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CHINESE ASTRONOMY AND ASTROPHYSICS

The sky brightness when the rising sun is in eclipse*

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Abstract Part of the "Xia-Shang-Zhou Chronology Project" is the study of a historical record of "double dawn" and its astronomical interpretation. We used the light meter on ordinary cameras to determine the sky variation during normal sunrises and sunsets, set up a way of calculating the variation when the rising sun is in eclipse, and identified the range and intensity of the double dawn phenomenon. For this, we organized a mass participation of the observation of the 1997–03–09 eclipse in Xinjiang Province. The observations are in good agreement with our model calculation and prove that an eclipsed sunrise could indeed give rise to the phenomenon of "double dawn"

Key words: solar eclipse—sky brightness—chronology

1. INTRODUCTION

China has a long history but, according to Shiji ("Historical Records") by Sima Qian, the great historian in the 1st century BC, exact chronology can only be traced back to 841 BC (the 1st year of Gonghe). Before this, discrepant statements are found in the early literature and there is no consensus on chronology. To push the records further back in time has been a constant endeavour of Chinese historians for the past two thousand years. The effort usually takes the following forms: analysis of old literature, archaeological discoveries, radioactive dating of ancient cultural relics and re-computation of astronomical records. "Xia-Shang-Zhou Chronology Project" represents the greatest effort on the largest scale so far in this line of research in China.

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The Bamboo Chronicle, written in about 300 BC and unearthed in the 3rd century AD from an old tomb, is a very important historical document. Unfortunately it disappeared later and only fragments survived. One of its records reads:

> During the first year of King Yi, the day dawned twice at Zheng.

King Yi preceded the time of Gonghe by four generations and Zheng was a place near the then capital, Hao (present Xi'an City). Liu Chao-yang[1] pointed out that this refers to an eclipsed sunrise. The sky had already begun to brighten; then a total eclipse took place and the sky got dark; after several minutes, the sky grew bright again. This succession of events would reproduce the record of "Double Dawn". Because such an event is not usual for a given place, it may be a hopeful means of fixing the 1st year of King Yi's reign.

What is the actual human sensation of the change in the sky brightness during an eclipsed sunrise ? This is the first question we need to ask when attempting to solve this problem by astronomical calculation. We need a comprehensive investigation of the phenomenon involving different solar altitudes, different eclipse factors and different weather conditions. Thus, the problems involves 3 factors. It needs both theoretical investigation and practical observation. For a given solar eclipse, observations at different places will cover the first two, solar altitude and eclipse factor. If we are lucky enough to have different weather conditions at different sites, then we have fully 3-dimensional data.

The best opportunity we have is the total solar eclipse on 1997 March 9, when eclipsed sunrise takes place in the northern part of Xinjiang Province adjoining Russia, Mongolia and Kazakhstan. For the other 4 eclipses before the end of this century, the proper places are all in the oceans.

2. VARIATION OF SKY BRIGHTNESS AROUND SUNRISE

In order to have as many observing sites as possible at the western end of the total eclipse belt and for reasons of economy, we organized participation by local residents and chose the automatic light meter on ordinary cameras as our standard instrument.

A camera adjusts film exposure by its aperture and shutter. Usual aperture settings are 22, 16, 11, 8, 5.6, 4, 2.8, 2, 1.4, 1 (i.e., by a factor of $\sim \sqrt{2}$ one to the next) and usual shutter settings are 1/2000, 1/1000, 1/500, 1/250, 1/125, 1/60, 1/30, 1/15, 1/8, 1/4, 1/2, 1 (by a factor of 2). All combinations of the two correspond to 21 steps of doubling the luminance of the object in the field. We label these luminance steps by what we call the "camera luminance index" which ranges from 0 (aperture 1, shutter 1) to 21 (aperture 22, shutter 1/2000). 21 doublings is equal to a factor of over 2 million and this covers from dim early dawn to brilliant daylight. The luminance index is a logarithmic measure of luminance and so conforms to the human sensation.

We define the above system with the sensitivity of films ASA100 or DIN21. We could get a larger range of luminance and finer divisions if we used special cameras.

