John A. Eddy

Climate and the Role of the Sun

It is true that from the highest point of view the sun is only one of a multitude—a single star among millions—thousands of which, most likely, exceed him in brightness, magnitude, and power. He is only a private in the host of heaven. But he alone, among the countless myriads, is near enough to affect terrestrial affairs in any sensible degree; and his influence upon them is such that it is hard to find the word to name it; it is more than mere control and dominance.¹

Our Need for Solar Constancy

Our utter dependence on the sun for daily light and heat is so obvious a fact of our existence that it is easily overlooked. To this one star we also owe all our food—through a chain of life that begins in simple plants and aquatic forms—the replenishment of oxygen through photosynthesis, and the generation of nearly all of the energy that we have ever used. In harnessing wind and water power we reap the solar energy that drives the atmospheric circulation and cycles the water from ocean to air and back again, and in burning wood, coal, or petroleum we are harvesting the sunlight that fell on the earth in the past.

The same logic leads us to look into the possible variability of the sun, and to examine the degree of our susceptibility to known or suspected solar variations. How constant is the sun, and how dependent are we upon its constancy? Our fate would be dire, indeed, were the sun to go out altogether, or loom to nova brightness. But what of more astronomically probable changes, say of 10 percent, or 1 percent in total solar flux? What might we feel from unseen and less energetic changes in the sun’s ultraviolet radiation, or in its output of atomic particles and magnetic fields? Could it be that terrestrial weather is controlled by variations on the sun?

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¹ Charles A. Young, The Sun (New York, 1896), 1.
The sun is the engine that drives the atmosphere; even minor changes in its output could alter atmospheric composition, temperature, or circulation. These changes, if persistent, could influence the long-term average of weather—called climate—and through climatic change bend the path of human progress. Present mathematical models of global climate suggest that a decrease as small as 1 percent in the total radiation output of the sun is adequate to lower the global temperature average by 1 or 2°C, and hence to bring about a little ice age, of the sort that gripped Europe and America throughout the seventeenth and eighteenth centuries. The same numerical simulations indicate that a change of only 0.1 percent in solar flux, if continued long enough, could bring about climatic changes of significant social and economic impact. And a change of 10 percent, in a negative direction, would be globally disastrous, inducing major glaciation and perhaps an ice-covered earth which could recover only after a far greater and less likely increase of about 50 percent.²

To date, however, nothing significant that has ever been recorded in the meteorology of the lower atmosphere of the earth requires any change in solar output for its explanation. The weather system, or our present limited understanding of it, could work well with a star of perfect constancy. The succession of day and night, the march of the seasons, and even the recurrence of the awesome ice ages are all nicely explained by the movements and orientation of the earth itself, with no need for any solar variability at all. Shorter excursions of climate and the vagaries of daily, local weather can be explained, if need be, by random variations or by any one of several competing mechanisms that are internal to the atmosphere itself.³

Thus the question of the role of the sun in bringing about changes in weather or in climate turns back to whether it is, or is not, a variable star.

**SUNSPOTS AND THE SOLAR CYCLE** We have long known that the sun varies. With the first telescopes, early in the seventeenth


century, came the realization that the sun, like all else in nature, was ever changing. Small dark spots were seen on its surface, and their number and positions changed from day to day (Fig. 1). Large sunspots can be detected with unaided eye under favorable observing conditions; descriptions of them can be found as early as 28 B.C. in records from the Orient. But it took the telescope to reveal their varied forms and regular motion, and to establish that they were indeed features of the sun itself and not intervening planets or objects in our own atmosphere.4

The concept of a blemished sun was at first resisted in Western thought and theology, although soon accommodated by the rationalization that the dark spots were only clouds that moved across the face of an otherwise perfect sun. Today we know that sunspots are deeply rooted disturbances; they mark the places where intense magnetic fields break through the solar surface. These varying magnetic fields produce other dynamic changes on the sun and identify it as a magnetically variable star. Although sunspots look small, their average size is about that of the earth

and the patterns of magnetic field with which they are associated cover all of the sun.

Since the middle of the last century we have known that the sun produces sunspots in a fairly regular cycle of about eleven years, during which time their number, counted on any day, rises from none, or almost none, to as many as several hundred, and then back to zero again. Many other features of solar variability follow this same rule, and thus the eleven-year sunspot cycle has come to be synonymous with solar variability and is probably the best known feature of the sun.

