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ASTRO-HISTORIOGRAPHIC CHRONOLOGIES OF EARLY CHINA ARE UNFOUNDED

Douglas J. Keenan

Several researchers have made proposals for a chronology of ancient China that rely on records of astronomical events—solar eclipses or five-planet conjunctions. It is shown herein that either the events did not occur or there is no reliable record of them, or both, and that such problems are unrectifiable. Hence chronologies that are based on astro-historiography are unfounded.

Acknowledgments: appreciative thanks to F. Richard Stephenson and Donald B. Wagner for detailed comments on drafts, and to Liu Ciyuan and David W. Pankenier for helpful discussions.

Introduction

The chronology of ancient China has been debated for centuries. The long history of China is regarded with much pride in the nation today, and the lack of an accepted chronology of the early dynastic period has led to considerable vexation. In 1996, the State Council of China (*Guowu yuan* 国务院) established a group that launched a major national research project, involving hundreds of researchers, whose goal was to resolve these debates.[1] In 2000, the project published its report[2]: a chronology, relying on a record of a solar eclipse, was officially adopted. This has been pro-claimed as a major achievement of Chinese research. Despite that, a different chronology has generally been adopted in the West[3]: it is based on records of conjunctions of the five visible planets. The present work considers the merits of these two different approaches.

Solar Eclipses

A solar eclipse occurs when the moon moves in front of the sun, covering some of it. If the sun is totally covered, it is called a *total eclipse*. If the sun is partially covered, it is called a *partial eclipse*. A given location on Earth will

1 S. Allan, trans., "China launches an ambitious multi-year Xia Shang Zhou chronology project," *Early China News* 9 (1996): 1, 10–14; E. Wilkinson, *Chinese history: a manual* (Cambridge, Mass.: Harvard University Press, 2000), at p.367.

2 *Xia-Shang-Zhou duandaigongcheng* [Xia-Shang-Zhou chronology project] (Beijing: Shijie Tushu Chuban Gongsi, 2000) (in Chinese; an extensive English summary is scheduled to be published in 2002.)

3 M. Loewe and E. L. Shaughnessy, eds, *The Cambridge history of ancient China* (Cambridge: Cambridge University Press, 1999). See especially E. L. Shaughnessy, "Calendar and chronology," in id., pp.19–25, and D. N. Keightley in id., pp.247–8.

experience a total eclipse, on average, once every 370 years; a partial eclipse will be experienced once every 2.6 years.[4] Hence total (or near-total) eclipses are useful in chronology, but partial eclipses tend not to be, unless there is more information to distinguish them.

Some recent chronological proposals, such as that accepted by the Chinese State Council, rely on a Chinese record, dating from the early first millennium BC, that tells of a "double dawn."[5] The proposals interpret this unique record as a description of a partial eclipse at dawn. This interpretation seems reasonable (the day begins to dawn, then there is darkening due to an eclipse, then the sun rises), but not certain. Eclipses at dawn that cover enough of the sun to substantially darken are very rare. An eclipse at dawn did occur on 21 April 899 BC, and this has been matched, by the proposals, to the record.

Calculations show that the 899 BC eclipse reduced the subjective brightness of the sky (as sensed by a human observer) by < 25%.[6] To substantiate their claim that such a reduction can give observers a "definite feeling of double dawn," some proposers surveyed observers of a 1997 partial eclipse at dawn.[7] All the observers, though, were in locations where the brightness reduction was either < 10% (where there was no "feeling of double dawn" reported by observers) or > 80% (where there was).[8] From these data, the proposers concluded that a brightness reduction of ≥ 10% results in observers having a "definite feeling of double dawn." This conclusion is plainly unwarranted. Indeed, a brightness reduction of 25% can be easily produced by passing clouds. (Also, in 899 BC, the eclipse maximum occurred well below the horizon; this makes the brightness calculations qualitatively different from those used for 1997.[9])

