THE MAUNDER MINIMUM: A REAPPRAISAL

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Abstract. A number of papers have questioned the reality of the Maunder Minimum of solar activity (A.D. 1645–1715). A recent study by Xu and Jiang (1982) of newly-discovered Chinese provincial records listing 21 naked-eye sunspot sightings in the 17th century is a case in point, as is Landsberg's (1980) report of 52 sunspots found in 'unexploited' German diary sources. We demonstrate that neither claim is cause to alter Eddy's (1976) quantitative description of the Maunder Minimum. The new Chinese data add at most three possible sunspots to the 600–1000 that were previously known in the Maunder Minimum years; moreover, the number of 17th century naked-eye reports drops after 1640 in the same manner as do known telescopic reports. The historical sunspots found by Landsberg are almost entirely duplicates of spots included in prior analyses, based on earlier studies of the same well-known sources. The principal evidence for secular solar variability is the precision record of tree-ring radioacarbon compiled in 1980 by Stuiver and his colleagues that establishes an unequivocal drop in solar activity during the Maunder Minimum and on three prior occasions in the current millennium.

1. Introduction

Much of what we know of secular changes in solar activity concerns 50–100 year episodes like the Maunder Minimum – an alleged period of depressed sunspot numbers, reduced auroral incidence, and anomalous cosmic-ray modulation between the middle 17th and early 18th centuries (Eddy, 1976). A number of similar episodes have been identified in the longer records of tree-ring radiocarbon (Eddy, 1977a, b; Stuiver and Quay, 1980; Stuiver and Grootes, 1980) and in auroral histories (Sisoe, 1980). But as the most recent of such events, and the only protracted one to fall in the era of the telescope, the Maunder Minimum has served as a kind of prototype of what now is widely accepted as a common feature of long-term solar behavior.

In the last few years at least ten articles have challenged the reality of this specific event, and with it, the broader concept of secular solar change (Link, 1977a, b, 1978; Gleissberg, 1977; Vitinsky, 1978; Schröder, 1979; Landsberg, 1980; Cullen, 1980; Xu and Jiang, 1982; Robinson, 1982). It has been the general pattern of these papers to focus on some restricted set of the historical data, and to report 'new' sightings of sunspots or aurorae made in the 1645–1715 period, which are then offered as evidence that solar activity was not abnormally depressed at the time.

The most recent and surely most interesting of these is a paper based on pre-telescopic sunspot reports that was originally published in China in 1979 by Xu and Jiang and later translated and republished in English in 1982. At both first and second appearances the article was summarized and interpreted by Western writers (Cullen, 1980; Robinson, 1982). A somewhat similar article by Landsberg (1980) purported to uncover lost

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sunspot and auroral reports from German diaries of the 17th century, which, he asserted, contradicted the Maunder claim.

Because so much of our understanding of secular solar behavior depends upon the reality of the Maunder Minimum, which in turn rests on historical data that are to many of us unconventional or esoteric, it is necessary to examine relevant observations critically, and in the light of other contemporaneous evidence. In this paper we attempt to do that for the papers by Landsberg and Xu and Jiang, which we take as typical examples.

2. Ancient Chinese Sunspots

Xu and Jiang (1982) base their paper on 21 naked-eye sunspot reports that were recently found in provincial histories from 17th century China – a significant addition to the 12 previously recovered for the same period from dynastic accounts (Table I).

Mention of dark features on the Sun, seen without the aid of a telescope, appear in Oriental histories as early as the first century, B.C. Earlier authors who have endeavored to interpret these intriguing solar records (Williams, 1873; Kanda, 1933; Needham, 1959; Yunnan Obs. Research Group, 1977; Clark and Stephenson, 1978; Stephenson and Clark, 1978) have utilized the well studied dynastic accounts that were part of the official records of each realm in China, and to a more limited extent in Japan and Korea. By custom, such histories included natural as well as political events, and in them are found, among other things, mention of supernovae (guest stars), comets, planetary conjunctions, and aurorae. Sunspots were reported as dark objects on the Sun, often in quaint and colorful terms ('Black moles on the Sun, now two now three, as big as chestnuts' (Yunnan Research Group, 1977)). Such reports are infrequent and their number varies considerably from century to century. The average in the millennium preceding the Maunder Minimum was about four per century; for long periods, however, there can be none, or many, as during the twelfth century, A.D. when 32 sunspot reports are found in Chinese and Korean dynastic accounts, with nine of them in a single decade (Stephenson and Clark, 1978).

