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The Maunder Minimum

The reign of Louis XIV appears to have been a time of real anomaly in the behavior of the sun.

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It has long been thought that the sun is a constant star of regular and repeatable behavior. Measurements of the radiative output, or solar constant, seem to justify the first assumption, and the record of periodicity in sunspot numbers is taken as evidence for the second. Both records, however, sample only the most recent history of the sun.

When we look at the longer record—of the last 1000 years or so—we find indications that the sun may have undergone significant changes in behavior, with possible terrestrial effects. Evidence for past solar change is largely of an indirect nature and should be subject to the most critical scrutiny. Most accessible, and crucial to the basic issue of past constancy or inconstancy, is a long period in the late 17th and early 18th centuries when, some have claimed, almost no sunspots were seen. The period, from about 1645 until 1715, was pointed out in the 1890's by G. Spörer and E. W. Maunder. I have reexamined the contemporary reports and new evidence which has come to light since Maunder's time and conclude that this 70-year period was indeed a time when solar activity all but stopped. This behavior is wholly unlike the modern behavior of the sun which we have come to accept as normal, and the consequences for solar and terrestrial physics seem to me profound.

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The Sunspot Cycle

Surely the best-known features of the sun are sunspots and the regular cycle of solar activity, which waxes and wanes with a period of about 11 years. This cycle is most often shown as a plot of sunspot number (Fig. 1)—a measure of the number of spots seen at one time on the visible half of the sun (*1*). Sunspot numbers are recorded daily, but to illustrate long-term effects astronomers more often use the annual means, which smooth out the short-term variations and average out the marked imprint of solar rotation.

There is as yet no complete physical explanation for the observed solar cycle. Modern theory attributes the periodic features of sunspots to the action of a solar dynamo in which convection and surface rotation interact to amplify and maintain an assumed initial magnetic field (*2*). Dynamo models are successful in reproducing certain features of the 11-year cycle, but with these models it is not as yet possible to explain the varying amplitudes of maxima and other long-term changes.

The annual mean sunspot number at a typical minimum in the 11-year cycle is about six. During these minimum years there are stretches of days and weeks when no spots can be seen, but a monthly mean of zero is uncommon and there has been only 1 year (1810) in which the annual mean, to two-digit accuracy, was zero. In contrast, in the years around a sunspot maximum there is seldom a day when a number of spots cannot be seen, and often hundreds are present.

Past counts of sunspot number are readily available from the year 1700 (*3*), and workers in solar and terrestrial studies often use the record as though it were of uniform quality. In fact, it is not. Thus it is advisable, from time to time, to review the origin and pedigree of past sunspot numbers, and to recognize the uncertainty in much of the early record.

A Brief History

Dark spots were seen on the face of the sun at least as early as the 4th century B.C. (*4*), but it was not until after the invention of the telescope, about 1610, that they were seen well enough to be associated with the sun itself. It would seem no credit to early astronomers that over 230 years elapsed between the telescopic "discovery" of sunspots and the revelation of their now obvious cyclic behavior. In 1843, Heinrich Schwabe, an amateur, published a brief paper reporting his own observations of spots on the sun for the period 1826 to 1843 and pointing out an apparent period of about 10 years between maxima in their number (*5*).

Rudolf Wolf, director of the Observatory at Bern and later at Zurich, noticed Schwabe's paper and shortly after set out to test the result by extending the limited observations on which the 10-year cycle was based. In 1848 he organized a number of European observatories to record spots on a regular basis and by a standard scheme, thus inaugurating an international effort which continues today. Wolf also undertook a historical search and reanalysis of old data on the sun in the literature and in observatory archives. More than half of the record of sunspot numbers in Fig. 1, and all of it before 1848, is the result of Wolf's historical reconstruction. The most reliable part of the curve thus comes after 1848, when it is based on controlled observations. Wolf found descriptions and drawings of the sun which allowed him to reconstruct daily sunspot numbers 30 years into the past—to 1818—although, unlike the real-time data, they came from a thinner sample and with less certain corrections for observers and conditions. He was able to locate sufficient information on the more distant past to allow reconstructed "monthly averages" of the sunspot number (that is, a minimum of one observation per month) to 1749, and approximate "annual averages" from more scattered data to 1700 (*3*). The reliability of the curve, and especially of its absolute scale, may be graded into four epochs: reliable from 1848 on, good from 1818 through 1847, questionable from 1749 through 1817, and poor from 1700 through 1748.

Wolf collected data to extend the historical curve the final 90 years to the telescopic discovery of sunspots in 1610 (*6*). He published estimated dates of maxima and minima for 1610 through 1699 but not sunspot numbers. That he elected to discontinue sunspot numbers at 1700 may be significant: perhaps he felt he had reached the elastic limit of the sparse historical record at the even century mark; it could also be that at 1700 he ran into queer results. In this article I shall point out that the latter probably applies. It seems fair to assume that, once he had confirmed and refined Schwabe's cycle, Wolf was biased toward demonstrating that the sunspot cycle persisted backward in time (*7*); thus, when the cycle appeared to fade, especially in dim, historical data, he would have been inclined to quit the case and to call it proven. In any event we should be especially skeptical of the curve in its thinnest and oldest parts (1700 through 1748), and to question anew what happened before 1700.

Even though we are aware of the varying quality of the Wolf sunspot record, most of us probably take it as evidence of a truly continuous curve, much like the sample of a continuous wave form that we see on the screen of an oscilloscope. We assume that, just as Schwabe's 17-year sample was enough to reveal the cycle's existence, so the 260-year record in Fig. 1 is adequate to establish its likely perpetuation to the future and extension through the past. Reconstructions of the solar cycle have been estimated from indirect data to the 7th century B.C. in the Spectrum of Time Project (STP) of D. J. Schove, but these heroic efforts are of necessity based on far from continuous information and are built on the explicit assumption of a continued 11-year cycle (*8–11*). Recent insights into the physical basis for the sunspot cycle and its origin in the fluid, outer layers of the sun give us new cause to suspect that at least some of the features of the present sunspot cycle may be transitory. If we accept the solar dynamo, we must allow that any of its coupled forces could have changed enough in the past to alter or suspend the "normal" solar cycle. Indeed, there is now evidence that solar rotation has varied significantly in historic time (*12*).

The "Prolonged Sunspot Minimum"

The possibility that sunspots sharply dropped in number before 1700 was pointed out rather clearly by two well-known solar astronomers in the late 19th century. In papers published in 1887 and 1889 the German astronomer Gustav Spörer called attention to a 70-year period, ending about 1716, when there was a remarkable interruption in the ordinary course of the sunspot cycle and an almost total absence of spots (*13*). Spörer was studying the distribution of sunspots with latitude and had found evidence that the numbers of spots in the northern and southern hemispheres of the sun were not always balanced. To check this observation he had consulted historical records, including Wolf's, and was surprised at what he found in the data of the 17th and early 18th centuries. Not long after, Spörer died. Meanwhile, E. W. Maunder, superintendent of the Solar Department, Greenwich Observatory, took up the case. In 1890 Maunder summarized Spörer's two papers for the Royal Astronomical Society and in 1894 gave a fuller account in an article entitled "A Prolonged Sunspot Minimum" (*14, 15*). In his second paper Maunder provided more details and pointed out that to acknowledge this unusual occurrence was to admit that the solar cycle and the sun itself had changed in historic time, and could again. He stressed that the reality of a "prolonged sunspot minimum" had important implications not only for our understanding of the sun but also for studies of solar-terrestrial relations.

It is not obvious that anyone in solar physics listened. In any case, nearly 30 years later, at 71, Maunder tried again with another paper of the same title on the same subject (*16*). Included were quotations from a paper by Agnes Clerke who had claimed that during the "prolonged sunspot minimum" there was also a marked dearth of aurorae (*17*). Maunder offered as well the interesting conjecture that the long delay between the telescopic discovery of sunspots and Schwabe's discovery of the solar cycle may have been due in part to this temporary cessation of the solar cycle during a part of the interim.

In their five papers Spörer and Maunder made the following striking assertions: (i) that for a 70-year period, from approximately 1645 to 1715, practically no sunspots were seen; (ii) that for nearly half of this time (1672 through 1704) not a single spot was observed on the northern hemisphere of the sun; (iii) that for 60 years, until 1705, no more than one sunspot *group* was seen on the sun at a time; and (iv) that during the entire 70-year period no more than "a handful" of spots were observed and that these were mostly single spots and at low solar latitudes, lasting for a single rotation or less; moreover, the total number of spots observed from 1645 to 1715 was less than what we see in a single active year under normal conditions.

Maunder supported these claims with quotations from the scientific literature of the period in question. The editor of the *Philosophical Transactions of the Royal Society*, in reporting the discovery of a sunspot in 1671 (in the middle of the "prolonged sunspot minimum"), had written that (*15*, p. 173) ". . . at Paris the Excellent Signior Cassini hath lately detected again Spots in the Sun, of which none have been seen these many years that we know of." (Following this, the editor went on to describe the last sunspot seen, 11 years before, for those who might have forgotten what one looked like.)

Cassini's own description of his 1671 sighting reads as follows (*15*, p. 174): ". . . it is now about 20 years since astronomers have seen any considerable spots on the sun, though before that time, since the invention of the telescopes they have from time to time observed them." Cassini also reported that another French astronomer, Picard, ". . . was pleased at the discovery of a sunspot since it was ten whole years since he had seen one, no matter how great the care which he had taken from time to time to watch for them" (*16*, pp. 141–142). And when the Astronomer Royal, Flamsteed, sighted a spot on the sun at Greenwich in 1684, he reported that "[t]hese appearances, however frequent in the days of *Scheiner* and *Galileo*, have been so rare of late that this is the only one I have seen in his face since *December* 1676" (*15*, p. 174).

Maunder did not have to look hard to find support for the strange case, for an absence of sunspots in the latter part of the 17th century had been matter-of-factly reported in astronomy books written before Schwabe's discovery of the cycle (*18*). William Herschel had mentioned it in 1801 (*19*). Herschel's source of information was LaLande's three-volume opus, *Astronomie*, of 1792, in which dates and details are given of the anomalous absence of sunspots, including some of the quotations that Maunder later used (*20*). Thus, neither Maunder nor Spörer had "discovered" the "prolonged sunspot minimum." These authors, like myself, were simply pointing back to an overlooked and possibly important phenomenon which in its time had not seemed unusual but which looms large in retrospect.

Questions

Maunder's assessment of the significance of the "prolonged sunspot minimum" was probably not an exaggeration. If solar activity really ceased or sank to near-zero level, it places a restrictive boundary condition on physical explanations of the solar cycle and suggests that a workable mechanism for solar activity must be capable of starting, and maybe stopping, in periods of tens of years. It labels sunspots as possibly transitory characteristics of the sun, and by association also flares, active prominences, and perhaps the structured corona. One of the enigmas in historical studies of the sun is the long delay in the naked-eye discovery of the chromosphere (*21*) and the lack of any ancient descriptions of coronal streamers at eclipse (*22, 23*). It may be more than curious coincidence that the discovery of the chromosphere (1706), the first description of the structured corona (1715), and a lasting, tenfold jump in the number of recorded aurorae (1716) all came at the end of the Maunder Minimum, when, it seems, the solar cycle resumed, or possibly began, its modern course. If Maunder's "prolonged sunspot minimum" really happened, it provides damning evidence (*24*) in the protracted debate over the production of sunspots by planetary gravitational tides, for through the years between 1645 and 1715 the nine planets were, as always, in their orbits. Finally, as Maunder stressed, this apparent anomaly in the sun's history, if real, offers a singularly valuable test period for studies of the connection between solar activity and terrestrial weather. If the Maunder Minimum really occurred, it may define a minimum of a long-term envelope of solar activity which could be more important for terrestrial implications than the 11-year modulation that has for so long occupied attention in solar-terrestrial studies (*25*).

