On Pre-telescopic Sunspot Records

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1 BACKGROUND

The only direct observations of solar activity from before the introduction of the telescope are accounts of sunspots seen with the unaided eye. These early records, almost entirely from the Orient, reach back more or less continuously to at least the second century BC, covering a span of time that is more than four times longer than that available from later telescopic records. Though fewer than 200 reports survive from the period before 1600, the series of pre-telescopic sunspot sightings is adequate in its densest parts to suggest the presence of the 11-yr cycle (Yunnan Obs. 1977; Ding You-ji et al. 1983; Wittmann & Xu 1987); it has also been used in conjunction with world auroral catalogues and the record of tree-ring radiocarbon to confirm periods of long-term change in solar behaviour (Eddy 1976; Stephenson & Clark 1978; Stuiver & Quay 1980; Stuiver & Grootes 1980).

Much has been written about the astrological bases for keeping the naked-eye record, the differences of philosophy and religion that seem to explain the almost total absence of similar records from the western world (e.g. Needham 1959), and the effects on the Oriental sunspot record of persistent and seasonal turbidity on the Asian continent (Willis, Easterbrook & Stephenson 1980). Our ability to interpret the record has been limited, however, by an ignorance of the techniques by which the observations were taken, the frequency of sampling, and the extent to which these data reflect the state of solar activity at the time.

Sunspots can be seen with the unaided eye when the bright disk of the sun is suitably attenuated, as through haze and clouds, or when it is near the horizon and naturally reddened. It has also been suggested (Needham 1959) that the Oriental astronomers who detected sunspots may have looked through attenuating filters of rock-crystal or polished jade, or by reflection through a pool of coloured liquid (Chu Wen-hsin 1934; Wang & Siscoe 1980; Bo Shu-ren 1983). Knowledge of observing technique is for many of the original records unimportant (e.g. from AD 1137 March 1: ‘Within the sun there was a black spot as large as a plum for ten days; then it dispersed’ (Yau 1988). Others could be considerably clarified were the observing methods or conditions known.

A first-order question, as yet unanswered, is the frequency of sampling: how often did the oriental astronomers examine the disk of the sun? The most valuable records come from the classical dynastic histories of China.
Fig. 1. Number of sunspots of angular dimension $d$ (and typical umbral diameter $u$, both in arcmin) reported per decade in the Royal Greenwich Observatory survey for the period 1874–1954.

(cheng–shih); additional reports are found in the provincial accounts (fang–chih). Most of the former histories contain astronomical treatises which are presumed to stem from systematic patrols of the night-time sky, and possibly of the day-time sky as well. In the cheng–shih is found, for example, a record since 240 BC of every appearance but one (164 BC) of Halley’s comet (Stephenson & Yau 1985). The dynastic histories have been of equal value in identifying pre-telescopic novae and supernovae, including the galactic supernova of AD 1054 that went virtually unrecorded in the Western world (Clark & Stephenson 1977).

The sunspot record, by comparison, presents something of an enigma: the number of reports from all known sources for the 18 centuries of available pre-telescopic histories is only about one sunspot per decade – far short of the number that one would expect to find were they the yield of a continuous, daily watch (Eddy 1980, 1983, 1988). A canonical figure of about 1 arcmin has been repeatedly employed as a measure of the minimal, angular size of a spot that can be detected on the sun by the human eye without the aid of a telescope (Newton 1955; Royal Greenwich Obs. 1955). By this criterion,
sunspots large enough to be discerned with the naked eye can be expected on more than 800 days, on average, in each 11-yr sunspot cycle (or about 750 days per decade), were the sun as active as it has been in the last 100 yrs (Fig. 1). The number of reports in Far Eastern annals is thus about 0.1 per cent of what could have been seen.

A likely explanation for a reduced number has been set forth by Yau (1988), who found that the distribution of sunspot reports from all known Oriental records peaked strongly on the first day of the lunar month. This sharp peak on the day of new moon accounts for about 25 per cent of the known reports, or about 50 sightings; the remainder are randomly distributed throughout the lunar month. Yau concludes that the sun was scrutinized particularly by the Oriental astronomers at the time of the new moon, in the course of astrologically more serious searches for the onset of eclipses of the sun. This suggests that sunspots were picked up in the course of these searches as accidental sightings and that the remaining reports are the product of chance sightings at other times.