According to photographic optics[5], we have ,

$$L = 0.972A^2/st \ , \tag{1}$$

where L is the luminance in cd/m^2, A is the aperture, s is the film sensitivity on the ASA system and t is the exposure time in seconds. Let e denote the camera luminance index. We have $L \propto 2^e$. The constant of proportionality is found by setting $s = 100$ and the values $(A = 1.4, t = 1)$ corresponding to $e = 1$ in (1); we then have $L = 0.00972 \times 2^e$, or

$$\log L = 0.301e - 2.012 \ . \tag{2}$$

The textbook[6] (Tab 5-2a) gives the following example: the luminance of fine sky 70° from the sun is 150 cd/m^2. We put this in (2) and get $e = 13.9$. From our camera light meter we found $e = 14$, thus proving our system to be practicable.

To investigate the variation in the sky brightness during an eclipsed sunrise, we first need to know the variation during a normal sunrise. Because of atmosphere scattering the sky begins to brighten when the sun is still below the horizon. This change is complex and is difficult to express quantitatively by some theoretical model. Conventionally, astronomical twilight begins when the altitude of the sun is $-18°$; nautical twilight, $-12°$; and civil twilight, $-6°$. To deal with this problem we have made a large volume of measurement of the sky brightness at dawn with the camera light meter.

At different directions of the sky, the luminance is different, depending mainly on the angle to the sun. The closer to the sun, the brighter the sky is. Measurements showed that the luminance ceases to change much when the angle is more than 60°. On the other hand, the closer to the horizon, the brighter the sky is, because of atmosphere scattering. Both variations are related to the transparency of the air: the clearer the sky is, the smoother the luminance variation. After considering these factors, we chose as our standard direction for measurement, the point on the northern meridian at altitude 50°.

Weather, of course, is another important factor in the sky luminance. According to our measurements at noon, $e = 14$ for very clear; $e = 15$ for thin cloud; $e = 14 - 15$ for bright cloud; $e = 13$ (sometimes $e < 13$) for dark cloud. Before sunrise, the situation is a little different: then, clouds cannot be shone on by the sun, so clear skies are always brighter than cloudy skies. Some regularities of sky luminance are described in Ref. [7].

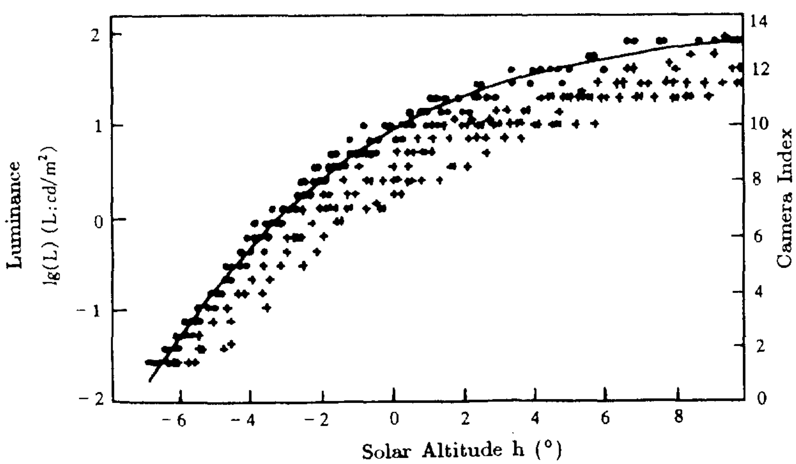

Fig. 1 Measured sky luminance as a function of the solar altitude

We made 450 measurements of sky luminance during 14 sunrises and 8 sunsets. The variation of the luminance is related to time, date and geographical location, but the astronomical factor it depends directly on is the altitude of the sun h. Negative values of h refer to below the horizon. Practical sunrise is at h =-0.85° (solar radius 0.25°, horizontal air refraction 0.60°). Our measurements as a function of the solar altitude are displayed in Fig. 1. Ordinate is logarithm of luminance in cd/m^2 (left) or the camera luminance index e (right). Dots refer to 156 measurements contained in 9 fine-weather sets, crosses, to 165 measurements contained in 8 cloudy-weather sets. The figure shows that the 156 fine-weather measurements all lie on a smooth curve. A least squares fitting gives

$$e = 9.78 + 0.733h - 0.0636h^2 + 0.027h^3 - 0.00004h^3 \ , \tag{3}$$

or

$$\log L = 0.932 + 0.221h - 0.0191h^2 + 0.00081h^3 - 0.000012h^4 \ . \tag{4}$$

The cloudy measurements are quite scattered because the clouds had different thickness, but for each given occasion the measurements are continuous and fall on a smooth curve, differing from the fine-weather curve only by a constant vertical offset. There was no clear difference between sunrise and sunset in the fine-weather measurements.

