HOW UNPRECEDENTED A SOLAR MINIMUM?


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[1] The end of the current solar minimum is at least 2 years late, and indicators of solar and geomagnetic activity are approaching or are at their historical lows. We examine current indicators to determine how unprecedented this solar cycle might be, comment on possible earlier analogs to the current situation, and discuss attempts to predict future sunspot maxima on the basis of geomagnetic and solar magnetic data. Accompanying the change in the solar magnetic field has been a significant, albeit small, change in the total solar irradiance. Thus, the coming solar cycle(s) may provide an opportunity to separate the climatic effects of solar and anthropogenic sources.


1. INTRODUCTION

[2] While the number and location of sunspots undergo a periodicity, the sunspot cycle is characterized by its variability as much as its regularity. (Italicized terms are defined in the glossary, after the main text.) The maximum sunspot count varies from cycle to cycle, as does the duration of the cycle. Sunspots are regions of strong photospheric magnetic fields that have two polarities, north and south, and while the count varies with an approximate 11 year period, their magnetic cycle is twice as long, during which time the leading and trailing polarities of magnetic regions in each hemisphere switch. Poleward transport of magnetic flux during the sunspot cycle changes the polarity of the polar magnetic fields approximately every 11 years. The two polar regions, also referred to as the polar coronal holes, supply much of the solar wind and interplanetary magnetic field that are carried to the Earth at 1 AU from the Sun and beyond the heliopause.

[3] The Earth’s magnetic field is influenced by the solar wind and interplanetary field. The momentum flux of solar wind, also called the dynamic pressure, determines the zeroth-order size of the magnetosphere. Typically, the pressure balance point between the solar wind and the Earth’s magnetic field lies about 10 Earth radii in front of the Earth. A long magnetotail stretches downstream. The velocity of the solar wind and the strength and direction of the interplanetary magnetic field affect the coupling of energy from the solar wind into the magnetosphere. Much of this energy is temporarily stored in the magnetosphere to be eventually deposited in the upper atmosphere in auroral processes and current-driven heating. These currents in turn produce times‐varying magnetic fields that have long been detected on the Earth’s surface and are referred to as geomagnetic activity. Many indices have been developed to characterize geomagnetic activity. These indices are correlated with the properties of the solar wind and interplanetary magnetic field with varying dependencies [e.g., Arnoldy, 1971; Hirshberg and Colburn, 1969; Russell and McPherron, 1973].

[4] It is clear that the current solar minimum, the one ending solar cycle 23, is unusual. Previous solar minima had occurred in 1996, 1986, 1976, and 1966, so the latest cycle had been expected to reach its minimum in 2006, but in 2007, the sunspot number and every other indicator of solar “activity” continued to drop, as they did through 2008, and, at this writing, through mid-2009. Many times, the new cycle’s onset has been prematurely announced, only for some new evidence of continued decline to appear. It is clear that this behavior is unprecedented in the space age. We have never seen solar wind and interplanetary conditions like we have today. However, is it unprecedented over the period for which we have geomagnetic records, over the longer period for which we have sunspot records, or over the longer period for which we have proxy measurements of solar activity?

[5] Understanding how unprecedented is the solar minimum is not just an academic exercise. Ultimately, we will learn much more about the Sun from this solar minimum, but currently, our space missions are optimized to study solar maximum conditions and not solar minimum conditions. It would be helpful to understand just how long we might need to wait until the next solar maximum and how strong that maximum will be. Deep solar minima have also been
associated with atmospheric cooling. In particular, the Dalton minimum (1795–1830), the Maunder minimum (circa 1635–1705), and the Spörer minimum (circa 1450–1550) have been associated with significantly cooler climates [e.g., Eddy, 1981]. These associations could be coincidental. For example, volcanic activity could lead to an increase in the Earth’s albedo and a decrease in the heat received from the Sun. We now monitor volcanic activity closely and can calculate the effects of any dust and aerosols injected into the upper atmosphere. Moreover, the relative impact of anthropogenic sources of global warming, such as the increasing atmospheric content of carbon dioxide versus natural sources such as volcanic dust and solar variations, is under debate. A period in which solar activity decreased would be helpful in sorting out the sensitivity of Earth’s climate to various forcing functions. A very long and deep solar minimum would be quite welcome in this regard.

The historical record may be an aid in judging what to expect in the ensuing years. In the absence of guidance from history, a priori there are several equally possible outcomes. Nothing much might follow. Deep solar minima occur randomly and the Sun recovers quickly. Alternatively, the deep solar minimum could be a warning, like the sea level drop before a tsunami; all solar hell may be going to break loose momentarily. Or possibly, a Maunder minimum is on the way, accompanied perhaps by very cold winters. Finally, this could be one of the very deep solar minima that occur every century or so that are followed by one or more weak solar maxima. Until the Sun recovers from these weak maxima, space weather will become more benign, resulting in less risk to our power and information transmission systems and to our assets in space. This latter scenario could result in a significant change in direction for magnetospheric and heliospheric research and lead to a reduction in space weather preparedness in the space-based communication and monitoring sectors, as well as in power transmission companies.

Finally, and possibly most importantly, the present solar minimum is making us question our basic understanding of the solar dynamo and its effects on the photosphere and the corona. We depend on sunspots and flares to define the solar cycle, but what really is a solar minimum or a solar maximum? What is the root cause deep below the photosphere? Could the dynamo process be continuing on its schedule but becoming weakly coupled to the photosphere? Is the dynamo currently reaching the phase that usually produces a solar maximum but not producing a strong enough magnetic field to energize active regions? If so, these are certainly interesting times for solar physicists!