It seems worthwhile to open, once again, the case of the missing sunspots, for it was never really solved. All the early work was based almost entirely on the same piece of evidence: the paucity of sunspot reports in the limited literature of the day. Spörer's original papers and Maunder's expansions of them leaned heavily on a lack of evidence in archival records and journals, and on contemporary statements that it had been a long time between sunspot reports. But in the words of a modern astronomer, absence of evidence is not evidence of absence (*26*). How good were the observers in the 17th century, and how good the observing techniques? How constant a watch was kept? How many spots were missing, and when? New evidence has come to light in the 50 years since Maunder's time: we now have better catalogs of historical aurorae, compilations of sunspot observations made in the Orient, a fuller understanding of tree-ring records, and a new tool in atmospheric isotopes as tracers of past solar activity. New understanding of the sun since Maunder's day can sharpen our assessment of the facts in the case: we now know the relationship of sunspots to solar magnetic fields and something of the relation of magnetic fields to the corona, and can thus examine more critically the evidence from total solar eclipses during the time.

Solar Observations in the 17th Century

History has left an uncanny mnemonic for the dates of the Maunder Minimum: the reign of Louis XIV, *le Roi Soleil*, 1643 through 1715. This was also the time of Milton and Newton; by 1642 Brahe, Kepler, and Galileo were gone. Astronomical telescopes were in common use and were produced commercially; they featured innovations and important improvements over the original miniature models which in 1612 had sufficed to distinguish umbrae and penumbrae in sunspots and by 1625 had been used to find the solar faculae. During the Maunder Minimum the Greenwich and Paris observatories were founded, and Newton produced the reflecting telescope; it was also the age of the long, suspended, and aerial telescopes with focal lengths that stretched to 60 meters and apertures of 20 centimeters and more (*27*). The more usual telescopes turned on the sun had focal lengths of 2 to 4 meters and apertures of 5 to 10 centimeters, which would describe most solar telescopes used in the 18th and 19th centuries as well. To observe sunspots then, as today, one projected the solar image on a white screen placed at a proper distance behind the eyepiece (Fig. 2). The image scale was adequate to permit one to see and to sketch not only spots of all sizes but their features and their differences; observers recorded details of white-light faculae, penumbral filaments, satellite sunspots, and most of the observational detail known of sunspots today (Fig. 3).

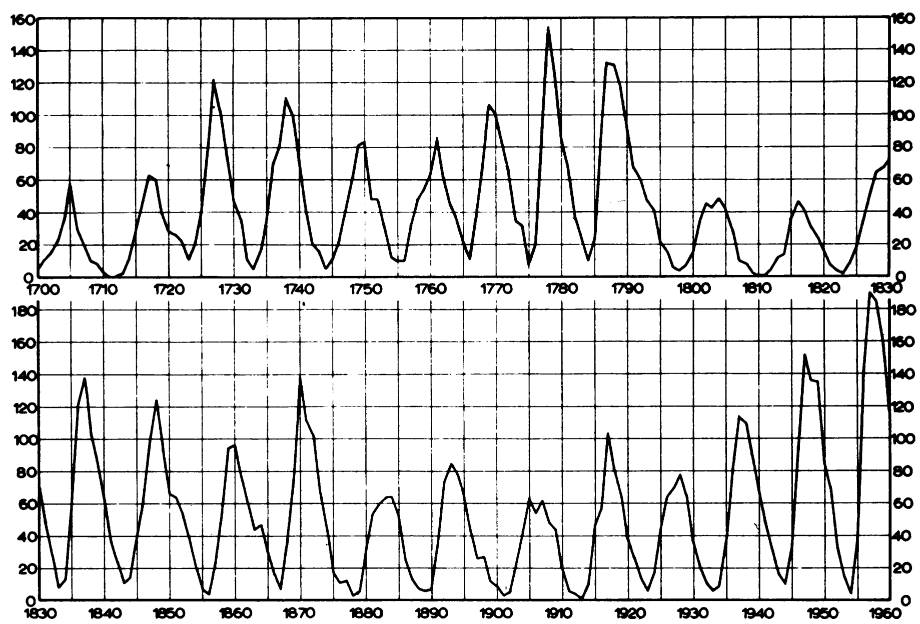


Fig. 1. Annual mean sunspot number, *R*, from 1700 to 1960. [From (3); courtesy of M. Waldmeier]

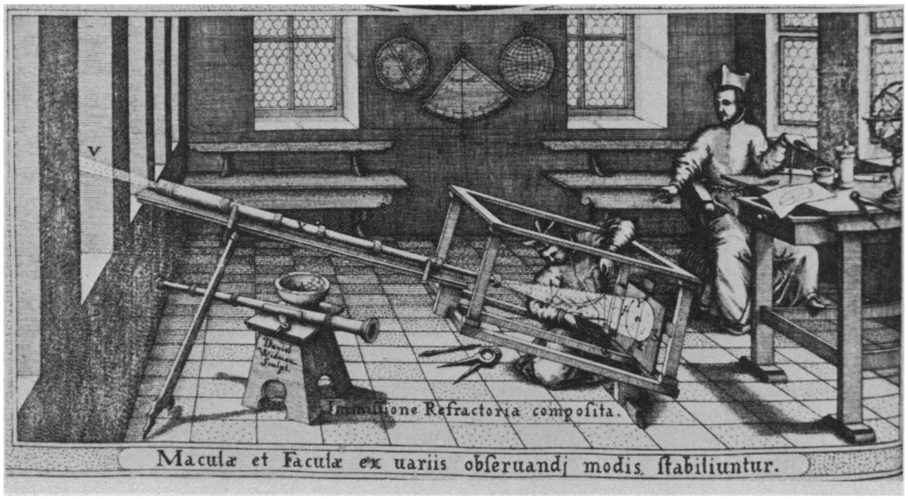


Fig. 2. Illustration of the technique used in the early 17th century for the observation of sunspots in which the solar image is projected on a screen [from a contemporary account by Scheiner (*31*)]. [By permission of the Houghton Library, Harvard University]

During the Maunder Minimum the same astronomers who observed the sun discovered the first division in Saturn's ring (in 1675) and found five of Saturn's satellites (1655 through 1684); the former discovery attests to an effective resolution of almost 1 arc second and the latter to an acuity to distinguish an 11th-magnitude object less than 40 arc seconds from the bright limb of the planet. During the 17th century astronomers observed seven transits of Venus and Mercury, which implies a certain thoroughness and a knowledge of other spots on the sun at the time. Römer determined the velocity of light (1675) from precise observations of the orbits of Jupiter's satellites. During the same century at least 53 eclipses of the sun—partial, annular, or total—were observed, including some in Asia and the Americas. It is significant that not one solar eclipse that passed through Europe was missed (*28*, *29*).

Active astronomers of the time included Flamsteed, Derham, Hooke, and Halley in England, both of the Huyghens in Holland, Hevelius in Poland, Römer in Denmark, the Cassinis, Gassendi, de la Hire, and Boulliau in France, Grimaldi and Riccioli in Italy, and Weigel and von Wurzelbau in Germany, to name but a few. And astronomers of that era were generous in their definition of astronomy and still included the sun among objects of respectable interest. During the years when the Cassinis were pursuing their investigations of Saturn in Paris, they also wrote scientific articles on their observations of the sun and sunspots (*30*). In 1630 Christopher Scheiner published a massive book, the *Rosa Ursina*, on sunspots and faculae and methods of observing them (*31*), and Hevelius produced in 1647 a detailed appendix on sunspots and a chapter on solar observation in his *Selenographia* (*32*).

In 1801 William Herschel commented that instrumental and observational shortcomings could explain most of the sunspot dearth between 1650 and 1713, and that, had more modern equipment been turned on the sun, many more spots would have been found (*19*); but we have little cause to think that he had looked very far into the matter, which then seemed of minor import, long before the discovery of the sunspot cycle. Maunder did not cite Herschel's dissenting view, but trumped it anyway, with a quotation from the more contemporary English astronomer William Derham, who in 1711 had given his view on whether observers of the time could have missed the spots (*16*, pp. 143–144):

> There are doubtless great intervals sometimes when the Sun is free, as between the years 1660 and 1671, 1676 and 1684, in which time, Spots could hardly escape the sight of so many Observers of the Sun, as were then perpetually peeping upon him with their Telescopes in *England*, *France*, *Germany*, *Italy*, and all the World over.

It seems clear that on this question Derham was right and Herschel wrong and that during the period of the Maunder Minimum astronomers had the instruments, the knowledge, and the ability to recognize the presence or absence of even small spots on the sun. And I might add that it does not take much of a telescope to see a sunspot.

Was a continuous watch kept on the sun? This is quite another question, and one for which direct evidence is lacking. Scheiner (1575–1650) and Hevelius (1611–1687) for at least a number of years made daily drawings of the sun and sunspots, but we cannot assume that this dutiful practice was continued by successors without interruption for 70 years. There were no organized or cooperative efforts, so far as we know, to keep a continuous diary of the sun, as is done today. But the motives of astronomers, then and now, are much the same: when a surprising dearth of sunspots was reported, as it was on repeated occasions during the span, we can expect that it would have inspired a renewed search to find some. In this respect it is significant that new sunspots were reported in the scientific literature as "discoveries," and that the sighting of a new spot or spot group was cause for the writing of a paper (*30*). This practice, were it followed today by even a few owners of 5-centimeter refractors, would produce an intolerable glut of manuscripts in the minimum years of the sunspot cycle and an avalanche in the years of maximum.

Comparisons with the present time are dangerous: toward the end of the 17th century the first learned societies were founded and the first journals came into existence. These journals were limited in number and scope and restricted in authorship and in that time bore little resemblance to the scientific periodicals we read and rely on for thorough coverage today. Absence of evidence may be a limited clue in such circumstances, as may uncontested and possibly unrefereed reports. Moreover, prevailing ideas of what something is influence how it is observed and reported. Sunspots were not thought to be what we know they are today. The original theological opposition to spots on the sun had been assuaged long before 1645, but, throughout the period of the Maunder Minimum and until Wilson's observations in 1774 (*33*), a prevalent concept of sunspots was that they were clouds on the sun, and who keeps a diary of clouds? Finally, we can suspect that sunspots, like all else in science, went in and out of vogue as objects of intense interest. After the initial surge of telescopic investigation, sunspots may have drifted into the doldrums of current science. If this is so, Scheiner's massive tome may have been in part to blame: the *Rosa Ursina* must have been considered a bore by even the verbose standards of its day, and it may have smothered initiative for a time (*34*, *35*).

Aurorae

Records of occurrence of the aurora borealis and aurora australis offer an independent check on past solar activity since there is a well-established correlation between sunspot number and the number of nights when aurorae are seen. The physical connection is indirect: auroral displays are produced when charged particles from the sun interact with the earth's magnetic field, resulting in particle accelerations and collisions with air molecules in our upper atmosphere. Aurorae register, therefore, those particle-producing events on the sun (such as flares and prominence eruptions) which happen to direct their streams toward the earth. Since these events arise in active regions on the sun, where there are also sunspots, we find a strong positive correlation between reported numbers of the two phenomena.

Aurorae are especially valuable as historical indicators of solar activity since they are spectacular and easily seen, require no telescopic apparatus, and are visible for hours over wide geographic areas. They have been recorded far back in history as objects of awe and wonder.

An increase in the number of reported aurorae inevitably follows a major increase in solar activity, and a drop in their number can generally be associated with the persistence of low numbers of sunspots, with certain reservations. As with sunspots, aurorae will not be seen unless the sky is reasonably clear, and an absence of either on any date in historical records could be due simply to foul weather. For the period of our interest we can exclude the possibility of years or decades of persistent continental overcast, since this would constitute a significant meteorological anomaly which would certainly have been noted in weather lore or cited by astronomers of the day (*36*).

In fact, the period between 1645 and 1715 was characterized by a marked absence of aurorae, as was first pointed out by Clerke. "There is," she wrote, ". . . strong, although indirect evidence that the 'prolonged sunspot minimum' was attended by a profound magnetic calm" (*17*, p. 206). Historical aurora catalogs (*37, 38*) confirm her assessment that there were extremely few aurorae reported during the years of the Maunder Minimum. Far fewer were recorded than in either the 70 years preceding or following.