3. VISUAL SKY BRIGHTNESS DURING ECLIPSED SUNRISE

The solar radiation during an eclipse can be computed by considering the blocked area and limb darkening[9]. Sky light comes from scattered sunlight, so the sky brightness during an eclipsed sunrise may approximately be regarded as a superposition of a normal sunrise and a solar eclipse. This assumption would entail large errors when the eclipse factor is very close to 1.0 because different points of space have different eclipse factors while they all contribute to the lighting of the sky. The actual variation of sky brightness will not be as sharp as it is computed by simple superposition.

In visual optics and ophthalmology, $\log L$ is usually used to express visual brightness, or human sensation of luminance (our camera index is on such a scale). In fact, such a relation is not suitable for dim situations. We developed the following relations[8] between visual brightness V and luminance L from visual optics:

$$V = \log L + 1.785 \qquad (2.0 > \log L \geq -0.419) \ , \tag{5}$$

$$V = 1.831 \times 10^{0.324 \log L} \qquad (-0.419 > \log L > -6.0) \ , \tag{6}$$

or

$$V = 0.301e - 0.254 \qquad (13.3 > e > 5.29) \ , \tag{7}$$

$$V = 0.408 \times 10^{0.0975e} \qquad (5.29 > e > -13.2) \ . \tag{8}$$

According to equations (5) and (7), the visual brightness is measured by the logarithm ofluminance when $\log L \geq 0.419$ (the sky brightness 20 minutes before sunrise). Visual brightness, V, is thus directly proportional to the sensation of the human eye. When we use V, we are discussing the human sensation of the sky brightness.

We illustrate the variation of visual sky brightness during an eclipsed sunrise with the series of graphs in Fig. 2. The different graphs all refer to the 1997–03–09 eclipse in Xinjiang in various circumstances. Horizontal axis is the time, centered at the eclipse maximum and each mark is 30 min. Ordinate is the visual brightness V. For expressiveness we mark out three characteristic levels of V, a, b, c, on the right: a—fine sky 70° from the sun ($h_0 > 15, e = 14, V = 4.0$), b—zenith at fine sunrise ($h_0 = -0.85, e = 9.1, V = 2.5$), c—zenith at beginning of civil twilight ($h_0 = -6.0, e = 2.5, V = 0.7$). The dotted line is the sky brightness when the rising sun is not in eclipse. The full line is the sky brightness when the rising sun *is* in eclipse; it is obtained by simply multiplying the corresponding dotted line by the dimming factor due to eclipse (the superposition assumption).