In dealing with these ancient reports one works, in even the most active epochs, with the statistics of small numbers. The task is made more difficult by what might be called sociological factors: in this case, the real question as to whether the numbers recorded were diminished or enhanced by changing emphasis, or distorted by political and astrological considerations (Stephenson and Clark, 1978). Nonetheless, there are compelling reasons to extract and savor whatever marrow remains in these dry bones of history, since before A.D. 1609 they are our only source of direct observations of the face of the Sun, and one of the longest series of direct, physical observations of anything in astronomy (Bray, 1974; Eddy, 1980).

A lack of naked-eye sunspot sightings in Kanda's (1933) list during the 1645–1715 period was cited in Eddy's (1976, hereafter called MM) reassessment of the Maunder Minimum, as weak but circumstantial evidence. Xu and Jiang (1982), however, tap a new and different source of Oriental data: the so-called fang-chi, which were provincial


<table>
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<tr>
<th>Dynastic histories (K, Y)</th>
<th>Provincial histories (XJ)</th>
<th>Estimated annual sunspot number (R) and relevant European data from accounts of Wolf and Maunder (Eddy, 1976)</th>
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<tr>
<td>1603 April 16</td>
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<td>1604 Oct. 25</td>
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<td>1616 Oct. 10</td>
<td>D 1616 Sept. 11–Oct. 10</td>
<td>(28) Spots seen in Europe March 1–11 by Galileo</td>
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<td>1617 (no date)</td>
<td>D? 1617 Jan. 11</td>
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<td>1618 April 25–May 23</td>
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<td>1618 June 20–22</td>
<td>D 1618 June 22</td>
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<td>1625 May 6–Aug. 2</td>
<td>(41) Probably Scheiner's large spot of May 11–23</td>
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<td>(40) Spots reported continually in Europe during this period</td>
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<td>1631 Feb. 25</td>
<td>NE</td>
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<td>1637 (no date)</td>
<td>NE</td>
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<td>NE. Spots reported in May</td>
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<td>1639 March 16</td>
<td>Many spots reported in Europe (none with date) in 1639</td>
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<td>1639 Oct. 26</td>
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<td>1643 June 16–July 15</td>
<td>(16) Probably the large spot seen by Hevelius June 18–23 (see text)</td>
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<tr>
<td>*1647 (no date)</td>
<td>NE</td>
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<tr>
<td>*1650 Oct. 25</td>
<td>(0) (Reported at noon during a total eclipse of the Sun)</td>
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<tr>
<td>*1655 April 30</td>
<td>(1) NE. Spots reported in Europe in February only</td>
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<td>*1656 Jan. 26–April 23</td>
<td>(2) Coincides with a train of large spots seen Feb. 9–21</td>
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<td>*1665 Feb. 20</td>
<td>(0) May contradict Paris Observatory</td>
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<tr>
<td>*1684 March 16–18‡</td>
<td>(11) NE. Spots groups seen continuously, mid-April to end of July</td>
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**Legend:**

* Reports during Maunder Minimum.
D Duplicate in Dynastic, Provincial histories.
NE No European data for the month.
K Kanda (1933).
XJ Xu and Jiang (1982).
‡ Cited in original paper.
as opposed to official dynastic histories from China. From these local histories (see Table I) they have gleaned probable reports of 21 sunspots for the period between 1613 and 1684. Based on this finding the authors suggest that ‘... the original evidence (for the Maunder Minimum) no longer stands and Eddy’s conclusion becomes shaky’.

3. The Chinese Findings in the Context of Other Data

Xu and Jiang’s analysis of the fang-chi offers new and valuable information in an area of research where new data are indeed rare. But the sunspot records that they find do not substantiate their conclusions; as we shall see, these new findings support, rather than refute, the case for a marked drop in the level of solar activity in the latter half of the 17th century.

