Andrew Ellicott Douglass (1867-1962). (photo by Charles W. Herbert, Western Ways, courtesy of the Laboratory of Tree-Ring Research, University of Arizona.)
Historical and Arboreal Evidence for a Changing Sun

John A. Eddy

Is the sun a constant star or does it change? And in what ways? Modern observations have not completely answered these questions but they leave little doubt that the sun is ever varying: sunspots appear and die in regular cycles, flares erupt, and prominences come and go. At every level the solar surface is in constant turmoil and the magnetic fields that rule the sun are never still. We generally assume that in the longer term, of centuries and millenia, the sun's behavior is more or less constant, but this is only a first assumption, based as much on hope as on fact or physical theory.

One of the intriguing problems of solar physics has been the testing of the premise of long-term solar constancy: the challenge to uncover, by whatever means available, the all-important history of our sun. It is as well a practical problem, for long-term solar variation could have climatic effects, and as in terrestrial affairs we can intelligently anticipate the future only when we know the past. Serious efforts began in about 1850, when, following the discovery of the sunspot cycle, Rudolf Wolf in Zürich searched historical accounts to recover sunspot numbers 150 years backward in time (1). Over this short span there seemed to be a constancy that may have long misled us. What other evidence is there, and how does one look farther into the past? For much of time we have only indirect or proxy data, as for example in the annual record kept by trees. In reading this record there have been false starts and false hopes, but with modern methods a new and consistent picture now emerges, with the promise of an even clearer one to come.

The Work of A. E. Douglass

In the early years of this century, when he was middle aged, Andrew Ellicott Douglass of Arizona took up the study of
tree-rings: a self-taught hobby that became, in time, a standard tool of archaeology and climatology. The development of dendrochronology is an illuminating story -- not so much for what it tells of trees and how they grow but for what it says of science and the way that fundamental ideas unfold: from the imagination of single minds, often spreading in unanticipated directions and seldom respecting the boundaries fixed by conventional disciplines.

Douglass was an astronomer and his original interest in trees, beyond an admitted love of piney forests, was based on the hope of finding there the history of the sun. It was an heroic quest in which he never gave up hope. Historical records of direct, solar observations had established that the well-known 11-year cycle of sunspots and solar activity had been in operation since at least 1700, and possibly 1610, when the telescope was first turned on the sun. But had the sun always behaved in this way? The answer must come from proxy data. Tree-growth, Douglass demonstrated, could be used as an objective diary of local conditions through the measurement of annual growth rings. In this record, that reached far back into prehistory, Douglass hoped to find the signature of unseen solar cycles of the past.

His hope, he well knew, was based on the problematical existence of a real connection between solar activity, measured in sunspot numbers, and local weather: that somehow rainfall and other meteorological inputs to tree growth were regulated by varying activity on the sun. Were this the case, one should be able to recognize an 11-year pattern in annual tree-ring widths, reflecting the observed cycle of annually-averaged sunspot numbers.

So simple a link between tree growth and sunspots now seems naïve, but we must remember that in the early 1900's there were louder, unfuteted claims for direct solar-weather connections, and a simpler and more innocent picture of global meteorology. At about the same time that Douglass began his search in trees, Charles Greeley Abbot began a similar study at the Smithsonian Institution in Washington, launching a long program to measure the solar constant, in which he also expected to find a dominant 11-year cycle (2). At about the same time Norman Lockyer, the best known solar physicist in England, had convinced himself and others that the 11-year cycle of solar activity controlled terrestrial climate and weather trends, particularly recurrent famines and monsoons in the tropics, where, he reasoned, solar influence would be more readily felt and more easily recognized (3).
Douglass' early work taught him that tree growth was itself a tangled product of many factors, and in patiently unravelling them he established the basic principles of modern dendrochronology. In the process he became convinced that he had found cycles in tree growth that were related to the 11-year cycle of activity on the sun (4). In tree-ring patterns these cycles were, admittedly, subtle things: sometimes there, sometimes not; present, weakly in some localities, and in others completely hidden. In the arid Southwest, where Douglass took most of his samples, and where dendrochronology was expected to be simpler, the anticipated solar imprint was not a particularly dominant feature; in the giant sequoias of California, where he secured his longest, continuous tree-ring chronologies, there seemed to be no cyclic solar influence at all. Douglass also noted the existence of prolonged periods, as between about 1650 and 1700, when Southwest treering were consistently narrow and when the alleged solar signal disappeared altogether (5).

