THE SUN SINCE THE BRONZE AGE

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Long-term, apparently random changes on the sun are linked to climate.

INTRODUCTION

I was originally given the subject "Outstanding and Unusual Solar-Terrestrial Events in History", which was meant, I suppose, as license to bring before you a kind of solar-terrestrial side-show of historical marvels: the Astounding Aurora of 1716, the Mysterious Dark Day of 1790, the Colossal White Light Flare of 1859, and so on. I for one would enjoy that, and it would probably be appropriate to end a symposium as long and large as this one on such a carnival note.

The difficulty is that we do not know, in the summer of 1976, what is outstanding in solar behavior and what is commonplace. We cannot distinguish the unusual from the usual. In particular, if we look beyond the immediate present, earlier than the last several hundred years, we discover that what we have always thought were common in modern solar history appear in longer view to be the freaks. We find that what we thought to be anomalies — like the Maunder Minimum — are really rather ordinary. We must allow that in the perspective of but a thousand years the aurora borealis is unusual, as may be the solar corona, and perhaps the solar chromosphere, prominences, and flares. It now seems quite possible that the common 11-year sunspot cycle is but a temporary feature of the most recent solar history, or that it gets switched off and on in a program that seems almost random.

This quandary, as you may know, is new in solar physics. A few years ago most of us were confident that the sun was a regular and repeatable star of near perfect constancy. We believed in a kind of solar "uniformitarianism", by which concept the modern behavior of the sun was taken to represent its normal course in a much longer span — certainly of hundreds or thousands of years. Many of us made use of Schroe's reconstruction of an early sunspot cycle (Schroe, 1968), which was built on the assumptions of solar regularity and uniformitarianism.

Some of us are now concerned that these superannuated assumptions of constancy and regularity may have long misled us, both in solar physics and in related disciplines. We urge caution in making the 11-year cycle the basis of physical understanding of solar activity or of terrestrial effects, since, when you look hard at the historical record there is little or no evidence that the 11-year cycle existed at all before very modern times — perhaps about

A.D. 1700 (Eddy 1976b). What now seem more important are gross changes of behavior which the sun experiences on more ponderous scale — of 100's to 1000's of years. During these excursions, of which there have been about 12 in the last 5000 years, the sun has been both a good deal less active, and probably more active than anything we have seen in the modern era (Eddy, 1976a). At first look, moreover, the pattern of occurrence of these major solar changes is probably not periodic, but possibly bimodal or stochastic.

Needless to say, solar-terrestrial physics is directly affected by these new realizations of solar behavior. Probably most affected are solar-weather and solar-climate studies, which face an embarrassingly long time scale. There are hang-ups on searches for relationships on the shortest time scales — with daily and annual sunspot number and with the 11-year solar cycle. Have so many in science ever worked so long in a mine of such low yield? I think it time we admitted that no convincing and enduring correlations of an important nature have ever been found. Surely a hundred years of frustration are enough to suggest that we try a different approach.

The New Solar Physics tells us that the 11-year cycle is but a ripple on an ocean of great and sweeping tides. It suggests we step back and look instead at the longer-term changes, when the sun drifts in and out of eras like the Maunder Minimum. It says that these changes may be the more fundamental on the sun, the more indicative of changes in the sun's energetic, radiative output, and the more important in terrestrial effect. And when we look at the record of climate we find indeed their clear and unmistakable signature.

Evidence which has prompted this solar reappraisal has come from two sources: a re-evaluation of the historical record which has confirmed an unappreciated epoch of solar "anomaly" in the 17th and early 18th centuries (the Maunder Minimum (Eddy 1976a)), and a subsequent re-evaluation of the $^{14}C$ record, which extends solar history to about 5000 B.C., almost halfway to the end of the last glaciation, and well beyond the reach of the written word.