The Maunder Minimum was never alleged to be a period of a total absence of sunspots. Maunder (1894) characterized it as a time when the sunspot curve was sunken in a such a way that only occasional crests appeared: ‘... just as in a deeply inundated country, the loftiest objects will still raise their heads above the flood, and a spire here, a hill, a tower, a tree there, enable one to trace out the configuration of the submerged champlain’. Eddy (MM, Table I) attempted to quantify the epoch with estimates of annual mean sunspot numbers based on Wolf’s historical compilation and other contemporary accounts. Days when no observations were available were allowed for by assuming that days on which reports were made were typical for the year. This assumption could easily underestimate or overestimate the true number. Years for which no observations were available or to which no contemporary generalized comments applied were not given estimated numbers. These rough estimates of $R$, uncertain to at least a factor of two, fall in the range 0–18, with a 70-year average of about $R = 3$. (The annual mean sunspot numbers for the minimum and maximum of the present sunspot cycle were, for comparison, 12.6 and 155.4.)

One must appreciate that sunspots may be seen on the Sun in a year that has a mean annual sunspot number, to one-digit accuracy, of zero, and that many are possible in years with an annual average of $R = 1$. The difference between ‘annual sunspot number’ and ‘the number of sunspots seen on the Sun in a year’ can amount to an order of magnitude or more. The crucial distinction is not so much in the definition of $R$ ($= k(10g + f)$, where $f$ and $g$ are counted numbers of spots and groups and $k$ is a calibration factor) as in the difference between an average and a summation of 365 daily numbers.

Historical telescopic accounts originally compiled by Rudolf Wolf and adopted by Eddy (MM, ref. 6, Table I and Fig. 9) document between 600 and 1000 individual sunspot reports during the 1645–1715 period, as best the numbers can be reconstructed from contemporary records. By contrast, in modern times of moderate to high solar activity ($R = 50$ to 100) many thousands of sunspots are noted in the course of a single year and as many as several hundred in a single day. The significance of reports of ‘new’ old sunspots needs always to be weighed with this in mind.

Nor does the case for the Maunder Minimum rest in any critical way on an utter
absence of naked-eye reports during the period in question. Periods of marked increase or decrease in the frequency of such reports in pre-telescopic times may serve as a qualified indicator of an 11-year cycle, or a qualitative measure of secular trends in solar activity, after compensation for discontinuities in the records and possible sociological influences (Yunnan Research Group, 1977; Clark and Stephenson, 1978; Stephenson and Clark, 1978; Eddy, 1980; Xu and Jiang, 1982; Ding et al., 1983). An additional leap of faith is taken when isolated sightings in times of sparse reports are taken to mark the phase of an assumed, early sunspot cycle, on the presumption that spots grow large enough to be seen only in years of maximum sunspot number (Kanda, 1933; Yunnan

![Graph](image_url)

Fig. 1. Annual mean sunspot numbers $R$ from Eddy (1976), shaded black during the Maunder Minimum. Dashed horizontal lines at right indicate average values of $R$ at minima and maxima of the modern solar activity cycle. Small triangle symbols for years in the poorly documented period before 1645 are schematic indications of solar activity levels based on contemporaneous, qualitative descriptions: triangles at $R = 18$ denote years when sunspots were noted but not counted; at $R = 8$, years when spots were noted to be rare. In 1639 an unusually large number of spots were noted. Vertical lines in row 'a' at bottom denote years in which naked-eye sunspots were reported in China (from Table I); naked-eye reports in 1647, 1650, and 1665 marked with large triangles constitute new information for the Maunder Minimum period. Vertical lines in row 'b' mark years for which Landsberg (1980) found sunspot reports in German diaries; in two years (1679 and 1687) the Landsberg spots (marked with triangles) offer new information.
Obs. Research Group, 1977; Xu and Jiang, 1982). In modern data the largest spots or groups indeed occur more frequently, on average, at times of greater sunspot number. But large sunspots, and even gigantic ones, can be seen in all phases of the 11-year cycle, including at solar minimum, when other spots are scarce. Thus the sighting of an naked-eye sunspot group is indicative of the general level of solar activity or the phase of the 11-year sunspot cycle only in the sense of statistical probability.

