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Astronomical function and date of the Taosi observatory

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The Taosi site in Xiangfen County, Shanxi Province, may be the capital of the Xia Dynasty. Archeologists recently discovered a large semi-circular stamped-earth platform, II FJT1, which has a clear and definite pounded-earth central core together with a curved wall perforated by twelve gaps. The platform is said to be an ancient observatory used to determine the seasons by watching the sunrise. Each feature of II FJT1 was precisely measured and the data are reproduced in this paper. An astronomical analysis of slots E2 and E12 was carried out using the azimuths of the slots' centerlines and the vertical angle of the mountain ridge opposite, above which the sun rises. The results show that at present the sun is close to the two slots but does not exactly enter them at summer and winter solstice sunrise. Using ^{14}C analysis archeologists dated the site to about 2100 BC. Because of the secular change in the obliquity of the ecliptic, at that date on the summer solstice the half-risen sun would have appeared inside slot E12 just to the right of the centerline, and on the winter solstice the sun would have been exactly on the centerline of slot E2. This result provides compelling proof that II FJT1 is an ancient observatory.

astro-archeology, astro-chronology, Taosi culture, ancient observatory, time service

1 The discovery of the Taosi observatory site

The southern part of Shanxi Province has long been thought to be one of the cradles of Chinese nationality. The prehistoric site discovered near Taosi village in Xiangfen County is one of the most famous of the eighty or so Longshan culture sites (ca 5,000—4,000 BP) in the south of Shanxi Province discovered in the 1950s. Between 1978 and 1987 large-scale excavations were carried out at Taosi. Over 1300 burials and large numbers of dwelling foundations reveal the social structure of the time. Excavated artifacts include large numbers of stone, pottery, and wooden objects used in daily life and production, as well as large chime stones, drums, and other ritual objects. ^{14}C analysis confirms that the Taosi culture is divided into three phases, Early, Middle, and Late, which existed between 2500 and 1900 BCE. During the past decade, scholars have increasingly linked the Taosi site with Yao's capital of Pingyang.

Since 1999, the Institute of Archaeology of the Chinese Academy of Social Sciences, the Shanxi Provincial Institute of Archaeology, and the Cultural Relics Bureau of Linfen City jointly carried out a new series of excavations at the Taosi site. They discovered and confirmed the presence of a small city of the Early Period, a large and a small city of the Middle Period, sacrificial area, storage area, and palace sites, etc. The most exciting of all was that the excavation revealed the semi-circular pounded-earth architectural foundation denoted by II FJT1. The archaeological data taken together indicates that the structure was built in the Taosi Middle Period (ca. 2100 BCE) and destroyed in the Late Period[1].

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On the whole the large Middle Period city is in the shape of a rectangle with rounded corners, oriented SE-NW, with an area of nearly 2800000 m^2. Outside the southeast part of the large city, a small, elongated section is walled in as a sacrificial area. II FJT1 is located within this walled section, and connected to Q6, the southern wall of the large city. II FJT1 is a semi-circular platform built of three layers of pounded earth. On the east side of the uppermost platform (the third) there is a series of pounded earth piers arranged in an arc. Probing showed that the piers extend to a depth of 2—3 m. Separating the piers is loose traces of pounded earth to a depth of 4—17 cm (in other words, on the top of the curved wall the remains of a series of narrow slots, 4—17 cm deep, were unearthed). The semi-circular platform II FJT1 backs on the wall of the large city and faces southeast. The pounded-earth piers and the upper surface of the walls revealed so far were razed during about the Taosi Late Period (4,000—3,900 BP), at a level presently located about 1 m below the ground surface. Archaeologists immediately realized that these pounded earth piers were possibly the foundation of a structure designed to observe the direction of sunrise in order to determine the seasons. In order to confirm this conjecture they made on-site observations over the course of a full year. To begin with, they identified the central point defined by the shape of the circular wall and piers, and assured that from this observation point it was possible to sight through every one of the slots or backsights. This point is about 10 m from observing backsights E1—E10 (see Figure 3). Then they constructed a 4 m high iron frame whose horizontal dimensions could be adjusted to completely conform to those of the backsights between the pounded-earth piers. In this way, when standing at the central observation point and looking through the backsight created by the iron frame it was possible to simulate the observations made by the ancient people. Figure 1 shows the state of the excavation and the iron frame used to simulate the observations[2,3]. The edges of the pounded earth piers are outlined with chalk, and the observing frame is installed in slot E5.