2. ASSESSING CURRENT CONDITIONS

The extended solar minimum has already produced unprecedented conditions in the solar wind and in the Earth’s magnetosphere when compared against the records we have obtained since the beginning of the space age. Figure 1 shows evidence for this in the solar wind velocity record and in the radiation belts monitored by the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) satellite. Figure 1 (top) shows the variation of the solar wind velocity over a 2 year period during the cycle 23–24 minimum. Figure 1 (bottom) shows the radiation belt fluxes in the inner magnetosphere that are thought to be controlled by the solar wind speed. The L value measures the distance at which these particles traverse the equator. The deep blue region is the usual energetic particle void called the “slot.” Typically, the median speed of the solar wind is 450 km s$^{-1}$ and consists of fast streams which rise from about 350 km s$^{-1}$ to about 600 km s$^{-1}$, and when these fast streams disappeared, the radiation belts measured by SAMPEX rapidly decreased in

Figure 1. (top) Solar wind speed since 2007 and (bottom) the SAMPEX energetic electron count rate in the L value range of 1–7; SAMPEX is in a low-altitude polar orbit (D. N. Baker, personal communication, 2009). When the stream structure, as defined by the periodic oscillations of the solar wind speed, disappeared at the end of 2008, the radiation belts weakened considerably. The dashed line at 500 km s$^{-1}$ shows the level at which in the past a fast solar wind stream was defined.
flux because the radiation belts depend on these high-speed streams for their energization.

The last three solar cycles (1976–2008) have had sufficient solar wind measurements to provide this solar minimum with a near-term perspective, but we note that, as the longer proxy record shows, these solar cycles have had greater solar activity than usual. In fact, this period has been called a "grand solar maximum" [e.g., Lockwood et al., 2009]. Figure 2 shows the sunspot number over the last three solar cycles and the descent to the present minimum. Here time is given in Carrington rotations, which mark the number of 27 day rotations since an arbitrary date. The unusual duration and depth of this solar minimum is immediately obvious at 1 AU in the ecliptic plane. Figure 3 shows the interplanetary magnetic field averaged over the 27 day solar rotation period during the same interval. A slight minimum each solar cycle followed by a slight rise can be seen in the top three cycles. In the descent to the minimum in the

Figure 2. Smoothed 27 day average sunspot number over the last three solar cycles, with the last plot showing the descent to the most recent minimum. Time is given in Carrington rotations, which count the number of solar rotations.

Figure 3. Smoothed 27 day averages of interplanetary magnetic field strength over the last three solar cycles, as observed at 1 AU by the Wind and ACE spacecraft. The last plot shows the descent to the most recent minimum.
fourth plot, a deeper minimum than ever before is seen with a
downward trend that has not yet turned around. A very similar
trend has been seen at high heliographic latitudes by Ulysses
[Smith and Balogh, 2008]. Figure 4 shows the same display
for the solar wind proton density at 1 AU in the ecliptic plane.
The density is more variable and the solar cycle maxima and
minima are not as discernible, but once the descent to the
minimum of cycle 23 begins, the density drops to lower va-
values. Figure 5 emphasizes this decrease in a joint occurrence
distribution for the solar wind number density and magnetic
field strength in the minima of ending solar cycles 22 and 23
[Lee et al., 2009]. It is clear that there has been a large and
significant shift in solar wind conditions.

3. PROXIMATE CAUSE

[10] The interplanetary magnetic field is rooted in the
photospheric field, and one would infer immediately from the
drop in the interplanetary field strength that the photospheric
magnetic flux must have changed. Figure 6 shows the mag-
netic flux emergence measured by the Wilcox Solar Observ-
atory over the last three solar cycles. Figure 6 (top) shows
the signed flux (including polarity), and Figure 6 (bottom)

Figure 4. Smoothed 27 day averages of solar wind proton density over the last three solar cycles,
as observed at 1 AU by the Wind and ACE spacecraft. The last plot shows the descent to the most recent
minimum.

Figure 5. Joint distribution of the solar wind number density and the interplanetary magnetic field strength
during the solar minima at the end of cycle 22 and cycle 23 [Lee et al., 2009]. The color bar codes the number
of observations in each bin.
shows the unsigned flux (scalar value). Solar cycles 21 and 22 were quite normal, but the magnetic field production weakened greatly in solar cycle 23.

[11] The resulting photospheric magnetic field is shown in yellow (positive) and blue (negative) in Figure 7. As the solar cycle progresses, the emerged magnetic flux drifts poleward in such a way as to cancel the existing polar magnetic field and replace it with the opposite polarity. In solar cycles 21 and 22, strong polar fields were produced by this flux transport, but the weak flux emergence in solar cycle 23 shown in Figure 6 produced only weak polar fields. The resultant polar magnetic field strength is quantified in the polar field records of the Wilcox Solar Observatory shown in Figure 8. The magnetic field has more than halved since solar cycle 21.

[12] The magnetic field configuration has also been simplifying recently. Figure 9 shows source surface maps of the magnetic field using the potential (current-free) model of the magnetic field near the Sun. This covers much of the portion of solar cycle 23 that we would consider to be solar minimum (to date). The red regions show the negative open field lines in the northern polar cap that fill the northern half of the heliosphere, and the green regions show the positive open field lines in the southern polar cap that fill the southern hemisphere. The blue lines are the fields that close inside the...

Figure 6. (top) The signed magnetic flux emerging from the photosphere as a function of time and latitude over the last three solar cycles and (bottom) the unsigned flux (J. T. Hoeksema, personal communication, 2009, http://wso.stanford.edu/gifs/Polar.gif).