Auroral occurrence is a strong function of latitude, or more specifically of distance from the geomagnetic poles. Analyses of auroral counts in the modern era (*39*) lead us to expect a display almost every night in the northern "auroral zone"—a band of geomagnetic latitude which includes northern Siberia, far-northern Scandinavia, Iceland, Greenland, and the northern halves of Canada and Alaska. But this region is also an area of sparse historical record for the 17th century, and it should probably be excluded from consideration for the present purpose. In a more populous band just south of this zone—which includes Sweden, Norway, and Scotland—we expect aurorae on 25 to about 200 nights per average year, the higher number at higher latitude. Progressively fewer are expected as we move south. For most of England, including the London area, we expect to see an average of 5 to 10 aurorae per year, or roughly 500 in 70 "normal" years. In Paris we can expect about 350 in the same period, and in Italy perhaps 50. From England, France, Germany, Denmark, and Poland, where astronomers were active during the Maunder Minimum, we might have expected reports of 300 to 1000 auroral nights, by the statistics of today. Fritz's historical catalog (*37*) lists only 77 aurorae for the entire world during the years from 1645 to 1715, and 20 of these were reported in a brief active interval, from 1707 to 1708, when sunspots were also seen. In 37 of the years of the Maunder Minimum not a single aurora was reported anywhere. Practically all reported aurorae were from the northern part of Europe: Norway, Sweden, Germany, and Poland. For 63 years of the Maunder Minimum, from 1645 until 1708, not one was reported in London. The next, on 15 March 1716, moved the astronomer Edmund Halley to describe and explain it in a paper that is now classic (*40*). He was then 60 years old and had never seen an aurora before, although he was an assiduous observer of the sky and had long wanted to observe one.

The auroral picture, which seems clear at first glance, is muddied by subjectivity and by the obscurity of indirect facts from long ago. Historical catalogs cannot record aurorae but only reports of aurorae. Clerke did not mention that auroral counts from all centuries before the 18th are very low by modern standards. The 77 events noted during the Maunder Minimum actually exceed the number recorded in any preceding century except the 16th, for which there are 161 in Fritz's catalog. By contrast, 6126 were reported in the 18th century and about as many in the 19th century (*41*).

The really striking feature of the historical record of aurorae (Fig. 4) is not so much the drop during the Maunder Minimum but an apparent "auroral turn-on" which commenced in the middle 16th century and surged upward dramatically after 1716. Were the historical record of

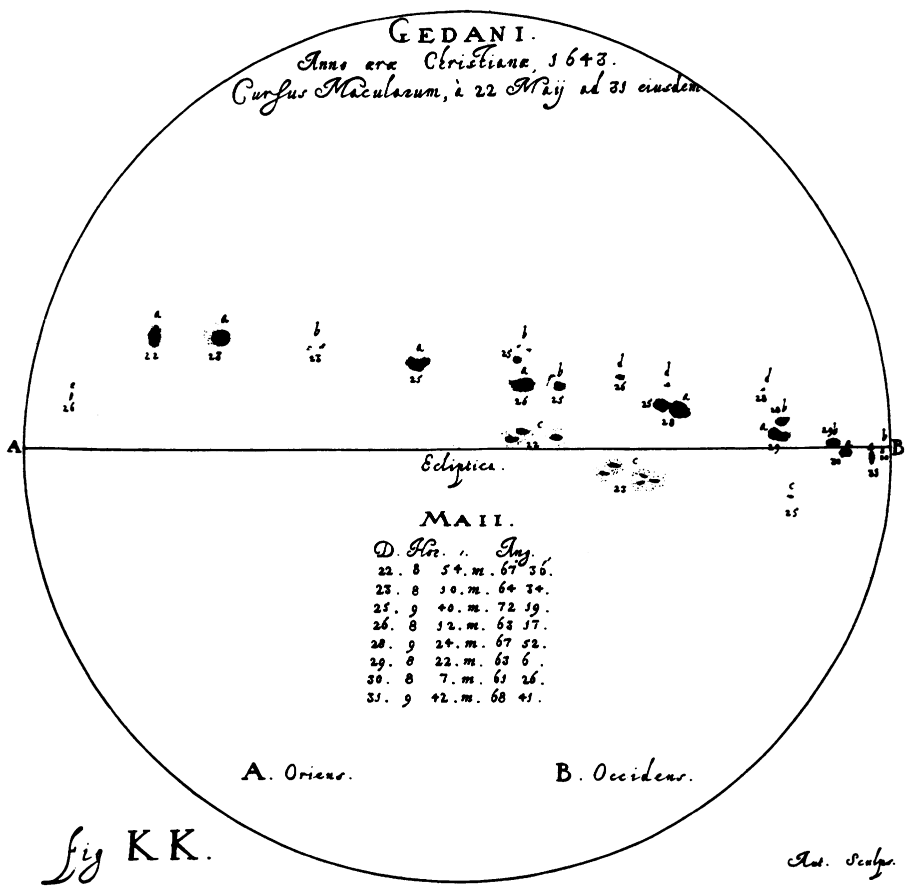


Fig. 3. A 17th-century drawing of the sun and sunspots by Hevelius (*32*). [By permission of the Houghton Library, Harvard University]

uniform quality (and it is not), this apparent "switching on" of the northern (and southern) lights would loom as the most significant fact of recent solar-terrestrial history. In truth, it must in part at least reflect the general curve of learning which probably holds for all of life in northern Europe at the time. The Renaissance came to auroral latitudes later than to the Mediterranean, and the envelope we see in Fig. 4 may be but its shadow. The effect is large, however, and a part of it could well represent a real change in the occurrence of aurorae on the earth, and, by implication, a change in the behavior of the sun. It is important that auroral reports do not increase monotonically with time as a learning curve might imply; the number reported rose in the 9th through 12th centuries and then fell off.

The separation of the physical from the sociological in Fig. 4 is a question of major importance in studies of the sun and earth. An acceptable solution would involve starting with a new and careful search for auroral data, particularly from northern latitudes, in the New World, Old World, and Orient. It must include careful allowance for superstition and vogues and restrictions in observing aurorae, shifts of population, and the possibly important effects of single events, such as the development of the printing press (about 1450), or Gassendi's decription of the French aurora of 1621 (*38*, p. 15) and Halley's paper in 1716 (*40*). One suspects that the dramatic jump in the number of reported aurorae after 1716 was a direct result of this important paper of Halley, which put the auroral phenomenon on firm scientific footing so that more aurorae were looked for and more regular records were kept.

As for the Maunder Minimum, its presence in the auroral record is surely real, appearing in Fig. 4 as a pronounced pause in the already upward-sweeping curve. Had Maunder looked first at Fritz's auroral atlas, he could have hypothesized a "prolonged sunspot minimum" from auroral evidence alone.

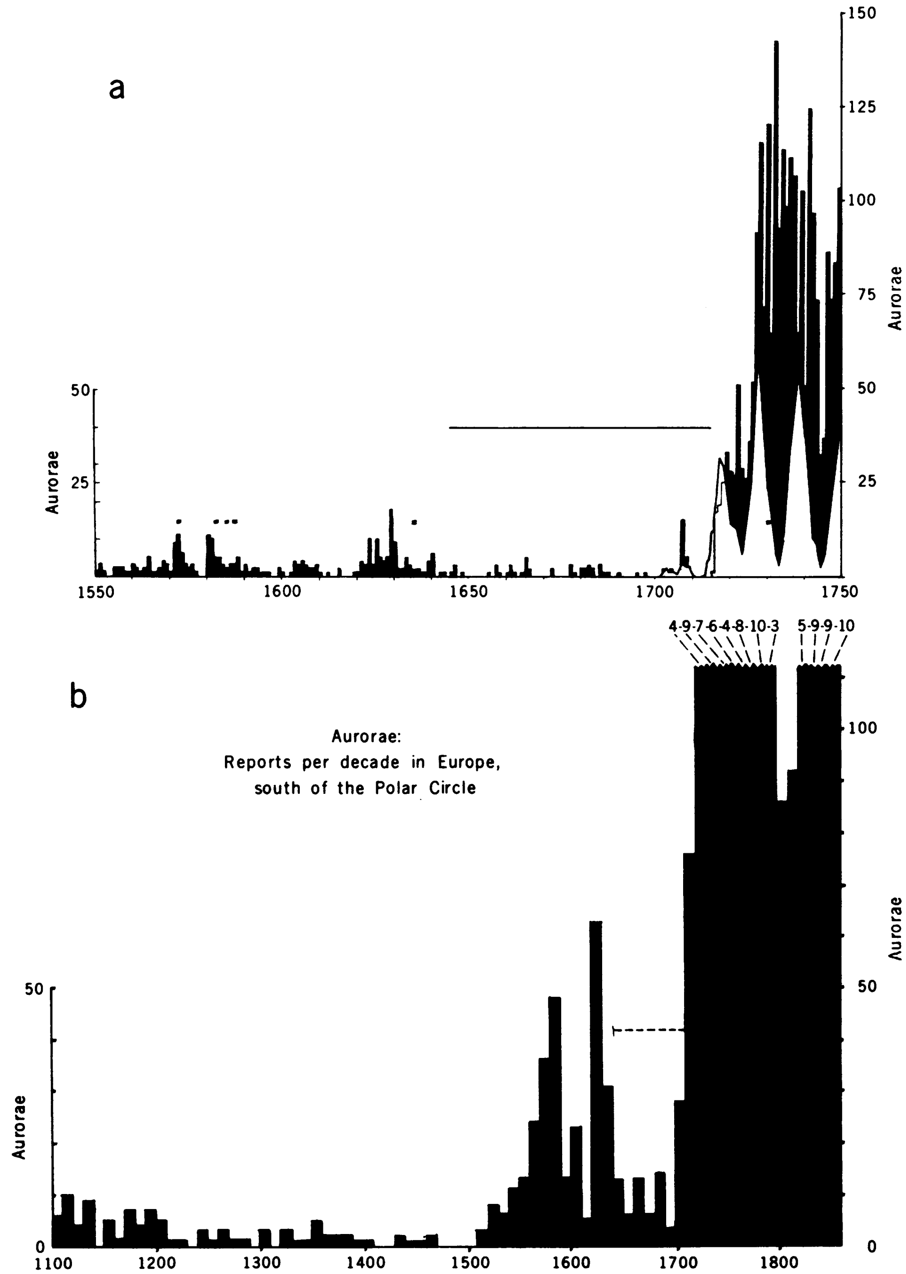


Fig. 4. Reported aurorae [from Fritz (37)]. (a) All reports, from 1550 to 1750 by year, with the annual mean sunspot number superposed as white curves at the right and Far East aurorae (*43*, *44*, *46*) shown as solid squares. (b) Reports per decade in latitudes 0° to 66°N; counts after 1715 must be multiplied by the numbers shown at the top right of the plot. The period of the Maunder Minimum is shown in each diagram as a horizontal line.

Sunspots Seen with the Naked Eye

Spots on the sun were seen with the naked eye long before the invention of the telescope (*42*) and were particularly noted in the Far East, where a more continuous record survives. They offer another check on the reality of an extended sunspot minimum, since naked-eye reports of sunspots might be expected were there any strong solar activity at the time. Large spots and large spot groups can be seen with little difficulty when the sun is partially obscured and reddened by smoke or haze, or at sunset or sunrise; small groups or small spots are beyond the effective resolution of the eye and cannot be seen. Thus reports of naked-eye sightings are biased toward times of enhanced solar activity, and attempts have been made to establish the epochs of past maxima in the solar cycle from naked-eye sunspot dates (*43*, *44*).

Pretelescopic sunspot observations probably come almost wholly from accidental observation. In Europe reports are rare and fragmentary (*4*). It is from the Orient, where sunspots were deemed important in legend and possibly in augury, that we find more extensive and useful records. But here, too, the numbers are small and can only be used as a very coarse indicator of past solar activity.

In 1933 (5 years after Maunder's death), Sigeru Kanda of the Tokyo Astronomical Observatory compiled a comprehensive list of 143 sunspot sightings from ancient records of Japan, Korea, and China, covering the period from 28 B.C. through A.D. 1743 (*43*). Most came after the 3rd century, so that the long-term average was about one sighting per decade. Were they distributed regularly (or just at solar maxima), we would thus expect six or seven events during the Maunder Minimum. It is significant that none was recorded between 1639 and 1720—a Far East gap that matches Western Hemisphere data very well.

As with aurorae, the evidence is necessary but not sufficient. Social practices or pressures could have suppressed observation or recording of spots during the time (*45*), leading to an apparent but unreal dearth. Moreover, the sunspot gap from 1639 to 1720 is neither the only nor the longest in Kanda's span of reports: there were 84 years without any reports of sunspot sightings ending in 1604, 117 years ending in 1520, and 229 years ending in 808 (Fig. 5a).