The physical reason for the cyclical production of sunspots is still not clearly understood. Many characteristics of the cycle can be reproduced in numerical models of the solar atmosphere as a product of the interaction of magnetic fields within the sun and the observed properties of solar surface rotation, through a mechanism known as the solar dynamo. Neither models nor measurements give reason to suspect that the total luminosity of the sun varies significantly with the solar cycle.\(^5\)

**SUNSPOTS AND WEATHER** Far more effort has been expended on the search for terrestrial implications of sunspots and the sunspot cycle than has ever been spent on their physical explanation. Much of this work has been highly speculative and subjective. Indeed, since their earliest discovery, sunspots have often been associated with mysticism and things occult. They were taken as omens by the Oriental astrologers who first recorded their appearance. Later telescopic identification was accompanied by only slightly more objective efforts to trace their effects on the earth, chiefly through their presumed diminution of sunlight.\(^6\)

Such speculations were common enough in the seventeenth and eighteenth centuries to be found in literary references. Andrew Marvell made allusion to the deleterious effects of sunspots on solar light in a poem written in 1667, as did John Milton, less directly, in *Paradise Lost* when he described the allegorical landing of Satan on the sun as like a sunspot seen through a “Glaz’d Optik

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Tube,” or telescope. In Gulliver’s Travels, written in 1723, Jonathan Swift included the fear of sunspots and their dimming of the sun among the grave celestial worries of the Laputan astronomers.7

In 1801 William Herschel, the renowned astronomer, attempted to quantify the association with a cautious correlation that he had found between times of unusual sunspot absence and the English weather, as reflected in historical records of the price of grain on the London market. Thus the search was launched long before the cyclical nature of sunspots was found. But it was the demonstration of the cyclical regularity of spots, with the work of Heinrich Schwabe in 1843, that sparked explosive interest in the subject. Cyclical phenomena have a hypnotic attraction, particularly felt at the fringes of science, and the apparent cosmic regularity and presumed significance of the sunspot cycle has drawn a steady stream of determined attempts to link its ups and downs with searched-for periods in weather, agriculture, economics, health, and human behavior.8

From the start these attempts have focused on a possible connection with weather. These efforts, by scientists and by laymen, began in earnest in the middle of the last century. The reason, surely then as now, lay not so much in scientific logic, for there were no measurements of periodic solar outputs and no previously recognized cycles of eleven years in weather records. Then, as now, the search was based instead on the hope of finding a key to practical weather prediction. If a significant weather connection could be found with what then seemed to be a regular, solar clock, the gross nature of climate variation could be predicted—a year, ten years, or 100 years in advance. Thus the original motivation was not a priori indications of a sun-weather

7 The poem is Marvell’s The Last Instructions to a Painter, written in 1667. It is discussed in Judith E. Weiss and Nigel O. Weiss, “Andrew Marvell and the Maunder Minimum,” Quarterly Journal of the Royal Astronomical Society, XX (1979), 115–118.
connection, or any solid rationale that there should be one, but rather the common good that would accrue if one were found.

There is nothing wrong with this approach. It was the logic often used, for example, by Thomas Edison in tackling technical problems, sometimes successfully, often not. But such an approach, when applied to investigative science, the ultimate goal of which is to understand a larger system (in this case, the atmosphere and weather) can be a crippling constraint.9

At first it seemed to work. The 1870s and 1880s were characterized by a flurry of scientific papers purporting to have found connections between solar behavior, and more particularly the eleven-year sunspot cycle, and the weather—as measured in monsoons in India, rainfall in Ceylon, temperature in Scotland, or the depth of the rivers Thames, Elbe, or Nile. A new day had dawned, some said, in which science had made possible the prediction of the future, bestowing an ability to anticipate and thus to conquer problems that had long plagued mankind. “The riddle of the probable times of occurrence of Indian Famines,” announced Sir Norman Lockyer in 1900, “has now been read, and they can be for the future accurately predicted.” That prediction, we need hardly explain, lay in a pattern of recurrence that, according to Lockyer’s own researches, seemed to fit the ups and downs of the sunspot cycle.10

And then the bubble burst. One by one, the simple relationships vanished when examined more critically or faded in the light of longer records. By and large scientists have come to recognize these early, naïve relationships as accidental coincidences in limited data sets—examples of what Langmuir would later call “pathological science,” in which our own desire to find a certain result influences what we see or do not see.11

Newer knowledge of both sun and weather make the simple cause-and-effect chains unlikely, or, if at work at all, more likely masked by a myriad of other, more energetic changes in the atmosphere. Moreover, modern measurements of the sun’s out-

puts have as yet failed to detect any unequivocal change in the total solar radiation with day to day changes on the sun, or with the sunspot cycle.\textsuperscript{12}