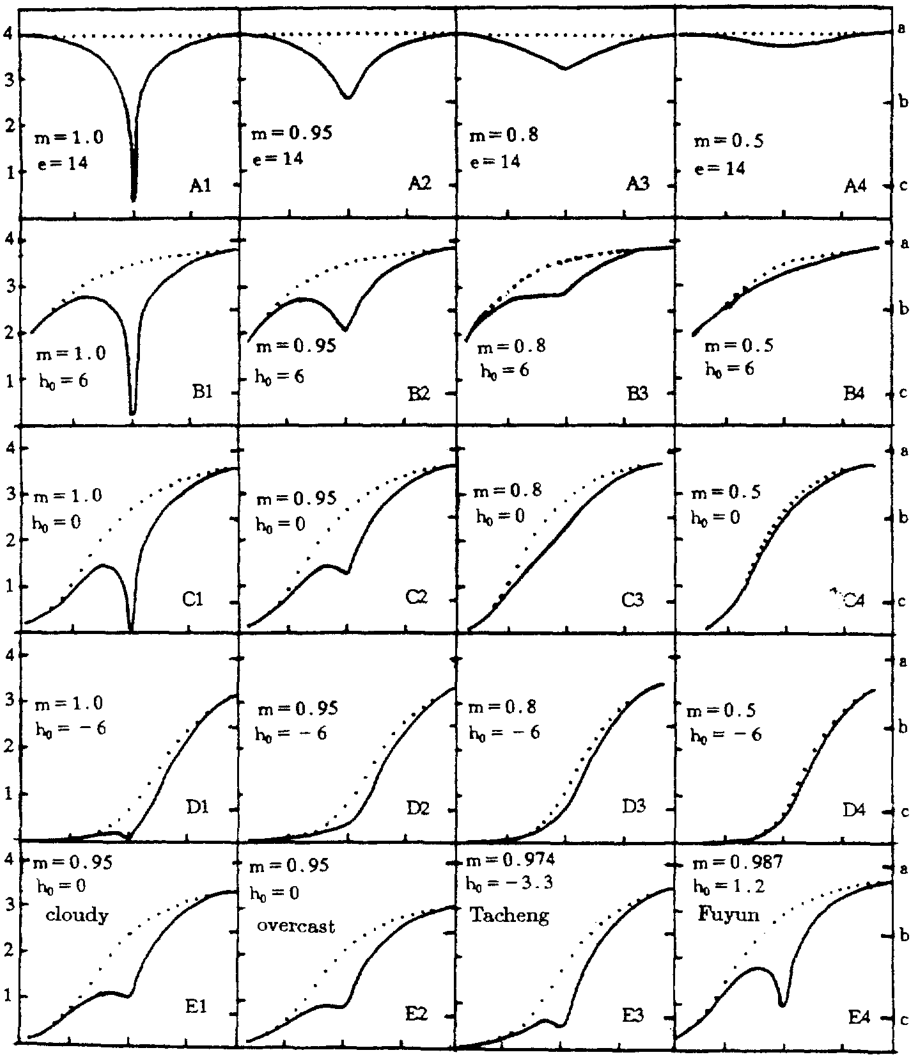

Fig. 2 Computed sky brightness when the rising sun *is* in eclipse (solid) and *not* in eclipse (dotted) for various eclipse factors m, and solar altitudes at eclipse maximum

The first row in Fig. 2 (A1–A4) refers to eclipses of different factors over a stable background. We note that even an eclipse as small as $m = 0.5$ can have a detectable variation in the sky brightness in this case.

Row 2 (B1–B4) refers to eclipse maximum occurring at altitude 6° (about one-half hour after sunrise). For $m = 1.0$ or 0.95, there is an obvious darkening; for $m = 0.8$, the sky stops getting bright for a while; for $m - 0.5$ there is no longer anything abnormal.

Row 3 (C1–C4) refers to eclipse maximum at altitude 0°. For $m = 1.0$, there is clear darkening; for $m = 0.95$, there is darkening; for $m_0 = 0.8$ or less, nothing abnormal.

Row 4 (D1–D4) refers to eclipse maximum occurring at altitude −6° (about one-half hour before sunrise). In this case, even if the eclipse is total, it would be difficult to detect anything abnormal.

Graphs C2(fine), E1(thin cloud), E2(thick cloud) show the results for different weather conditions and the same astronomical circumstances ($m = 0.95, h_0 = 0$). We note that the darkening process is not so obvious in cloudy as in fine weather. The eclipse factor was nearly the same for Tacheng (E3) and Fuyun (E4), but different h_0 led to thoroughly different results. Generally speaking, the sky brightness during an eclipsed sunrise has the following two features: 1. The depression in sky brightness due to the eclipse is very much smoothed out by the rapid increase of the light of the dawn sky. 2. The darker the background brightness is, the less obvious the eclipse depression is.

4. REPORT AND ANALYSIS OF THE 1997–03–09 ECLIPSE IN XINJIANG

To verify our theory and computation, we organized a widely spaced observing network in Xinjiang to monitor the variation of the brightness of the dawn sky. We have received 35 reports from over 60 amateur astronomers at 18 different sites. The details will be published in another paper[10]. Here we give a brief introduction and analysis.