The number reported in Eastern annals on days of new moon are still fewer (by a factor of more than 100) than we would expect to see were one to look at the sun on only new moon days today. Moreover, to explain as chance sightings the 75 per cent that do not fall on days of new moon implies, using the 1-arcmin criterion, that the Oriental astronomers, far from patrolling the sun, examined the disk only once in about every three years. Alternatively, we could reconcile the small numbers reported by relaxing the expected threshold of visibility from 1 arcmin to about 3 arcmin, limiting detection to truly gigantic spots subtending about 140000 km on the sun. This aspect of the enigma can be tested empirically.

2 THE CROSBY STUDY

In an accompanying paper, J.E. Mossman (1989), an experienced amateur observer in Crosby, near Liverpool, reports on an extensive survey that bears directly on the questions that we have asked. For thirteen months, near the maximum of the last solar cycle, Mossman systematically scrutinized the sun without the aid of a telescope. To our knowledge Mossman's survey, made in 1981–2, is the most extensive test that has yet been made to answer questions regarding the visibility of sunspots to the unaided eye.

Mossman found that he could see features on the disk as small as 0.3 arcmin allowing him to detect sunspots on three days out of four in the years of maximum solar activity in which he made his survey. He was also able to distinguish elementary shapes of spots, to identify as many as five separate spots or groups on a single day, and to resolve close pairs of spots. He found that he could distinguish solar features best at the end of the day, just before sunset, over an ocean horizon, although most of the 278 sunspots that he saw on the 233 days that he could see the sun from Crosby were observed through clouds or with the aid of a dark filter through which he could look at the bright sun at any time of day. Tests on inexperienced, volunteer observers demonstrated that most of them, using Mossman's filter, could easily discover sunspots that were as small as 0.16 arcmin in umbral diameter.
The principal finding is that, without the aid of a telescope, Mossman saw more sunspots in 13 months at Crosby than are found in 18 centuries of pre-telescopic, Oriental histories. If we accept only those that he detected without a filter, his rate of sighting sunspots with the unaided eye (50 in 233 days), when adjusted for cycle phase is still 200 times the long-term rate from the Orient.

The impact of his study, if we presume that the Oriental astronomers were as capable as he, is to verify and even lower the canonical 1 arcmin criterion, establishing that what survives from the Orient is indeed a very thinly sampled record of the sun. His extensive survey implies that either (i) solar activity was much reduced for almost two millennia before the time of the telescope – a possibility that we can surely dismiss on the basis of the contemporary record of tree-ring radiocarbon (Stuiver & Quay 1980; Stuiver & Grootes 1980), or, (ii) that the sunspots that were recorded were for any era an almost negligible fraction of those that could have been seen, raising questions as to the value of so thinly sampled a record. Yau’s findings, in the light of an even lower threshold of detection, also imply that searches of the sun’s disk on the days of possible solar eclipses were extremely selective as to candidate new moons.

3 ASSESSMENT

Two points that need first to be established are whether Mossman’s observing techniques were representative of what the early astronomers could have accomplished, and the extent to which his own naked-eye findings are corroborated by telescopic records made of the surface of the sun in 1981–2. We have tested the second point by comparing Mossman’s observing records, which he kindly made available to us, with daily white-light photographs of the disk made at the Manila Observatory (Badillo 1981, 1982), and with larger-scale focal-plane drawings that were made each day by the NOAA global network (McKinnon, 1987b).