Figure 1(a) displays the years of reported naked-eye sunspots from Table I on a plot of the annual sunspot numbers that were previously reconstructed from historical, telescopic reports (MM, Table I and Fig. 9). We note first that only 6 of the naked-eye reports fall during the years of the Maunder Minimum; the other 27 occur during a prior epoch which we presume to be of normal, though declining solar activity – as sampled by occasional synoptic drawings of the full disk made at the time by Galileo, Scheiner, and Hevelius. Moreover, the majority of these pre-Maunder Minimum sightings fall in years when extant telescopic records indicate that naked-eye spots should have been frequently seen (Figure 1(a) and Table I).

Of the 6 Maunder Minimum naked-eye spots (all from the fang chi record) three (1655, 1656, 1684) fall in years when sunspots were reported telescopically. One, in 1684, falls in the year of the highest estimated sunspot number in the 70-year span. Another, in 1656, is almost surely coincident with European reports of a train of large sunspots noted on the Sun at the same time (MM, ref. 6). We may presume that in these cases the naked-eye reports sample the same spot groups seen by telescope in Europe. If that is so, they offer a useful confirmation of the general reliability of the fang chi records. (In addition, two pre-Maunder Minimum spots in the series were fortuitously reported on days when European observers left us detailed pictures of the spotted disk of the Sun, and in both cases we can identify a possible feature in the European drawings that seems to confirm them. One can see large, candidate sunspots, each more than 1' in dimension, that correspond to fang chi reports on 1625, May 6 – August 2 and 1643, June 16 – July 15, in drawings made by optical projection by Christopher Scheiner (published in his Rosa Ursina in 1630) and by Johannes Hevelius (in the 1645 Selenographia). The first of these is shown in Figure 2.)

The three remaining spots (in 1647, 1650, and 1665) constitute the new information in the Xu and Jiang study insofar as the Maunder Minimum is concerned.

The 1647 sighting falls early in the Maunder Minimum in a year for which there were no European data available to estimate the sunspot number; the second, on October 25, 1650, falls in a year for which telescopic observers reported no sunspots, and for which Eddy estimated $R = 0$ (MM, Table I). In both cases the fang chi data introduce useful new information, although a single spot is far from sufficient to alter the estimated annual sunspot number, for reasons cited earlier. Moreover, as a probable sunspot description the 1650 report is unusual and possibly suspect. Naked-eye sightings are made most easily (though not exclusively) when the Sun is dimmed, as at sunrise or sunset; the 1650 phenomenon was reported at noon, and on the day of an eclipse of the Sun that was total at midday in the province of Jurong where the report was made (Xu and Jiang, 1982; Oppolzer, 1962). A total eclipse may signal attention to the Sun,
Fig. 2. Christopher Scheiner's drawing of the solar disk showing successive daily appearances of a very large sunspot (1.5’ dimension) during the period May 11–23, 1625. The original was made by optical projection with a solar telescope of about 1.5 m focal length, and published in his Rosa Ursina in 1630. The same spot may have been seen with unaided eye by Chinese provincial astronomers who described the following for the period May 6 – August 2, 1625 (Xu and Jiang, 1982): 'Star(s) seen inside a lackluster Sun. Black spots by its side. Thus for ten-odd days'.

but it does not facilitate the unaided observation of features on the photospheric disk. Given the extreme rarity of a local total eclipse at any fixed site one could question whether the 1650 report, of 'wine cup(s)' on the Sun at noon (Xu and Jiang, 1982), might as well be an allegorical reference to an eclipse phenomenon. The choice of words is not unique, however; the phrase 'wine cup(s) seen on the Sun' was interpreted to mean sunspots in two other instances by Xu and Jiang, for 1626 and 1639, in years when
European reports establish that sunspots were prevalent (Table I). Whether solar eclipses were seen (or possibly predicted) on the dates ascribed to the 1626 and 1639 sightings is less certain, although there is cause for speculation: the 1639 date was recorded as that of a new moon (Xu and Jiang, 1982), and hence a potential eclipse day, though in fact there was none. However, on the last day of the 1626 winecup report (August 21) there was an Eastern-hemisphere annular eclipse of the Sun that may have been just visible in partial phase, at sunrise, in the northeastern province of Xiang Yuan where the report was made (Oppolzer, 1962). Still, we must assume, as Xu and Jiang have done, that each of these is more probably a sunspot report.