Figure 7. The photospheric magnetic field over the last three solar cycles. This diagram shows clearly how the magnetic field of one dominant polarity is transported to the polar region to cancel the preexisting polarity there and to establish a new polarity at the poles. It also shows the weakness of recent transport and the weakness of the current polar magnetic field (D. H. Hathaway, personal communication, 2009).
source surface at 2.5 solar radii. The black line in each map is the neutral line where the closed fields reach their maximum altitude. In the potential field source surface model this is the coronal neutral line. The latitude and number of oscillations per solar circumference indicate the complexity of the solar magnetic field. As the recent solar cycle has declined, the neutral line has moved toward the equator and changed from a tilted quadrupolar (two-cycle) pattern to a more dipolar, almost untilted pattern. The Carrington rotations with patches of green or red at low latitudes show the existence of low-latitude coronal holes. Such features lead to the production of stream interactions, including compression and shocks in the solar wind flow. In fact, the persistence of stream interactions [Jian et al., 2006], even though the solar current sheet has become flatter, suggests that the heliospheric current sheet is not a simple extension of the coronal neutral line in the heliosphere and that the solar wind speed is very variable.

[13] A nice synopsis of how current sheet or the neutral line and the solar magnetic field evolved over the last three solar cycles is presented in Figure 10. In solar cycles 21, 22, and 23, the cycle begins with a low-latitude neutral line at solar minimum. Soon after the rise of sunspot numbers begins, the neutral line moves to higher northern and southern latitudes and stays that way until the declining phase. However, at the end of cycle 23 (Figure 10, fourth plot), the neutral line only slowly moved to low latitudes and now, almost 3 years “late,” has not yet started to extend toward the poles.

[14] In short, the proximate cause of the unusual solar minimum is that the solar magnetic dynamo, or the emergence of its fields through the photosphere, has weakened; this, in turn, has weakened all that the photospheric field affects. That the solar magnetic dynamo can change so significantly on decadal scales is somewhat of a surprise and should lead to an improved understanding of how the observed solar field is generated.

4. USING GEOMAGNETIC ACTIVITY CYCLES TO ASSESS THE CURRENT MINIMUM

[15] In sections 2 and 3, we have noted that the velocity of the solar wind and its variability have changed, the density of the solar wind has dropped, and the magnetic field strength has decreased. We can only say that this behavior is unusual over the last 30–40 years because we do not have even semicontinuous records much before 1970. However, we do have geomagnetic records going back about 170 years. Geomagnetic activity is most strongly dependent on the solar

![Figure 8](image)

**Figure 8.** The smoothed difference in the signed polar field strengths over the last three solar cycles (J. T. Hoeksema, personal communication, 2009).

![Figure 9](image)

**Figure 9.** Source surface field maps of the whole surface of the Sun at four times during the recent descent to the solar minimum (Carrington rotations 2054, 2064, 2074, and 2083). The blue lines indicate field lines that reach the neutral line (black) at 2.5 solar radii and the return to the surface of the Sun. This delineates the closed field region. The red regions denote open field lines into the Sun, and the green regions denote open field lines out of the Sun.
wind velocity and the interplanetary magnetic field. It would be highly desirable to separate these two parameters using the characteristics of the response of the geomagnetic indices to the solar wind and interplanetary magnetic field. One way to do this is to examine different time variations. One obvious such pair is the 22 year variation of the magnetic solar cycle and the 11 year variation of the sunspot cycle [Russell, 1975]. This approach used the \textit{aa} index, a 3 h antipodal index made from two midlatitude northern and southern stations, 180° in longitude apart. It separated the geomagnetic variation into two separate time series that might correspond to the strength of the Sun’s polar field and to the velocity of the solar wind, but the time series was unsatisfyingly short and the overlap with ground truth data needed for calibration was almost nonexistent. The major interest in this result at the time seemed to be from those puzzled by the apparent 22 year periodicity of droughts in the Midwest (S. K. Runcorn, personal communication, 1980). Many held the belief that long-term solar variations influence terrestrial climate, possibly through the solar wind. Later, the geomagnetic record was extended to almost 1840, and the analysis was extended on both ends [Russell and Mulligan, 1995], but because this technique depends on 22 year data points, it lacks sufficient overlap between observed values and predictions to calibrate the variations seen.

[16] A more recent attempt to derive heliospheric parameters from the geomagnetic record uses annual means and therefore has a larger number of samples with which to calibrate the method [Lockwood et al., 2009]. They, too, chose the 3 h \textit{aa} index, but they also analyzed the 1 h \textit{m} index. They posit that the 3 h index is more sensitive to the solar wind speed and the 1 h index is more sensitive to the interplanetary magnetic field. Figures 11 and 12 show the results of their procedure. The solid line in Figure 11 shows the predicted magnetic field strength, and the dots show the observed annual average of the field. The close correspondence shows that the technique is performing credibly, and we can use the predicted values to assess the precedence of the current magnetic field strength of 3.7 nT (in January–June 2009). There are no values this low back to 1905. Thus, it appears that in the last century, this solar minimum may very well be unprecedented. Examining Figure 12, which shows the annual predicted solar wind speeds, we see a much weaker correlation with observations, even though those observations were used through this period to develop the techniques. The current value of 370 km s\(^{-1}\) is certainly the lowest average observed value. However, given the large variance of the dots (observations) about the line (predictions) in Figure 12, the lower predicted values such as the 300 km s\(^{-1}\)
in 1912–1913 are not accurate enough to compare with the cycle 23–24 values, so we cannot tell if the current solar wind speed is preceded or not.