Additionally, the brightness-reduction calculations for the 899 BC eclipse use an incorrect estimate for Earth's rate of rotation (see Appendix for details). When a valid rate is used, the timing of the eclipse changes so that the calculated brightness reduction is < 10% (this holds even for a parabolic coefficient as small as 29.3—see Appendix for explanation).[10] Furthermore, even these calculations overestimate the brightness reduction, for at least three reasons:

- They are for the brightness of the northern sky, whereas the brightness of the eastern sky is relevant for dawn; at dawn, the northern sky is very dim, which (due to the way human vision works) makes subjective brightness change extra rapidly with luminance: this overstates the brightness reduction.[11]
- They assume that there was no atmospheric scattering of sunlight; such scattering, however, always occurs, and it lessens the brightness reduction.[12]
- They assume that there were no intervening clouds or fogs.

(In addition, the location at which the 899 BC eclipse was supposedly observed is unknown; the above assumes a far-eastward position that would be plausible: a more westward position would substantially decrease any brightness reduction.[13]) Thus, the claim that observers in 899 BC would have experienced a double dawn is strongly contradicted.

[4] F. R. Stephenson, *Historical eclipses and Earth's rotation* (Cambridge: Cambridge University Press, 1997), at p.54.

[5] *Xia-Shang-Zhou duandai gongcheng*; see too Liu Ciyuan, Li Jianke and Zhou Xiaolu, "Study on 'double dawn'," *Science in China (Series A)* 42 (1999): 1224–32, and M. Chown, "Double dawn," *New Scientist* 2203 (1999): 16. K. D. Pang, K. Yau, and H.-h. Chou, "The Earth's palaeorotation, post-glacial rebound and lower mantle viscosity from analysis of ancient Chinese eclipse records," *Pure and Applied Geophysics* 145 (1995): 459–85, also adopt the "double dawn" record.

[6] Liu et al., "Study on 'double dawn'," table 1.

[7] Liu Ciyuan and Zhou Xiaolu, "The sky brightness when the rising sun is in eclipse," *Chinese Astronomy and Astrophysics* 23 (1999): 249–57 (a translation of *Acta Astronomica Sinica* 39 (1998): 278–86).

[8] Liu and Zhou,"The sky brightness when the rising sun is in eclipse."

[9] In 1997, the eclipse maximum occurred with the sun at altitude > -3°, whereas in 899 BC, the eclipse maximum occurred at altitude < -6° (calculated by the author). According to Liu and Zhou, "The sky brightness when the rising sun is in eclipse," the calculation for subjective brightness is qualitatively different depending on whether or not the angle is > -4.25°.

[10] Calculated by the author, applying figure 2 from Liu et al., "Study on 'double dawn'"; also confirmed by Liu Ciyuan, private communication, November 2000.

[11] Liu and Zhou, "The sky brightness when the rising sun is in eclipse."

[12] Ibid.

[13] Liu et al., "Study on 'double dawn'."

Five-Planet Conjunctions

There are five planets that are visible with the naked eye. When two or more of these planets appear to be close to each other, they are said to be *in conjunction*. It is unclear how close planets would had to have been in order for the ancient Chinese to have considered them to be in conjunction. Some researchers have suggested that the planets only had to be within an arc of 30° (i.e. spanning 30° of the sky).[14] Conjunctions of all five planets that span ≤ 30° occur, on average, every 40 years.[15] Thus, if the suggestion is correct, conjunctions would tend not to be useful in chronology. There are seven historical texts from after the Han 漢 period (ended AD 220) that record five-planet conjunctions: three of these refer to occasions when the planets spanned > 30°.[16] There is no evidence that ancient observers considered differently from post-Han ones. Hence the suggestion seems conservative.

The evidence that conjunctions, as defined by the ancient Chinese, occurred often has been largely disregarded by chronological proposals that rely on conjunctions. The main such proposals rest on a trio of five-planet conjunctions, in 1953 BC, 1576 BC, and 1059 BC.[17] There was, however, no five-planet conjunction in 1576 BC, only a four-planet conjunction: at the time of the "conjunction," Venus was over 40° away from the other four planets (see Figure 1)[18]; attempts to promote the proposals have essentially ignored this. Four-planet conjunctions are relatively common, under any reasonable choice of maximum-allowed degrees-of-arc span; they thus have negligible value in chronology.