RADIOCARBON

The $^{14}C$ isotope is produced in the upper atmosphere of the earth as a result of bombardment by galactic cosmic rays. The cosmic ray flux is not constant, and thus the production rate of the isotope varies with time. Among the important modulators is solar activity, which affects terrestrial $^{14}C$ production in an inverse way: when solar activity is high, the earth is more shielded from galactic cosmic rays and $^{14}C$ production goes down; when solar activity is low we receive an increased flux of galactic cosmic rays and the $^{14}C$ production rate increases. The solar modulation of galactic cosmic ray flux is well established (e.g., Simpson and Wang, 1970), as is its effect on $^{14}C$ production (Damon, 1970; Greb and Damon, 1970). Other effects are also important — among them the variable shielding introduced by the changing strength of the earth's magnetic field, which varies by about a factor of two in a period of roughly 10,000 years (Bucha, 1969, 1970; Damon, 1970; Suess, 1970).
If we had a record of how much $^{14}C$ was present in the atmosphere in the past, we could in principle deduce the history of solar activity. Such a record exists in carbonaceous fossil material, and most useful in trees, where $^{14}C$ is assimilated as CO$_2$ in the process of photosynthesis. Individual tree rings preserve a record of the prevailing $^{14}C$ abundance ratio in the lower atmosphere at the time they were formed. The record can be read in living trees, such as the bristlecone pine, to about 3000 B.C., and extended in well-preserved dead wood to beyond 5000 B.C.

In interpreting the tree ring record for evidence of changes in solar activity, we must allow for several important effects. Of fundamental importance is an appreciable delay in the atmospheric reservoir between instantaneous changes in $^{14}C$ production in the upper atmosphere and resultant $^{14}C$ abundance variations in the biosphere. This lag is on the order of 10 to 50 years (Damon, 1976). It tends to smear and wash out short-term changes such as the 11-year solar cycle, and to displace all effects in time. In tree rings formed this year, for example, is the smeared record of nucleonic flux variations of 10 to 50 years ago. Thus, we find the Maunder Minimum (A.D. 1645-1715) in tree rings formed somewhat later than the historically established time of the real drop in solar activity and aurorae.

Figure 1 is a compilation of $^{14}C$ data by Lin, Fan, Damon, and Wallick (1975), who have assembled tree-ring derived $^{14}C$ results from a number of laboratories. Plotted is the deviation of relative $^{14}C$ abundance from the 1890 normal, expressed in parts per thousand with positive deviation (increased $^{14}C$) downward, to agree in sense with solar activity. The 1890 norm ($^{14}C/^{12}C$) is shown as a dashed, horizontal line. The observations have been fitted with a sinusoidal curve derived by Lin, Fan, Damon and Wallick (1975). They point out that it matches very well the smoothed curve of changing magnetic moment of the earth which is obtained from paleomagnetic data. The strength of the earth's dipole moment reached a maximum in about A.D. 200, at which time we should expect $^{14}C$ production to minimize, as indeed the data show. Half a cycle earlier, about 5000 B.C., the earth's magnetic moment was at a minimum; at that time we should expect maximum galactic cosmic ray flux and a maximum in $^{14}C$ production, as is shown. Thus, to a first approximation, the overall envelope of the observed $^{14}C$ curve is explained as the result of slow and apparently cyclic changes in the strength of the terrestrial magnetic field.

Some of the remaining structure on the compiled $^{14}C$ curve is probably observational error, but we can expect the significant observed deviations from the smoothed sinusoidal curve to be of likely solar origin, as has been pointed out by many authors (e.g., Suuver, 1961, 1965; Bray, 1967; Suess, 1965, 1968, 1970; Dagg, 1970; Lin, Fan, Damon, and Wallick, 1975). Thus the two dips (increased $^{14}C$) at the recent end of the curve, labelled "S" and "M" are the probable signature of marked decreases in solar activity, and the opposite excursions about A.D. 1200, labelled "GM", the result of a marked and prolonged increase. Other major excursions can be readily identified. In a recent review, Damon (1976) has shown that the increased amplitude of excursions in the earliest part of the record (about 5000 to 7000 years B.P.) is not observational noise but an effect of the weaker geomagnetic shielding at the time, which tends to increase the relative effect of solar modulation. Thus the excursions in this era, including marked maxima at about 6000 and 6500 B.P. and a remarkable minimum at about 7200 B.P., are probably real solar effects.