The third Maunder Minimum report, on February 20, 1665, is of especial interest in that it falls during a decade interval described by the contemporary French astronomers Cassini and Piccard as nearly devoid of spots (see MM, p. 1190). The fang chi account is here unambiguous – ‘Two black spots on the Sun, moving about for a long time’ – leaving little doubt that what was seen was a bona fide sunspot group. The 1665 spot group is one of many that are not confirmed in the dynastic histories. Clark and Stephenson (1980) have stressed that the latter are intrinsically more reliable in that they can be checked for completeness (by noting the presence of reports of other sky phenomena), and for these reasons they question the reliability of the less substantiated provincial accounts. We have shown in this paper, however, that at least some of them are quite likely confirmed by coincident telescopic sightings. Xu and Jiang argue as well that the general absence of late 17th century sunspot reports in dynastic histories may be due to some accident in transcription, or loss of records. Why an obvious sunspot group was missed by European astronomers armed with telescopes is another question, and one which we can probably never answer. Perhaps we have here another case like the Crab supernova eruption, that also passed unnoticed or at least undocumented in Europe, in A.D. 1054, when for several weeks Chinese astronomers reported it visible by day. Were the provincial Chinese more diligent watchers of the Sun in the decade of the 1660’s than their technically equipped contemporaries at the Paris Observatory? Or was northern France overcast for two weeks in February of 1665?

We could take the 1665 fang chi sighting as a crucial contradiction of the generalization made at the time by Cassini and Piccard and later by Derham (MM, refs. 15, 16) that the years between 1660 and 1671 were remarkably free of sunspot activity, and an indication that there were many others that slipped away, like uncaught fish, from a leaky European net. Given the limited significance of a single sunspot sighting, however, and the weight of other direct and proxy evidence for uncommonly low solar activity at the time, the enigma of the 1665 sunspot group is surely academic. The facts are that in the Xu and Jiang paper there are three to five possible new sunspots for the Maunder Minimum period, to add to the hundreds that were previously known.

What is more, as is apparent in Table I, and as Clark and Stephenson (1980) first pointed out, patterns in the frequency of naked-eye reports in the 17th century are wholly consistent with a sharp drop in solar activity during the Maunder Minimum. In Figure 3 we compare decade sums of naked-eye reports with decade-averaged sunspot number for the same intervals (from MM, Table I) and note a remarkable similarity. In each case
the numbers drop abruptly and by about the same fraction after 1640, and remain correspondingly low for the ensuing years of the century.

4. The Enigma of Naked-Eye Sunspot Reports

What has never been satisfactorily explained is why the number of historical, naked-eye sunspot reports should correspond to any objective index of solar activity, given the small sample size. Maunder (1902), as others since, noted that in a year of average solar activity literally hundreds of spots and spot groups appear that are large enough to be detected without optical aid by an observer with normal vision – i.e., an ability to resolve a feature 1' in diameter. If a continuous Oriental patrol were operative in pre-telescopic times, as Stephenson and Clark (1978) have suggested, it was woefully inefficient, catching only about 1 in 10,000, in long-term average, of the spots that could have been seen. One can demonstrate to oneself that the explanation is not to be found in the resolution criterion, for with a properly attenuated Sun, as at sunrise or sunset, spot groups covering 1' can indeed be seen without optical aid. Nor can we reasonably attribute the loss of 9999 of 10,000 seeable naked-eye spots to cloudiness or other weather effects. Indeed, Willis et al. (1980) have suggested that typical atmospheric conditions in Chinese Asia may well have been ideal for the naked-eye observation of sunspots, because of persistent haze and turbidity from upwind continental deserts. A most likely explanation for the obvious undersampling of potential naked-eye sunspots in the Oriental accounts is that naked-eye observations of the Sun were made not routinely but randomly, in the nature of an occasional and possibly accidental probe, as
evidenced by the poor correspondence between dates of dynastic and provincial reports (Table I): at most 3 coincidences in 33 sightings. If that is so we can be impressed at the apparent utility of so minute a sample, for as some have shown, both the 11-year cycle and secular trends in the general level of solar activity are marginally detectable in these sparse and sometimes enigmatic accounts (Yunnan Obs. Research Group, 1977; Stephenson and Clark, 1978; Xu and Jiang, 1982; Ding et al., 1983). At the same time we must recognize the hazards in interpreting so limited a sample too literally.