[14] Zhang Peiyu, [untitled article], *Early China* 15 (1990): 133–50 (responses, id., pp.151–96), at 146; Huang Yilong, "A study of five-planet conjunctions in Chinese history," *Early China* 15 (1990): 97–112 (responses, id., pp.151–96), at 97.

[15] Huang Yilong, ibid., p.97 (response, id., pp.179–80); Zhang Peiyu, [as in n.14 above], p.146.

[16] Huang Yilong, "A study of five-planet conjunctions in Chinese history," pp.109–10 (response, id., pp.179–80).

[17] D. W. Pankenier, "Mozi and the dates of Xia, Shang, and Zhou," *Early China* 9–10 (1983–85): 175–83; id., "The cosmo-political background of Heaven's mandate," *Early China* 20 (1995): 121–76; D. S. Nivison, *The riddle of the Bamboo Annals* (manuscript) (summarized in *Sino-Platonic Papers* 93 [1999]).

[18] See, too, Pankenier, "The cosmo-political background of Heaven's mandate," table 1.

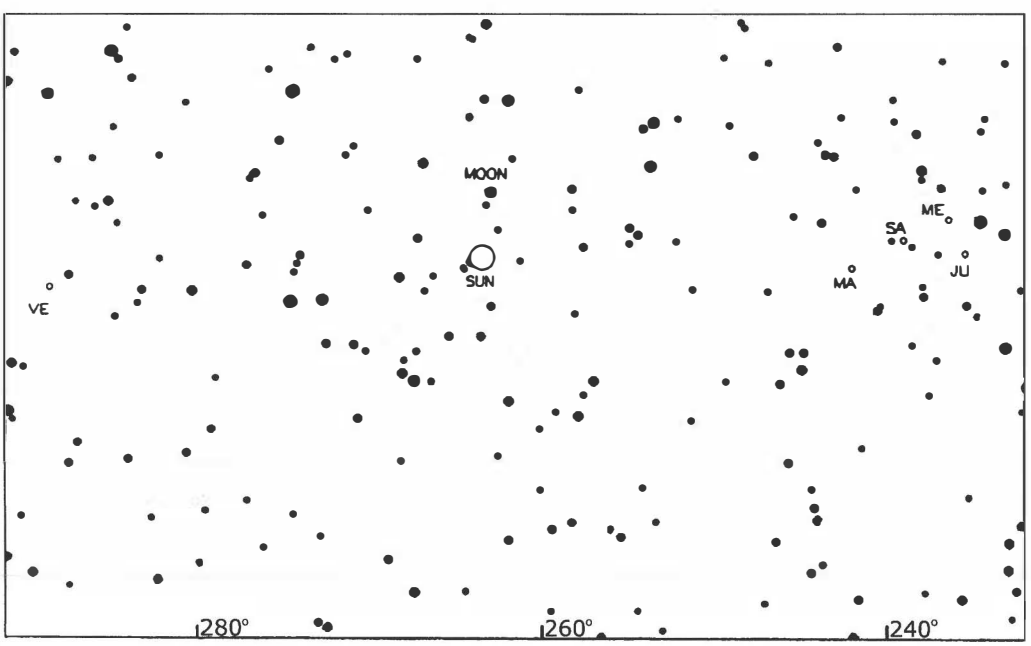

Figure 1

The sky in late 1576 BC, when a five-planet conjunction is claimed to have occurred. Displayed are the SUN, MOON, stars, and the five planets that are visible with the naked eye: VEnus, MArs, SAturn, MErcury, and JUpiter. As shown, Venus was distant (over 40°) from the other planets: the claim of a conjunction is false. (Figure adapted from Pankenier, "The cosmo-political background of Heaven's mandate," figure 2.)