One of the clearest cases of pronounced 11-year power in ring widths was found in a number of Scotch pines grown over an 80-year period in a controlled forest at Eberswalde near Berlin (Fig. 1). We can understand why this isolated example was not uniformly convincing. Aha! detractors must have said, you have selected an artificial case. These trees are grown under enforced conditions, and we all know what the Prussians are like: the trees, like the people, have learned to obey orders! Not so, said Douglass, who had convinced himself that there had been no enforced pattern of cultivation or watering; these very trees, well-nourished, less subject to certain insect scourges and the complications of crowding by older trees, were in his view ideally selected to demonstrate potential solar influence.

Douglass used various methods to identify cyclic tree-ring patterns, including ingenious optical devices called the "periodograph" and the "cycloscope" that could recognize and display periods of subtle, recurrent patterns (6). But when he died, at 95 in 1962, the situation was still not clear. Skeptics who looked closely at Douglass' major reports on the subject could say that he had found only scattered cases of accidental relationships between tree-growth patterns and the solar cycle. Those who liked cycles, or who were otherwise convinced of cyclic, sun-weather relationships, could, on the other hand, select data — like the Prussian pines — that bolstered their cause.
Figure 1. Section of a Scotch pine from a tended forest at Eberswalde, Prussia, planted in about 1820 and cut in 1912. Arrows, placed by Douglass, mark years of maximum sunspot number, showing, in this selected sample, an apparent correlation with maximum annual tree growth. From Douglass (4), Vol. I, pp. 37-39, 74-76.
Recent Studies of Tree-Rings and Climate

To clarify the case, in 1972 LaMarche and Fritts, both at Douglass' Laboratory of Tree-Ring Research in Tucson, tried more objective tests, applying the power of digital computers and a variety of modern, statistical techniques to some of the same, Southwest tree-ring chronologies that Douglass had used. In none of their cases could they find evidence of any significant power at periods of 11-years. There were small but significant peaks at 20-29 year periods in certain of the tree-ring records, but LaMarche and Fritts could find no convincing relationship between these possible 22-year waves and the double sunspot cycle, and concluded that they were probably unrelated to the sun.

Their conclusions, based on powerful and repeatable studies of 49 tree-ring chronologies of western North America, seemed to confirm the more negative, modern consensus against a significant connection between the sunspot cycle, weather, and regional tree-growth. And there the story seemed to end.

Recently, however, Stockton and Meko of the same Tree-Ring Laboratory came almost by accident upon new evidence in tree-rings for a significant 22-year cycle that could be sun-related. When the western U.S. was divided into climatic regions, and years of drought identified in each as narrow tree-ring growth, Stockton and Meko found that the number of regions showing significant drought suggested a cycle of about 20 years, that has persisted since at least 1700. Their finding was not inconsistent with that of LaMarche and Fritts, for they too had seen a suggestion of power at the same frequency in certain localities. The more dominant signal in Stockton's data would follow if the apparently recurrent drought wandered over the American West in its area of maximum impact. Were this the case the solar signal, if that was what it was, could escape detection in tree-ring records from single sites.

More recently, Mitchell, Stockton and Meko subjected the Western drought record to exhaustive statistical tests, and have established that the 22-year period in recurrent Western drought is the strongest periodic signal present, closely in phase with the cycle of solar activity. Their tentative finding, potentially the strongest evidence yet for an important solar-weather connection, opens again the old question of a significant link between the sunspot cycle and the weather. Because of the regionally-complex nature of the Mitchell, Stockton and Meko result, however, it offers at best a slippery grasp on the opposite problem of reading solar history in tree-ring widths. If the sun modulates
drought in a way that distributes it more or less randomly over a large area, an unknown solar signal derived from such a pattern would have to be reconstituted from wisely selected samples — like piecing together a coded message from shredded scraps scattered over a large area. History derived in this way, though better than none, would seem far less authoritative than Douglass's early hope of finding in every tree a redundant book.