Initial observations confirmed that the winter solstice sunrise occurred near but not within backsight E2; a few minutes later when the sun did enter E2 it had already risen above the mountain ridge (see Figure 5). Considering that the obliquity of the ecliptic 40 centuries ago was about a half degree greater than that at present, preliminary calculation showed that at that date winter solstice sunrise ought to have occurred within backsight E2[4]. The situation at summer solstice was similar: Preliminary calculation showed that 40 centuries ago summer solstice sunrise fits in with backsight E12, though not at present. The observational results for winter and summer solstice prove with some confidence that the pounded-earth piers were constructed to observe seasonal sunrises, the remaining backsights ought to indicate particular dates in the calendar at the time, and backsight E1 may have to do with lunar observation.

Figure 1 Taosi site II FJT1 excavation and the observing frame placed in slot E5.

Before October of 2004 when the on-site simulated observations had begun, the remains of the Taosi Middle Period observation point were still buried under an earthen platform (temporarily left in place to facilitate simulated observation). Subsequently, when that platform was completely cleared away, a surprising discovery was made. Right underneath the supposed observation point, a four-layered foundation core of pounded earth, 25 cm in diameter, was discovered, whose center was merely 4 cm to the observation point previously chosen for the purpose of simulating observations. This discovery further confirmed the astronomical function of site II FJT1[5]. Further excavation on the west side of the observation point was unable to discover any trace of sunset observation.

Many experts in the history of astronomy studied the archaeological reports and made on-site surveys, and all are of the opinion that the site is connected with sunrise observation and sacrifices to heaven[6].

Ancient texts and artifacts confirm that using the sun's shadow to determine the seasonal dates is a very

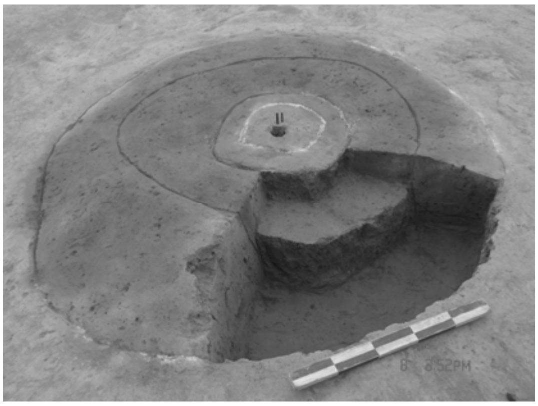

Figure 2 The circular pounded-earth base of the central observing point.

ancient tradition in China, which is clearly different from other civilizations. Very seldom ancient Chinese sources offered any evidence of the use of sunrise and sunset locations to fix the seasons, and no sites associated with such practices previously were found. This peculiarity already was pointed out by Liu[7]. Consequently, the discovery of II FJT1 is of especially great significance for research in the history of Chinese astronomy. Its archaeological context and preliminary astronomical analysis all indicate that such practices already existed 40 centuries ago.

2 Survey results

Using GPS, Beijing Qiaheng Technologies Inc. precisely measured the coordinates of the original central observation point to be 111°E 29′ 54.99635″ 35°N 52′ 55.84645″, and 572 m above sea level. At a point 200 m northwest of the original center a reference point was established, and using GPS its location and the azimuth of the line connecting it to the original point were calculated, to serve as a baseline for azimuth measurements. Using a steel rule and "total station", measurements were made of the position of specific features of the site (the four corners of each pounded-earth pillar) from the original observation point, as shown in Table 1 (see Figure 3 also). Azimuth figures are in degrees; y is based on due north, x is based on due east, and units are in meters.