The text cited as recording a five-planet conjunction in 1953 BC is as follows:

> ... the three Miao tribes were in great disorder and Heaven decreed their destruction. The sun came out at night and for three days it rained blood. A dragon appeared in the ancestral temple and dogs howled in the market place. Ice formed in summertime, the earth split open until springs gushed forth, the [cereal crops] grew differently, and the people were filled with a great terror. Kao Yang gave the command in the Dark Palace, and Yu ... grasped the jade staff of authority and set out to subdue the ruler of the Miao. Amidst the din of thunder and lightning, a spirit with the face of a man and the body of a bird came bearing a jade baton to wait upon Yu. The general of the Miao was felled by an arrow ... .[19]

(Kao Yang 高陽 and Yu 禹 are legendary emperors. The Miao 苗 referred to here are perhaps the ancestors of the Miao [i.e. Hmong] people who are based in Southeast Asia today.[20]) The proposals interpret the Dark Palace (*xuan gong* 玄宮) as indicating an area of the sky known as the "lodge of *Shi* 室": indeed, some ancient Chinese texts do use "Dark Palace" to denote the lodge[21] of *Shi*. The climatic events and bearing of a jade baton are interpreted as a five-planet conjunction in the lodge of *Shi*.[22]

The above text is like the main text cited as recording a "conjunction" in 1576 BC, and the proposals adduce this likeness as demonstrating that the two texts record like events. The proposals' claim that the text for 1576 BC records a four-planet conjunction, however, indicates (by their reasoning) that the above text also records a four-planet conjunction. As well, if the above text is considered on its own, there seems to be no reasonable justification for interpreting it as a record of a conjunction—a conclusion also drawn by other researchers.[23] In particular, "Dark Palace" has traditionally been taken to mean the northern part of the emperor's residence,[24] and jade artefacts were commonly associated with ancient Chinese élites.

There was a true five-planet conjunction in 1059 BC (the planets spanned about 7°).[25] There are also records from roughly that time that explicitly tell of a five-planet conjunction. Moreover, some records tell of a red bird bearing a jade baton, and the proposals' interpret this as indicating that the location of the conjunction was by the large[26] Vermilion Bird (*zhu niao* 朱鳥) constellation. Additionally, there is supposedly a record of an eclipse, near the time of the conjunction, on (cyclic[27]) day *bingzi* 丙子 in the first (lunar) month of the year, and there was a total *lunar* eclipse that matches this on 12 March 1065 BC.

The proposals' interpretation of the bird bearing a jade baton conflicts with the proposals' interpretation for the text of 1953 BC—yet the texts are alike, as the proposals indeed say. The interpretation is also speculative. In addition, the records explicitly tell where the conjunction occurred: in the lodge of *Fang* 房. The conjunction of 1059 BC, however, was 120° away from *Fang*.[28] Further discussion of this is below. The lunar eclipse is discussed in the Excursus.

[19] Adapted from B. Watson, trans., *Basic writings of Mo Tzu, Hsün Tzu, and Han Fei Tzu* (New York: Columbia University Press, 1967), Mo Tzu at sect.19, with assistance from E. W. Maeder.

[20] E. G. Pulleyblank, "The Chinese and their neighbors in prehistoric and early historic times," in *The origins of Chinese civilization*, ed. D. N. Keightley (Berkeley, Calif.: University of California Press, 1983), pp.411–66, at 423–9.

[21] For a description of lodges and their locations in the sky, see C. Cullen, *Astronomy and mathematics in ancient China: the Zhou bi Suan jing* (Cambridge: Cambridge University Press, 1996), at pp.17–19.

[22] Pankenier, "Mozi and the dates of Xia, Shang, and Zhou"; Pankenier, "The cosmo-political background of Heaven's mandate," p.132.

[23] K. D. Pang, "Extraordinary floods in early Chinese history and their absolute dates—reply," *Journal of Hydrology* 110 (1989): 377–82, at 380–1; Huang Yilong, "A study of five-planet conjunctions in Chinese history," pp.107–8.