We may extend the naked-eye data in a sense by adding dates of reported aurorae in Japan, Korea, and China. All of these lands lie at low auroral latitudes, where displays are expected no more than once in 10 years. As in the case of sunspots seen with the naked eye, aurorae reported in the Orient are presumed to sample only intense solar activity. And, as with the sunspot sightings, no Far East aurorae were reported during the Maunder Minimum, and more specifically between 1584 and 1770 (*43, 44, 46*). The oriental data (sunspots and aurorae) confirm that there were no intense periods of solar activity during the Maunder Minimum and probably no "normal" maxima in the solar cycle.

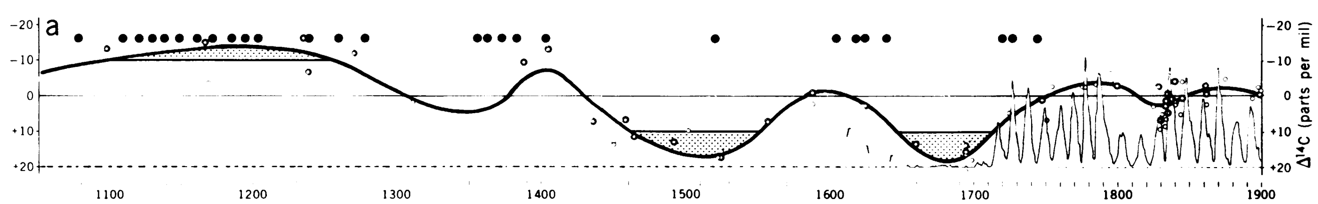
We may use the long span of oriental sunspot data as a coarse check on possible earlier occurrences of prolonged sunspot minima, or other gross, long-term modulations of sunspot activity. Of particular note is an intensification of sunspot and aurora reports in the 200-year period centered at around 1180, which is about halfway between the Maunder Minimum and a more extended period of absence of Far East sunspots and aurorae in the 7th and early 8th centuries. As I will show below, the naked-eye maximum coincides with a similar maximum of solar activity in the ^{14}C record. If this is a real long-term envelope of solar activity, its period is roughly 1000 years. We may be measuring only social effects, but, as with historical European aurorae, the subject is one of potential importance which deserves more specific attention by historians.

Carbon-14 and the History of the Sun

Modern confirmation for Maunder's "prolonged sunspot minimum" may be found in recent determinations of the past abundance of terrestrial ^{14}C. Carbon and its radioactive isotopes are abundant constituents of the earth's atmosphere, chiefly as carbon dioxide (CO_2). When CO_2 is assimilated into trees, for example, the carbon isotopes undergo spontaneous disintegration at well-known rates. Thus, by a technique now well established, it is possible to determine the date of life of a carbon-bearing sample, such as wood, by chemical measurement of its present ^{14}C content and comparison with a presumed original amount. The method requires a knowledge of the past abundance of ^{14}C in the atmosphere, and this value is found by analyzing, ring by ring, the ^{14}C content of trees of known chronology. The history of relative ^{14}C abundance deviations is now fairly well established and serves as the basis for accurate isotopic dating in archeology (*47–50*).

The ^{14}C history is useful in its own right as a measure of past solar activity, as has been demonstrated by a number of investigators (*51, 52*). The isotope is continuously formed in the atmosphere through the action of cosmic rays, which, in turn, are modulated by solar activity. When the sun is active, some of the incoming galactic cosmic rays are prevented from reaching the earth. At these times, corresponding to maxima in the sunspot cycle, less than the normal amount of ^{14}C is produced in the atmosphere and less is found in tree rings formed then. When the sun is quiet, terrestrial bombardment by galactic cosmic rays increases and the ^{14}C proportion in the atmosphere rises. There are other terms in the ^{14}C equilibrium process, as well as significant lags, but, were there a prolonged period of quiet on the sun, we would expect to find evidence of it in tree rings of that era as an abnormally high abundance of ^{14}C.

Such is the case. The first major anomaly found in the early studies of ^{14}C history was a marked and prolonged increase which reached its maximum between about 1650 and 1700 (*53*), in remarkable agreement in sense and date with the Maunder Minimum. The phenomenon, known in carbon-dating as the DeVries Fluctuation, peaked at about 1690 and is the greatest positive excursion found in the ^{14}C record—corresponding to a deviation of about 20 parts per mil from the norm. Subsequent stud-



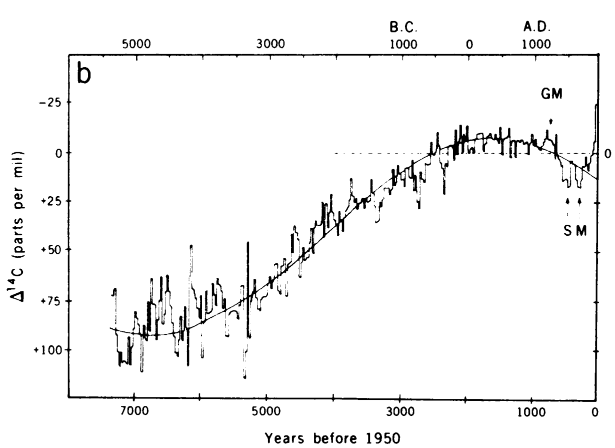


Fig. 5. (a) History of deviations in the relative atmospheric ^{14}C concentration from tree-ring analyses for the period 1050 to 1900 (*54*): single open circles, Northern Hemisphere data; double open circles, Southern Hemisphere data (a heavy line has been drawn through the Southern Hemisphere data); closed circles, dates of reported sunspots seen with the naked eye from Kanda (*43*). The annual mean sunspot number, R, is shown as a light solid line where known for the period after 1610, from Waldmeier (*3*) and this study. Periods when the relative ^{14}C deviation exceeds 10 parts per mil are shaded. They define probable anomalies in the behavior of the solar cycle: 1100 to 1250, Grand Maximum; 1460 to 1550, Spörer Minimum; 1645 to 1715, Maunder Minimum. (b) Measured ^{14}C deviation (in parts per mil) since about 5000 B.C., with observed (smoothed) curve of sinusoidal variation in the earth's magnetic moment [from (*61*), figure 2]. At about A.D. 100 the magnetic moment reached a maximum of about 10^{24} gauss per cubic centimeter. Shorter-term ^{14}C excursions attributed in this article to solar cause are marked with arrows: *M*, Maunder Minimum; *S*, Spörer Minimum; *GM*, Grand Maximum in the 12th to 13th centuries. The sharp negative ^{14}C deviation at the modern end of the curve is the Suess effect, due to fossil fuel combustion.

ies have established the DeVries Fluctuation as a worldwide effect.

Figure 5a shows a curve (open circles and heavy line) of the relative deviation in the ^{14}C concentration based on recent measurements of tree rings (*54*), plotted with increasing concentration downward for direct comparison with solar activity; also shown are annual numbers of sunspots, from (*3*) and the present work (light line), and the years of early naked-eye sunspot sightings from Kanda (closed circles) (*43*). The three quantities give a wholly consistent representation of the Maunder Minimum. We also note a clustering of naked-eye sunspot sightings at times when the ^{14}C record indicates greater than normal activity, and a general absence of them when the ^{14}C record indicates less than normal activity. Where annual sunspot numbers are plotted, the ^{14}C curve seems a fair representation of the overall envelope of the sunspot curve. It thus seems valid to interpret the ^{14}C record as an indicator of the long-term trend of solar activity and of real changes in solar behavior in the distant past, before the time of telescopic examination of the sun (*55–57*).

We may calibrate the ^{14}C curve for this purpose by noting that the years of the Maunder Minimum define a time when the relative deviation of ^{14}C exceeded 10 parts per mil. If we can make allowance for other effects on ^{14}C production and equilibrium, we may infer that, whenever the ^{14}C deviation exceeded $\pm$ 10 parts per mil, solar activity was anomalously high or low, with the Maunder Minimum corresponding to a definition of "anomalous." We must remember that the ^{14}C indications will tend to lag behind real solar changes by periods of 10 to 50 years, because of the finite time of exchange between the atmosphere and trees. By this criterion there have been three possible periods of marked solar anomaly during the last 1000 years: the Maunder Minimum, another minimum in the early 16th century, and a period of anomalously high activity in the 12th and early 13th centuries. We can think of these as the grand minima and a grand maximum of the solar cycle, although we cannot judge from these data whether they are cyclic features.

The earlier minimum, which we might call the Spörer Minimum, persisted by our 10-parts-per-mil criterion from about 1460 through 1550. Its ^{14}C deviation is not quite as great as that during the Maunder Minimum, although that distinction is not a consistent feature of all representations of the ^{14}C history (*58*). We can presume that the Spörer Minimum was probably as pronounced as the Maunder Minimum and that during those years there were few sunspots indeed. It appears to have reached its greatest depth in the early 16th century when there were also very few aurorae reported.

We noted earlier the possibility of an intensification of solar activity in the 12th and 13th centuries, on the basis of naked-eye sunspot reports from the Orient. Evidence for the same maximum is found in the historical aurora record (Fig. 4): the number of aurorae in Fritz's catalog (*37*) is about constant for the 9th, 10th, and 11th centuries (23, 27, and 21 aurorae per century, respectively), rises abruptly for the 12th century (53 aurorae), and then falls for the next three centuries (16, 21, and 7 aurorae). The ^{14}C record (Fig. 5a) shows a similar anomaly in the same direction: a decrease in ^{14}C which could be attributed to a prolonged increase in solar activity.

We must take care in assigning any of the ^{14}C variations to a solar cause for there are other important mechanisms. The overwhelming long-term effects on ^{14}C production are ponderous changes in the strength of the earth's magnetic field (*59, 60*). Archeomagnetic studies have shown that in the past 10,000 years the earth's magnetic moment has varied in strength by more than a factor of 2, following an apparently sinusoidal envelope with a period of about 9000 years, on which shorter-term changes are impressed. The terrestrial moment reached maximum strength at about A.D. 100, at which time we would expect to find a minimum in ^{14}C production because of enhanced shielding of the earth against cosmic rays.

The good fit of the observed (smoothed) curve of geomagnetic change to the long-term record of fossil ^{14}C is shown in Fig. 5b, from a recent compilation (*61*), here replotted with increasing ^{14}C in the downward direction to display increasing solar activity and increasing geomagnetic strength as upward-going effects. Damon (*57*) has stressed that the long-term trends in the radiocarbon content of the atmosphere have been dominated in the past 8000 years by the geomagnetic effect, while the shorter-term fluctuations have probably been controlled by changes in solar activity. This point seems clear in Fig. 5b, where, near the modern end of the curve, the Maunder Minimum (*M*) and Spörer Minimum (*S*) stand out as obvious excursions from the long-term envelope of geomagnetic change. And at about 1200 we find a broad departure in the opposite direction, which might fit the 12th- and 13th-century maximum in sunspot and auroral reports. Whether the sun was indeed responsible is open to question, however, for Bucha (*59*) has pointed out that this ^{14}C decrease follows a similar short-term increase in the earth's magnetic moment (not shown in Fig 5b), which had its onset at about A.D. 900. Moreover, there is uncertainty in the fit of the smoothed archeomagnetic curve to the radiocarbon data, and a shift to the right or left will change the apparent contrast of these shorter-term excursions.

We should like to know how solar activity in a possible 12th-century Grand Maximum compares with the present epoch, but the present is an era of confusion in ^{14}C. The ^{14}C concentration has been falling steeply since the end of the 19th century, and the deviation ($\Delta^{14}C$) is now about -25 parts per mil. Were this a solar effect, it would be evidence of anomalously high solar activity. In fact, the sharp drop is an effect of human activity—the result of fossil fuel combustion, which introduces CO_2 with different carbon isotopic abundance ratios—the so-called Suess Effect (*47*). If fossil fuel combustion is responsible for all of the modern ^{14}C trend, then during the 12th-century Grand Maximum (when industrial pollution was not significant), the natural ^{14}C deviation may have been much greater than at present and the sun may have been more active than we are accustomed to observing in the modern era. There were possibly more spots on more of the sun during the 12th-century Grand Maximum, and, if the 11-year cycle operated then, there may have been higher maxima and higher minima than any we see in Fig. 1.