We do know that the ultraviolet and x-ray radiations from the sun vary appreciably with solar activity, and that the sun's flow of atomic particles and magnetic fields are constantly changing. But these are all minor perturbations in the total budget of solar energy that we receive, and in each case they affect the earth directly only at the topmost layers of the atmosphere. If these upper atmosphere effects are to influence the denser troposphere, far below, we need to find a way for the tail to wag the dog. It is still possible that these subtle changes in some way make their mark on weather, and so the search goes on. But it is a search that now looks not so much for practically important connections as for minor perturbations through far more subtle chains.\textsuperscript{13}

\textbf{LONG-TERM SOLAR VARIABILITY} \hfill \textsuperscript{}

It is possible that we have missed the forest for the trees. Driven by pragmatic hopes of finding keys to weather prediction, we run the risk of concentrating too much on time scales of more practical consequence—of days, months, or years. In taking a longer view we see the problem in clearer perspective. We may also expect to identify extremes of sun or weather behavior that can serve as more sensitive tests.

Physics and logic are here on our side. If there exist immediate sun-weather connections that hide in the noise of random weather variations or are masked by patterns of stronger, competing effects, we can hope that they would become more visible and better defined when solar behavior reaches long-term extremes. Moreover, because of the physical inertia of the earth's atmosphere, we expect persistence to win out over impulse; the longer a solar effect is applied, the more likely it is to exert a real influence on the atmosphere. If solar behavior changes consistently for long enough we can expect to find the mark of even as


subtle an effect as a recognizable signature in climate records. The vast scale of the sun and the appreciable depth of the solar convective zone argue as well for slower changes, moderated by thermal and mechanical inertia that put constraints on allowed variations in the sun’s radiative output of energy. These constraints relax as we consider longer and longer time periods.

The sun is now thought to be about 5 billion years old. During this fraction of its expected life it has evolved considerably and, since stellar evolution is a continuous process, there is no reason to think that in our present era the sun rests, as on a cosmic Sabbath. We have often erred when we presume our present time or place in any way unusual.

From geological and paleontological evidence we can put coarse limits on the range of possible past excursions in the output of solar radiation. Because we find in rocks primitive forms of life that are 2 billion years old, we conclude that in subsequent time the earth has probably not been so hot that all the water boiled or so cold that all the oceans froze. These considerations allow us to put limits, using present climate models, of about ±10 percent on changes in total solar radiation, assuming that the composition of the atmosphere has remained constant during this time.14

Between these inferences on geological time scales and the hard evidence from the modern era of detailed observations of the solar surface, there are both time and opportunity for much to have happened. Our intensive observations of the sun span at most a century—less than .00001 percent of the time that it has thrown its light and heat upon the earth. Is this brief sample typical? So small a fraction is surely inadequate to tell us all the history of the sun. It is presumptuous to suppose that we have been so lucky to have seen, in the wink of time that we have watched the sun, all of the changes that it knows, or that the spectrum of solar behavior allows evolutionary changes of billions of years, and immediate changes of eleven years or less, but nothing in between.

The problem is that solar history, like all history, is imper-

fectly known. In taking the longer view we see farther but less distinctly, and look through mists of time that soon close in, leaving us with dim generalizations derived from facts inferred or indirectly obtained. The sun appears early in history and even pre-history as a common symbol, an object of worship, and a device to tell the time of day or year. But accounts of its physical appearance, which we need to describe the sun's behavior as a star, do not begin until late in human history.

The earliest known of these direct physical observations tell of sunspots seen with naked eye in the first century B.C., in China, giving us a potential record of 2,000 years. Uncertainties in all the naked eye accounts, and their sporadic nature, severely limit their utility. We generally speak of reliable solar history as beginning with the telescope, in 1610.

The limits of direct historical solar observations Our oldest direct record of solar behavior is the relative sunspot number, a measure of the number of spots seen on the sun with simple telescopes in unfiltered light. It is most often presented, as in Figure 2, as an annual average of daily measurements made at cooperating observatories over the earth. The sunspot number has been determined from direct observations in this way since 1848, when the quantity shown was first defined. Earlier values, shown to 1610 in Figure 2, were reconstructed from historical data and are much less reliable. The quality of the historically derived record is itself far from uniform, for the older records are successively poorer, particularly with respect to amplitudes of the peaks. This lack of uniformity is not because the older observers were less able, or less careful, but that the records are less continuous, making annual averages less meaningful since the observed sunspot number varies appreciably from day to day and is strongly modulated by solar rotation. Moreover, the sunspot number, as defined, includes a subjectively determined correction factor to account for sky conditions, the telescope used, and the idiosyncrasies of the observers. These factors are at best poorly recovered from historical data.15