A more expanded plot of $^{14}C$ data covering only the Christian era, also from Damon (1975), is shown in Figure 2. Again the sinusoidal archaeomagnetic curve is shown as a solid curve, which can be taken as an approximate baseline in identifying other meaningful excursions. We see in Figure 2 that the same features noted in Figure 1. Also apparent are less certain features of a more minor nature: an apparent minimum in solar activity about A.D. 650-750 which seems confirmed in catalogs of aurorae and naked-eye sunspots (Eddy, 1976b) and a possible maximum about A.D. 100, in the Roman era.
the Mauder Minimum comes late enough -- after the development of the telescope -- that we have adequate historical records to describe with some certainty the behavior of the sun at the time. In this sense the Mauder Minimum is the Rosetta stone which has allowed us to translate the quantitative solar information in the radiocarbon record.

The 1645-1715 period was a time of unique solar behavior in recent historical time, and it probably qualifies as an "Outstanding and Unusual Solar Terrestrial Event." Eddy (1976a) has verified that during the long span sunspots were very rare, as shown in Figure 3. For 70 years solar activity hovered at a level somewhat lower than that characteristic of the minima of the present 11-year cycle, and for periods of up to 10 years no sunspots were seen at all. None was found in the whole northern hemisphere of the sun for 32 years. The possibility that the sunspot dearth was an artificiality of inadequate observers or poor technique seems untenable when one considers the advances made in other areas of astronomy and the exquisite and detailed drawings of the sun and sunspots made before and during the period. Reports of aurorae throughout Europe fell sharply during the Mauder Minimum and rose abruptly after it. The solar electron corona was either severely weakened or absent altogether; observers of the sun at total eclipses during the Mauder Minimum described a narrow ring of light around the moon, reddish in color and of uniform breadth -- which fits the description of Fraunhofer corona (or zodiacal light) with the continuum corona stripped away. Spots were reported on the sun from time to time, but usually as isolated features and always at low latitudes. This pattern of appearance suggests, literally, a "prolonged sunspot minimum", as Mauder first described the period, but it seems impossible to determine whether or not the 11-year cycle continued to operate at a suppressed or nearly invisible level.

Nor is it certain whether the 11-year cycle operated in the 1640-1645 period, after the introduction of the telescope and before the onset of the Mauder Minimum. In truth, 1700, or perhaps 1750, are the earliest dates for

THE MAUNDER MINIMUM

A yardstick which is useful in scaling the solar significance of the radiocarbon record is the Mauder Minimum, A.D. 1645-1715, marked "M" in Figures 1 and 2. Unlike the other excursions pointed out earlier in the curve,
which we have unambiguous evidence of an 11-year cycle (Eddy, 1976b). When
Galileo first turned his telescope on the sun, in about 1611, the surface was
practically featureless and in any time in the ensuing century, and we may
assume, the sun was probably near a moderate maximum of activity. The numbers
soon fell, however, as best we can determine from a few continuous records.
Rudolf Wolf assigned probable dates of maxima and minima of a continued 11-
year cycle for the 1610-1700 period, (Wolf, 1696, 1698, Waldmeier, 1961) but
these were largely extrapolations in which he felt little confidence. He was
also unsure, by the way, of the reconstructed 1700-1750 sunspot numbers which
we use today. Eddy, Gilman, and Trotter (1976) have shown that solar rotation
was truly anomalous in the period just before spots disappeared in the Maunder
Minimum; equatorial regions rotated about 3% faster than at present and the
differential rotation was enhanced by about a factor 3.

A HISTORY OF THE SUN IN THE LAST 5000 YEARS

We may presume that the 15th century period labelled "S" in Figures 1 and 2
was another era of solar behavior much like the Maunder Minimum, since the
14C record at the time seems almost identical to that of the 1645-1715 period.
Historical records are poorer for this earlier, Sporer Minimum, but its reality
seems confirmed in a paucity of auroral counts, an absence of naked-eye
sunspot reports, and corona-less descriptions of the eclipses seen. It was
again probably almost no sunspots, and we may presume, similar drifts of
flares and prominences. By the same reasoning the marked change in 14C be-
tween about 1100 and 1300 (an upward feature labelled "GM" in Figures 1 and 2)
suggests a time of prolonged high solar activity, probably higher than that we
have seen in modern times, although a definitive comparison is made difficult
by the Suess effect in the modern 14C record. During this medieval maximum,
auroral reports were higher than in preceding or succeeding centuries, and
there was a marked increase in the frequency of reports of naked-eye sunspots
(Eddy, 1976a, b).