The 233 days on which the sun was visible at Crosby sampled a wide range of solar activity, with daily sunspot numbers from 44 to 263. When there were spots within 0:8 $R_0$ of disk centre (+3 or +4 days from central meridian passage) with an umbral dimension as large as 0:5 arcmin Mossman saw them, as well as some as small as 0:3 arcmin. When there were no features that met these conditions none was reported. Close pairs of large spots whose umbrae were separated by 1:5 arcmin (and on one occasion, only 1 arcmin) were perceived and reported as pairs. Tight clusters of small spots that were sufficiently developed to fill an area about 0:7 arcmin or larger within 0:8 $R_0$ of disc centre were also discerned. In these regards, the Crosby survey was a wholly reliable patrol in detecting spots or groups of spots that were within 0:8 $R_0$ of disk centre and that had umbral diameters of at least 0:5 arcmin. As is the case with high-contrast photographs, it was principally spot umbrae that Mossman perceived, and not the whole spot dimensions (including penumbra) that were used in the RGO photoheliographic studies (1955) to fix the 1 arcmin (whole spot) criterion. A spot about 1 arcmin in diameter will have, typically, an umbral dimension of 0:4 to 0:6 arcmin. The limiting angular resolution of the human eye under static, test conditions is about
0.5 arcmin (Longhurst 1973). When Mossman discerned sunspot umbrae that were about 0.3 arcmin in diameter he might have employed small, involuntary eye movements which are known to improve the acuity of the human eye (Longhurst 1973).

Oriental pre-telescopic sunspot reports are frequently interpreted as marks of maxima in the 11-yr solar cycle (e.g. Yunnan Obs. 1977; Ding You-ji et al. 1983; Wittmann & Xu 1987; Yau 1987) on the premise that spots large enough to be seen are statistically more prevalent when the sunspot number is high. How did the Crosby survey perform in this regard, as an index of the daily level of solar activity?

Figures 2 and 3 show the efficacy of the Crosby survey as a function of daily sunspot number \( R_z \). The first demonstrates the success of the survey in sighting sunspots, as a function of the level of solar activity. Whenever the daily \( R_z \) exceeded 195, Mossman detected sunspots. Similarly, although the daily sunspot number was seldom this low, his threshold for detecting signs of activity seems clearly to be about \( R_z = 50 \). Between these limits the Crosby search had mixed success as a binary (yes/no) indicator of activity: at \( R_z = 100 \) he was as likely to report activity as not. If we can apply Mossman's visual acuity to pre-telescopic observers, it would imply that when spots were recorded on the sun there is a 50:50 chance that the daily sunspot number was 100 or more, and a smaller probability that the sun was in the maximum half of the solar cycle (+3 yrs of maximum phase), since both large spots and daily sunspot numbers greater than 100 are sometimes encountered outside of that range (McKinnon 1987a). Under the same assumption of applicability, we could be almost certain that when spots were detected by the unaided eye by early observers the daily sunspot number was greater than about 50. A daily value of 50 would discriminate, statistically, against the two or three years that describe minima of the sunspot cycle (McKinnon}
Since, as we comment later, the Crosby survey is probably an optimum test, threshold values for most pre-telescopic observers in the Orient were probably somewhat higher. In this case the reporting of spots in early accounts might imply a minimum daily sunspot number of about 70, with equal probability of seeing spots, or missing them, at perhaps $R_z = 120$. These somewhat higher thresholds sharpen the value of the Oriental record as a sensor of maxima in the 11-yr cycle. A daily sunspot number of 70 or higher would eliminate, statistically, about four or five years at the minimum phase of the cycle, making the detection of a naked-eye spot a fair indicator that the phase of the cycle was in the maximum half of the 11-yr period.

A stricter test of the Crosby survey is demonstrated in Fig. 3, where we show the values of daily $R_z$ (and their mean value) as a function of the number of spots that Mossman discerned. Statistically, this simple index seems a useful indicator of the general level of activity, although the spread in any category is considerable. When a single spot was seen, for example, the daily sunspot number was somewhere between limits of 61 and 232, and when none was seen, between $R_z = 0$ (in this case 44) and 179. The principal reason for the wide ranges in both Figs 2 and 3 is that the Wolf sunspot number reflects only the number of spots and spot groups, irrespective of their sizes.