**Radiocarbon**

In the meantime, a new way of reading solar history in tree-rings had been developed: a more powerful method that did not depend upon vagaries of local tree growth, or on assumptions of the solar control of weather. In the 1960's, Stuiver, Damon, Suess, and others (10) demonstrated that radiocarbon in plant cellulose could be interpreted as a gross record of past solar activity.

Radiocarbon, or $^{14}$C, is produced in the upper atmosphere of the earth through the impact of high energy galactic cosmic rays (11). Our receipt of cosmic rays is modulated, in turn, by solar activity, through the action of the extended magnetic field of the sun, that scatters or deflects a fraction of the cosmic ray flux (12). When the sun is more active, it shields the earth from some of the high energy cosmic rays (as established by measurements of nucleonic flux) and the production of radiocarbon in the upper atmosphere is diminished. When the sun is less active, as, for example, at minima in the 11-year solar cycle, we receive more cosmic rays and radiocarbon production is increased. Thus, if we had a record of how much radiocarbon was in the atmosphere in the past we could in principle deduce the state of solar activity at the time.

Trees keep that record for us, for atmospheric radiocarbon (as carbon dioxide) enters their leaves in photosynthesis and is preserved, as cellulose, in new growth wood. Growth rings of many temperate-latitude trees, as Douglass demonstrated, can be identified as an annual diary that extends, in long-lived species such as the bristlecone pine, for many thousands of years.

There are, to be sure, significant limitations. The half-life of radiocarbon, 5730 years, limits the amount of the isotope available for analysis in very old wood, eventually erasing the record. A more real restriction is imposed by the atmosphere and oceans of the earth: radiocarbon is produced high in the upper atmosphere and the trees are at the bottom. Between, in the varying patterns of atmospheric circulation, diffusion, and ocean absorption is a complex, low-pass filter
that delays and dilutes real variations in the radiocarbon production, severely attenuating changes shorter than about 20 years (13). As a result there are as yet no unambiguous identifications of the 11-year solar cycle in tree-ring radiocarbon. Only longer-term, gross effects get through in presently-readable form, and these are shifted in time (14). Moreover since the sun is not the only modulator of cosmic rays or radiocarbon, we expect the $^{14}$C record of tree-rings to be written over with other histories, including certain anthropogenic effects, the changing strength of the earth's magnetic moment, and variations in the ocean-atmosphere filter.

A 2000-year record of deviations in tree-ring radiocarbon ($^{14}$C/$^{12}$C ratio), compiled by Damon, is shown in Figure 2 (15). We have here plotted it upside down, with increasing radiocarbon downward, to agree in sense with solar activity. Excursions, in parts per thousand, are shown relative to an arbitrary, 19th century reference level. The curve should be familiar to archaeologists, who have reason to despise it and would like to see it flat, for the $^{14}$C excursions that interest us here are the very features that have necessitated troublesome readjustments in radiocarbon dates in the last few years -- illustrating the adage that one man's signal is another man's noise.