4.1 Altai (computed elements for the city:—8:33 sunrise, 8:41 maximum, eclipse factor 0.998)

Inside the city and on a small hill near the city, weather fine, sunrise and eclipse could not be seen because of obstruction by mountains to the east. Six reports: "At 8:40, the sky suddenly became very dark, after having been bright before. People felt depressed, withdrawn and gloomy. The stars reappeared. After a few minutes, the sky brightened again and people felt a lot better."

Desert, 25 km south of the city, no mountains to the east. Five reports: "Due to dense fog, the sun and eclipse could not been seen. At 8:30, the sun must have risen (so one felt). At 8:32 the sky began to darken; at 8:38 it was very dark; at 8:40 as dark as night for 1.5 min. Then it turned bright again; at 8:46 it became quite bright." The camera meter gave the same result.

Analysis: In the city, the eclipse factor was as high as 0.998, but the mountain blocked the sun. People had a strong feeling of "double dawn" after the stars reappeared. When the sun had climbed over the mountains, the eclipse was already quite small and it was not easily detected. It was very interesting in the desert. Even though no mountains blocked the sun, the dense fog facilitated a perception of a "double dawn" anyway. The change of sky brightness inside the city was a little smaller than graph C1 of Fig. 2; it was even smaller in the desert.

4.2 Fuyun (8:28 sunrise, 8:40 maximum, eclipse factor 0.988).

The Altai Mountain is to the east. At 8:00, first light appeared in the east, color changed from pale grey to yellow. At 8:41 the sun was still blocked by the mountain; the eastern half of sky was darker than the western half. The eastern sky became darker and darker, and the dark portion got larger and larger. The observers felt like falling into a dark world for about 3 minutes. Then a patch of yellow light gradually expanded. At 8:50 the eclipsed sun jumped over the mountain suddenly. Analysis: The eclipse maximum was after sunrise and people could not see it because of the mountain, but they did see the sky becoming dark, and the feeling of "double dawn" was quite strong. The eclipse could easily be found later since the mountain is not so high as in Altai city. See E4 of Fig. 2 for the theoretical result.

4.3 Tacheng (8:39 maximum, eclipse factor 0.974, 8:53 sunrise)

Weather fine. During astronomical twilight, Comet Hale-Bopp was bright. At 8:00, first light appeared in the eastern sky; At 8:10 stars started to fade; At 8:20 the comet faded; At 8:30 sunlight pierced the eastern horizon; At 8:35 light was withdrawn, and turned from orange to dark red, and then to pale gray, the whole sky turned dark; At 8:38 the comet reappeared suddenly, looking very bright for more than 2 min; At 8:45 and from then on, the sky turned bright, and the stars faded. At 8:53 the eclipsed sun climbed over the mountains. The sky darkened for 5 min but it was not very strongly felt. Analysis: The eclipse maximum was 14 min before the sunrise and the sky was usually quite dark at that time. So, even if the eclipse eclipse factor was large, the feeling of "double dawn" was not clear, unless people paid special attention to it. Graph E3 of Fig. 2 shows this situation. Note particularly the fact that the eclipse depression is near the level of the "civil twilight" mark, which caused the comet to fade and reappear, so producing a most obvious sign of "double dawn".

4.4 Urumqi (8:33 sunrise, 8:34 maximum, eclipse factor 0.94)

Inside the city. ene observer said that "the fog was dense and the sky was not bright". Another observer reported that everything was fine, and nothing unusual took place. At South Mountain, 70km southwest of the city, weather very fine. Two reports: "After 8:30, the sky brightness was holding steady; after 8:45, it brightened rapidly". Camera light meter showed that the sky brightness was unchanged from 8:25 to 8:35. Analysis: Since the eclipse maximum was at sunrise, the sky turned bright rapidly and also because the eclipse factor was not very large, the sky brightness was unchanged before the eclipse maximum but climbed rapidly after that. Referring to C2 of Fig. 2, the small depression did seem to have been seen.