The twelve backsights formed by these specific slot features are shown in Figure 3, numbered E1-E12. In the figure, due north is up and horizontal and vertical units are in meters, and the point marked "0" on the left scale is the original observation point discovered during excavation. In the figure each point given in Table 1 is indicated, as well as the relevant lines outlining the edges

Table 1 Positions of slot features in relation to the original observation point

No.	Azimuth	y	x
E1-1	131.25	−7.14	8.15
E1-2	132.45	−8.17	8.93
E1-3	129.57	−6.92	8.38
E1-4	130.89	−7.95	9.18
E2-1	125.66	−6.44	8.98
E2-2	126.20	−7.26	9.92
E2-3	124.27	−6.25	9.18
E2-4	124.43	−6.97	10.17
E3-1	119.21	−5.45	9.75
E3-2	119.24	−6.10	10.91
E3-3	118.46	−5.32	9.81
E3-4	118.53	−5.95	10.95
E4-1	112.96	−4.37	10.32
E4-2	113.32	−4.94	11.45
E4-3	112.03	−4.20	10.37
E4-4	112.40	−4.76	11.55
E5-1	106.45	−3.15	10.67
E5-2	106.35	−3.49	11.91
E5-3	105.65	−3.00	10.70
E5-4	105.40	−3.29	11.94
E6-1	101.44	−2.19	10.82
E6-2	100.68	−2.28	12.07
E6-3	100.59	−2.03	10.85
E6-4	99.94	−2.12	12.10
E7-1	94.95	−0.96	11.03
E7-5	94.84	−0.98	11.61
E7-2	95.28	−1.13	12.28
E7-3	94.08	−0.78	10.86
E7-4	92.85	−0.61	12.30
E8-1	89.62	0.07	10.84
E8-2	89.63	0.08	12.28
E8-3	88.60	0.26	10.74
E8-4	88.55	0.31	12.27
E9-1	82.76	1.34	10.54
E9-2	82.56	1.59	12.15
E9-3	82.05	1.46	10.45
E9-4	80.83	1.95	12.11
E10-1	75.30	2.78	10.58
E10-2	74.90	3.18	11.80
E10-3	74.29	2.98	10.59
E10-4	74.25	3.35	11.88
E11-1	67.22	4.53	10.78
E11-2	67.83	4.64	11.38
E11-3	64.68	5.97	12.61
E11-5	64.93	6.30	13.46
E11-4	64.70	6.71	14.20
E12-1	61.06	6.81	12.32
E12-5	61.40	7.15	13.12
E12-2	61.26	7.54	13.74
E12-3	59.22	7.23	12.13
E12-4	59.64	7.98	13.63
E13-1	55.73	8.07	11.84
E13-2	56.53	8.72	13.20