Is there evidence for solar modulation in the radiocarbon record in Figure 2? The gradual fall from left to right (increasing $^{14}$C/$^{12}$C ratio), is, as we shall see, probably not a solar effect but the result of the known, slow, decrease in the strength of the earth's magnetic moment, exposing the earth to ever-increased cosmic ray fluxes and increased radiocarbon production (16). The sharp upward spike at the modern end of the curve, representing a marked drop in relative radiocarbon, is generally attributed to anthropogenic causes -- the mark of increased population and the Industrial Age (17). The burning of low-radiocarbon fossil fuels -- coal and oil -- and the systematic burning off of world forests for agriculture (18) can be expected to dilute the natural $^{14}$C/$^{12}$C ratio in the troposphere to produce an effect like the one shown, although other contributions, including a real increase in solar activity, may be hidden under the rapidly rising curve. Much of the remaining structure is probably measurement error, for the curve comes from amalgamating radiocarbon results from different laboratories and widespread tree locations. Three striking features of the curve, however, are probably marks of a changing sun: an upward excursion (decreased radiocarbon) about AD 1200, indicating high solar activity, and two marked and prolonged dips, like a "W", in the direction of decreased solar activity at roughly AD 1500 and AD 1700. These distinctive dips (increased relative radiocarbon) were the first
Figure 2. Radiocarbon deviation derived from dated tree-ring samples, AD 1 to present, from Damon (15). Deviations of $^{14}$C relative to $^{12}$C, in parts per mil, are plotted with positive excursions (increased relative $^{14}$C) downward, in the direction of decreased solar activity. Zero level is arbitrary norm for 1890. Arrows mark persistent features identified as possible solar anomalies: right to left, Maunder Minimum, Sporer Minimum, Medieval Maximum.
major excursions noted in the radiocarbon history and called the "DeVries Effect"; first found in 1958 (19) they are a consistent global feature of the tree-ring record. That the DeVries effect could be the mark of the sun was soon pointed out (10). But was it really solar? And if so, what did it tell of the sun's behavior at the time? The more recent of the dips, lasting from the middle 17th century to the early 18th, fell fortunately within the time of "modern" observation of the sun, after the introduction of the telescope, when detailed observations of the sun began; it thus became the key, and potential yardstick, for the interpretation of the remainder of the radiocarbon record.

The Maunder Minimum (1645-1715)

That something unusual happened on the sun between the middle 17th and early 18th centuries was first pointed out by Spörer and Maunder late in the last century (20) and more recently reaffirmed (14,21). First-hand, historical accounts of the era tell of a surprising absence of sunspots and other signs of solar activity, including a marked, coincident drop in auroral reports between about 1645 and 1715.

It was a time of active interest in astronomy, and detailed interest in the sun. During the time the Greenwich and Paris observatories were founded, there were rapid advances in telescope technology, and the first scientific journals appeared. Distinguished astronomers such as Flamsteed, Halley, Cassini, and Hevelius, whose work in other areas seems above suspicion, tell in specific terms of an unusual absence of spots on the sun, and of looking, for as long as 10 years, before finding any, making it seem irresponsible to attribute the apparent absence to ignorance or oversight. Occasional spots were observed from time to time but they were restricted, throughout the 70-year period -- through six ordinary solar cycles -- to largely single spots and to belts of latitude near the equator of the sun, as at the minimum of the normal sunspot cycle. We may assume, as did Maunder, that the 11-year sunspot cycle was in operation during the time, at a greatly reduced or submerged level, but there is as yet no convincing evidence one way or the other on the question, for spots and aurorae that were reported are too infrequent for a convincing test. Eclipses of the sun during the time were assiduously observed, but no one tells of a structured corona, and we may presume that a coincident absence of organized magnetic fields on the surface of the sun greatly suppressed or even erased the corona as we see it in the modern range of solar activity. The character of solar surface rotation, as reconstructed from historical sunspot drawings, seems to have altered significantly between 1623 and
Figure 3. Annual mean sunspot number, AD 1610–1975, from Waldmeier (1) and Eddy (14), based on controlled observation from 1853 and reconstructed from less complete observations in earlier periods. Period from 1645–1715 is the Maunder Minimum.
the onset, in 1642-1644, of the Maunder Minimum (22) a finding consistent with what is currently known of the mechanism of operation of the normal sunspot cycle.

Thus it seems that the major feature of the radiocarbon curve within the grasp of detailed, historical test was indeed a time of anomalous solar activity -- an excursion at the proper time and in the proper direction, of prolonged solar quiet, to explain the nature of the radiocarbon anomaly. The historical record of sunspots (Fig. 3), aurorae, solar rotation, and appearance of the sun at eclipse during the Maunder Minimum may be adequate to provide a meaningful yardstick to scale the solar information in the radiocarbon curve (14,23). Further, weaker confirmation comes from pressuring the same historical records further, to the time of the two earlier radiocarbon excursions noted in Figure 2: the earlier prolonged dip of the DeVrie Effect, about AD 1450-1540, and the possible rise in solar activity in the 12th century. Aurora counts, eclipse descriptions, and the far weaker record of pre-telescope sunspot reports made with naked eye are all consistent with a solar cause for both of these two events, that we could call the Spörer Minimum and the Medieval Maximum. During the Medieval Maximum there were more reports of aurorae and of naked eye sunspots than in three centuries before or after it, and during the Spörer Minimum both indicators fell to anomalously low levels (24).