The sunspot number describes solar activity as it is seen in

Fig. 2  Annual Mean Sunspot Number, A.D. 1610-1975.


a single, shallow layer of the solar atmosphere called the photosphere—the part of the sun most easily observed and from which most of its light and heat emanate. Modern solar observations of higher regions of the solar atmosphere, made with monochromatic filters in the visible spectrum and by other techniques in ultraviolet, x-ray, and radio wavelengths, have shown that the layer in which sunspots appear is deceptively quiet. Thus the sunspot number is not an especially sensitive indicator of solar activity or solar change.

In an analogy with the stock market, the sunspot number is a kind of subjectively defined Dow-Jones average that serves as a general indicator of other, more specific, and often more important variations. Like the Dow-Jones average, the relative sunspot number is used largely because of historical precedent, is subject to rapid daily fluctuations, and is difficult to predict.

The pre-telescopic reports of sunspots are so sparse that it is in practice almost impossible to derive from them any unequiv-
ocal information of the past behavior of the sunspot cycle. Neverthe-
less attempts at doing so have been made for limited periods
by attributing naked-eye reports to times of maxima in the sun-
spot cycle. It may be possible to derive from these early records
indications of long-term, secular behavior, as Eddy, and Stephen-
son and Clark have suggested; however, these interpretations are
always subject to questions of intended suppression of sunspot
reports (because of their astrological implications) or, in the op-
posite sense, an unusual interest in them during a given era. Such
sociological effects could indeed color the record.16

The most recent, and best catalog of naked-eye sunspot re-
ports is that of Stephenson and Clark for China, Japan, and Korea.
Where possible, they used original sources, which are most often
dynastic records. A total of 141 sightings were documented, be-
tween 28 B.C. and A.D. 1604, or an average of about one per
decade. Such an average is of little meaning, however, since only
six are reported before A.D. 300 and the rest come largely in
bunches; 51 of the 141 sightings came, for example, from the
particularly active period between A.D. 1077 and 1278, during the
Sung and Yuan dynasties in China. According to Stephenson
and Clark, these dynasties were particularly noted for diligence
and accuracy of astronomical reports.17

Another possible index of solar activity that extends nearly
as far as the sunspot records can be found in observations of the
sun made at times of total eclipse. We now know that the form
of the solar corona and the occurrence of prominences at the edge
of the sun change systematically with solar activity, or sunspot
number. The reliable eclipse record, however, reaches back only
to the early eighteenth century, if we seek unambiguous, physical
descriptions of the eclipsed sun; this period overlaps but cannot
extend the sunspot record. Moreover, the most useful eclipse
data, from photographic observations, do not begin until late in
the nineteenth century, with a dramatic increase in technique and

Solar Output, 51–71; Siguru Kanda, “Ancient Records of Sunspots and Auroras in the Far
East and the Variation of the Period of Solar Activity,” Proceedings of the Imperial Academy
(Japan), IX (1933), 293–296; A Wittmann, “The Sunspot Cycle before the Maunder
Minimum,” Astronomy and Astrophysics, LXVI (1978), 93–97; Eddy, “The Maunder Min-
imum,” Science, CXCII (1976), 1189–1202; Clark and Stephenson, “Sunspot Records,”
404–409.
17 Ibid., 390–399.
in photographic plate sensitivity occurring about 1890. As with historical sunspot data, we can always hope that new discoveries of older descriptions of the eclipsed sun will turn up in historical sources. In this regard it is curious and frustrating that the usable record is so short; Newton and Eddy have raised the question of why there are no descriptions of the structured solar corona before the eighteenth century when it is, to modern observers, so singularly exciting a spectacle.18

The next longest direct record of solar behavior is that of the measured diameter of the sun, begun at the Greenwich Observatory in 1750 and continued in several observatories to this day. Although a nearly continuous daily record, it requires considerable care in interpretation; a number of studies have suggested that the shape or the diameter of the sun may vary secularly.

All other direct measurements of solar activity and solar behavior, such as the occurrence of flares, the ultraviolet or x-ray flux, solar magnetic fields, the total solar radiation, the flow of atomic particles from the sun, or the flux of neutrinos from the solar interior have been recorded for at most a few solar cycles in the present century; thus they tell us only of the most recent interval in the life of the sun.