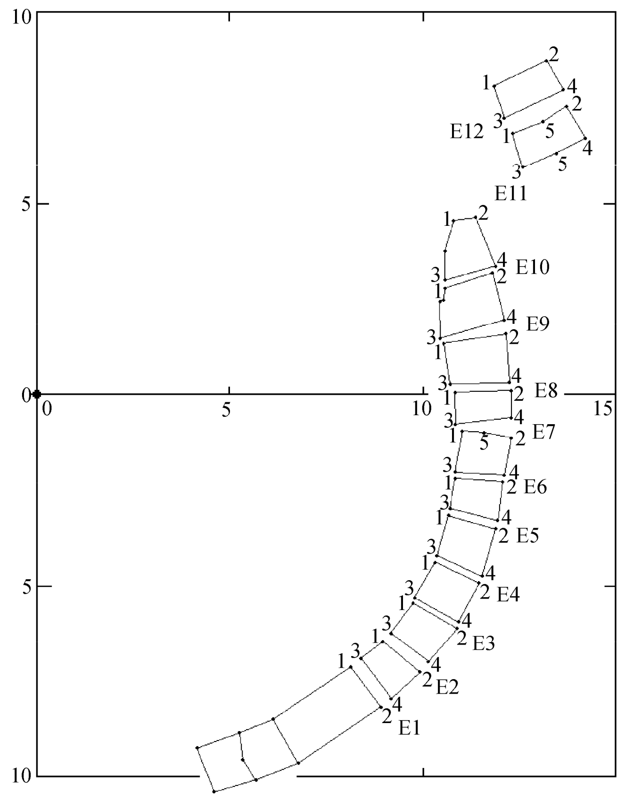

Figure 3 Diagram of the original observation point and traces of pounded-earth.

of the pounded-earth piers.

From Table 1, it is possible to compute the azimuth of the centerline of each backsight together with its width. The vertical angle between the perpendicular from each backsight's centerline and the distant mountain in the background (about 10 km away) at their point of intersection is measured separately. Table 2 gives these figures (the vertical angle of backsights E5—E7 was measured by Beijing Qiaheng Technologies Inc., and the other vertical angles were measured by Feng Jiusheng using the Japanese made SOKKIA total station belonging to the Shanxi team of the Institute of Archaeology of the Chinese Academy of Social Sciences. The apparent widths (as seen from the original point), azimuth, and vertical angle are in degrees; backsight widths and the depth of the surviving slot are given in centimeter.

Backsights E1—E10 was excavated from the top of a curved wall, 2—3 m deep (1.2—1.6 m thick), with surviving slot depths at present of 4—17 cm, each slot being U-shaped or V-shaped in cross-section. Most of these slots are elongated and 20 cm wide; some are slightly wider (E1, E2), and some are trumpet-shaped (E7, E9) possibly as a result of later damage. Backsight E12 is formed by two more distant pounded-earth piers, and the situation of backsight E11 is even more peculiar, which possibly have a connection with the ritual function of the structure. One can speculate that using the distant mountain as a backsight the ancients observed solstice sunrises, and then using a plumb line they brought the distant mark points on the mountain (or artificially established distant markers) down to the curved wall where they cut out slots to provide guides for further construction of the backsights. The subsequent structure built with stone or pounded-earth ought to have reached a height of 2—3 m, in order to facilitate the use of the backsights to observe sunrise from the original observation point, but these structural features have not survived.

Table 2 12 figures for each backsight (slot)

No.	Width	Depth	Azimuth	v. angle	a. width
E1	30	6	131.068	5.559	0.36
E2	25	6	125.046	5.809	1.23
E3	20	4	118.872	5.538	0.68
E4	20	9	112.680	6.131	0.56
E5	20	10	106.000	7.203	0.70
E6	20	9	100.638	5.780	0.09
E7	20—50	16	94.464	4.266	0.76
E8	20	8	89.106	3.324	1.02
E9	15—40	8	82.304	2.261	0.53
E10	20	4	74.592	1.906	0.61
E11			66.080	1.125	2.29
E12	40	17	60.349	1.267	1.42

3 Using the values of vertical angles and azimuths for backsights E2 and E12 to solve the date

3.1 Formulas to solve declination given latitude, vertical angle, and azimuth

One may solve the declination of a body using the latitude of the observer, the vertical angle of the body, and its azimuth.

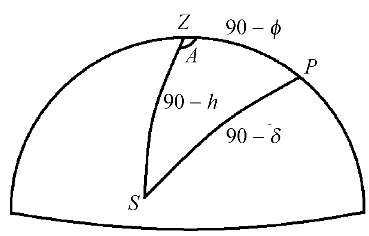

Figure 4 The relationship between the latitude, vertical angle, azimuth and declination of a celestial body.

In the figure, Z is the zenith, P the north celestial pole, S the celestial body, A the azimuth of the body, h the vertical angle, δ the declination, and φ the latitude of the observer.

