomy Fundamental Reference Star Catalog, China Nataional Astronomical Data Center (NADC), doi:10.12149/100877
He, B. L., & Zhao, Y. H. 2024, AstTI, 2, 150
Hu, W. J. 1998, Studies in the History of Natural Sciences, 17, 139, (in Chinese)
Maeyama, Y. 1977, in Prismata: Naturwissenschaftgeschichtliche Studien, Festschrift für Willy Hartner, ed. Y. Maeyama & S. WG (Weisbaden: Franz Steiner), 211
Maeyama, Y. 1984, Cent, 27, 280
Pan, N. 2009, History of Chinese Stellar Observations (2nd ed.; Shanghai: Xuelin Publishing House) (in Chinese)
Qian, B. C. 1937, Quarterly Publication of the State University of Zhejiang, 1, 1, (in Chinese)
Shingō, S. 1928, Dongyang Tianwenxue shi yanjiu (Research in the History of Astronomy in the Far East) (Hongwen Tang)
Sun, X. C. 1994, Studies in the History of Natural Sciences, 13, 123, (in Chinese)
Sun, X., & Kistemaker, J. 1997, The Chinese Sky During the Han: Constellating Stars and Society, 38 (Leiden: Brill)
Ueta, J. 1930, Pub. Kwasan Observatory (Kyoto Imperial University), 1, 17
van Leeuwen, F. 2007, A&A, 474, 653
Verbunt, F., & van Gent, R. H. 2012, A&A, 544, A31
Vondrák, J., Capitaine, N., & Wallace, P. 2011, A&A, 534, A22
Yabuuchi, K., & Kong, Z. J. 1984, The Chinese Journal for the History of Science and Technology, 5, 14–18 (in Chinese)