**INDIRECT HISTORICAL RECORDS** Observations of astronomical phenomena that respond to solar changes can be interpreted as indirect indicators of the past behavior of the sun. In general the most valuable accounts will come, as do sunspot records, from the post-telescopic era, but often useful data exist for far earlier periods.

Measurements of the brightness of the planets and their moons are now made to monitor possible changes in solar radiation, since these objects shine by reflected sunlight; historical planetary data, and especially the photographic plates taken in the last 100 years or so, can serve as an indirect record of solar luminosity. Observations of the zodiacal light—the faint cone of

light that reaches above the horizon in dark skies at dusk and before the dawn—may possibly tell of changes in solar activity, if correlations found in modern analyses are correct. Accounts of the zodiacal light, called the “false dawn” by Muhammad, are contained in records kept by Arab astronomers in the first millennium A.D. The brightness and color of the moon at times of lunar eclipse have been shown to follow a possible relationship with solar activity. These may be explained by known changes of solar activity on the density of the upper atmosphere of the earth, through which sunlight is refracted to give the eclipsed moon its characteristic copper color. This relationship has been applied to descriptions of the eclipsed moon as early as the seventeenth century. Comet tails change their shape and add characteristic spikes when they are swept by high speed streams of atomic particles directed outward from the sun; thus historical descriptions of comets, one of the more common sky phenomena reported in records from the Orient or Occident, can be interpreted in terms of past conditions of the solar wind. Instrumented records of disturbances in the earth’s magnetic field, documented for more than 100 years, provide another source of indirect data because of well-established relationships between solar activity and geomagnetic storms.19

By far the most useful of the indirect indices are reports of the aurora borealis and aurora australis, the northern and southern lights. Aurorae are especially valuable because their relationship to solar activity is direct and relatively simple, and because reports of these phenomena are common and extend far back into history. No telescope is required to see an aurora and they have long been noted as objects of awe and superstition.

Displays of the northern or southern lights result when streams of charged atomic particles from the sun interact with the earth’s magnetic field, resulting in particle accelerations and collisions with air molecules that then emit light of characteristic green or red or (combined) white color. Since many of these solar particle streams originate in active regions, where sunspots lie, we find a strong correlation between times of high sunspot num-

bers and times of frequent auroral occurrence. An even better correspondence is found between the occurrence of large solar flares and subsequent auroral displays.20

A number of investigators have made useful catalogs of historical auroral reports and these are under steady revision in the light of newer data or more critical assessment. In the catalog of Fritz, one of the earliest and probably the best known, aurora reports are listed from 503 B.C. onward, although the early reports are sparse—fewer than one per year—until the time of the Renaissance. A large part of this early scarcity may be attributed to the difficulty of securing reports from so remote an age; another factor is the strong dependence of aurorae on latitude and the fact that early historical records for the sparsely populated, high latitude auroral regions are rare.21

Auroral counts are commonly substituted for sunspot number in historical reconstructions of solar activity. They are, however, an indirect index of limited utility. Comparison of auroral reports with sunspot number in the era of best, modern observations shows a correspondence that is less than perfect and at times almost non-existent. Aurorae are seen, particularly at high latitudes, at times when solar activity and the sunspot number are approaching their lowest levels; moreover, the peak in auroral frequency lags behind the peak of sunspot number by several years. Thus the appearance of frequent aurorae is indicative of high, or else declining, levels of solar activity; a marked paucity of aurorae is almost always the mark of low solar activity; and a moderate number could indicate anything.22

Only in the last few years, with the discovery of large open-field regions of magnetic polarity called "coronal holes" on the sun have we come to understand the reason for this less than ideal correlation. Aurora-causing particles from the sun can come from active regions, where sunspots are, but they can also come in high-speed particle streams from coronal holes, where sunspots are generally absent. Coronal-hole aurorae are believed to be more frequent at times of declining solar activity. There is hope of

21 H. Fritz, Verzeichniss Beobachter Polarlichter (Vienna, 1873).
sorting the two types of aurorae by the terrestrial latitudes at which aurorae are produced. Sunspot-caused aurorae are initiated by higher energy particles that produce their displays at latitudes farther from the poles of the earth. Coronal-hole-produced aurorae are caused by lower energy particles and are seen nearer the magnetic poles of the earth, at high latitudes.23

THE MAUNDER MINIMUM In each of the longer records of solar history we can find evidence of possible secular changes in solar behavior that transcend the shorter oscillations of the eleven-year sunspot cycle. In the record of naked-eye sunspot reports and in auroral catalogs these appear as prolonged periods when reports of these events were significantly more, or less frequent than the average. In the curve of annual mean sunspot number (Fig. 2) we can identify similar trends in the range of values reached at peaks of the sunspot cycle. They are not of uniform height but rise and fall under an apparent long-term envelope that may or may not be periodic. After the 1959 maximum, following a run of four cycles of successively higher amplitudes, the annual averaged sunspot number reached an all-time high from which it now seems to be falling. A similar trend occurred nearly 100 years ago, after an obvious long-term minimum in solar activity that persisted between about 1800 and 1820. A more striking and protracted minimum appears in the same figure in the late seventeenth and early eighteenth centuries, if we can believe the reconstructed sunspot numbers for that period of time.