For the spherical triangle PZS, one should use the cosine formula:

$$\cos(90-\delta) = \cos(90-\varphi)\cos(90-h) + \sin(90-\varphi)\sin(90-h)\cos A,$$

$$\delta = \arcsin(\sin\varphi \sin h + \cos\varphi \cos h \cos A). \quad (1)$$

Substituting the observer's latitude and the vertical angle and azimuth of the sun yields the sun's declination. Since at the solstices the sun's declination is equal to the obliquity of the ecliptic, one may further solve the date that satisfies this value for the obliquity of the ecliptic.

Polar motion changes latitude of any place on the Earth. Nutation and other periodic elements affect the declination of the Sun on solstices. However, those elements are not more than several arc seconds, which is too small to impact our discussion.

3.2 Sunrise assumptions and calculation

During sunrise the sun's position continually changes. Choosing different points on the sun as the sunrise marker will result in very different dates for the observation. Therefore, we employ several different assumptions in carrying out the experiment.

Winter solstice corresponds to backsight E2; the centerline of the slot intersects the mountain in the distance at a vertical angle of 5.809°, and azimuth 125.046°. Summer solstice corresponds to E12; the centerline of the slot intersects the mountain in the distance at a vertical angle of 1.267°, and azimuth 60.349°. This corresponds to a definition of sunrise based on the center of the sun, and we call it the "half-risen sun" case. The sun's average semi-diameter is 16′ (0.267°). If we add to or subtract the sun's semi-diameter from the vertical angle, we respectively obtain the situations of "sun fully risen" and "sunrise". Consider that when sunrise is observed with the naked eye, and in reality a portion of the sun has already appeared, we need to add a category for "sun already appeared", corresponding to that when 2′ of the sun's upper limb is exposed. This roughly corresponds to how much the sun's altitude changes around winter and summer solstice sunrise at the locality of Taosi in about 12 s.

For the calculation and its results, see Table 3. The units for the vertical angle and declination in the table are degrees, for atmospheric refraction the units are minutes of arc, and the date in century counted from J2000.

First, using the above definitions, from "sun half-risen" we obtained the apparent vertical angle at the time of "sun fully risen", "sun already risen", and "sunrise", respectively, as in the first row of Table 3. Subtracting the correction for atmospheric refraction produces the true vertical angle of the sun's center (not shown in Table 3).

3.3 Atmospheric refraction near the earth's surface

Atmospheric refraction near the earth's surface is extremely complicated, as it involves atmospheric pressure, temperature, and the wavelength of light, all of which are subject to change and are non-uniform, and thus it is only possible to apply an approximate correction. Through comparison it is found that in each case, for vertical angles between 1—5° one may still obtain a match within one arc-minute. We employed the formula provided in the *Explanatory Supplement to the Astronomical Almanac*[8] to calculate the correction for atmospheric refraction (Table 3, the second row):

$$R = [P/(T+273)]\,(0.1594+0.0194H+0.00002H^2)/(1+0.0505H+0.0845H^2), \quad (2)$$

where H stands for the apparent vertical angle; P is the atmospheric pressure, units in milli-bars; T is temperature in degrees Celsius. The elevation at Taosi is 572 m above sea level (standard atmospheric pressure 945), temperature at the time of winter solstice sunrise is −10℃, and at summer solstice sunrise the temperature is 20℃.

Substituting the true vertical angle h, azimuth A, and latitude of the place φ in formula (1), one obtains the sun's declination δ (Table 3, the third row).