Other, similar features are recognizable in the remainder of the 14C re-
cord. In Table 1 we have selected the most obvious of these presumed solar
effects and show them in Figure 4a in a simplified, schematic manner to ex-
amine the trend of possible major solar change. Although the 14C history
extends to nearly 6000 years B.P., we have limited this survey to the last
5000 years, for this time scale, the 18-year cycle is the primary feature. The zero
level in Figure 4a is the smoothed, sinusoidal curve from Figure 1, which re-
represented the effect of changing strength of the earth's magnetic field.
Amplitudes, relative to unit value for the Maunder Minimum, are given in
Table 1, with a corrected value (used in Figures 4a) which attempts to allow
for the geomagnetic shielding effect pointed out by Damon (1976). The cor-
rected amplitude A' for each date t was obtained from the measured value A(t)
by the following assumed relationship:

\[ A'(t) = A(t) \frac{h(t_0)}{H(t)} \]

<table>
<thead>
<tr>
<th>Feature (Fig. 4)</th>
<th>Beginning &amp; End in Radiocarbon Record</th>
<th>Probable Extent in Real Time</th>
<th>Amplitude: 14C Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern Maximum</td>
<td>AD 1800? --- AD 1780? ---</td>
<td>7 7</td>
<td></td>
</tr>
<tr>
<td>Maunder Minimum</td>
<td>AD 1660 AD 1770 AD 1440 AD 1710</td>
<td>-1.0 -1.0</td>
<td></td>
</tr>
<tr>
<td>Sporer Minimum</td>
<td>AD 1420 AD 1570 AD 1400 AD 1510</td>
<td>-1.0 -1.1</td>
<td></td>
</tr>
<tr>
<td>Medieval Maximum</td>
<td>AD 1140 AD 1340 AD 1120 AD 1280</td>
<td>0.7 0.8</td>
<td></td>
</tr>
<tr>
<td>Medieval Minimum</td>
<td>AD 600 AD 770 AD 640 AD 710</td>
<td>-0.6 -0.7</td>
<td></td>
</tr>
<tr>
<td>Roman Maximum</td>
<td>AD 1 AD 1400 AD 600 AD 600</td>
<td>0.6 0.7</td>
<td></td>
</tr>
<tr>
<td>Grecian Minimum</td>
<td>420 BC 300 BC 440 BC 360 BC</td>
<td>-2.0 -2.1</td>
<td></td>
</tr>
<tr>
<td>Homeric Minimum</td>
<td>800 BC 980 BC 820 BC 640 BC</td>
<td>-2.0 -2.0</td>
<td></td>
</tr>
<tr>
<td>Egyptian Minimum</td>
<td>1400 BC 1200 BC 1420 BC 1260 BC</td>
<td>1.5 1.4</td>
<td></td>
</tr>
<tr>
<td>Stonenenge Maximum</td>
<td>1800 BC 1700 BC 1870 BC 1760 BC</td>
<td>1.6 1.3</td>
<td></td>
</tr>
<tr>
<td>Pyramidal Minimum</td>
<td>2350 BC 2000 BC 2370 BC 2060 BC</td>
<td>1.4 1.1</td>
<td></td>
</tr>
<tr>
<td>Sumerian Minimum</td>
<td>2700 BC 2650 BC 2720 BC 2610 BC</td>
<td>1.7 1.3</td>
<td></td>
</tr>
</tbody>
</table>

where H is the geomagnetic field intensity (from Damon, 1976, Fig. 8) and
H(t) its value at middle range (t, 4200 yrs. B.P.) We should not place
too much significance in the corrected values, since the original amplitudes
are necessarily subjective. It is within the range of interpretation, and of
possible physical interest, that all major excursions could be of equal cor-
rected amplitude -- a possibility which follows from Damon's analysis of the
change in apparent amplitude of excursions with phase of the geomagnetic cycle.