5. INFERENCES FROM THE SUNSPOT RECORD

[17] We know of no method to predict the solar wind velocity, density, or interplanetary magnetic field strength from the sunspot number. Nevertheless, we can obtain several quantitative parameters from sunspot observations that can give us qualitative indicators of the depth of a solar minimum. Figure 13 shows the butterfly diagram of sunspot locations when the latitude of each emerging spot is plotted. Over the course of the solar cycle, sunspots emerge at different latitudes, high at the beginning and low at the end. Thus, the latitude of emerging sunspots is a measure of solar cycle phase independent of sunspot number. We see that the latitudinal range of sunspot changes from cycle to cycle and the overlap between cycles varies. In the current minimum there appears to be a break in the sunspot occurrence so that there is no overlap at all. The low-latitude sunspots stopped emerging before high-latitude sunspots started a new cycle. There was also little overlap in the minima of 1902 and 1913. Figure 13 (bottom) shows the daily sunspot area, and that too varies widely. We note that the sunspot area for solar cycle 23 was not small but rather exceeded that of all the cycles from 1880–1930. We defer to later discussion that sunspots are not the only phenomenon with a latitude-dependent age in and near the photosphere.

[18] Another parameter specifically designed to be a gauge of solar minimum is the number of spotless days per month, as shown in Figure 14. This index maximizes, of course, at
until 1800. These authors claim that this period from 1793 to 1800 marks a lost solar cycle, and we should have a different count of solar cycles than we currently use. A slightly different interpretation has been offered by B. J. I. Bromage (personal communication, 2009), who has overlaid the sunspot number for this period on a synthesized but regular sunspot series based on a mean solar cycle shown in Figure 17a. She finds that the solar cycle phase advanced almost half a solar cycle in the years before cycle 4 when compared to the expected precisely periodic cycle. The phase, then, adjusted itself over a period of 4.5 years in the declining stage of the cycle. A subsequent lengthy sunspot minimum finally brought the sunspot cycle in phase with the expected period cycle for the start of the Dalton minimum. Whether a cycle was lost or the phase shifted, the behavior of that cycle is similar to the behavior seen in cycle 23, where the cycle which peaked around the year 2000 appears to be 3–4 years ahead of the synthetic curve as shown in Figure 17b. We are now in a much better position to determine the cause of extended solar minima as we have much better observations and detailed diagnostics of the photosphere and some insight into what occurs beneath the photosphere.

[21] Since the Dalton minimum is associated with a cool period, we should also carefully study the present solar irradiance measurements and the correlated terrestrial response, controlling as well as we can for other factors. Figure 18 shows the existing record of total solar irradiance. The total variation is small, only 0.1% over a solar cycle. Nevertheless, at the current solar cycle 23 minimum, we see what appears to be a significant departure from the behavior at the previous two minima. It is hard to understand how such a small change in irradiance could cause a measurable terrestrial response, but it is at least a change in the “expected” direction given the purported cooling during the Dalton minimum.

6. PROXY DATA

[22] Galactic cosmic rays have an easier time reaching the Earth when the solar wind and its magnetic field are weaker than average. Thus, cosmic rays tend to maximize at solar minimum. Second, the cosmic ray flux has easier access for one orientation of the solar polar field than the other, presumably enabled by the reconnection of the solar and interstellar field. The greater flux of cosmic rays in turn produces \(^{14}\)C and \(^{10}\)Be in the atmosphere. Carbon-14 finds its way into plants and, most importantly, into trees whose growth cycles are recorded in tree rings. Beryllium-10 can precipitate out in snow and be captured in the Greenland ice cap. This record can be recovered by drilling ice cores from the Greenland ice cap.

[23] Figure 19 shows solar activity as recorded in tree rings by \(^{14}\)C. It clearly indicates the modern maximum, the Dalton minimum, the Maunder minimum, the Spörer minimum, the Wolf minimum, and the Oort minimum, as well as a few smaller, unnamed features. So proxy data have some value in identifying and validating events even if we cannot determine precisely a quantitative strength of the causative process such as the solar wind velocity.
Tree ring data are limited by the age of trees and the preservation of wood. The ice cores on Greenland allow us to go back 10,000 years but perhaps with less quantitative understanding of the meaning of the record. Figure 20 shows what is called the solar modulation parameter measured in MeV [Lockwood et al., 2009]. Several key points can be gleaned from Figure 20. First, the present epoch is a time of strong activity. This has been called the modern maximum. Only one period appears to be much stronger than that at the present epoch. Second, there are many past quiet periods when solar activity must be greatly reduced over the present values. This suggests that in the long term this solar minimum is not unprecedented at all.

7. CAN WE PREDICT THE SIZE AND TIMING OF THE NEXT SOLAR CYCLE?

Several methods have been proposed for predicting the sunspot number from geomagnetic activity measurements of the preceding cycle. We mention just three of these and a fourth method using solar magnetism. The first, by Ohl [1966], used the correlation of the geomagnetic $aa$ index at solar minimum with the sunspot number at the next maximum to construct a predictive algorithm. This, of course, has the weakness that you cannot make a prediction until solar minimum; in fact, you cannot make a prediction until the new cycle has started. Feynman [1982] postulated that the $aa$ index had contributions due to the sunspot number of the current cycle plus a solar wind component that was predictive of the next sunspot maximum. This is an improvement in predictive capability because it uses the data from the preceding solar maximum. A third technique is that of Thompson [1993], who showed that the number of geomagnetically disturbed days during a cycle with $Ap > 25$ was proportional to the sum of the amplitudes of that cycle and the future cycle. This has greater lead time than the Ohl technique but less time than the Feynman technique. Each of these techniques had high correlations between the predicted value and the observed subsequent maximum sunspot number [Hathaway, 2008].