Table 3 Solving the date using the vertical angle and azimuth of the solstices at Taosi

Backsight	E2 (winter solstice)				E12 (summer solstice)			
Sun rise	fully risen	half-risen	already appeared	sunrise	fully risen	half-risen	already appeared	sunrise
Vertical angle	6.076	5.809	5.575	5.542	1.534	1.267	1.033	1.000
Refraction	8.4	8.7	9.0	9.1	18.6	20.1	21.6	21.8
Declination	–23.712	–23.900	–24.064	–24.088	24.410	24.225	24.060	24.037
Date	–21.4	–37.7	–55.0	–58.1	–	–85.0	–54.5	–51.8

3.4 Obtaining the date from the obliquity of the ecliptic

The usually used third-power expression for T to find the obliquity of the ecliptic is inappropriate here. To cater for the applications involving epochs far removed in time Laskar[9] proposed an up to tenth-power iterative formula:

$$\varepsilon = 23°26'21.448'' - 4680.93U - 1.55U^2 + 1999.25U^3 - 51.38U^4 - 249.67U^5 - 39.05U^6 + 7.12U^7 + 27.87U^8 + 5.79U^9 + 2.45U^{10}, \quad (3)$$

where U is the time calculated from J2000, in units of 10000 years (U<1).

At the time of summer and winter solstice the declination of the sun is either positive or negative ε. According to formula (3), from ε one may solve U, and also express the result in centuries from J2000, yielding the corresponding dates in the last row in Table 3.

3.5 Results

Table 3 shows that different "sunrise assumptions" yield markedly different results. Applying a "paired set" criterion that includes both winter and summer solstice, we may simultaneously derive both the sunrise assumption and the date.

Looking at the tabulated results, and assuming "sun already risen" as the definition for sunrise at both summer and winter solstice best fits the data, the resulting date also seems about right and is the most acceptable. The "sunrise" that corresponds closest to the results, i.e., "sun already risen", is also the most reasonable (sunrise as mathematically defined in reality being unobservable). Therefore, we conclude that the date matching most closely backsights E2 as winter solstice and E12 as summer solstice is about 55 centuries BP (or about –3500). The corresponding observations take as normative the case when 2′ of the upper limb of the sun is exposed.

4 Discussion

The above-described astronomical calculation of the date of the Taosi site is based on the following premises: The remains of the pounded-earth piers formed the backsights, and their midline perpendicularly extended to and intersected with the distant mountain, serving as the standard means for observing winter and summer solstice sunrise at the time. That is to say, the ancients had to build 2—3 m high vertical pillars in order to create the narrow slots shown by the outlines of the pounded-earth piers, as well as maintain the strict consistency of their centerlines. The eye of the observer had to be located precisely on the perpendicular extending upward from the center of the 25-cm diameter of the pounded-earth platform.

Archaeological research and ^{14}C analysis date the installation and use of the site to the Middle Period of the Taosi culture, about 41 centuries BP. Figure 5 shows the astronomical phenomena at present (2000), in Middle Taosi Period (–2100), and at the date obtained by means of astronomical calculation (–3500). That is, the path of the rising sun on the winter and summer solstice is as seen through the corresponding narrow backsights, by extending the surviving pounded-earth piers upward to the level of the mountain in the background.

The figure shows the path of the sun's center during sunrise at summer and winter solstice based on measurement and calculation. The horizontal scale shows the azimuth, and the vertical scale is a vertical angle, both in degrees. The gray area shows the backsight formed by the pillars and the distant mountain ridge. The three

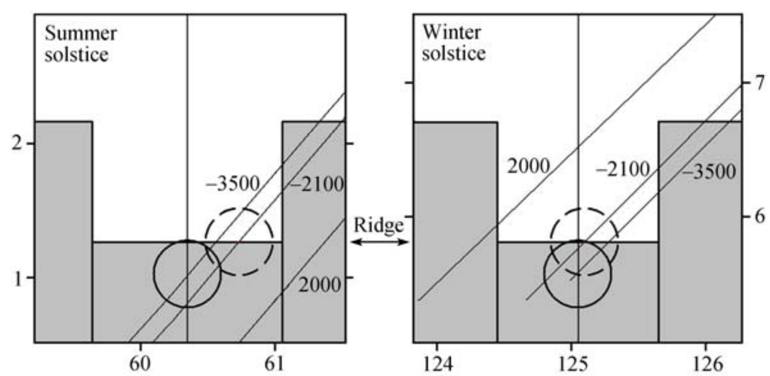

Figure 5 Measured and calculated paths of the sun's center during sunrise at summer and winter solstice.

slanted lines show the path of the center of the sun during sunrise at 2000, −2100, and −3500, respectively. The circle shows the size of the solar disc.