4.5 Places where no darkening was reported

Kuitun, Klamayi, Shihezi: eclipse factor 0.94-0.96, the maximum was before sunrise by 5-10 min, similar to D2-E2 of Fig. 2. Camera light meters showed that the sky brightness was unchanged from 8:25 to 8:35, then rose quickly while there were no naked-eye reports of any unusualness. Pavlodar, Kazakhstan: Although the eclipse factor was very high (0.996), nothing special was noted because the eclipse maximum took place 34 min before sunrise and the background brightness was too dark (compare D1 of Fig. 2). Huocheng, Bole: nothing special found, eclipse factor 0.93, eclipse maximum 20 min before the sunrise, see D2 of Fig. 2.

4.6 Lintong (7:04 sunrise, 8:26 maximum, eclipse factor 0.79)

Fine with very thin clouds. For 5 minutes around the eclipse maximum, people indoors clearly felt the sky turning dark. Light meters showed the luminance decreasing to one-half. Analysis: As the sun was 16° high at eclipse maximum and the background sky brightness remained unchanged, even a small eclipse led to eclipse depression. The situation is like A3 of Fig. 2.

From the above reports we see that there is a very good agreement with our model calculation and the actual observations. The camera light meter is not a precision instrument and it cannot reach down to very dim levels, but it is objective and can be compared with one another. A situation such as graph D2 of Fig. 2 could hardly be described by the human sensation, while the light meter gives a clear indication[10].

5. THE ASTRONOMICAL CONDITIONS OF "DOUBLE DAWN"

Fig. 2 gives the variation in the sky visual brightness for various eclipse factors, solar altitudes and weather conditions. From the graphs we can see that the main feature is a depression in the otherwise increasing sky brightness. The depression is formed in a short time so it gives people a sense of impact. To give "double dawn" a quantitative measure, we define the decrease in the visual brightness within a 10-minute period as the "intensity of double dawn", to be denoted by I. We only consider depressions occurring when the sun is below 10° altitude, for otherwise we would not be dealing with a "dawn" phenomenon (cf. Fig. 1).

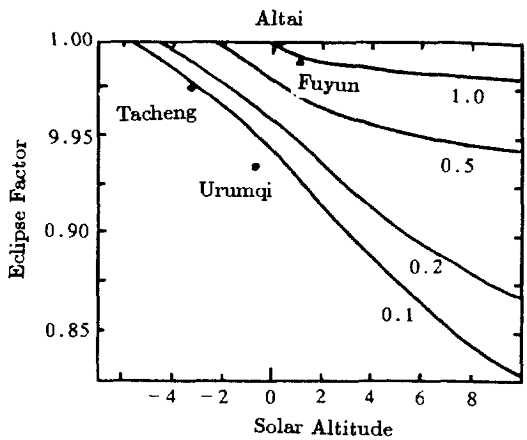

Fig. 3 Lines of constant intensity of double dawn in the eclipse factor–solar altitude diagram

In Fig. 3, we illustrate the dependence of I on the eclipse factor and the solar altitude with four lines of constant I (=0.1, 0.2, 0.5, 1.0) on the eclipse eclipse factor–solar altitude diagram. The locations of the four observing sites (Altai, Fuyun, Tacheng, Urumqi) for the 1997-03-09 eclipse are also marked on the diagram.

We can now link the subjective feeling of the observers with the isodensity lines of I from our model calculation. With reference to the reports (for Tacheng, Fucheng, Altai, we have, respectively $I = 0.09, 0.83, > 1.0$) we may identify $I \geq 0.1$ as defining the region of "definite feeling of double dawn", and $I \geq 0.5$ as defining the region of "strong feeling of double dawn".

More details on this eclipses are given in Ref. [10]. From that paper it was clear that we could have done with more sites in northeast Xinjiang, or even in Kazakhstan, Mongolia and

Russia. We should remember this on future occasions. Fig. 3 was made for that Xinjiang eclipse. Different eclipses differ slightly mainly because of differences in the speed of sunrise. Therefore Fig. 3 is applicable to middle–low latitudes generally. On the other hand, we should note that Fig. 3 refers to fine weather and that overcast sky and dark clouds decrease I (see graph C2-E1-E2 of Fig.2).

In conclusion, both theory and practice have proved that obvious or strong "double dawn" can be sensed around the west end of the central belt of eclipse. Its range and intensity can be numerically expressed by the visual brightness of the sky and the method has been proven by practical observation.

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