Figure 16. (a) The sunspot number during the solar cycles 3, 4, 5, and 6, covering the entry into the Dalton minimum. (b) Recently scaled solar images of this period showing the sunspot number giving evidence for a break in cycle 4. (c) A butterfly diagram for solar cycles 3 and 4. (d) Cycle length if one assumes that cycle 4 is a long cycle and if cycle 4 is really two cycles [Usoskin et al., 2009].
The fourth predictive technique uses measurements of 
the polar magnetic field of the Sun [Schatten et al., 1978]. The 
problem with this technique is that it can be tested only over 
three solar cycles. However, it is physically based, proposing 
that the strength of the next sunspot cycle depends on the 
polar field generated by the current sunspot cycle. Since the 
solar magnetic cycle is “22 years” long, it is not surprising 
that successive 11 year cycles are so related. This hypothesis 
also helps explain why the Ohl, Feynman, and Thompson 
predictions have been successful. Geomagnetic activity in a 
cycle is proportional to the strength of the magnetic field in 
the solar wind and that field, in turn, is proportional to the 
strength of the polar field of the Sun. These three techniques 
were simply responding to that fact. In the case of Ohl’s 
method, a strong polar field would create stronger than usual 
geomagnetic activity at solar minimum. In the case of 
Feynman’s technique, the preexisting strong polar field during 
the preceding solar cycle produced a stronger interplanetary 
magnetic field that made the solar wind–associated 
geomagnetic activity stronger, and in the case of the 
Thompson technique, the stronger polar field in the preceding 
cycle produced more disturbed days. Thus, the Schatten et al. 
[1978] hypothesis provides a framework for the validity of all 
three models, and the unusual solar minimum and the 
unusually low polar field strength of the Sun during solar 
cycle 23 allow a test of these four prediction techniques.

Table 1 shows the prediction of the four techniques for 
cycle 24 according to Hathaway [2008]. The RMS errors are 
the results of a test by Hathaway et al. [1999] over earlier 
cycles. The Schatten et al. method could not be tested over as 
long a period because of the availability of the polar magnetic 
field data. The Ohl method cannot be used for a prediction at 
this time because the minimum seems not to have been 
reached, but when it is reached, one would expect the pre-
dicted maximum sunspot number for cycle 24 to be quite low 
because geomagnetic activity is currently quite low. The 
Feynman method predicts the highest value of 154 ± 25. 
Since it is the technique that attempts the longest-range 
forecast, it was affected most by the continued decline of the 
polar magnetic field through cycle 23. The Thompson 
method that uses geomagnetic activity over the entire solar 
maximum phase should, as observed, predict a lower value 
than Feynman’s method since many of the disturbed days 
during a solar cycle occur during the declining phase (e.g., the 
Halloween events of 2003 and subsequent storms were the 
largest of the solar cycle). Finally, the lowest value is pre-
dicted by the Schatten et al. method using the observed polar 
magnetic fields. In short, this unusual solar minimum will 
provide a good opportunity to test and improve our predictive 
techniques for forecasting sunspot number. This test will not 
be complete until the next solar maximum, whenever that 
maximum occurs, but at this juncture it appears that the 
Schatten et al. prediction, based on the polar magnetic field 
strength, is the most accurate and does predict far enough in 
advance to be useful. The other three predictions discussed 
appear to depend on the validity of the Schatten et al. 
hypothesis that the activity of the next solar cycle depends on 
the polar magnetic field strength and are useful in the absence 
of knowledge of the solar polar magnetic field strength.

The fact that the solar magnetic cycle is 22 years long 
on average compared to the sunspot cycle’s 11 years opens up 
a method of predicting the time of the next sunspot maximum 
through examination of what has been called the “extended 

Figure 17. (a) Smoothed sunspot series (solid line) overlaid 
on a steady, constant-period 11.1 year cycle (dotted line) for 
solar cycles 0–13. (b) Smoothed series overlaid on synthetic 
series for solar cycles 10–23 (B. J. I. Bromage, personal com-
munication, 2009).

Figure 18. Total solar irradiance over the last three solar cy-
cles illustrating the recent contained decline of the optical out-
put of the Sun [Fröhlich, 2009].
Figure 19. Carbon-14 content of tree rings, illustrating the Oort, Wolf, Spörer, and Maunder minima as well as the Medieval maximum (adapted from the figure produced by L. McInnes, available at http://en.wikipedia.org/wiki/File:Carbon14_with_activity_labels.svg using the $^{14}$C record from Reimer et al. [2004]. Deviations given in parts per thousand.