Indirect evidence for a period of prolonged solar inactivity consistent with the Maunder and Spörer minima has been presented recently by Forman, Schaeffer, and Schaeffer (25) who measured concentrations of an argon isotope $^{39}$Ar in recent meteorite falls. Like radiocarbon, $^{39}$Ar on meteor surfaces is produced by high energy cosmic rays that are modulated by the extended field of the sun; in their travels through the solar system, and before they fall beneath the protective blanket of our atmosphere, meteors continuously sample interplanetary cosmic ray levels and thus indirectly record a time integral of past solar activity. The half-life of $^{39}$Ar, 269 years, makes it suitable for testing levels of solar system cosmic ray fluxes over about the last 400-500 years. Were the averaged level of solar activity during this time significantly lower than the present it should appear in meteor samples as unusually high abundances of the isotope. In the 30 meteorites studied by Forman, Schaeffer, and Schaeffer, $^{39}$Ar abundances were remarkably similar, and all were consistently high, consistent with conditions of almost no solar modulation of galactic cosmic rays during the period of the Maunder and Spörer minima.
Figure 4. Radiocarbon deviation, as in Figure 2, from tree-ring samples since about 5000 B.C., from Lin, Fan, Damon, and Wallick (26). Solid curve, also from (26), represents strength of earth's magnetic moment, derived from paleomagnetic data by Buch (16). Features selected as possible solar excursions in Table 1 are marked with arrows.
Reading the Radiocarbon Record

With the Maunder Minimum defined and clearly identified in the radiocarbon record, and with weaker evidence for the reality of the two other, preceding solar effects, we can turn to the longer record of radiocarbon history to identify other possible features of solar cause. A compilation of tree-ring-derived radiocarbon data by Lin, Fan, Damon, and Wallick (26) is shown in Figure 4, spanning the remarkable range of over 7000 years, including data from trees that lived before the dawn of the Bronze Age. At the right-hand, modern end of the curve we recognize the same features that were identified in Figure 2: the fossil fuel effect, the Maunder and Spörer minima, and the Medieval Maximum. But the dominant feature in this longer record is the possibly cyclic undulation in overall level that reaches a minimum at about 5000 B.C. and a maximum shortly after the time of Christ. The radiocarbon data has been fit by Lin, Fan, Damon, and Wallick with a smoothed curve (solid line) based on values of the earth's magnetic moment derived from paleomagnetic data by Bucha (16). The remarkable fit establishes the changing strength of the earth's magnetic field as the dominant modulator of radiocarbon production.

Excursions above or below this averaged curve could be noise, for the radiocarbon record is in a yet imperfect, early state. They could conceivably be shorter-scale excursions in the strength of the earth's magnetic moment (27). We may assume, however, that some of the excursions -- and all the major ones if we take the record of the last 2000 years as typical -- are of solar cause. Damon has pointed out that solar modulation can be expected to be the principal cause of radiocarbon excursions once the smoothed, geomagnetic modulation is removed (29); he has also demonstrated (30) that the nature of the excursions in the data of Figure 4 are consistent with what we would expect from real, external causes: they are of greatest amplitude at the early end of the curve when the earth's magnetic moment was at its minimum, and are distinctly suppressed at the time of maximum field strength, ca. AD 200, as we would expect were solar modulation being squelched by a competing modulation of longer term exerted by the earth's magnetic moment. Thus in interpreting the amplitudes of any real excursions we must make correction for this effect.