The shallow dip and rise in the 14th and early 15th centuries (Fig. 5a) suggest the presence of a subsidiary solar period of about 170 years, but these features seem for now too slight to warrant speculation; we may expect that additional ^{14}C data will clarify the case. The information available at present allows one to describe the history of the sun in the last millennium as follows: a possible Grand Maximum in the 12th century, a protracted fall to a century-long minimum around 1500, a short rise to "normal," and then the fall to the shorter, deeper Maunder Minimum, after which there has been a steady rise in the envelope of solar activity (*25*).

This last phase, which includes all detailed records of the sun and the sunspot cycle, does not appear in the ^{14}C history as very typical of the sun's behavior in the past, particularly if the *phase* of the long-term curve is important. During most of the last 1000 years the long-term envelope of solar activity was either higher than at present, or falling, or at grand minima like the Maunder Minimum. As with the present climate, what we think of as normal may be quite unusual. The possibility that solar behavior since 1715 was unlike that in the past has already been proposed to help explain the sudden auroral turn-on. Another piece of evidence comes from records of the sun's appearance at eclipse.

Absence of the Corona at Eclipse

Historical accounts of the solar corona at total eclipse offer another possible check on anomalies in past solar behavior. We know that the shape of the corona seen at eclipse varies with solar activity: when the sun has many spots, the corona is made up of numerous long tapered streamers which extend outward like the petals of a flower. As activity wanes, the corona dims and fewer and fewer streamers are seen. At a normal minimum in the solar cycle the corona seen by the naked eye is highly compressed and blank except for long symmetric extensions along its equator. We now believe that coronal streamers are rooted in concentrated magnetic fields on the surface of the sun, which, in turn, are associated with solar activity and sunspots. As sunspots fade, so do concentrated surface fields and associated coronal structures. Continuous, detailed, observations of the solar corona in x-ray wavelengths from Skylab have confirmed the association of coronal forms with loops and arches in the surface fields and have shown that in areas where there are no concentrated fields, loops, or arches there is no apparent corona (*62*).

Were there a total absence of solar activity, we would still expect to observe a dim, uniform glow around the moon at eclipse: the zodiacal light, or false corona, would remain, since it is simply sunlight scattered from dust and other matter in the space between the earth and the sun. At times of normal solar activity the corona seen at eclipse is a mixture of the true corona (or K corona) and the weaker glow of the zodiacal light (or F corona). The latter is a roughly symmetric glow around the sun which falls off in brightness from the limb and is distended in the plane of the planets where interplanetary dust is gravitationally concentrated. If the F corona were ever seen alone, we would expect it to appear as a dull, slightly reddish, eerie ring of light of uniform breadth and without discernible structure.

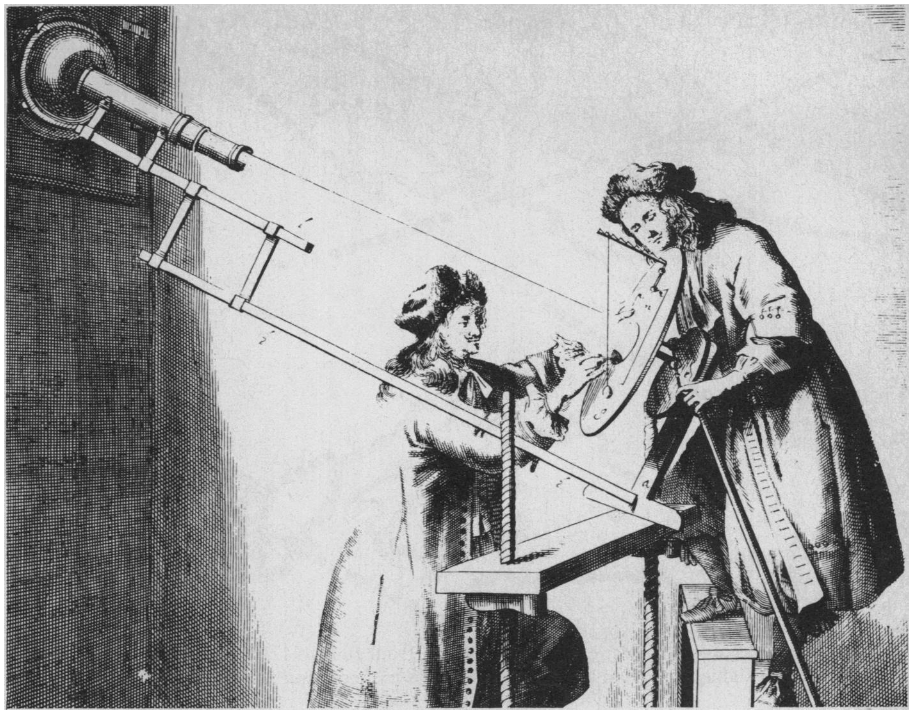


Fig. 6. Early 17th-century observation of a solar eclipse, by projection in a darkened room, as depicted in (*80*). Hevelius himself is depicted at the left, marking the obscuration of the sun by the lunar disk. [By permission of the Houghton Library, Harvard University]

In fact, firsthand descriptions of total solar eclipses during the Maunder Minimum seem entirely consistent with an absence of the modern structured corona, but proof seems blurred by the customs of observing eclipses in the past and by the fact that scientists seldom describe what is missing or what is not thought to be important. The solar origin of the corona was not established until the late 19th century; before that it seemed equally well explained as sunlight scattered in our own atmosphere, or on the moon. Solar eclipses were regularly and routinely observed throughout the 17th century but not to study the physical sun. They were occasions to test the then popular science of orbit calculation: careful measurement and timing of solar obscuration by the moon offered checks on lunar and terrestrial motions and opportunity to measure the relative sizes of solar and lunar disks. Such details are best obtained not at the eyepiece of a wide-field telescope in the open air but in a darkened room, by projection of the disks of the moon and sun upon a card, as we see in a contemporary drawing from Hevelius (Fig. 6). Under these restrictive conditions a corona, structured or not, could escape detection, particularly since it appeared so briefly and at just the time when undivided attention was demanded to observe the precise minutia of obscuration (*63*).

Nor was it so important to seek out geographic places on the central path of a total eclipse. The corona—K or F—is so faint that it cannot be seen except in exact totality. But if one's purpose were astronomical mensuration and timing, a partial or near-total eclipse was almost as good as a total eclipse and could be observed more accurately in the familiar conditions of permanent observatories. Since partial solar eclipses can be seen over large areas and thus occur frequently at any location, there was not the impetus of today to travel far and wide to set up camp for one-time tries in distant, hostile lands. Eclipse expeditions are a modern fad that did not take hold until about the 19th century (*64*).

These fundamental differences severely limit the number of cases we can test. There were 63 opportunities to see the sun eclipsed between 1645 and 1715 (*65*), but only eight of them passed through those parts of Europe where astronomers did their daily work (Fig. 7). Another case (1698) comes from the New World. Only a few of the European eclipses reached totality near any permanent observatory, and the three best observed occurred at the end of our period of interest—in 1706, 1708, and 1715, when spots had begun their return.

Nevertheless, from this list comes a handful of accounts which bear on the question and answer it consistently. They are descriptions of the corona from the eclipses of 1652, 1698, 1706, and 1708, the only contemporary firsthand descriptions of the sun eclipsed that I

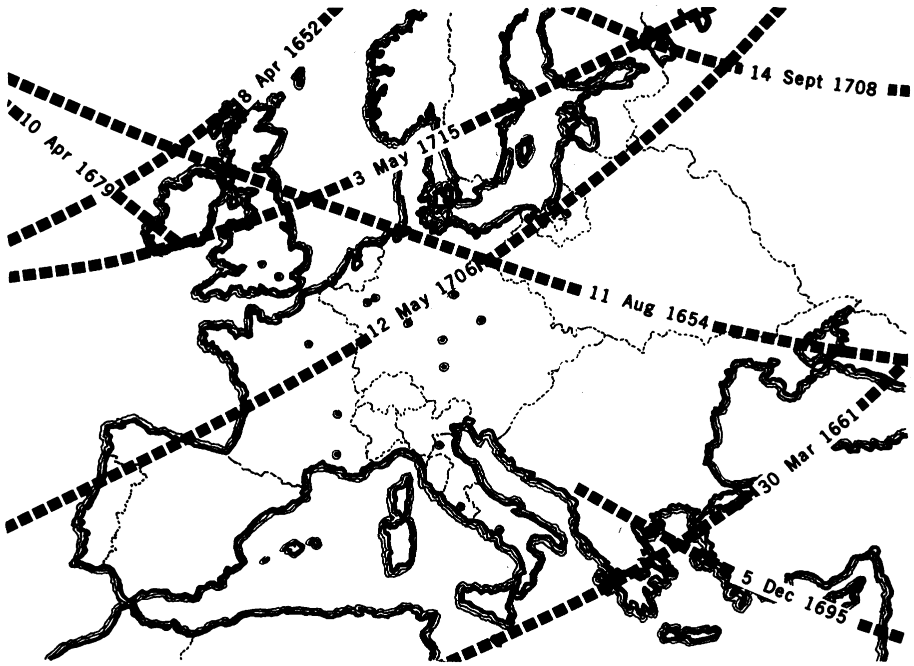


Fig. 7. Paths of totality for solar eclipses in Europe, from 1640 to 1715, from Oppolzer (*65*). Sites of observatories which reported eclipse observations in the period are shown as double circles.

can find (*66*). They were written, in general, by amateurs and nonconformists who watched the spectacle with eyes open to all of it. None describes the corona as showing structure. Not one mentions the streamers which at every eclipse in the present time are so easily seen with the naked eye to stretch as much as a degree or more above the solar limb. All describe the corona as very limited in extent: typically only 1 to 3 arc minutes above the solar limb. In each case the corona is described as dull or mournful, and often as reddish. No drawings were made. Every account is consistent with our surmise of what the zodiacal light would look like at eclipse, were the true corona really gone.

By 1715, the annual sunspot number had reached 26 and was climbing. At the eclipse of that year, at the end of the Maunder Minimum, the corona is fairly well described, and for the first time we have drawings of it. For the first time distinct coronal structures are described emanating from the sun. R. Cotes of Cambridge University described the corona (in a letter to Isaac Newton) as a white ring of light around the moon, its densest part extending about 5 arc minutes above the limb; he then added the following (*67*):

> Besides this ring, there appeared also rays of a much fainter light in the form of a rectangular cross. . . . The longer and brighter branch of this cross lay very nearly along the ecliptic, the light of the shorter was so weak that I did not constantly see it.

We may presume that the light of the shorter branch was the polar plumes which we see today at times of sunspot minimum and that the longer, brighter branch was the familiar equatorial extensions seen at times of low sunspot activity. Thus by 1715 we find the corona described in modern terms and fitting a familiar form.

In her paper on the dearth of aurorae Clerke mentioned, without example, that it appeared to her probable that during the "prolonged sunspot minimum" the radiated structure of the solar corona was also "in abeyance" (*17*). Recently Parker has repeated Clerke's conjecture (*68*). The case for a disappearance of the structured corona during the Maunder Minimum might seem more solid were it not for the fact that the earliest description yet found for the rayed or structured corona at *any* eclipse is that of Cotes in 1715.

R. R. Newton has expressed the situation very explicitly, on the basis of his own researches for definite accounts of the corona as positive documentation of historical solar eclipses (*23*, p. 99):

> The corona is mentioned in most modern discussions of total solar eclipses, and to most people it is probably the typical and spectacular sight associated with a total eclipse. In view of this, it is surprising to see how little the corona appears in ancient or medieval accounts. . . .

Newton continues (*23*, p. 601):

> . . . there is no clear reference to the corona in any ancient or medieval record that I have found. The most likely reference is perhaps the remark by Plutarch . . . but the meaning of Plutarch's remark is far from certain.

I should add that here Newton is referring to *any* unambiguous description of the corona, K or F.