At least two phenomena on the Sun exhibit an overlapping 18 year cycle that is very distinct from the fairly separate wings of the familiar 11 year sunspot butterfly diagram in Figure 13. The first of these, discussed by Wilson et al. [1988], is based on observations of the Fe XIV line coronal emission features at 530.3 nm that can be seen from the surface of the Earth, as monitored at the National Solar Observatory at Sacramento Peak with a photoelectric coronal photometer [Altrock, 1997]. A feature present in the pattern of these emissions, observed at the limb, is a 530.3 nm emission emerging at 50° or 60° latitude and migrating toward the equator, eventually merging with the butterfly diagram. This is the extended solar cycle. Figure 21 shows the latitude–time history of these emissions for the three recent cycles [Altrock et al., 2008]. In 1980, 1990, and 2000, there are high-latitude features that extend toward the poles. This so-called “rush to the poles” behavior is also observed in polar crown prominence images. These latter two phenomena are both related to the evolutionary behavior of the solar magnetic field observed on the photosphere. The Fe XIV emission features represent heated coronal loops connecting lower-latitude large-scale magnetic field regions to the polar region fields [Altrock, 2007] while the prominences follow the photospheric magnetic neutral lines underlying these loops as they migrate toward the poles. The early trajectory of this feature has proven useful to predict the timing of the next solar maximum [Altrock, 2003]. On the basis of past observations, the solar maximum should occur 1.5 years before the extrapolated rush to the poles reaches the poles. Figure 22 [Altrock, 2010] shows that the rush to the poles began in the northern hemisphere in 2005 but is proceeding toward the north pole at a rate much less than in the previous three cycles. No rush to the poles has yet been identified in the southern hemisphere. This may mean only that it is not yet visible (it is a weak phenomenon in noisy data), it is delayed, or it will not occur. In any case, we can use the northern hemisphere data to predict when solar maximum will occur in the northern hemisphere. On the basis of the current rate, estimated to be 4.6° yr⁻¹ (compared to the 9.4° yr⁻¹ average in the previous three cycles [Altrock, 2003]), the extrapolated rush to the poles will reach the north pole at 2016.3. If we apply the previously determined 1.5 year offset, this would imply solar maximum at 2014.8. However, using that offset could be somewhat dubious, considering the slow rush of this cycle. A possibly more reliable method is using the indication that solar maximum occurs when the centerline of the rush to the poles reaches a critical latitude. In the previous three cycles, this latitude was 76°, 74°, and 78°, for an average of 76° (this can be determined from the figures of Altrock [2003]). At the current rate, this will occur at 2013.3. Thus, the two methods using the coronal rush to the poles result in predictions for solar maximum at 2013.3 and 2014.8. This behavior, if it occurs, would provide a phase shift that resembles the one that occurred at the beginning of the Dalton during the minimum between sunspot cycles 4 and 5 and that is discussed above in section 5 and illustrated in Figure 17.

A more recent approach makes use of the observations of the torsional oscillations that occur 0.01 $R_S$ beneath the photosphere and are observable via helioseismology with the Global Oscillation Network Group (GONG) and the Solar and Heliospheric Observatory (SOHO) [Howe et al., 2009]. The close correspondence between the Fe XIV coronal activity and the toroidal oscillation shear is shown in Figure 23. Poleward extending features are seen in both records and clearly coincide, suggesting a relationship between the two phenomena [Altrock et al., 2008]. However, Howe...

Figure 20. Proxy measurements ($^{14}$C and $^{10}$Be) used to create a solar modulator parameter of the access of cosmic rays into the solar system. Most often in the past, the inferred solar activity has been much less than in the most recent past [Lockwood et al., 2009; see also Steinilber et al., 2008].
et al. [2009] have proposed that cycle onset time may be obtained not from the poleward moving feature but rather from the time the equatorward moving bands in the torsional oscillation patterns reach a critical heliolatitude of about 23° (see http://spd.boulder.swri.edu/solar_mystery). In contrast, Salabert et al. [2009], on the basis of the analysis of low-degree solar mode frequency shifts, suggest that solar activity cycle 24 began in late 2007, despite absence of activity in the photosphere. This interpretation is consistent with the interpretation of the cycle 4–5 transition by Usoskin et al. [2009], who interpreted the phase change period as two shortened cycles (see Figure 16) rather than one longer cycle. Thus, these recent observations challenge our very understanding of what defines a solar minimum and a solar maximum and illustrate that we very poorly understand what drives the solar and sunspot cycles.

8. DISCUSSION AND CONCLUSIONS

The geomagnetic, sunspot, and proxy records of solar activity all indicate that the last half century has been a time of unusually high solar, solar wind, and geomagnetic activity. Thus, the solar wind we have studied and characterized so well since the 1960s may not be typical. It well may be that the Sun will return to less active conditions and will do so for a relatively long period of time. It is clear that we need to monitor carefully the polar regions of the Sun, which is best done from high-inclination orbit around the Sun. This was attempted with the Ulysses mission, but Ulysses was not instrumented with magnetographs, and its orbital period was too long for a practical solar monitor. At the time of the Ulysses mission, the only means of reaching high solar latitudes was to use the strong gravitational field of Jupiter, which of necessity produces a long-period orbit, but now we can use other approaches to raise the inclination. One approach is to use multiple flybys of Venus, but this has an upper limit of close to 30° inclination. Another technique is to use an ion propulsion engine or a solar sail. The advantage of the latter approach is that a large fuel load is not needed. The advantage of the former is that proven technology could be used.

If we were to guess what the next solar cycle was going to be like from the behavior of the declining phase of solar cycle 23 to date, we would select solar cycle 4 beginning in 1785 as the analog of solar cycle 23 and solar cycles 5 and 6 as the analogs of the upcoming cycles 24 and 25. At this writing, the similarity of the inability of the new cycle to take hold with significant new cycle activity at high latitudes is striking. The epoch of cycles 5 and 6 has also been called the Dalton minimum, during which the sunspot number maximized at close to 50. It was also a period of global cooling. Thus, if a Dalton-like minimum does occur, we should carefully study

<table>
<thead>
<tr>
<th>Prediction Method</th>
<th>RMS Error</th>
<th>Cycle 24 Prediction</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohl’s method</td>
<td>29.7</td>
<td>no prediction</td>
<td>based on aa index at minimum</td>
</tr>
<tr>
<td>Feynman’s method</td>
<td>29.5</td>
<td>154 ± 25</td>
<td>based on interplanetary component of geomagnetic activity</td>
</tr>
<tr>
<td>Thompson’s method</td>
<td>24.1</td>
<td>115 ± 27</td>
<td>based on number of disturbed days</td>
</tr>
<tr>
<td>Schatten et al.’s method</td>
<td>33.6°</td>
<td>75 ± 30</td>
<td>based on strength of polar magnetic fields near minimum</td>
</tr>
</tbody>
</table>

*Over cycles 21, 22, and 23 only.