We need also question whether and when the long series of Oriental naked-eye sunspot reports was finally contaminated and vitiated as a homogeneous index of solar behavior by the influence of the telescope. The instrument was introduced in China by Jesuit missionaries in 1612 (D’Elia, 1960), less than three years after it broke upon the world of Western science. Father Schall wrote a short book in Peking about the telescope, in the Chinese language, in 1626, that included an account of its remarkable discoveries, among them, sunspots. An earlier Jesuit book on astronomy, that also mentioned these dramatic findings, had been printed in Chinese in 1615 (D’Elia, 1960). Schall announced the important conclusions that these dark spots were not only common, but features of the Sun itself – two critical findings that could reasonably have altered the emphasis of subsequent, naked-eye searches for them.

We do know that in 1634, ten years before the onset of the Maunder Minimum and 80 years before its end, the Emperor of China was presented a gift telescope, the first of many that were later introduced (D’Elia, 1960). We can only guess whether these astronomical gifts, or Schall’s astronomical treatise, were shown to Chinese court astrologers, and, if known, whether they were in any way adopted. These early and repeated introductions may or may not have influenced the nature of naked-eye patrols of the sky or the frequency of reported sunspots – which were among the easiest of all celestial phenomena to detect with the new instrument. But the established presence of telescopes in 17th century China surely adds another caveat to quantitative interpretations of sunspot reports made there at the time.

5. Rediscovered Sunspots in German Diaries

A different claim was published in 1980 by Landsberg, in which he documents 52 ostensibly new sunspot observations (and a number of faculae) from what he terms ‘unexploited diary sources’ of 17th and early 18th century German astronomers.

The sources invoked by Landsberg are the well-studied accounts of the 17th century German astronomers Gottfried and Maria Kirch, their children, and the diary of Christoph Arnold, a contemporary, amateur astronomer of Leipzig. Landsberg assumed that the Kirch and Arnold diaries had been omitted in earlier compilations and contends that the ‘new’ sunspots (and twelve possible auroral reports that fell in the century before the Maunder Minimum) effectively refute other evidence for the reality of the event. Landsberg, a climatologist, questions as well the possible connection of what he calls ‘the so-called Maunder Minimum’ with the Little Ice Age, a longer, contemporaneous climatic trend whose connection with solar behavior, as suggested by Eddy (1977a, b),

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is indeed equivocal (Robock, 1979; Stuiver, 1980; Harvey, 1980). Landsberg implicitly equates the Maunder Minimum with a literal absence of sunspots or aurorae – in the sense that if one is found there must be more – and then endeavors to demonstrate how easy it is to find them.

In fact, the Kirch and Arnold diaries that Landsberg read were included in the sources that Wolf had used in his landmark studies of historical sunspot accounts (MM, ref. 6); they were therefore acknowledged in the early surveys of 17th century solar activity by Sporer and Maunder (MM, refs. 13–16) and explicitly included in Eddy’s quantitative estimates of sunspot numbers for the Maunder Minimum (MM, Table I). It is therefore not surprising that the years in which Landsberg finds sunspot reports so closely track the published curve of estimated sunspot number, as we see in Figure 1(b). Of the 52 sunspots found by Landsberg 41 are duplications of reports given in the list of historical spots for the period 1610–1715 compiled by Wolf, who attributed many of these spots to the same diaries that Landsberg used. In the more extensive Wolf compilation, moreover, are an additional 41 sunspots in the 1680–1714 period accredited to the Kirch diaries that were not included by Landsberg, who thus found fewer sunspots in his restricted test of the Maunder Minimum than did earlier interpreters of the same German sources. Of the 11 sunspots that are unique to Landsberg’s reading of the diaries, 2 fall in a year (1681) when there were a number of other known reports of spots and another 3 in years (1688, 1703, 1708) when sunspots were more than usually prevalent for the Maunder Minimum, with annual sunspot numbers (MM, Table I) of 5, 8, and 8.