An interpretation of the long-term radiocarbon curve, from (28), is given in Figure 5 and Table 1. In Figure 5a we show the major excursions from the radiocarbon record of Figure 4, with a linear correction for amplitude (28) and with the background, geomagnetic curve removed. 18 tentative
Figure 5. Interpretation of radiocarbon deviations in terms of solar effects, with climate correlation from Eddy (28). Curve (a): persistent radiocarbon deviations from Figure 4, plotted schematically and normalized to feature 2 (Maunder Minimum): downward excursions, as in Figures 2, 4 indicate increased $^{14}$C and imply decreased solar activity. Circled numbers identify features described in Table 1. Curve (b): interpretation of (a) as a long-term solar activity envelope (of possible sunspot cycle). Curve (c): four estimates of past climate. Step curve $G_1$: times of advance and retreat of Alpine glaciers, after Le Roy Ladurie (35); curve $G_2$: same, for worldwide glacier fluctuations, from Denton and Karlen (36); curve $T$: estimate of mean annual temperature in England (scale at right) after Lamb (34); curve $W$: winter-severity index (colder downward) for Paris-London area, from Lamb (33, 34).
<table>
<thead>
<tr>
<th>Feature (Fig. 5)</th>
<th>Beginning &amp; End in Radiocarbon Record</th>
<th>Probable Extent in Real Time</th>
<th>$^{14}$C Amplitude Corrected</th>
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<tr>
<td>2. Maunder Minimum</td>
<td>AD 1660 AD 1770</td>
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<td>3. Spörer Minimum</td>
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<td>5. Minimum</td>
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<td>6. Maximum</td>
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<td>20 BC AD 80</td>
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<td>440 BC 360 BC</td>
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<td>8. Minimum</td>
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<td>9. Minimum</td>
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<td>1870 BC 1760 BC</td>
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<td>11. Maximum</td>
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<td>2370 BC 2060 BC</td>
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features have been identified, and are listed in Table 1. Their starting and ending dates have been corrected for a delay of 40 years between change in radiocarbon production and tree assimilation, derived from comparing the historical dates of the Maunder Minimum with its signature in the radiocarbon record (14,28). Amplitudes have been scaled, after making the amplitude correction described above, to unit excursion for the Maunder Minimum, which we have taken as our yardstick for solar change.

In identifying major excursions in the radiocarbon curve and labelling them as real we have accepted the fit of the solid, geomagnetic curve in Figure 4 as exact. It should be obvious that shifts in the fit of this curve, to right or left, up or down, will change the magnitude and apparent duration of some of the identified features. And we should keep in mind the imperfect nature of the radiocarbon curve. Most of the data that make up the radiocarbon curve represent averages over time intervals of about 10 years, taken by analyzing wood from many adjacent rings, to explore the general form of variations. Finer resolution, that now seems possible, should clarify and sharpen details of individual excursions, and identify the ones that are not real.

In Figure 5b we have used our Maunder Minimum yardstick to interpret the 18 radiocarbon excursions as features of a smoothed curve of changing solar activity. We may think of this shaded curve -- drawn with obvious artistic license -- as the upper envelope of a possibly-continuous 11-year cycle of solar activity, for from the time of the Maunder Minimum to the present era the radiocarbon curve has closely approximated the envelope of observed sunspot numbers (14). By this interpretation we presume that the sunspot cycle was suppressed to very low levels (as during the Maunder Minimum) at times of features numbered 2, 3, 7, 8, 9, etc, when we may assume there were few spots on the sun and few aurorae. At times numbered 4, 6, etc, the envelope of a hypothetical sunspot curve would have been unusually high. As yet, however, we can only assume the existence of an 11-year sunspot cycle in any period before about AD 1700, for there is no unequivocal evidence for its operation before that time (24).