Figure 21. Annual northern plus southern hemisphere averages of the number of coronal activity maxima from 1973 through 2006 [Altrock et al., 2008]. Note that solar cycle 24 had already begun as early as 1998 in this display of the Fe XIV extended cycle.

Figure 22. Seven-rotation averages of the number of coronal activity maxima from 1973 through 2009 [Altrock, 2010]. Note the cycle 24 “rush to the poles” indicated by the label and the upward sloping line in the top right corner. Previous rushes to the pole can be seen earlier at slightly higher latitudes and in the southern hemisphere for cycles 21–23 but not cycle 24.
In late October and early of the solar sur-
Coronal activity (shading) from Figure 21 plot-
A measure of geomagnetic activity derived
Regions of strong magnetic field on the
Highly relativistic energetic
The latitude versus time plots of
The corona is the outer atmosphere
Dark regions that appear in X
A technique that utilizes measure-
A period of sunspot number, named
The ratio of light diffusely reflected by an object
to incident light.
Butterfly diagram: The latitude versus time plots of
sunspot or active region locations on the solar disk, showing
a pattern of equatorward drift during each solar activity cycle.
The onset of a new cycle’s active regions then starts with the
disappearance of the last low-latitude regions of the previous
cycle and the appearance between ∼30° and 50° latitude of the
new cycle regions. The appearance of the plot looks like suc-
cessive, nested pairs of butterfly wings, hence the name.
Carrington rotation: One complete rotation of the Sun
as seen from the Earth orbiting the Sun. It is named after
Richard Christopher Carrington, who determined the solar
rotation rate from low-latitude sunspots in the 1850s and
found the sidereal rotation period relative to the stars to be
25.38 Earth days. Because the Earth is orbiting the Sun, the
Carrington rotation period is 27.2753 Earth days.
Coronal emissions: The corona is the outer atmosphere
of the Sun that becomes visible via scattered sunlight during
solar eclipses or when a coronagraph blocks the bright stellar
disk. X-ray and extreme ultraviolet images suggest that the
corona is structured by the solar magnetic fields. The most
visible features at these wavelengths are hot loops that seem
to be heated material trapped in the magnetic fields connected
to active regions. The reason why the material in these loops
is hotter than the surroundings is still under investigation.
There are also especially dark regions rooted in the weak
magnetic fields of the Sun called coronal holes.
Coronal holes: Dark regions that appear in X-ray and
extreme ultraviolet images of the Sun. Research has estab-
lished that the magnetic fields rooted in these regions are
“open,” meaning they extend out into interplanetary space.
These open field regions seem to be the sources of the solar
wind.
Dalton minimum: A period of sunspot number, named
after the English meteorologist John Dalton. The minimum
lasted from about 1790 to 1830, with a maximum sunspot
number of close to 50. It coincided with a period of lower-
than-average global temperature.
Galactic cosmic rays: Highly relativistic energetic
particles that enter the solar system from outside. They are
composed of protons, electrons, and fully ionized nuclei of
light elements.
Geomagnetic activity: The time-varying magnetic field
caus ed by electric currents in the Earth’s ionosphere and
above. Geomagnetic activity is controlled by the solar wind
and the interplanetary magnetic field.
Halloween events of 2003: In late October and early
November 2003, the solar activity was very intense. Many
X-class flares and fast coronal mass ejections were observed
during this period.
Heliopause: The boundary between the solar wind and
the interstellar wind.
Helioseismology: A technique that utilizes measure-
ments of motions of material over the solar surface to infer
the structures and motions inside the Sun. This technique
relies on some of the same concepts as are used when earth-
quakes occur, sending pressure waves throughout Earth’s

Figure 23. Coronal activity (shading) from Figure 21 plotted on top of annual running mean averages of the Mt. Wilson
toroidal oscillation shear [Altrock et al., 2008].

the factors known to control global temperatures and monitor
the total solar irradiance carefully to see if solar and terrestrial
influences on the Earth’s climate can be separated, and, if they
can be, how influential each is.

Our current solar program is centered on studying the
active Sun. A period of solar quiescence is both unexpected as
well as off-putting to those studying solar activity. However,
there is much to be learned about the Sun, even at quiet times.
There are magnetic regions appearing. There are coronal
holes, fast and slow streams, and time variations in the solar
wind. There are advantages to the lower rate of activity in
minimizing the confusion of the source of any activity. In
many ways, the study of the Sun right now is easier, and our
conclusions can be more certain. Still, we caution the reader.
We have much reason to believe that the low field strengths
currently on the Sun presage a low-activity cycle, but we do
not understand the Sun well enough to have complete con-
fidence that this is the way it will play out. We need to wait
and see what happens. And when strong solar and geomag-
etic activity returns, we should be prepared for it. We should
not have to learn the space weather lessons of the last half of
the twentieth century all over again.

GLOSSARY

aa index: A measure of geomagnetic activity derived
from measurements at two midlatitude antipodal sites, origi-
nally Greenwich and Melbourne. Daily values are formed
from an average of the eight 3-hourly values.
Active regions: Regions of strong magnetic field on the
Sun that are sometimes also the locations of sunspots. They
are generally observed with instruments called magnetogra-
phs, which take magnetic field “images” of the solar sur-
face. The strong fields of active regions appear to emerge
from below the photosphere, where they are somehow pro-
duced by the solar dynamo. This emergence occurs in cycles
and patterns, producing such behavior as the butterfly dia-
gram of sunspots.