These generalizations drawn from the Crosby study must be tempered by the fact that the modern study was probably an optimum case. Mossman was a practised observer, as was demonstrated in his comparisons with inexperienced test-subjects. As an accomplished amateur and science
educator he began the survey with the advantage of a modern knowledge of solar rotation and of what to look for and to some extent where to look on the sun. His survey was directed at finding sunspots: a motivation which probably did not apply to the Oriental astronomers, as Yau has shown (1988). Mossman enjoyed another considerable advantage in occasional post facto reference to a telescope: a practice that could not help but influence what he looked for on ensuing days. Finally, because of the frequent reliance on optical filters, the Crosby study was only occasionally a test of the strictly unaided eye: 82 per cent of Mossman’s sightings were made with the help of a filter package. While the Oriental astronomers may have used optical attenuation of some sort, we can be sure that Mossman’s aluminized mylar and yellow cloud filter were far superior in optical quality.

4 CONCLUSIONS

Mossman’s comprehensive survey at Crosby enables historians of astronomy to sharpen considerably their evaluation of early reports of sunspots made without the use of a telescope. We must now allow that, under good conditions and with some experience, observers could have detected sunspots with umbrae as small as 0.3 arcmin with the unaided eye. Mossman has shown that elementary shapes of spot groups can also be detected, lending credence to historical reports from the Orient that described features such as ‘Within the sun was the form of a flying swallow’ (AD 299 February/March; from Yau 1988).

Mossman’s test established that for experienced observers under optimum conditions the daily sunspot number must be at least \( R_x = 50 \) before sunspots will be seen; for less experienced observers the number is perhaps 70. In our view the higher threshold is probably more applicable to early Oriental astronomers. In this case, the report of a sunspot seen without a telescope is a statistical indication that the phase of the sunspot cycle was within \( \pm 3 \) years of maximum. Thus the Far Eastern records, no matter how poorly sampled, should serve as an indicator of the general level of activity on the sun. Low-frequency sampling should be able to distinguish epochs like the Maunder Minimum (AD 1645–1715) or Spoerer Minimum (1420–1530) as times of fewer (though not necessarily zero) sunspots.

The Crosby survey eliminates all possibility that the sightings recorded in the cheng-shih were the fruit of anything like the continuous patrol that has been invoked to explain reports in the same annals of the night-time sky. The number of sunspots contained in recent catalogues of naked-eye sunspots (Wittmann & Xu 1987; Yau 1988) account for as few as \( 10^{-3} \) of what could have been seen. This is hard to understand when we know that the Oriental astronomers were regularly watching the sun for other astrological signs, such as solar haloes and parhelia (Ho Peng Yoke 1966). Mossman has shown what it is possible to accomplish with the unaided eye under optimum conditions, if one sets out to find sunspots. To explain the paucity of reports of naked-eye sunspots in early annals we must conclude that the Oriental astronomers only infrequently scrutinized the sun; moreover, when they did, either (i) the size of spot needed to capture their attention was much larger than what was possible to discern or (ii) they saw a large number of spots that
did not find their way into the final histories. It could be that black spots on
the sun were so commonly known and so easily found that reports were only
occasionally kept, much as one saves but a few of the seashells found in a
stroll along the beach.

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REFERENCES

Bo Shu-ren, 1983. Report on the experiment to simulate the ancient Chinese methods to observe
the solar eclipse, Kejishiwenli, 10, 193.
Chu Wen-hsin, 1934. Li Tai Jih Shih Kao [A Study of the Solar Eclipses Down the Ages],
Commercial Press, Shanghai.
In: Secular Solar and Geomagnetic Variations in the Last 10,000 years, pp. 1–23, ed.
Paris.
for Solar-Terrestrial Physics, Boulder, Colorado.
McKinnon, J. A., 1987b. Private communication: original drawings from NOAA solar
observatories in New Mexico and Puerto Rico.
Mossman, J. E., 1989. A comprehensive search for sunspots without the aid of a telescope, Q.
University Press.
Royal Greenwich Observatory, 1955. Sunspot and Geomagnetic-Storm Data Derived from
Hilger, London.
Stuiver, M. & Grootes, P. M., 1980. Trees and the ancient record of heliomagnetic cosmic ray
R. B., Pergamon, New York.
Stuiver, M. & Quay, P. D., 1980. Changes in atmospheric carbon-14 attributed to a variable sun,
Science, 207, 11.


Yunnan Observatory Ancient Sunspot Records Group, 1977. A re-compilation of our country's records of sunspots through the ages and an inquiry into possible periodicities in their activity, *Chinese Astronomy*, 1, 347.