[24] W. A. Rickett, *Guanzi I* (Boston: Cheng & Tsui, 2001), at pp.150–3.

[25] Pankenier, "The cosmo-political background of Heaven's mandate," table 1.

[26] Pankenier, "The cosmo-political background of Heaven's mandate," at p.124, says that the Vermilion Bird constellation spanned about 60°; J. Needham, *Science and civilisation in China*, vol.3 (Cambridge: Cambridge University Press, 1959), p.246, says that in its widest sense the constellation was considered to span about 80°.

[27] In ancient China, there was a 60-day cycle, which was independent of the month and year; this is similar to the 7-day cycle of modern times (i.e. the weekly cycle).

[28] Huang Yilong, "A study of five-planet conjunctions in Chinese history," pp.105–6.

Record Reliability

An important issue in chronology is the reliability of records. Emperor Shi Huangdi 始皇帝 (reigned 221–210 BC) of the Qin 秦 had most books burned; although some books were retained at the palace, these were largely destroyed in the civil war that followed his death. Thus records from before the emperor's reign tend to be relatively poor. Even so, after 841 BC, the chronology of China is agreed upon.[29] We will first consider the reliability of records of astronomical events during 841–221 BC.

The *Bamboo Annals* (Zhushu jinian 竹書記年)[30] is perhaps the ancient text most often used for chronology. It explicitly records one solar eclipse after 841 BC; that eclipse, in 776 BC, did not occur.[31] The *Spring and Autumn Annals* (Chunqiu 春秋)[32] is an ancient text with records of many solar eclipses (both total and partial). It records solar eclipses on 3 April 645 BC, 15 May 592 BC, 19 September 552 BC, and 18 July 549 BC; yet there were no eclipses on those dates.[33] This text also records many other solar eclipses that did occur.[34] Thus, although the text seems to be a valuable historical document, no single record from it should be assumed to be accurate. The *Song shu* 宋書[35] is an ancient text that contains the sole record of a five-planet conjunction during 841–221 BC. This tells of a five-planet conjunction shortly before 679 BC; yet there was not such a conjunction then (here defining the maximum span as 30°).[36]

Astronomical records from before 841 BC are naturally expected to be even less reliable, in general, than those from after 841 BC. Causes of unreliability are many. None of the texts that are relied on for developing pre-841 BC chronology are contemporaneous. Thus, errors could have been introduced accidentally, as the text was re-recorded during its transmission across the centuries—e.g. errors due to inaccurate transcription or editing. Errors could also have been introduced deliberately, for at least three reasons. First, the ancient Chinese assumed astrology was valid, and later recorders might have fabricated (or greatly redated) astrological events to "justify" earlier historical events. Second, rulers might have rewritten history to give legitimations to their own rule. Third, there was fraud. Many known or suspected examples of these are given in the standard bibliography of ancient Chinese texts.[37] Indeed, the bibliography comprises 64 chapters, each devoted to a different text, and almost all chapters have a section that discusses "authenticity."

(The authenticity of some records in the *Bamboo Annals* has been studied by textual-related analyses.[38] The study concluded that the records likely were generally authentic, and it has often been cited in support of authenticity. The study, though, has been greatly criticized at length.[39] As an example, the study assumes that each strip of bamboo, on which the text was originally written, contained exactly 40 characters: there is strong evidence against this assumption and only weak evidence for it. Here, we refer to the criticism and consider the study to be unsound.)

[29] Shaughnessy, "Calendar and chronology"; Wilkinson, *Chinese history: a manual*, pp. 180–1.

[30] For a translation, see J. Legge, *The Chinese classics III: the Shoo King* prolegomena (1865; reprint ed., Taipei: Southern Materials Center, 1985); for annotations, see D. S. Nivison, "Chu shu chi nien," in M. Loewe, ed., *Early Chinese texts: a bibliographical guide* (Berkeley, Calif.: Society for the Study of Early China, 1993), pp.39–47, and N. Barnard, "Astro-nomical data from ancient Chinese records: the requirements of historical research methodology," *East Asian History* 6 (1993): 47–74.