Albedo: The ratio of light diffusely reflected by an object
to incident light.
interior and providing information on its internal layers and core. In the case of helioseismology, detectable up and down motions due to the presence of sound waves in the near-surface gas provide information on large-scale motions such as rotation all the way to the Sun’s core and on smaller-scale motions just below the surface. These measurements have revealed some critical clues on the likely operation of the solar dynamo, which depends on shear or relative motions of different layers, as well as less-ordered “turbulent” or irregular motions on all scales. The techniques of helioseismology are still improving and may represent our best chance of understanding how the solar dynamo works.

**Interplanetary magnetic field:** The solar magnetic field carried by the solar wind into interplanetary space.

**Magnetosphere:** A highly magnetized region that creates a cavity in the solar wind flow.

**Maunder minimum:** A period when sunspots were exceedingly rare, roughly spanning from 1645 to 1715. It is named after the solar astronomer Edward W. Maunder. It coincides with the middle and the coldest part of the Little Ice Age.

**m index:** Derived from the median standard deviation of hourly average geomagnetic data from a set of stations.

**Momentum flux of solar wind:** The rate of transfer of momentum across a unit area. Momentum flux of the solar wind is the product of the density and the square of solar wind velocity. The radial component of the solar wind momentum flux is also called the dynamic pressure.

**Neutral line:** The line that separates magnetic fields of opposite polarity. The solar neutral line is often taken to be at a distance of 2.5 solar radii.

**Potential field source surface model:** This model calculates the magnetic field of the solar corona on the basis of the observed photospheric magnetic field, assuming that the magnetic field is radial and there are no currents between the photosphere and the source surface radius.

**Proxy measurements:** Measurements that do not directly reflect a quantity but are strongly affected by the quantity that an author wishes to measure and can substitute for the desired quantity in the absence of direct measurements.

**Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX):** This satellite’s instruments are a complementary set of high-resolution, high-sensitivity particle detectors used to conduct studies of solar, anomalous, galactic, and magnetospheric energetic particles. It was launched on 3 July 1992.

**Solar activity:** Occurrence of sunspots, flares, coronal mass ejections, and many other phenomena.

**Solar cycle:** The cycle of sunspots and solar magnetic activity. The solar cycle is often quantified by counting the frequency and placement of sunspots visible on the Sun. Its length varies from cycle to cycle, but the average is about 11 years. Because magnetic fields can be both positive and negative pointing, and these fields reverse every sunspot cycle, the magnetic solar cycle is on average 22 years long.

**Solar dynamo:** The interior of the Sun is a hot mixture of highly compressed gas that has circulation patterns and other less organized motions similar to weather in a planetary atmosphere. The combination of these motions, and the existence of magnetic fields threading the solar interior, somehow creates the solar magnetic cycle with consequences observed in various phenomena from sunspot number to coronal emissions to interplanetary magnetic fields and solar wind. This solar dynamo is still a subject of intensive research, with helioseismology as the main tool for probing the solar interior’s dynamics.

**Solar maximum:** The period of greatest solar activity in a solar cycle. During this period, the Sun’s magnetic field is the most distorted and therefore carries the maximum energy.

**Solar minimum:** The period of least solar activity in a solar cycle. During this period, sunspot and solar flare activity diminishes.

**Solar modulation parameter:** A parameter characterizing solar modulation of galactic cosmic rays. Its value can vary by a factor of more than 3 from solar maximum to solar minimum.

**Solar wind:** A flow of ionized solar plasma carrying a remnant of the solar magnetic field that pervades interplanetary space. It is accelerated by the huge pressure difference between the solar corona and interstellar space, created by an as yet poorly understood heating source.

**Space weather:** Disturbances in the Earth’s plasma and energetic (radiation belt) particle environment caused by solar and solar wind activity that can influence the performance and reliability of space-borne and ground-based technological systems and endanger human life or health.

**Sunspot:** Dark areas on the Sun’s photosphere in a white light image. In sunspots, the magnetic field is intense, so convection is inhibited and the surface temperature is cooler than in other regions.

**Sunspot cycle:** The interval determined by counting the frequency and determining the solar latitude of sunspots visible on the Sun. It is about 11 years on average.

**Sunspot number:** Devised by Rudolph Wolf in 1848 on the basis of a number of sunspot groups on the solar disk and the total number of individual spots in all the groups. There are two official sunspot numbers in common use. One is the daily “Boulder sunspot number” from the NOAA Space Environment Center, and the other one is the “international sunspot number” published daily by the Solar Influences Data Center in Belgium.

**Torsional oscillations:** The rotation of the Sun is generally determined by tracking surface features across the disk. Historical observations showed that these features do not generally take the same time at all latitudes. Instead there is a pattern suggesting faster rotation at the equator (at a period of ~25 days) and slower rotation at high latitudes nearer the poles (~30 days). However, the average trends of this latitude dependence are perturbed by jet stream–like bands that move faster or slower than the average in each hemisphere. These bands are referred to as torsional oscillations. These bands seem to follow the latitudes of the main photospheric field features, e.g., with one band drifting toward the equator with the band of sunspot activity as the cycle progresses. The origin and consequences of these torsional oscillations
is still under investigation. They also appear to be present beneath the photosphere according to helioseismological measurements.

**Ulysses:** A joint mission of NASA and the European Space Agency and also the first mission to study the unexplored region of space above the Sun’s poles. It was launched in October 1990 and ended in 2008 on its third polar orbit.

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**REFERENCES**


Wilson, P. R., R. C. Altrock, K. L. Harvey, S. F. Martin, and H. B. Snodgrass (1988), The extended solar activity cycle, *Nature*, 333, 748, doi:10.1038/333748a0.