The duration given for the solar features in Table 1 and Figure 4 have
been corrected for a presumed lag of 40 years between cosmic ray flux changes
and resultant 14C abundance variation in tree rings. We have also arbitrarily
truncated the span of each feature (by 20 years at start and end) to delineate
the more likely duration of the most pronounced effect. The rationale for
these rough corrections was derived from the example of the Maunder Minimum,
for which the tree-ring radiocarbon indication lagged and extended longer than
the historically-observed effect on the sun. Obviously, at this early stage of
interpretation of an imperfect 14C history all dates are uncertain to at
least 500 and possibly 1500 years.

The names presumptuously assigned the solar features in Table 1 are meant
for easy, preliminary identification; for features occurring earlier than the
Maunder and Sporer minima they describe the general historical period in which
the apparent anomaly falls: for example, the "Egyptian" solar minimum
(feature 6) between about 1420 and 1280 B.C. occurred during the "Golden Age"
could be masked by noise in the 14C record or destroyed in the process of selection. We find more minima than maxima in most of the period covered, and they do not alternate. The Sporer and Maunder minima may be parts of a single minimum in a long cycle of about 2500 years, of which the Egyptian, Homeric, and Greco-Roman minima (features 7, 8, and 9) are one full cycle away. J. R. Bray, who has pioneered the study of long-term solar change, has noted a cycle of this length in earlier, more preliminary radiocarbon data (Bray, 1958, 1970, 1971a). More recently Damon (1976) has subjected the data in Figure 4 to power spectrum analysis to search for obvious cyclic effects. He divided the data into 2000 year periods and found, interestingly, that statistically significant periods appeared, but of different length in different epochs, as though solar activity were subject to some kind of frequency modulation. In the first 2000 years B.P., Damon found significant power at periods of 56, 69, 162, and 400 years; between 2000 and 4000 B.P. the significant periods were 286 and 500 years, and from 4000 to 6000 B.P. they were 100, 286, and 1000 years. These are very preliminary findings but they suggest that the pattern of long-term solar behavior is not what purists would call well-behaved. At this point I prefer to describe long-term solar variability as meandering.

**AN INTERPRETATION OF THE MAJOR 14C EXCURSIONS**

Figure 4b interprets the schematic 14C data of Figure 4a as a direct representation of solar activity. The interpretation rests on the established correspondence between post-1650 (A.D.) radiocarbon dates and historical observations of the sun from the Maunder Minimum through the onset of the Sporer effect (ca. 1850). For these historically accessible periods, the 14C residuum (the difference between observed radiocarbon deviations and the sinusoidal terrestrial magnetic curve) followed very closely the observed envelope of the annual sunspot number (Eddy, 1974). We have therefore assumed that the general, long-term level of solar activity (or the envelope of the curve of annual sunspot numbers) can be read almost directly in the radiocarbon residuum: bottoming out in departures like the Maunder Minimum and maximizing when the radiocarbon residuum reaches the large negative levels of the A.D. 1100-1300 Medieval Maximum. For the modern end of the curve which is affected by the Sporer effect, we have simply used the observed envelope of sunspot number, which indicates a continued rise in the level of solar activity from A.D. 1715 at least through the 19S9 maximum. The rounded, connecting curve in most of Figure 4b is an arbitrary and wholly artistic connection between the maxima and minima of Table I and Figure 4a.

The “floor” imposed on the interpreted curve in Figure 4c acknowledges that solar activity has a zero level below which it cannot go and which was nearly reached during the Maunder Minimum. That there are deeper minima in the first two millennia B.C. (Figure 4a) is interpreted as the result of the longer persistence of these three, earlier events and from their clumping in time, since the radiocarbon data necessarily reflect a temporal integration in the atmospheric reservoir.
In the reconstructed solar activity curve is a possible explanation for the solar and terrestrial history (Eddy and the "auroral turn-on" in the early 18th century and the apparent absence or suppression of auroral activity before the same general date. If we accept that activity-related aurorae and the solar corona are both threshold phenomena which correspond to a certain minimum long-term level of solar activity, then their absence or suppression in much of early history seems a logical interpretation. However, the apparent pattern of excursions of aurorae and the prominent and extended aura of aurorae only during periods like the present, which are times of maxima in Table 1 and Figure 4. In the past three millennia these conditions have applied very infrequently -- perhaps no more than 10% of the time: for several centuries during the Medieval Maximum and an even shorter interval during the Roman Maximum. When these limited opportunities are combined with the rise of civilization, and the difficulties of social and political trends in the Roman context, and the difficulties of scientists of ancient times, the enigma of the missing aurorae and coronae in the literature remains. Ironically, these spectacular displays of nature would seem to have been withheld or suppressed during some of the more vigorous times of learning on the earth, including the era of early Greek interest in science and natural philosophy.