[31] Calculated by the author. See too below.

[32] A. Cheng, "Ch'un ch'iu, Kung yang, Ku liang and Tso chuan," in Loewe, *Early Chinese texts: a bibliographical guide*, pp.67–76.

[33] F. R. Stephenson and K. K. C. Yau, "Astronomical records in the Ch'un Ch'iu chronicle," *Journal for the History of Astronomy* 23 (1992): 31–51.

[34] Ibid. (It has not been proven, however, that these records are not due to later calculations.)

[35] Wilkinson, *Chinese history: a manual*, sect. 45.1.

[36] Huang Yilong, "A study of five-planet conjunctions in Chinese history," pp.99–101, with additional calculations by the author.

[37] Loewe, *Early Chinese texts: a bibliographical guide*.

[38] E. L. Shaughnessy, "On the authenticity of the Bamboo Annals," *Harvard Journal of Asiatic Studies* 46 (1986): 149–80.

[39] Barnard, "Astronomical data from ancient Chinese records: the requirements of historical research methodology."

The sole *Bamboo Annals* astronomical record from after 841 BC—the eclipse of 776 BC—is almost certainly a forgery. The most difficult part of eclipse calculations is to find the locations on Earth where the eclipse was observable. Determining that there was an eclipse—somewhere on Earth—is easier. Thus, we would expect a period in Chinese history when astronomical knowledge was sufficient to calculate that an eclipse occurred at some particular time, but insufficient to correctly calculate the eclipse's location. There was an eclipse in 776 BC on the most-likely date indicated by the record (6 September), but it was not observable in ancient China. (It reached near-totality around the Barents Sea—in the Arctic.) That an actual eclipse would match the record's date just by chance is very improbable. In addition, the error is one that would be expected if the record was forged using astronomical formulae available after the Han period (ended AD 220).[40] Hence the *Bamboo Annals* record is almost certainly bogus.

The *Bamboo Annals* is the text that records a double dawn. The text tells that the double dawn occurred during the reign of a King Yi 懿.[41] Since Yi was apparently a very poor ruler,[42] it is reasonable to suspect that later recorders fabricated a record of an omen for his reign; such a suspicion is particularly appropriate here, since the event is recorded as occurring during the first year of Yi's reign. Clearly the record is unreliable.

Records of a five-planet conjunction that have been proposed to refer to the conjunction in 1059 BC were cited above. Those records claim that the conjunction occurred at the time of the succession of the long-lived Zhou 周 dynasty (the succession is usually dated to 1200–1000 BC). Five-planet conjunctions were believed to portend very beneficial times, so the veracity of the records should be considered inherently doubtful. That the conjunction is recorded as occurring in the lodge of *Fang* has been attributed to "portentological revisionism."[43] Such revisionism, though, would seem to be at least as likely to affect the conjunction's recorded historical timing as its location in the sky. As to the supposed record of a lunar eclipse, it is from a text that is suspected of being fabricated.[44]

The main proposal that depends on the double dawn[45] rejected the records of a conjunction because of the above concerns about revisionism. The dependence on the record of a double dawn, though, was claimed to be justified because the portents associated with a double dawn are unknown. This claim is clearly illogical.

Discussion

Within the People's Republic of China, a major national project on early dynastic chronology was initiated by the State Council of China. For the chronology of the Early Zhou period (i.e. Western Zhou, ended 771 BC), the project adopted the record of a double dawn, dated to 899 BC, as the principal foundation for its conclusions.[46] Yet, the record is far from reliable; its interpretation is not certain; and there was not a perceptible dawn darkening

40 W. Eberhard and R. Mueller, "Contributions to the astronomy of the Han period III," *Harvard Journal of Asiatic Studies* 1 (1936): 194–241.