An important question concerns the present level of solar activity, of the last 100 or 200 years, from which all our careful observations of the sun, and all our generalizations have come. Can we take it as the normal level of solar behavior -- as is usually done -- or is it anomalous, in the sense of being unusually active? We cannot find the answer directly in the radiocarbon curve, for the fossil fuel effect apparently overwhelms or masks the natural radiocarbon record
of the last century or more. There are other indications, however, that suggest that the present era is indeed a time of higher than usual activity on the sun (14); evidence for this comes from a dramatic and sustained increase in aurora reports in the early 18th century, an utter lack of descriptions of the structured corona at eclipses before that time, and the fact that since the end of the Maunder Minimum the envelope of the sunspot cycle has been consistently rising. The curve of Figure 5b has been drawn with this interpretation, and it suggests that in the long run of thousands of years, the present levels of sunspots, flares, coronal transients, and perhaps the appearance of the corona itself -- may well be unusual, applying but a fraction of the time, and only during the upward excursions of the long-term curve. By this interpretation features like the Maunder Minimum, of which many appear in the radiocarbon record, may be just as common as today's solar behavior, or perhaps more so.

Do these first looks at solar variability from tree-ring radiocarbon say anything of long-period, cyclic variations on the sun? In answering the question we must be careful, for we are again limited by the preliminary nature of the radiocarbon curve, and by possible errors in identifying major excursions from the fitted, geomagnetic curve. Errors in this process would probably act to hide or confuse any real, cyclic trends. Indeed, if we take Table 1 and Figure 5 at face value there is little evidence for any persistent, long-term cycles: the identified long-term minima and maxima do not alternate, but come as often in multiple sets, as in the successive Spörer and Maunder minima and other, similar features earlier in the curve. An independent, mathematical analysis of the same radiocarbon data by Damon (30) found no persisting long-term cycles in the range of several hundred years. On the other hand, if the multiple minima or maxima are grouped as single, longer features, we see evidence of a major, long-term cycle of about 2500 years period. A possible solar cycle of this length has been pointed out in earlier radiocarbon data by Bray (31), who suggested its relationship to climatic changes; it also appears as a pronounced feature in Mitchell's power spectrum of terrestrial climate (32). In Figure 5 it shows up most distinctly between about 5000 and 200 B.C., when two full cycles can be identified. The combined Spörer and Maunder minima, considered as a single feature, fall at about the right time for the next minima of a 2500-year cycle, but preceding them, in place of an expected maximum, we find a possible, shallow depression. The missing maximum, at about AD 400, would have occurred near the time of greatest geomagnetic squelching, when we might expect its imprint to be diminished.
If the 2500-year cycle of long-term solar modulation is real we are today early in one of its maxima, and on this basis we might expect solar activity to continue at the level of the present era for at least several hundred years.

Conclusions

The solar variations found in tree-ring radiocarbon history are in the overall level of solar activity and surely relate to other basic changes on the sun. In the modern period of overlap with historical records of sunspots and aurorae they represent a gross modulation, as cause or effect, in the 11-year cycle of solar activity -- depressions to very low levels, as during the Maunder Minimum, and amplifications to states of prolonged high activity at other times. The modulation is slow and ponderous and could easily be missed in real-time observation; as in the case of the Maunder Minimum it can probably best be recognized in retrospect, in the peaks of recorded sunspot numbers or in compressed and integrated records such as the long history of tree-ring radiocarbon.

In earlier parts of the radiocarbon record, where we have no historical checks, the purported solar fluctuations tell us directly only of changes in the sun's modulation of cosmic rays, and therefore of changes in the solar wind and the sun's extended magnetic field. But as in the case of sunspots, these changes probably relate to other, deeper-lying changes in the sun. We have cited evidence that the nature of solar surface rotation varies significantly with long-term trends in solar activity, like the Maunder Minimum (22). This suggests, in turn, that these long-term activity variations tell of circulation changes deeper within the solar atmosphere, in the convective zone, and possibly of variations in the outward flow of radiation.