THE SUN AND CLIMATE HISTORY

We must all agree that these massive solar changes -- not ripples, but tides and tidal waves -- could have an pronounced effect on terrestrial climate, and through regional and global climate change, on the course of civilization. Through the Medieval Maximum of the Roman period and the year to year changes, and the 11-year cycle, could be such minor perturbations in the life of the sun that their imprint, if any, on earth and climate could be lost in more energetic and self-generated changes in the atmosphere itself. The close correspondence of the Maunder Minimum, the Sames Minimum and the Medieval Maximum of solar behavior with the long-term record of climate has been pointed out before (Gray and McIntyre, 1968; Eddy, 1975). It is particularly striking when one allows for the 40-year delay between the tree ring record of CO2 and the initiating changes in the upper atmosphere. Times of depressed solar activity correspond to times of global cold. The Maunder and Sporer minima match the two coldest extremes of the Little Ice Age, when global temperatures were depressed 0.5 to 1°C. High levels of solar activity seem to relate to periods of high global temperatures: the Medieval Maximum to the middle Ages warm epoch, or Climatic Optimum (Gray and McIntyre, 1975).

The correspondence is no less striking when the earlier solar record is compared with even earlier climate history, best as it is known. In part C of Figure 4 we show this comparison, on the same time scale as the rest of the figure. The step function depicts the advance (downward) and retreat (upward) of Alpine glaciers, taken from the climate summary of Le Roy Ladurie (1967). Curves T and N are temperatures (scale at right) and estimates of winter severity (colder downward) for England and Paris-London, respectively, from the historically reconstructed data of H. H. Lamb (Gray and McIntyre, 1975). The correspondence, feature for feature, is, I think, almost of a key in lock. Whenever a dip in solar activity occurs (as in features 2, 3, 5, 7, 8, and 9) the climate swings coldward, and glaciers advance. When we have a prolonged maximum of solar activity (as in features 4 and 5) glaciers retreat and the earth warms. We should recognize that we deal here with very coarse data, particularly in the record of reconstructed climate, and we should also be aware that the "climate" curves may represent only regional (European) trends. Gray, (1965, 1968, 1970, 1971, 1972, 1973), however, has demonstrated the global applicability of many of these same climate epochs, and indeed has pointed out the same long-term sun-climate correspondence shown here.

The physical connection with solar changes could be through the recognized increase in ultraviolet solar flux with solar activity, and the effect of that increase on chemical processes in the upper atmosphere. Were the case, however, I would expect more obvious correlation of shorter-term solar activity and weather. It could also come about through changes in the particle flux from the sun and some triggered reaction necessary to amplify the wholly inadequate energies in these fluxes. I am not ready to entertain either of these more complex mechanisms until we examine the simplest and most straightforward process: namely, that the total radiative output of the sun, or solar constant, is slowly and ponderously changing, and that these possible modulating changes are reflected in sign and magnitude in the overall envelope of solar activity. By this notion the curves of Figure 4 are proposed as records of the solar constant, with peak-to-peak amplitudes of perhaps 1%, the amount that we see clearly in global climate models to change the terrestrial temperature by 1° or 2°C. Long-term changes of this amount in the solar constant, by the way, would be very difficult to detect directly, and would be unnoticeable in observations of other G stars.