Landsberg’s case for normal solar behavior thus rests on reports in two years of 6 possible, ‘new’ spots, which Wolf excluded in his studies of the same diary sources. These are spots purportedly seen on August 14 and 15, 1679, May 28–31, October 1, and November 1, 2, and 6, 1687. If, as we may reasonably presume, the last three were consecutive sightings of one and the same spot, the ‘new’ number of spots is reduced to 5. In any event, this is surely insufficient support for Landsberg’s claim of having found ‘good evidence that the basic solar rhythms were maintained.’

Landsberg invokes similar reasoning in citing a number of isolated European auroral reports from a period preceding the Maunder Minimum (1547 through 1612) and a paper by Schröder (1979) that lists 90 possible auroral nights during the Maunder Minimum that were not included in the 1873 auroral catalog that Eddy used (MM, ref. 37). 54 of these aurorae fall in years of higher than normal sunspot activity for the Maunder Minimum – 30 of these in the interval of generally ascending activity near the end of the period, between 1704 and 1715. For these years the average, estimated annual sunspot number is 9.4, with years as high as $R = 18$ (MM, Table I). At that level of activity we expect auroral displays between 50 and 55 degrees latitude in Europe. It should be pointed out, however, that in Schroder’s list are 36 auroral nights, chiefly in Germany, in years in which Eddy’s estimate of the annual sunspot number was zero.

Aurorae are far from a $1:1$ proxy of sunspot activity, and particularly at higher geomagnetic latitudes, where they are seen throughout the solar activity cycle. Displays in a tighter auroral oval are prevalent in years of declining and minimum activity in the
11-year sunspot cycle. These aurorae are today attributed to high speed solar wind streams from coronal holes, that are quite unrelated to sunspots or flares (Sheeley, 1978; Feynmann and Silverman, 1980). Similar arguments could be applied to the papers citing Maunder Minimum aurorae published by Link (1977a, b, 1978). Moreover, in a more comprehensive study of the historical auroral record published after the Schroder paper, Siscoe (1980) establishes that a dramatic drop in auroral incidence during the Maunder Minimum is well-documented in contemporary and subsequent historical accounts, in both Europe and America.

6. Conclusions

We can anticipate that the number of historical reports of auroral nights or sunspot days during the Maunder Minimum or any other period of intensive examination will only grow with determined efforts in searching for them. The implications for secular solar behavior will depend on how much the numbers grow, and how they compare with adjacent, equivalent periods that are subjected to equivalent scrutiny. A meaningful contradiction of alleged secular variations must surely consider the entire body of evidence on which the existence of episodes such as the Maunder Minimum is based. Important in terms of consistency is the objective record of tree-ring radiocarbon, that establishes the existence of protracted periods now identified as the Maunder Minimum, the Spörer Minimum (A.D. 1420–1530), the Wolf Minimum (1280–1340), and the Oort Minimum (1010–1050), when solar activity measured in cosmic-ray modulation efficiency fell below levels characteristic of minima in the present 11-year solar activity cycle (Stuiver and Quay, 1980; Stuiver and Grootes, 1980). The precision radiocarbon data are a proven proxy of the level of solar activity measured in sunspot numbers, in that they demonstrate a clear correspondence with the envelope of annual sunspot number during well documented periods of overlap, as between ca. 1750 and 1850 (Stuiver and Quay, 1980). The Maunder Minimum is a distinctive feature in the radiocarbon record. Historical accounts of sunspots and aurorae, and perhaps of the Sun at eclipse, can help refine our knowledge of solar behavior during periods such as the Maunder or Spörer minima. But they are not the only evidence for a marked depression of solar activity during these times.

It is not impossible to find in 17th century records a neglected sunspot or a forgotten aurora, and perhaps we should renew our efforts to do that, to add more detail to what is known of these quiescent episodes in the current life of the Sun. But unless we unearth many hundreds of sunspots and scores of low-latitude aurorae in the 1645–1715 period we cannot have refuted the reality of Maunder’s minimum. Were we to find such evidence, we would face a formidable problem in explaining the established sequence of contemporaneous and wholly consistent anomalies in the world-wide radiocarbon record.
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