A misleading statement common in popular stories of eclipses is that the solar corona was seen in antiquity much as we would describe it today. Usually cited are two early accounts, one by Plutarch (about A.D. 46 to 120) and another by Philostratus (about A.D. 170 to 245). Both reports are ambiguous at best, and neither distinguishes between a structured or an unstructured appearance (*69*). The situation in all subsequent descriptions before the 18th century seems to be no different. At the eclipse of 9 April 1567 Clavius reported seeing "a narrow ring of light around the Moon" at maximum solar obscuration (although Kepler challenged this as possibly an annular eclipse). Jessenius at a total eclipse in 1598 reported "a bright light shining around the Moon." And Kepler himself reported that at the eclipse of 1604 (*70*): "The whole body of the Sun was effectually covered for a short time. The surface of the Moon appeared quite black; but around it there shone a brilliant light of a reddish hue, and uniform breadth, which occupied a considerable part of the heavens." None of these or any other descriptions that I can find fit a rayed or structured corona; in many are the words "of uniform breadth," and it seems to me most likely that we are reading descriptions of the zodiacal light, or of a K corona so weak that its radiance is overpowered by the glow of the F corona.

It could be that, until the scientific enlightenment of the 18th century, no one felt moved to describe the impressive structure of the solar corona at eclipse. Indeed, there are other examples from the history of eclipse observation where large and striking features were missed by good observers who were watching other things (*71*). Perhaps the rays of the corona at eclipse were thought to be so much like the common aureole around the sun that they were not deemed worthy of description. Other excuses could be offered. It will be hard for anyone who has seen the corona with the naked eye to accept these explanations and to believe that, of the thousands of observers at hundreds of total eclipses, not one would have commented on a thing so breathtaking and beautiful. It thus seems to me more probable that, through much of the long period of the Maunder Minimum and the Spörer Minimum, extending between perhaps 1400 and 1700, the sun was at such a minimum of activity that the K corona was severely thinned or absent altogether. The same may have been true for a much longer span before 1400 and for different reasons may apply as well to the Grand Maximum of the 12th and 13th centuries and possibly earlier. But here the records are so dim and scant that conclusions seem unwarranted. In any case the corona as we know it may well be a modern feature of the sun. It is an interesting question, and another important challenge for historians.

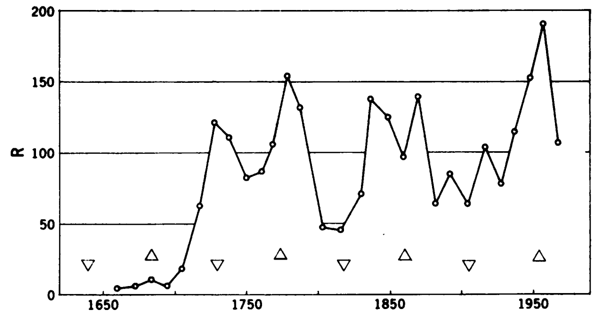


Fig. 8. Annual mean sunspot numbers at maxima in the 11-year cycle, from 1645 to the present, to demonstrate long-term trends in solar activity. Evident is the well-known 80-year cycle (extrema shown as triangles) imposed on a persistent rise since the Maunder Minimum. The 78- or 80-year cycle was first noted by Wolf (*81*) and later studied in detail by Gleissberg (*82*). The solar constant has also been slowly rising through the period during which it has been measured, since about 1908 (*25, 72*).

Summary and Conclusions

The prolonged absence of sunspots between about 1645 and 1715, which Spörer and Maunder described, is supported by direct accounts in the limited contemporary literature of the day and cited regularly in astronomy works of the ensuing century. We may conclude that the absence was not merely a limitation in observing capability because of the accomplishments in other areas of astronomy in the late 17th and early 18th centuries, and because drawings of the sun made at the time show almost all the sunspot detail that is known today. Major books by Scheiner and Hevelius, published just before the onset of the Maunder Minimum, describe wholly adequate methods for observing the sun and sunspots. We may assume that a fairly steady watch was kept, since the dearth of spots was recognized at the time and since the identification of a new sunspot was cause for the publication of a paper. We can discount the possibility of 70 years of overcast skies, since there is no evidence of such an anomaly in meteorological lore and since nighttime astronomy was vigorous and productive through the same period. Evidence which confirms the Maunder Minimum comes from records of naked-eye sunspot sightings, auroral records, the now-available history of atmospheric ^{14}C, and descriptions of the eclipsed sun at the time.

I can find no facts that contradict the Maunder claim, and much that supports it. In questions of history where only a dim and limited record remains and where we are blocked from making crucial observational tests, the search for possible contradiction seems to me a promising path to truth. I am led to conclude that the "prolonged sunspot minimum" was a real feature of the recent history of the sun and that it happened much as Maunder first described it.

Earlier in this article I reviewed the possible impact of a real Maunder Minimum on theories of the sun and the solar cycle. For some implications the distinction between no sunspots and a few (annual sunspot numbers of one to five) is crucial; it is important to know whether during the great depression of the Maunder Minimum the solar cycle continued to operate at an almost invisible level, with so few spots that they were lost in our fuzzy definition of "zero." Maunder held that there were enough instances of sunspot sightings through the period to make this case likely, and that the isolated times when a few spots appeared enabled one to identify the crests of a sunken spot curve "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 champaign" (*16*). This explanation seems to me unlikely, since the known, visible crests are not at regular spacings. We can hope that more thorough investigation of contemporary literature will enable us to make this important distinction which for now seems beyond the limit of resolution.

The years of the Maunder Minimum define a time in the ^{14}C record when the departure from normal isotopic abundance exceeded 10 parts per mil. If we take a ^{14}C deviation of this magnitude as a criterion of major change in solar behavior, we may deduce from ^{14}C history the existence of at least two other major changes in solar character in the last millennium: a period of prolonged solar quiet like the Maunder Minimum between about 1460 and 1550 (which I have called the Spörer Minimum) and a "prolonged sunspot maximum" between about 1100 and 1250. If the prolonged maximum of the 12th and 13th centuries and the prolonged minima of the 16th and 17th centuries are extrema of a cycle of solar change, the cycle has a full period of roughly 1000 years. If this change is periodic, we can speculate that the sun may now be progressing toward a grand maximum which might be reached in the 22nd or 23rd centuries. The overall envelope of solar activity has been steadily increasing since the end of the Maunder Minimum (Fig. 8), giving some credence to this view. Moreover, throughout the more limited span during which it has been measured, the solar constant appears to have shown a continuous rising trend which during the period from 1920 through 1952 was about 0.5 percent per century (*72*).

The coincidence of Maunder's "prolonged solar minimum" with the coldest excursion of the "Little Ice Age" has been noted by many who have looked at the possible relations between the sun and terrestrial climate (*73*). A lasting tree-ring anomaly which spans the same period has been cited as evidence of a concurrent drought in the American Southwest (*68, 74*). There is also a nearly 1 : 1 agreement in sense and time between major excursions in world temperature (as best they are known) and the earlier excursions of the envelope of solar behavior in the record of ^{14}C, particularly when a ^{14}C lag time is allowed for: the Spörer Minimum of the 16th century is coincident with the other severe temperature dip of the Little Ice Age, and the Grand Maximum coincides with the "medieval Climatic Optimum" of the 11th through 13th centuries (*75, 76*). These coincidences suggest a possible relationship between the overall envelope of the curve of solar activity and terrestrial climate in which the 11-year solar cycle may be effectively filtered out or simply unrelated to the problem. The mechanism of this solar effect on climate may be the simple one of ponderous long-term changes of small amount in the total radiative output of the sun, or solar constant. These long-term drifts in solar radiation may modulate the envelope of the solar cycle through the solar dynamo to produce the observed long-term trends in solar activity. The continuity, or phase, of the 11-year cycle would be independent of this slow, radiative change, but the amplitude could be controlled by it. According to this interpretation, the cyclic coming and going of sunspots would have little effect on the output of solar radiation, or presumably on weather, but the long-term envelope of sunspot activity carries the indelible signature of slow changes in solar radiation which surely affect our climate (*77*).

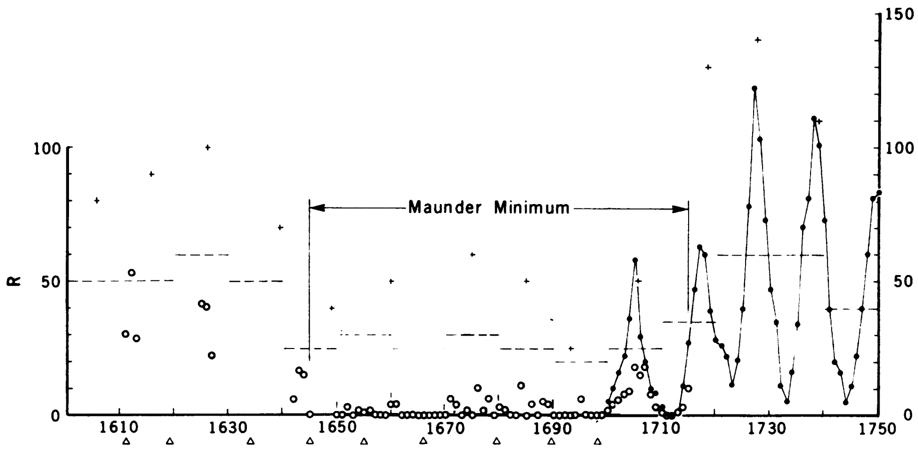


Fig. 9. Estimated annual mean sunspot numbers, from 1610 to 1750: open circles are data from Table 1; connected, closed circles are from Waldmeier (*3*); dashed lines (decade estimates) and crosses (peak estimates) are from Schove (*8–11*); triangles are Wolf's estimated dates of maxima for an assumed 11.1-year solar cycle (*3, 6*).

from the sun, with possible terrestrial effects. Our present understanding of the solar wind is that its flow is regulated by closed or open magnetic field configurations on the sun (*78*). We can only guess what effect a total absence of activity and of large-scale magnetic structures would have on the behavior of solar wind flow in the ecliptic plane. One possibility is that, were the sun without extensive coronal structure during the Maunder Minimum, the solar wind would have blown steadily and isotropically, and possibly at gale force, since high-speed streams of solar wind are associated with the absence of closed structures in the solar corona. During an intensive maximum, as is suggested for the 12th and 13th centuries, the solar wind was probably consistently weak, steady, and with few recurrent streams.

The existence of the Maunder Minimum and the possibility of earlier fluctuations in solar behavior of similar magnitude imply that the present cycle of solar activity may be unusual if not transitory. For long periods in the historic past the pattern of solar behavior may have been completely different from the solar cycle today. There is good evidence that within the last millennium the sun has been both considerably less active and probably more active than we have seen it in the last 250 years. These upheavals in solar behavior may have been accompanied by significant long-term changes in radiative output. And they were almost certainly accompanied by significant changes in the flow of atomic particles

The reality of the Maunder Minimum and its implications of basic solar change may be but one more defeat in our long and losing battle to keep the sun perfect, or, if not perfect, constant, and if inconstant, regular. Why we think the sun should be any of these when other stars are not is more a question for social than for physical science.

Table 1. Estimated annual mean sunspot numbers, *R*, from 1610 to 1715; X, sunspots noted but not counted; XX, unusual number of sunspots noted but not counted; (X), unusually small number of sunspots noted but not counted. Schove's values are for the maxima of each supposed cycle.