Are these long-term changes in the level of solar activity related to changes in our climate? Available evidence of climate history -- which is far from complete -- suggests strongly that they are (28). The Maunder and Spörer minima in solar behavior fall during the two most severe dips in world temperature in the last 1000 years, and their combination -- the "W" in the radiocarbon record -- coincides with a more protracted period of world cold known as the Little Ice Age (33). And the modern era of climate, like the modern era of solar behavior, seems to describe a similar, possibly anomalous case: in the perspective of 1000 years, we live in a climate unusually warm and benign, and perhaps significantly, under an unusually active sun.
The correlation with the presently known history of climate change is shown in Figure 5c, from (28). European temperature and winter severity estimates of Lamb for the last 1000 years (34,33) are a remarkable fit to this best-established period of solar history. For the longer climate record, times of temperate-latitude glacier advance, derived for the Alps by Ladurie (33) and for world average by Denton and Karlén (36), match well the extended solar history curve for radiocarbon. When solar activity falls to suppressed levels like the Maunder Minimum, temperate-latitude glaciers advance; when solar activity rises to high levels, they retreat. In the global glacier record of Denton and Karlén in Figure 5 we also see the purported 2500-year period in climate oscillation, that also appears in our radiocarbon record, presumably reflecting changes on the sun.

We could be misled. It is possible that climate itself is controlling the radiocarbon content of the troposphere, in which case we should expect a 1:1 correlation in Figure 5 quite independent of the sun. This could come about through alterations in the atmosphere and ocean reservoirs that control circulation and residence times of carbon dioxide (37). Present models of the effect of temperature and pressure changes seem inadequate to distinguish between the relative amplitudes of atmospheric and solar effects. In assuming that the features we have identified are solar we can only rely on the historical record that shows the Maunder Minimum as a real solar change, unrelated to climate, on the weaker evidence for a solar Spörer Minimum and Medieval Maximum, and on the recent evidence for past low levels of solar activity from meteorites (25).

If, as is suggested, interglacial climate changes of 100 to 1000 year duration are dictated by changes on the sun, what is the mechanism that links them? It is possible that the direct solar effect measured in radiocarbon production -- the modulation of cosmic rays, and related changes in solar particle fluxes -- may be an effective trigger of climate change. The climate correlation noted by Mitchell, Stockton and Meko may add substance to such a link, for the 22-year period found in Western drought patterns points to the solar magnetic cycle as a likely cause. It could also be that activity-related changes in solar ultraviolet flux drive the climate in long term, for we now that these short-wave radiations follow solar activity (38). The ultraviolet flux received from the sun may well mimic the curve of Figure 5b, falling at times like the Maunder Minimum and rising in the present era. Were this an important, long-term climatic effect, however, we might expect a stronger correlation of climate with the 11-year sunspot cycle.
The lack of demonstrated 11-year correlations between sun and climate may be an important clue in seeking an explanation for a possible, longer-term connection. Climate seems to follow the modulation of the curve of solar activity, as read in the integrated radiocarbon record, and not the 11-year, carrier wave. This suggests that the climatically-significant changes on the sun may be the same that modulate the solar cycle, causing the depression and amplification in long-term records of sunspot numbers. The simplest mechanism for this effect could be long-term changes in the total flow of radiant energy from the sun -- the so-called solar constant -- which could depress or amplify sunspot production through the action of convective changes and the solar dynamo. By this hypothesis, were the flow of radiant energy constant, the envelope of solar activity would be more nearly so. Slow and ponderous changes in the solar constant, which would certainly be felt in climate, would in passing through the sun leave their mark by slowly modulating the long-term level of solar activity. In this case, Figure 5b could represent a history of total solar radiative flux, which by present climate models need only vary through limits of about 1% to produce climatic changes like the Little Ice Age (14). So slow and small a change, occurring over periods of about 100 years, would have escaped detection in any of our past attempts to measure changes in the solar constant and indeed would be undetectable in other stars of solar type.

As both radiocarbon and climate records improve, we can hope for a much clearer picture of their possible connection. For now, perhaps the most we can assert with assurance is that neither sun nor climate is constant. Since people are by nature poorly equipped to register any but short-term changes, it is not surprising that we fail to notice slower changes in either climate or the sun. But the trees that long outlive us remember well, keeping histories that we may only have begun to read.

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References and Notes


27. The nature of the auroral anomalies accompanying the Maunder Minimum, the Spörer Minimum, and the Medieval Maximum make it unlikely that any of these features of the radiocarbon curve was the result of short-term excursions in the earth's magnetic moment (28).


32. J. M. Mitchell, Jr., Quaternary Res. 6, 481 (1976).