41 Legge, *The Chinese classics III: the Shoo King* prolegomena," p.152; Liu et al., "Study on 'double dawn'," p.1224.

42 Legge, *The Chinese classics III: the Shoo King* prolegomena, p.152; Ssu-ma Ch'ien, *The grand scribe's records I: the basic annals of pre-Han China*, ed. W. H. Nienhauser, jr. (Bloomington, Ind.: Indiana University Press, 1994), ch.4, p.140.

43 Pankenier, "The cosmo-political background of Heaven's mandate," n.17.

44 Shaughnessy, *Sources of Western Zhou history*, pp.222–3; Barnard, "Astronomical data from ancient Chinese records: the requirements of historical research methodology," n.17.

45 *Xia-Shang-Zhou duandai gongcheng*.

46 Ibid. (Bronze inscriptions were also used, as well as transmitted texts of dubious reliability, but it was the double dawn that was essential.)

in 899 BC. The project also advanced a precise chronology for the Late Shang (immediately preceding the Early Zhou). This chronology, however, depends on the correctness of the chronology for the Early Zhou—which is invalid. The Late Shang chronology was claimed to be verified by records of five lunar eclipses[47]; those records, though, are inherently uncertain in application (as exemplified in the Excursus), and moreover, at least one of the records used is highly-unreliable hearsay.[48] Thus the project's chief conclusions are unfounded.

Outside China, the standard authoritative work is *The Cambridge History of Ancient China*.[49] This work has followed the consensus view among Western researchers: it has provisionally adopted a chronology based on five-planet conjunctions. This has been done without proper consideration for defining how large a span of the sky is appropriate. Moreover, the conjunction of 1576 BC did not occur; records for 1953 BC do not record a conjunction; and records of the other conjunction, in 1059 BC, are not reliable enough to form the basis of a chronology. Thus the chronology is without foundation.

47 Ibid. (The eclipses could be partial or total; the records are inscribed on oracle bones.)

48 D. N. Keightley, "Shang China is coming of age—a review article," *Journal of Asian Studies* 41 (1982): 549–57, at 550–1.

49 Loewe and Shaughnessy, *The Cambridge history of ancient China*.

Excursus: the Lunar Eclipse of 1065 BC

The eclipse record reads thus: on day *bingzi* in the first month, "at the ceremony paying homage to the full moon ... the king announced, 'The many [...] eclipse(s) is/are untimely; you shall begin planning succession'."[50] It is far from clear that this is a record of an (a total?) eclipse on the specified day. Moreover, a given location will experience a total lunar eclipse every 2.3 years (and a lunar eclipse of some magnitude every 1.1 years), on average[51]; so without the specifying day and month, the record would have no chronological value. The lunar eclipse of 1065 BC occurred well after midnight, actually on 13 March; thus the eclipse day (in the 60-day cycle) depends on whether the ancient Chinese day began at midnight or at dawn: the former is usually assumed,[52] but only the latter matches *bingzi*.[53] Additionally, there were at least three,[54] or more likely four,[55] different calendars, each with a different first (lunar) month; intercalary months seem to have been interpolated after any regular month[56] and so erratically that some years had 14 months[57] (thereby increasing the number of months that could be first): hence the chance that 12 March matched with the first month of some calendar is large. Overall, then, the record does not substantiate the proposed conjunctional date.

50 D. W. Pankenier, "Astronomical dates in Shang and Western Zhou," *Early China* 7 (1981–82): 2–37, at 5–7.

51 Stephenson, *Historical eclipses and Earth's rotation*, sect.3.5.2.

52 Shaughnessy, "Calendar and chronology," p.19; *Xia-Shang-Zhou duandai gongcheng*.

53 E. L. Shaughnessy, *Sources of Western Zhou history* (Berkeley, Calif.: University of California Press, 1991), at p.222.

54 Wilkinson, *Chinese history: a manual*, p.171.

55 R. Reynolds, "A note on chronology," in Ssu-ma Ch'ien, *The grand scribe's records VII: the memoirs of pre-Han China*, ed. W. H. Nienhauser, jr. (Bloomington, Ind.: Indiana University Press, 1994), pp.xv–xix; Zhang Peiyu, [as in n.14 above], pp.142–3.