Year	*R*	Waldmeier (*3*)	Schove (*9*)	Year	*R*	Waldmeier (*3*)	Schove (*9*)	Year	*R*	Waldmeier (*3*)	Schove (*9*)
1610	X			1646				1681	2		
1611	30	Minimum		1647				1682	0		
1612	53			1648				1683	0		
1613	28			1649		Maximum	40	1684	11		
1614				1650	0			1685	0	Maximum	50
1615	X			1651	0			1686	4		
1616	X	Maximum	90	1652	3			1687	0		
1617	X			1653	0			1688	5		
1618	(X)			1654	2			1689	4		
1619		Minimum		1655	1	Minimum		1690	0	Minimum	
1620				1656	2			1691	0		
1621	X			1657	0			1692	0		
1622	X			1658	0			1693	0	Maximum	30
1623	X			1659	0			1694	0		
1624	X			1660	4	Maximum	50	1695	6		
1625	41			1661	4			1696	0		
1626	40	Maximum	100	1662	0			1697	0		
1627	22			1663	0			1698	0	Minimum	
1628				1664	0			1699	0		
1629	(X)			1665	0			1700	2	5	
1630				1666	0	Minimum		1701	4	11	
1631				1667	0			1702	6	16	
1632	(X)			1668	0			1703	8	23	
1633											
1634	(X)	Minimum		1669	0			1704	9	36	
1635	(X)			1670	0			1705	18	58	50
1636				1671	6			1706	15	29	
1637				1672	4			1707	18	20	
1638	X			1673	0			1708	8	10	
1639	XX			1674	2			1709	3	8	
1640		Maximum	70	1675	0	Maximum	60	1710	2	3	
1641				1676	10			1711	0	0	
1642	6			1677	2			1712	0	0	
1643	16			1678	6			1713	2	2	
1644	15			1679	0			1714	3	11	
1645	0	Minimum		1680	4	Minimum		1715	10	27	

Appendix: Sunspot Numbers

I have used contemporary accounts of telescopic observation of the sun to reconstruct estimated annual mean sunspot numbers for the period from 1610 to 1715 (Table 1 and Fig. 9). Principal sources were Wolf's compilations (*6*) and (*13–16, 19, 20, 28–32*). The journal sources are, for the most part, the same as those that were used by LaLande, Spörer, and Maunder; thus, except for the direct numerical data from Wolf, Scheiner, and Hevelius, sunspot numbers given here are simply a literal quantification of Maunder's descriptive account. Full reliance has been placed on unchallenged statements in contemporary literature which specify periods in which no sunspots were seen, as, for example, between 1656 and 1660, 1661 and 1671, 1689 to 1695, 1695 to 1700, and 1710 to 1713.

Earlier I classified Wolf's historical sunspot data; by the same criteria the data in Table 1 should be given a reliability grade of "poor," since they come from largely discontinuous sets and since allowance for observer and site can only be guessed. The estimated annual sunspot numbers are uncertain to at least a factor of 2, and zero as an annual average means 0 to perhaps 5. The fact that the telescopes of Flamsteed and Cassini were in less than perfect observing sites could have caused these observers to miss a class of tiny, isolated spots which might be detected and counted by keen observers today. The more important point is that their sites and instruments were certainly adequate to detect any level of activity higher than that at the minima of the present solar cycle; they might have missed a few spots but they could not have missed a large number.

My sunspot numbers for the period 1700 to 1715 are somewhat lower than those given for the same period by Waldmeier (*3*), who took them from Wolf. Both values are shown in Table 1 and Fig. 9. The general agreement seems heartening, but the difference may be important since it is in the only span of overlap with other direct numerical compilations. It is also in the least reliable part of Wolf's data and the period of recovery from the Maunder Minimum, for which a more gradual rise seems reasonable. Auroral data and eclipse observations from the period of overlap seem to me to support the more suppressed sunspot curve (Fig. 9). I find it hard to justify Wolf's numbers for his first and possibly second cycles and suspect that his unusual-shaped maximum for 1705 was an artificiality of unrealistic correction factors. Wolf did not have confidence in most of the data for 1700 to 1749 (*6*), and his numbers toward the beginning of that period may represent, more than anything else, a wishful extrapolation of normalcy. I also show in Fig. 9 and Table 1 Schove's estimates of decade-averaged and peak sunspot numbers from the STP (*8–11*), which we can also expect to be systematically high (*79*).

Numbers given for 1625 to 1627 and 1642 to 1644 (from Scheiner and Hevelius) are probably more reliable than any subsequent data in Table 1, since they are based on more nearly continuous daily drawings. Data for 1611 through 1613 come from the observations of Galileo. Waldmeier (*3*) and Schove (*8–11*) have apparently followed Wolf in assuming that these three islands of data before 1650 sample extrema of the sunspot cycle: Galileo and Scheiner at maxima, Hevelius at minimum. If these periods are all nearer maxima, as I suspect, they give some hint of the fall to the long minimum that followed. The nature of the fall suggests that the telescope was invented barely in time to "discover" sunspots before their numbers shrank to nearly zero. Had the invention of the telescope been delayed by as little as 35 years, the telescopic discovery and more thorough counting of sunspots could have been postponed a full century, burying forever the principal evidence for the Maunder Minimum.

References and Notes

1. The Wolf sunspot number (or sunspot relative number) is defined as $R = k(10g + f)$, where f is the total number of spots (irrespective of size), g is the number of spot groups, and k is a normalizing factor to bring the counts of different observers, telescopes, and sites into agreement.
2. R. B. Leighton, *Astrophys. J.* **156**, 1 (1969).
3. M. Waldmeier, *The Sunspot-Activity in the Years 1610–1960* (Schulthess, Zurich, 1961).
4. R. J. Bray and R. E. Loughhead, *Sunspots* (Wiley, New York, 1965), p. 1.
5. H. Schwabe, *Astron. Nachr.* **20** (No. 495) (1843). For an interesting discussion of Schwabe, his lonely work, and the prejudice against the idea of cyclic solar behavior before that time, see M. J. Johnson, *Mem. R. Astron. Soc.* **26**, 196 (1858).
6. R. Wolfe, *Sunspot Observations, 1610–1715*, facsimile of a typescript from Eidgen Sternwarte in Zurich (in G. E. Hale Collection, Hale Observatory Library, Pasadena, Calif.). The 11-page manuscript lists the days of each year on which spots were or were not seen, the numbers of spots (where known), and notes and references. Other more condensed accounts of the period by Wolf include: *Astron. Mitt. Zürich* **1**, viii (1856); *ibid.* **24**, 111 (1868).
7. In (*3*, p. 8), Waldmeier states that "Wolf intended to prove for a longer interval the sunspot-periodicity discovered shortly before by . . . Schwabe." In one of his papers [*Astron. Mitt. Zürich* **1**, viii (1856)] Wolf explained that, in periods where data were sparse, he assumed the continued operation of the 11.11-year cycle.
8. D. J. Schove, *Terr. Magn. Atmos. Electr.* **52**, 233 (1947); *J. Br. Astron. Assoc.* **71**, 320 (1961).
9. ———, *J. Geophys. Res.* **60**, 127 (1955).
10. ———, *Ann. N.Y. Acad. Sci.* **95**, 107 (1961).
11. ———, *J. Br. Astron. Assoc.* **72**, 30 (1962).
12. J. A. Eddy *et al.*, *Sol. Phys.*, in press.
13. F. W. G. Spörer, *Vierteljahrsschr. Astron. Ges. (Leipzig)* **22**, 323 (1887); *Bull. Astron.* **6**, 60 (1889).
14. E. W. Maunder, *Mon. Not. R. Astron. Soc.* **50**, 251 (1890).
15. ———, *Knowledge* **17**, 173 (1894).
16. ———, *J. Br. Astron. Assoc.* **32**, 140 (1922).
17. A. M. Clerke, *Knowledge* **17**, 206 (1894).
18. Late examples include: E. H. Burritt, *The Geography of the Heavens* (Huntington & Savage, New York, 1845), p. 180; R. A. Proctor, *The Sun* (Longmans, Green, London, 1871), p. 164.
19. W. Herschel, *Philos. Trans. R. Soc. London* **265** (1801). In this wide-ranging and oft-cited paper Herschel reveals his belief in the influence of solar fluctuations on weather, based on his own observation of a correlation between the price of wheat in London and the number of visible sunspots. In making his point, he uses the extreme periods of spot absence of the Maunder Minimum, during which time the price of wheat rose. Herschel attributes the connection to reduced rainfall when the sun was less spotted, and to the inexorable workings of the law of supply and demand. This paper reveals, among other things, that the quest for a solar-weather connection predated the discovery of the solar cycle. It was not Herschel's worst mistake: in the same paper he tells of his belief in a habitable and possibly inhabited sun.
20. J. LaLande, *Astronomie* (Desaint, Paris, 1792; and Johnson Reprint Corporation, New York, 1966), vol. 3, pp. 286–287. This encyclopedic work was probably the unacknowledged source of most of the 19th-century descriptions of past periods of prolonged sunspot absence. LaLande's references included original journal reports and Jacques Cassini's *Éléments d'Astronomie* (Imprimerie Royale, Paris, 1740), pp. 81–82, 182. Jacques Cassini was the son of G. D. (Jean) Cassini, who discovered the sunspot of 1671 and the moons of Saturn.
21. G. E. Hale, "Photography of the solar prominences" [thesis, Massachusetts Institute of Technology (1890); reprinted in *The Legacy of George Ellery Hale*, H. Wright, J. Warnow, C. Weiner, Eds. (MIT Press, Cambridge, Mass., 1972), p. 117]; C. A. Young, *The Sun* (Appleton, New York, 1896), p. 193.
22. R. R. Newton, *Ancient Astronomical Observations and the Acceleration of the Earth and Moon* (Johns Hopkins Press, Baltimore, 1970), p. 39.
23. ———, *Medieval Chronicles and the Rotation of the Earth* (Johns Hopkins Press, Baltimore, 1972), pp. 99, 600–601.
24. C. M. Smythe and J. A. Eddy, *Bull. Am. Astron. Soc.*, in press.
25. J. A. Eddy, *Bull. Am. Astron. Soc.* **7**, 365 (1975); *ibid.*, p. 410.
26. Attributed to M. J. Rees, in *Project Cyclops*, J. Billingham, Ed. (NASA publication CR 114445, Stanford/NASA Ames Research Center, Moffett Field, Calif., 1973), p. 3.
27. H. C. King, *The History of the Telescope* (Sky Publishing, Cambridge, Mass., 1955), pp. 50–59.
28. A. H. Pingré (and M. G. Bigourdan), *Annales Célestes du Dix-Septième Siècle* (Gauthier-Villars, Paris, 1901).
29. This invaluable year-by-year diary (*28*) of astronomical advance in the 17th century was begun by Pingré in 1756 and completed by Bigourdan in 1901. It illuminates a most interesting century in astronomy and by length alone (639 pages) attests to the vigor of observational work at the time.
30. See, for example, G. D. Cassini, *Anc. Mem.* **10**, 727 (1688); J. Cassini, *Hist. Acad. R. Sci. (Amsterdam)* (1701), pp. 132, 356; *ibid.* (1702), pp. 185, 194; *ibid.* (1703), pp. 18, 141, 148, 151.
31. C. Scheiner, *Rosa Ursina sive Sol ex Admirando Facularum* (Apud Andream Phaeum Typographum Ducalem, 1630).
32. J. Hevelius, *Selenographia sive Lunae Descripto* (Gedani, Danzig, 1647).
33. A. Wilson, *Philos. Trans.* **64**, 6 (1774).
34. The *Rosa Ursina* (*31*), although large (25 by 36 by 8 cm) and beautifully set, has not enjoyed kind reviews; comments on the book range from "voluminous," "enormous," and "ovrage considérable renfermant plus de 2000 observations" to the less couched words of astronomer Jean Delambre: "There are few books so diffuse and so void of facts. It contains 784 pages; there is not matter in it for 50 pages" [*Histoire de l'Astronomie Moderne* (Imprimerie de Huzard-Courcier, Paris, 1821), vol. 1, p. 690; cited in (*35*)].
35. R. Grant, *History of Physical Astronomy* (H. and G. Bohn, London, 1852), p. 216.
36. The Maunder Minimum coincided with a prolonged period of distinct climatic anomaly—years of severe winters and abnormal cold, but there is no evidence of unbroken overcast. Astronomers are neither so mute nor so long-suffering that they would have kept quiet through year after year of continuous, frustrating cloud cover. The time was one of vigorous growth and