The period of depressed solar activity from 1645 to 1715, known as the Maunder minimum, has been given special scrutiny in studies of solar variability since it represents the clearest case within reach of telescopic records of a significant secular change in the behavior of the sun. One can question, based on our historical reconstructions of solar activity then, whether the eleven-year sunspot cycle continued to operate during the time or whether it was simply so severely depressed as to be hidden in the uncertainty of the available records.24

The period is also used as an historically verified solar anomaly to calibrate the longer, proxy record of solar history found in tree-ring radiocarbon. It is also taken as evidence of a possible solar-climate connection, since the years of the Maunder Sunspot Minimum coincide with a period of extreme cold during the little ice age.25

We have recently re-investigated the period by reviewing the historical reports of sunspots and other direct solar observations and by applying as well all available indirect or proxy data. In every case the available facts were found to be consistent with the interpretation expressed by Spörer and Maunder when they called attention to the phenomenon in 1887 and 1890. During this seventy-year span, solar activity, as measured in sunspots, fell to prolonged levels so low as to be wholly unlike the run of solar behavior in subsequent time. Fixing reliable annual sunspot numbers for the period is more difficult, and it may be impossible ever to establish whether in general level they hovered near zero or more nearly ten, or possibly twenty on the scale shown in Figure 2. But it seems clear, from direct historical data and the combined weight of the indirect and proxy data, that for seventy years the behavior of the sun was truly anomalous. Curiously the period coincides almost exactly with the reign of Louis XIV, le Roi Soleil.26

Telescopes more than adequate to see sunspots were in common use during the time and astronomers were interested in the sun’s behavior. In the scientific literature of the day, the unusual absence of spots was often noted, and the discovery of a new one was regarded as a reason for writing a paper. There was a noticeable drop of naked-eye sunspot reports during the time, as recorded in China, Japan, and Korea. The form of the solar corona, described in accounts of the sun at eclipses during the time, does not fit what we now know of its appearance when the

sun is active today. The number of aurorae reported in Europe, America, and the Orient during the time fell to uncommonly low levels.

Some investigators, although they acknowledge a drop in auroral incidence, have questioned the reality of the Maunder minimum as a real solar anomaly since there were aurorae reported during the period. This criticism ignores the fact, mentioned earlier, that auroral incidence is not a perfect proxy indicator of solar activity and that aurorae resulting from recurrent magnetic disturbances related to coronal holes on the sun are now known to occur near the times of the minimum of a normal sunspot cycle. Thus our modern knowledge of solar activity would predict a significant number of aurorae, caused by lower-energy particles in recurrent solar wind streams, during a time of anomalously low solar activity like the Maunder minimum.27

Evident in any critical examination of the Maunder minimum is the fact that the prolonged dearth of sunspots between 1645 and 1715 was routinely discussed, and apparently generally accepted in articles and books published from the time of its occurrence until about 1850, when the eleven-year solar cycle was at last established. The general acceptance of a uniform sunspot cycle seems to have erased all belief in an earlier period that did not seem to conform. The episode may say something about the ways of science and scientists, our regard for history when it fails to fit modern experience, and the sudden manner in which the mind of science changes. Before Schwabe’s belated discovery of the sunspot cycle, in 1843, there were adamant denials of any periodicity of these features of the Sun. After and particularly following von Humboldt’s espousal of Schwabe’s finding in 1851, no one seemed to challenge whether the sunspot cycle had always been in operation, and in full force. It was a sudden reversal of opinion much like the one that characterized the acceptance of continental drift in our own time.28