This proposed association is based on a hunch, on an admittedly distaste for trigger mechanisms, and on a preliminary finding (Oppenheimer, 1968; Eddy, 1975) that the average value of the measured solar constant increased steadily in the first half of the 20th century -- by about 0.25%, or the right amount to explain the established increase in world temperature during the same span (Gray and McIntyre, 1975). During the same half century the envelope of sunspot number was also monotonically increasing. It may be significant that while the solar constant was presumably rising, between about 1900 and 1950, its measured fluctuations did not seem to follow the 11-year cycle, although we can question whether the measurements were adequate to sense these more noise-limited changes. More recent and precise measurements of the solar constant, from spacecraft in six-month periods in 1969 and 1975, also failed to detect significant short-term changes (Fronclnich, 1976).

If the solar constant does not follow the wiggles in daily or annual sunspot number, how can it follow the envelope? A simple answer is that the solar constant may not follow the sunspot number at all; rather, the sunspot number may follow changes in the solar constant, through a kind of amplitude modulation or an observed more uniform cycle (Eddy, 1975, 1976a). A mechanism for this modulation exists in the solar dynamo, which we now think responsible for the maintenance of the 11-year sunspot cycle. By this hypothesis,
were the flow of radiation through the outer solar atmosphere perfectly constant, we might expect a sunspot cycle whose peaks were almost uniform in amplitude. If the flow of radiation were slowly increased, we would expect an overall enhancement of sunspot production, which would be most visible in retrospect, in the run of heights of the 11-year peaks. If the flow of radiation were slightly reduced, the peaks of the cycle would be depressed. And if the radiation fell below some critical level, perhaps only a drop of 1% or less, the amplitude of the cycle might be damped so much that the cycle would shut down, or appear to shut down, as during the Maunder Minimum, and presumably the Sporer Minimum and the earlier cases we have pointed out.

An intriguing consequence of this hypothesis is that individual ups and downs of the 11-year cycle, or of shorter-term solar variability, are almost wholly unrelated to the problem: they would tell little of changes in the solar output and predict almost nothing of consequence in terrestrial meteorology. If one sought a solar-weather connection of periods shorter than climatic time scales he would be always frustrated in what he found, and driven to ever more elaborate restrictions and ever more intricate mechanisms, much as pre-Copernican astronomers were driven into epicycles. And that, I would submit, may be just exactly what has happened in the past century of solar-weather research.

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REFERENCES


LONG-TERM ASPECTS OF MAGNETOSPHERIC VARIABILITY

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The structure and dynamics of the magnetosphere vary in response to changes in the solar wind and in the geomagnetic field. The time scales for these changes range from minutes for solar wind shock waves to several hundred thousand years for the durations between geomagnetic field reversals. Solar variability is known only over historic times and solar wind variability only since the beginning of the space age. The long-term variability of the geomagnetic field is better known. The dipole component of the geomagnetic field dominates on the order of 95 percent of geological time (at least in the last 80 M yr), and when it dominates the dipole axis remains nearly parallel to the rotational axis, but its intensity varies in a Gaussian manner about an average slightly larger than the present value with a standard deviation of about 1/2 the present value (these values are derived from data covering the last 40 M yr). A set of dipole magnetosphere scaling relations are used to predict magnetospheric variability in terms of solar wind and geomagnetic variability. The results illustrate the long-term behavior of the auroral zones, the scale sizes of magnetospheric boundaries, energy transfer rates, and energetic trapped particle properties.

Nondipolar magnetic components are important and perhaps dominant on the order of 1 to 5 percent of the time (again at least in the Cenozoic) corresponding to the brief (10^7 to 10^8 yr) intervals of geomagnetic reversals and excursions. A global magnetic map of one of these events does not yet exist, and progress depends on investigating the properties of a number of nondipolar models. The solar wind stagnation point altitude is calculated for present solar wind conditions and the present nondipolar field. The altitude has marked diurnal and seasonal variations, but it lies typically at 1 to 2 Re. Thus a well defined nondipolar magnetosphere enclosing the earth is predicted for this model. The auroral zones in a pure quadrupole magnetosphere are found and illustrated for the present quadrupole moment. They lie in four intersecting great circles. We estimate that the area enclosed by the zones (corresponding to a polar cap area) and the area of frequent auroral occurrence cover the order of 50 percent of the earth.