With regard to the present epoch, Figure 5 shows that the sun cannot pass through backsight E12 on the summer solstice, and at winter solstice, when the sun crosses the centerline of backsight E2 is it is already clearly higher than the mountain ridge. At epoch −2100 (i.e., the date based on archaeological estimates), at winter solstice when the sun is already half exposed, the sun's center is almost exactly on the backsight's centerline; however, on the summer solstice there is some misalignment: When the sun is half-risen the solar disc has already reached the right side of the slot. The dotted outline of the sun's disc shows the situation. With regard to epoch −3500, whether at winter or summer solstice, when the upper limb of the sun has just appeared (two arc-minutes exposed), the center of the sun is both precisely on the backsight's centerline.

In Figure 5 the width of the two backsights is drawn to scale based on the measured values. Hence, it is not difficult to estimate from Figure 5 the astronomical date to which the two sides of the slot correspond. Taking the winter solstice backsight as an example, if we choose the center of the sun (sun half-risen), the left side corresponds to about epoch 1300, and the right side to about epoch −6500.

Because the change in the obliquity of the ecliptic is very slow, if one uses the azimuth of sunrise to establish the date, the error is potentially very large. The central observation point of the Taosi II FJT1 site is about 11 m from the backsights formed by the pillars (summer solstice is 14 m). At a distance of 11 m, 1 cm subtends an angle of 3.1′. In other words, if the original point of observation or the centerline of the backsight is off by 1 cm, the misalignment will be 3.1′. From formula (3) one will see that the change in obliquity of the ecliptic is 47″ per century, so 3.1′ misalignment would correspond to four centuries. No matter whether it is a question of the ancients' measurements or present-day reconstruction of their work, the errors involved will far exceed this value. As a result, the date obtained by astronomical methods involves significant error, and can certainly not threaten the archaeologically established dating (accurate to at least one or two centuries). If we imagine that the observer's eye moved to the left by 5 cm (the distance between an individual's two eyes is 6—7 cm), or if we imagine that the present edge of a pounded-earth pier originally lay 5 cm to the right, in both situations in −2100 one could observe the sun half-risen in the center of slot E12. Errors like these, in view of the observing standards of the time and the irregularity of the surviving pillar outlines, are hardly to be wondered.

If the original structure and observations were as conjectured in our ideal scenario, it is not hard to imagine that observers in Middle Period Taosi (about −2100) could have taken the half-risen sun as the standard, so the sun on the midline at winter solstice and to the right of the center on the summer solstice would have marked the arrival of those turning points.

Based on the analysis using astronomical methods and precise measurement, it is possible to draw the following conclusions:

Backsights E2 and E12 of the Taosi pounded-earth structure II FJT1 respectively correspond to the direction of winter solstice and summer solstice sunrise, to an accuracy of minutes of arc, and at the archaeologically established date (41 centuries BP) the match is far better than that at present. This proves convincingly that the Taosi semi-circular platform and backsights were meticulously constructed by the ancients for the purpose of observing the direction of sunrise to determine the seasons, that is, with the aim of "observing the phenomena to bestow the seasons", thus are the site of China's oldest surviving observatory.

It is difficult to understand that all the backsights (E2—E12) are not in the same arc. He[2] thought E11 was a Sun receiving gate for worship ceremony, while Pankeneir (private communications) preferred that they were built at different times. The 9 backsights are apparently the result of even division. They divided the time between solstices into 10 parts. It is a natural concept, although it is different from the 24 solar terms, which started near two thousand years later. However, whether it shows a ten-months calendar is still an open question.

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