Impersonal diaries of natural events written in annual growth rings of trees offer a potential way of recovering solar history that can reach far beyond the limits set by historical records. Of particular interest to solar history is radiocarbon, an isotope of carbon that enters the leaves of trees as carbon dioxide through photosynthesis and is then deposited in the wood of annual growth. The amount of radiocarbon in the atmosphere, and hence the amount taken each year into trees, varies with time, and one of the factors that causes variation is the sun. Thus in measuring the amount of radiocarbon in the wood of dated growth rings we measure, to some degree, the condition of the sun in the year in which the ring was formed. Since species such as the bristlecone pine live to be several thousand years old, and since continuous tree-ring chronologies now exist for nearly 8,000 years into the past, we have the potential for reading solar history back to the time of the late neolithic and early bronze ages.29

It will be an imperfect history, written over with other, unrelated events and blurred in time. Radiocarbon is formed in the upper atmosphere of the earth through the action of high-energy galactic cosmic rays that reach the earth from all directions in space. One of the dominant factors that regulates our receipt of galactic cosmic rays, and hence the production rate of radiocarbon, is the sun; another is the changing strength of the earth’s magnetic field. From real-time measurements we know that when the sun is more active, and more spotted, the extended magnetic field of the sun shields the earth from some of the galactic cosmic rays, causing radiocarbon production to fall. When it is less active, as at minima of the sunspot cycle, or during the Maunder sunspot minimum, we receive more cosmic rays and radiocarbon production goes up.30

But the radiocarbon is formed at the top of the atmosphere and the trees live far below; between are complex processes that we cannot fully reconstruct in detail. This year’s radiocarbon, as gaseous carbon dioxide, makes its way to the trees through slow processes of vertical diffusion and atmospheric circulation; some

is absorbed in the oceans. In the process it will be mixed and
diluted with radiocarbon formed in earlier and later years, so that
when it finally enters the trees it will be an amount averaged over
the natural variations of several decades. Thus we do not expect
to find the signature of the eleven-year sunspot cycle in tree-ring
radiocarbon, even though we know that cosmic rays, and radio-
carbon production at the top of the atmosphere, show the cycle
clearly. We do expect to find evidence of long-term changes in
the overall level of solar activity, like the Maunder minimum,
which lasted seventy years, or, as a smaller modulation, the pro-
tracted solar minimum of the early 1800s.

These effects are clearly present in measurements of radio-
carbon taken from tree-rings formed during these periods, giv-
ing us confidence in this method of objective solar-history recon-
struction (Fig. 3). The Maunder minimum appears as a sharply
defined increase of about 2 percent in the amount of radiocarbon,
as an integrated effect that lasted 80 to 100 years. It marks the
most severe, naturally-caused change in radiocarbon level found
in tree-rings that were grown since the time of the telescope. It

Fig. 3 History of Relative Radiocarbon Concentration, from Tree-
Ring Analyses.a

![Graph showing radiocarbon concentrations](image)

a Plotted are concentrations of $^{14}$C relative to $^{12}$C, in parts per mil, from data compiled
by P. E. Damon, University of Arizona. Increased radiocarbon abundances are plotted
downward from the A.D. 1890 norm, which is shown as a dashed line. Solid curve is a
sinusoidal fit which matches very closely the recorded change in the strength of the earth’s
magnetic field. Remaining significant features are of probable solar origin. M = Maunder
minimum, S = Spörer minimum, GM = medieval maximum. Eddy, “Maunder Mini-
mum.”
confirms our reading of the historical records and offers a yardstick of solar variability with which we can scale the even longer record of tree-ring radiocarbon to identify the nature of other solar effects.

When we do this we find repeated instances like the Maunder minimum in the tree-ring record, all of which come before the time of the telescope and hence beyond the reach of historical records. The most recent of these, before the Maunder minimum, is a similar event, called the Spörer minimum, between about A.D. 1450 and 1540. A less distinct high level of solar activity, which we have called the medieval maximum, is seen in tree-ring radiocarbon records from the twelfth century. It was the last time that the sun was as active as in the present era and, incidentally, a time of warmer climate (known in climatology as the medieval climatic optimum) when the earth was last as warm as now.

The Spörer minimum and medieval maximum of suspected solar activity, scaled from radiocarbon records using the Maunder minimum as a yardstick, show up in records of naked-eye sunspot sightings from the Orient as well as in catalogs of aurora reports.31

Eighteen features like the Maunder minimum or the medieval maximum have been tentatively identified in the 7,500-year radiocarbon record from tree-rings. The present radiocarbon record, however, is at best a first approximation, for it comes from compilations by a number of different laboratories and it is under continued improvement as more wood is analyzed and as techniques improve. In time we should have a clearer account that will tell us much more about the real history of the sun.32

For now, however, there can be little doubt that the sun changes secularly. And it seems to change in such a way that the present era of solar behavior, in which we have made all our detailed observations of the sun’s surface, is not in the long-term an especially representative sample. Times of suppressed solar activity, like the Maunder minimum, seem far from unique in the longer life of the sun. It may be our own age that is unusual.