discovery in observational astronomy, as, for example, in the important revelations of Saturn already cited. Throughout the 70 years of the Maunder Minimum comets were regularly discovered and observed. We may conclude that during these years skies were at least tolerably clear, and certainly adequate to allow at least sporadic if not normal sampling of aurorae and sunspots, had they been there to see.
37. For this study I have used H. Fritz, *Verzeichniss Beobachter Polarlichter* (C. Gerold's Sohn, Vienna, 1873), which is still probably the most thorough published compilation of ancient aurorae. If criticized, it is more generally for sins of commission than omission; some of the ancient aurorae listed may not have been aurorae at all but meteors or comets [C. Stormer, *The Polar Aurora* (Oxford Univ. Press, New York, 1955), p. 14; (*38*, p. 20)].
38. S. Chapman, in *Aurora and Airglow*, B. M. McCormac, Ed. (Reinhold, New York, 1967).
39. E. H. Vestine, *Terr. Magn. Atmos. Electr.* **49**, 77 (1944).
40. E. Halley, *Philos. Trans. R. Soc. London* **29**, 406 (1716). Halley mentions that the aurora borealis had rarely been seen since the early 17th century.
41. Schove (*8–11*) has noted a tendency for auroral counts to alternate by century, with more in even centuries (such as the 16th and 18th) and fewer in odd, in which most of the Maunder Minimum took place.
42. Galileo and the other "discoverers" of sunspots were well aware of the existence of sunspots and naked-eye reports of them before they looked at the sun with telescopes [G. Abetti, in *IV Centenario della Nascita di Galileo Galilei* (Barbèra, Florence, 1966), p. 16].
43. For example, see S. Kanda, *Proc. Imp. Acad. (Tokyo)* **9**, 293 (1933). Kanda's compilation is more valuable in its own right than as a clue to past epochs of maxima, since large spots have been known to occur during years of minimum activity.
44. More recent studies of specific ancient oriental sunspot reports have been carried out by D. J. Schove and P. Y. Ho [*J. Br. Astron. Assoc.* **69**, 295 (1958); *J. Am. Orient. Soc.* **87**, 105 (1967)].
45. S. Nakayama [in *A History of Japanese Astronomy* (Harvard Univ. Press, Cambridge, Mass., 1969), pp. 12–23] has discussed the limitations of the "Institutional Framework of Astronomical Learning" in early Japan and the resultant repression of ideas and research. I have found no evidence that the Maunder Minimum was a unique period in this regard, however, and the almost precise coincidence with other evidences from Europe make the Far East sunspot gap seem real to me.
46. S. Matsushita, *J. Geophys. Res.* **61**, 297 (1956). I have taken from Matsushita's list only those auroral reports that he deemed "certain" or "very probable."
47. H. E. Suess, *J. Geophys. Res.* **70**, 5937 (1965).
48. P. E. Damon, A. Long, D. C. Grey, *ibid.* **71**, 1055 (1966).
49. I. U. Olson, Ed., *Radiocarbon Variations and Absolute Chronology* (Almqvist & Wiksell, Stockholm, 1970).
50. P. E. Damon (personal communication) has compiled radiocarbon data from five laboratories (University of Arizona; State University of Gronigen, Netherlands; University of California, San Diego; University of Pennsylvania; and Yale University).
51. M. Stuiver, *J. Geophys. Res.* **66**, 273 (1961); *Science* **149**, 533 (1965); J. R. Bray, *ibid.* **156**, 640 (1967); P. E. Damon, *Meteorol. Monogr.* **8**, 151 (1968); J. A. Simpson and J. R. Wang, *Astrophys. J.* **161**, 265 (1970).
52. H. E. Suess, *Meteorol. Monogr.* **8**, 146 (1968).
53. H. DeVries, *Proc. K. Ned. Akad. Wet. B* **61** (No. 2), 94 (1958).
54. J. C. Lerman, W. G. Nook, J. C. Vogel, in (*49*, p. 275). There are several available compilations of relative ^{14}C concentration; the most commonly cited is probably that of Suess (*47*) for Northern Hemisphere trees. P. E. Damon has kindly provided a compilation of ^{14}C data from five world radiocarbon laboratories (*50*), which has been very helpful in establishing real features. I have used the recent Groningen data cited here since they include a large sampling from trees of the Southern Hemisphere, where the larger ocean surface might be expected to bring about, in effect, faster tree response to real changes in atmospheric concentration. Fluctuations in ^{14}C atmospheric concentration are severely damped out in tree-ring concentrations because of the finite time of exchange between the atmosphere and the trees; the time constant is on the order of 10 to 50 years. The presence of absorbing oceans in the equilibrium process acts as an added sink, or leak, and, since the problem is analogous to that of determining changes in the rate of water flow into a bucket by noting its level, a leaky bucket makes a slightly more responsive system. In fact, there are only minor differences between the historical curve of Lerman *et al.* and that given by Suess and others; they show the same extrema at about the same times.
55. The use of ^{14}C data to deduce solar changes in the past and the possible relation of these changes to the history of the terrestrial climate have been the subject of numerous papers; for example, see (*51, 52, 56*); J. R. Bray, *Nature (London)* **220**, 672 (1968); P. E. Damon, A. Long, E. J. Wallick, *Earth Planet. Sci. Lett.* **20**, 300 (1973).
56. J. R. Bray, *Science* **171**, 1242 (1971).
57. P. E. Damon, in (*49*, p. 571).
58. The earlier compilations by Suess (*47*) and by Damon (*48, 50*) show that the deviation at 1500 is approximately equal to that of the Maunder Minimum period.
59. V. Bucha, *Nature (London)* **224**, 681 (1969); in (*49*, p. 501).
60. R. E. Lingenfelter and R. Ramaty, in (*49*), p. 513.
61. Y. C. Lin, C. Y. Fan, P. E. Damon, E. J. Wallick, *14th Int. Cosmic Ray Conf.* **3**, 995 (1975).
62. G. S. Vaiana, J. M. Davis, R. Giaconni, A. S. Krieger, J. K. Silk, A. F. Timothy, M. Zombeck, *Astrophys. J.* **185**, L47 (1973).
63. The 17th-century style of observing solar eclipses is well described throughout Pingré's compendium (*28*). A principal result from each eclipse was a table giving times of obscuration and the amount of the disk covered in "digits"—12 digits corresponding to the solar diameter and total obscuration.
64. A. J. Meadows, *Early Solar Physics* (Pergamon, London, 1970), p. 9.
65. T. R. von Oppolzer, *Canon of Eclipses* (reprinted by Dover Publications, New York, 1962).
66. V. Wing, *Astronomia Instaurata* (R. and W. (Leybourn, London, 1656), pp. 98–102; (*35*, pp. 364, 376–391; *28*, p. 570); J. Cassini, *Mem. Acad. Sci. (Amsterdam)* (1706), p. 322.
67. Cited in A. C. Ranyard [*Mem. R. Astron. Soc.* **41**, 503 (1879)]. Cotes might have given a more thorough account had he been free of a perennial eclipse nuisance, for, according to Halley, Cotes "had the misfortune to be oppressed with too much company" (*35*, p. 379). Halley's own description of the 1715 corona, from the same reference, follows: "a few seconds before the sun was all hid, there discovered itself round the moon a luminous ring . . . perhaps a tenth part of the moon's diameter in breadth. It was of pale whiteness . . . [and] concentric with the moon."
68. E. N. Parker, in *Solar Terrestrial Relations*, D. Venkatesan, Ed. (University of Calgary, Calgary, 1973), p. 6; *Sci. Am.* **233**, 42 (September 1975).
69. The Plutarch reference is to his account of the solar eclipse of 27 December A.D. 83; his description follows, as given by R. R. Newton (*22*, p. 114; *23*, pp. 99–100): ". . . [during a solar eclipse] a kind of light is visible about the rim which keeps the shadow from being profound and absolute." Newton feels that Plutarch's "kind of light" could be the rim of light visible during an annular eclipse or light from solar prominences, but that, if it is the corona, this is the earliest extant account. In any case it does not help us in answering whether the K corona was seen, since Plutarch's description could as well or better be the zodiacal light. The reference to Flavius Philostratus is from a passage in his fictional and controversial *Life of Apollonius of Tyana*, written about A.D. 210. Newton avoids it completely, but we should probably expose it to light: "About the time that [Apollonius] was busy in Greece a remarkable phenomenon was seen in the sky. A crown like a rainbow formed around the sun's disk and partly obscured its light. It was plain to see that the phenomenon portended revolution and the Governor of Greece [the tyrant Domitian] summoned Apollonius . . . to expound it. 'I hear, Apollonius, that you have Science in the supernatural' " [translation of J. S. Phillimore (Clarendon, Oxford, 1912) of book VIII, chap. 23]. In Philostratus's story the "crown" (Στεφανος) portends the name of Stephanus who later murdered Domitian. The use of the word is thus couched in symbolism and gives no evidence that Philostratus had ever seen either a total solar eclipse or the structured corona.
70. R. Grant (*35*, p. 377–378) gives the Clavius, Jessenius, and Kepler accounts.
71. J. A. Eddy, *Astron. Astrophys.* **34**, 235 (1974).
72. E. Öpik, *Irish Astron. J.* **8**, 153 (1968); see also (*25*). A change in solar luminosity of 0.5 percent per century corresponds to 0.005 stellar magnitude per century and is thus outside the limits of practical detection in other G stars.
73. For example, see G. Manley, *Ann. N.Y. Acad. Sci.* **95**, 162 (1961); Suess (*52*); Bray (*56*); *Adv. Ecol. Res.* **7**, 177 (1971); S. H. Schneider and C. Maas, *Science* **190**, 741 (1975).
74. A. E. Douglass, *Climatic Cycles and Tree Growth* (Publication 289, Carnegie Institution of Washington, Washington, D. C.), vol. 1, p. 102 (1919); vol. 2, pp. 125–126 (1928). Douglass found that from 1660 to 1720 the curve of Southwest tree growth "flattens out in a striking manner," and, before knowing of Maunder's work, he described the end of the 17th century as a time of unusually retarded growth in Arizona pines and California sequoias.
75. A good review of past climate history is given in (*76*), from which the climate incidents cited here were derived. The Little Ice Age lasted roughly from 1430 to 1850; it was marked by two severe extremes of cold, roughly 1450 to 1500 and 1600 to 1700, if we take H. H. Lamb's index of Paris-London Winter Severity as a global indicator.
76. W. L. Gates and Y. Mintz, Eds., *Understanding Climate Change* (National Academy of Sciences, Washington, D.C., 1975), appendix A.
77. If changes in the solar constant are reflected in the envelope of solar activity, and if the rate of change has held to the 0.5 percent per century rate cited earlier (*72*), then we can estimate that during the Maunder Minimum the solar flux was about 1.4 percent lower than at present—a number not inconsistent with temperature estimates during that coldest period of the Little Ice Age (*76*).
78. A. Hundhausen, *Coronal Expansion and the Solar Wind* (Springer-Verlag, Berlin, 1972); A. S. Krieger, A. F. Timothy, E. C. Roelof, *Sol. Phys.* **29**, 505 (1973).
79. The solar emphasis of the Spectrum of Time Project (STP) was first directed at fixing the epochs of presumed 11-year maxima of the past solar cycle (*10*). Amplitudes of past cycles (10-year averages) and of past maxima of the cycle were estimated on the basis of the best information available: auroral counts and other unspecified data, with an arbitrary correction for what fraction of aurorae was recorded in a given century (*11*). Moreover, in the STP there was a built-in constraint to generate nine solar cycles in each 100 years, regardless of whether there was evidence for them or not (*9*). These and other assumptions tend to dilute possible drastic changes in the past (like the Maunder Minimum) and to nullify possible long-term drifts in the amplitude of solar activity. The Maunder Minimum shows up as a significant drop in the number of sunspots in the STP, but with $R_{max} = 30$ at its weakest "maximum," in 1693, which falls in the middle of a 5-year period for which direct accounts from the contemporary literature report that no spots were seen. It is unfair to press the comparison since the STP covers a much longer span than the Maunder Minimum and, more to the point, it should be noted that the STP shows Maunder's "prolonged sunspot minimum" in figure 1 and table 2 of (*9*).
80. J. Hevelius, *Machina Coelestis* (Simon Reiniger, Danzig, 1673).
81. R. Wolf, *Astron. Mitt. Zürich* **14** (1862).
82. W. Gleissberg, *Publ. Istanbul Univ. Obs. No. 27* (1944).
83. I am indebted to the libraries of Harvard College, the U.S. Naval Observatory, and the Hale Observatories for the privilege of access. I thank O. Gingerich, H. Zirin, T. Bell, J. Ashbrook, D. MacNamara, G. Newkirk, M. Stix, M. Altschuler, L. E. Schmitt, and P. E. Damon for help and suggestions. I am most indebted to E. N. Parker for calling my attention to Maunder's papers, and for personal encouragement in all the work reported here. This research was funded entirely by NASA contract NAS5-3950. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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