56 Shaughnessy, *Sources of Western Zhou history*, sect.4.3.3, and id., "Calendar and chronology," p.20.

57 Li Boqian, "Some remarks on the inscription on the square tripod of Shu Ze," *Wen Wu* 2001.8: 39–42 (in Chinese, with English abstract), and D. N. Keightley, *Sources of Shang history: the oracle-bone inscriptions of Bronze Age China* (Berkeley, Calif.: University of California Press, 1978), at ch.4, n.98.

APPENDIX: EARTH'S HISTORICAL ROTATIONAL RATE

The rate of rotation of Earth varies over time (which affects how eclipses are observed). This variation implies changes in the length of the day. The sum of those changes (a function of time, here measured in centuries from

AD 1820) can be approximately modelled by a parabola. Liu et al. claim that the parabola's coefficient can be 28,[58] and they cite Stephenson and Morrison[59] to justify this. Stephenson and Morrison analysed many records of observations in the period since 700 BC. They showed that a maximal range for the coefficient of an approximating parabola is 29.3–31.8 and that the data "indicate a solution closer to the upper bound." Their analysis also concluded that for 700–500 BC, a coefficient of 31 is likely a little too small—and the disparity increases with age. Later analysis by Stephenson[60] and Morrison and Stephenson,[61] which included (near-contemporaneous Babylonian) records of observations from as early as 721 BC, confirmed this conclusion. Hence, for the 899 BC eclipse considered by Liu et al., the coefficient should likely be > 31 and unquestionably be > 29.3. An error of at least 1.3 in the parabola's coefficient implies a timing error of at least $1.3 \times (18.20 + 8.98)^2 = 960$ seconds, i.e. 16 minutes; during this time Earth would rotate 4° of longitude.

[58] Liu et al., "Study on 'double dawn'."

[59] F. R. Stephenson and L. V. Morrison, "Long-term fluctuations in the Earth's rotation: 700 BC to AD 1990," *Philosophical Transactions of the Royal Society—London* A 351 (1995): 165–202, at sect.5.

[60] Stephenson, *Historical eclipses and Earth's rotation*.

[61] L. V. Morrison and F. R. Stephenson, "Historical eclipses and the variability of the Earth's rotation," *Journal of Geodynamics* 32 (2001): 247–65

METHODS: ASTRONOMICAL CALCULATIONS

Most astronomical calculations used herein were checked using data from the Horizons system.[62] This data is the most accurate solar system dynamical data generally available. It is online, with documentation, at <http://ssd.jpl.nasa.gov/horizons.html>. Horizons gives the data in the form of tables. The relevant tables are known as *ephemerides*. Determining celestial positions from these ephemerides is straightforward. Determining the brightness reduction during a solar eclipse requires first determining the eclipse magnitudes at different times during the eclipse.[63] (The *magnitude* is the fraction of the sun's diameter covered by the moon.) Magnitude is calculated via the following four steps:

1. Find the angle formed by Sun–Observer–Moon, at the time, date, and location required. Call this angle A. ("Output Quantities" should include `Sun-Observer-Target angle`; "Target Body" should be the moon, for this step and the next.)
2. Find the angular diameter of the moon. Call this M. ("Output Quantities" should include `Target angular diameter`, for this step and the next.)
3. Find the angular diameter of the sun. Call this S. ("Target Body" should be the sun.)
4. The magnitude is $(S/2 + M/2 - 3600A)/S$. (If this is negative, there was no eclipse.)

(This magnitude is approximate, due to uncertainty about Earth's rotational rate—see Appendix—but it is accurate enough for our purposes here.) The times of interest are those when the angle A is near its minimum (and thus the eclipse is near its maximum). This minimum can be readily found by having the system give data for several times at once.

[62] J. D. Giorgini, D. K. Yeomans, and eight others, "JPL's on-line solar system data service," *Bulletin of the American Astronomical Society* 28 (1996): 1158.

[63] Liu et al., "Study on 'double dawn'."

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