A POSSIBLE CONNECTION WITH CLIMATE CHANGE

These long-term, secular excursions in the level of solar activity, recognized in the frequency of sunspots and aurorae in historical records and

farther into the past through the proxy record of tree-ring radiocarbon, occur in a distinctive, irregular pattern. If it shows any periodicity, it is one of about 2,500 years. What is striking, however, is the fit of the pattern to the corresponding record of climate, even though the climate record is at present poorly known (Fig. 4).33

The correspondence of the Maunder minimum (1645–1715) with one of the cold extremes of the little ice age has been pointed out by a number of authors as a possible indication of a strong sun-climate relationship, in the sense that when the sun enters a prolonged period of low activity, the earth responds with a cooler interlude. With only one case the connection could be pure co-

Fig. 4 Past Solar Variability (top two curves) Compared with Climate Reconstructions (bottom).*

* Top curve (a): persistent deviations in radiocarbon from Figure 3, plotted schematically and normalized to feature 2 (Maunder minimum); downward excursions, as in Figure 3 imply decreased solar activity.
   Middle curve (b): interpretation of curve (a) as a long-term envelope of solar activity.
   Bottom curves (c): four estimates of past climate.
   Step curve G1: times of advance and retreat of Alpine glaciers, after Le Roy Ladurie, *Times of Feast, Times of Famine*.
   Curve T: estimate mean annual temperature in England (scale at right).
   From Eddy, "Climate and the Changing Sun."

33 Ibid., 183.
incidence, as is, we can hope, the coincidence of the Maunder minimum with the reign of the Sun King of France.34

But, as more of these long-term solar excursions are identified, we can apply a more crucial test. The Spörer minimum recognized in the radiocarbon record and confirmed with weaker evidence in aurorae and naked-eye sunspot reports, coincides with a similar cold dip in climate reconstructions of the little ice age. The medieval maximum of solar activity in the thirteenth century, as established in the same indices, coincides with the medieval climatic optimum, when the climate was last as warm as now. In the sequence of earlier solar excursions derived from the tree-ring radiocarbon record, we find a continued correspondence with climate, as defined by epochs of mid-latitude glacial advance and retreat. The correspondence is of two non-periodic signals, the records of climate and of the envelope of long-term solar variability, and the fit seems almost that of a key in a lock.35

We are not accustomed to finding curves of diverse phenomena that fit so well and for this reason we should be cautious in attributing their correspondence to a real sun-earth connection. A real concern is whether the climate itself could be directly modulating the radiocarbon concentration in the lower atmosphere through changes in circulation or in atmospheric and oceanic temperatures. In this case we should expect to find a close correspondence between climatic records and the radiocarbon found in trees. Such a correspondence would leave us, however, with the unexplained correspondence of the Maunder minimum, Spörer minimum, and medieval maximum with climatic deviations, for in each of these cases—the only ones within reach of historical confirmation—we have good evidence of real changes on the sun. Thus the burden of proof of a possible connection between long-term solar changes and climate falls back on the reliability of the historical records, including the weaker ones from pre-telescopic times.

If the connection with climate is real, what is causing it? It cannot be sunspots themselves; moreover the connection with solar activity, if real, seems to ignore the ups and downs of the

eleven-year sunspot cycle. The simplest explanation, and the one that must be dealt with first, is that we see in each curve—in climate and in the envelope of solar activity—the result of a common, simple cause, which is that of slow, ponderous changes in the total solar radiation, now called the “solar constant.” Excursions of but ±1 percent in total solar flux taking place slowly over time scales of centuries could explain the little ice age and other climate features. The same changes in the flow of radiation through the outer layers of the sun could modulate the amplitude of sunspot production, through circulation changes in the atmosphere of the sun, brought about by the action of the solar dynamo. Changes of 1 percent in the solar constant over 100 years would be impossible to detect, even with present instruments. But they might be seen, in retrospect, through their modulation of the peaks achieved in annual sunspot numbers where Spörer and Maunder first found evidence of long-term solar change.

If this explanation is right it could also explain why attempts to correlate climate with the ups and downs of the eleven-year sunspot cycle, or with day-to-day solar activity, have been so frustrating and generally so fruitless, for a slowly-varying solar constant should bear no relationship, other than accidental, to the short-term behavior of solar activity. If this is so we may have been watching the wrong things on the sun for a long, long time.