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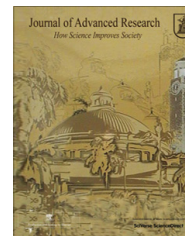Jian, LK
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ORIGINAL ARTICLE

How unprecedented a solar minimum was it?

C.T. Russell [a],[*], L.K. Jian [a], J.G. Luhmann [b]

[a] *Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA*
[b] *Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA*

Abstract   The end of the last solar cycle was at least 3 years late, and to date, the new solar cycle has seen mainly weaker activity since the onset of the rising phase toward the new solar maximum. The newspapers now even report when auroras are seen in Norway. This paper is an update of our review paper written during the deepest part of the last solar minimum [1]. We update the records of solar activity and its consequent effects on the interplanetary fields and solar wind density. The arrival of solar minimum allows us to use two techniques that predict sunspot maximum from readings obtained at solar minimum. It is clear that the Sun is still behaving strangely compared to the last few solar minima even though we are well beyond the minimum phase of the cycle 23–24 transition.

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Introduction

The sunspot cycle and solar activity in general is powered by the magnetic flux that reaches the photosphere. This field is generated deep in the solar convection layer and may be strong or weak there, but if it does not reach the photosphere, there will be no sunspots, no active regions, and no substantial coronal mass ejections. Thus both production and transport are critical processes and a change in either might be cause for a change in solar activity from one solar maximum to the next. It is clear there has been a change between cycle 23 and 24, the preceding and current sunspot cycles and it is clear that the change is not going to disappear quickly. The Sun does not

seem to be getting back to normal, as defined by what we have experienced since the onset of the space age in the 1960s. We have monitored the solar wind for only 50 years at present and the solar magnetic field for only about twice this long. Even through the much longer term proxies of geomagnetic and sunspot records, it is difficult to say what normal really is. Moreover, it is difficult to tell what is going to happen next. The Sun could recover quickly. The drop in activity could even presage a large increase in solar activity just as the water level drops in the harbor before the tsunami arrives. The solar cycle has been linked to the weather with cold surface temperatures expected during extreme solar minima like the Maunder and Dalton minima. This might be a good epoch in which to see if such linkages exist. Finally while the Sun has always recovered from deep solar minima in the past, it can take a solar cycle or two to do so.

The beginning and maximum of the 23rd solar cycle appeared to be quite typical compared to previous recent cycles. Sunspot maxima reached ~170 in 2000 and the smoothed maximum was ~120. Then the sunspot number dropped well below what was expected, with sunspot minimum stretching
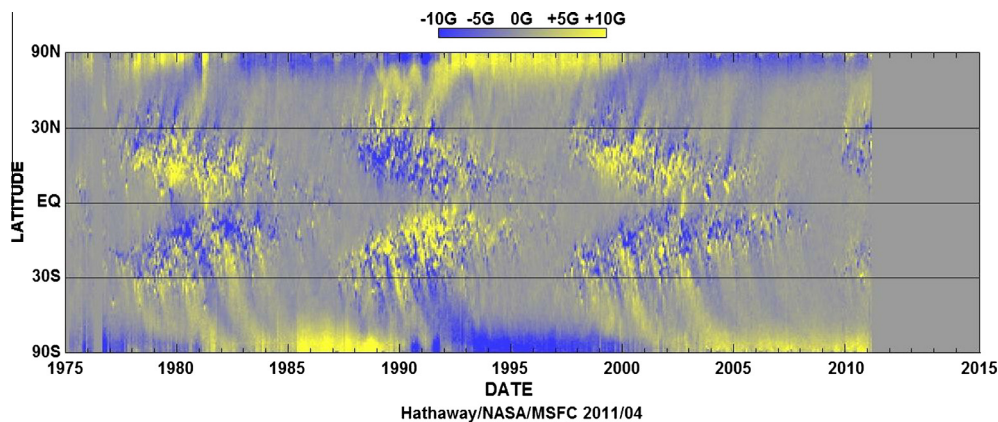
Fig. 1 The photospheric magnetic field over the last three solar cycles. This diagram shows clearly how magnetic field of one dominant polarity is transported to the polar region to cancel the pre-existing polarity there, and establish a new polarity at the poles. It also shows the weakness of recent transport and the weakness of the current polar magnetic field [3]. Recent solar maxima have been December 1979, July 1989 and March 2000.
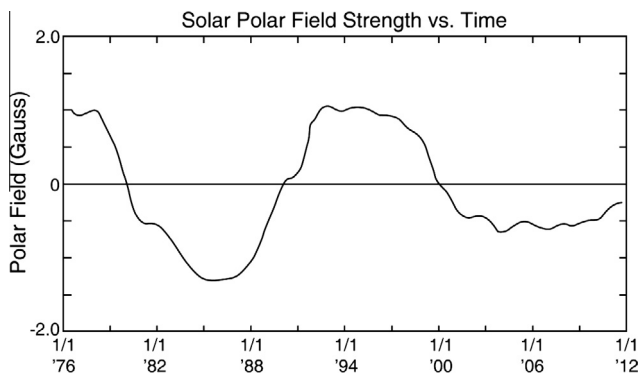

Fig. 2 The smoothed average of the polar field strengths over the last three solar cycles [4].

through 2006, 2007, 2008, 2009, and only beginning to rise in 2010. This article gives us opportunity to examine how the Sun and its magnetic field are recovering at the onset of cycle 24.

Material and methods

We have measurements of the solar wind and the magnetic field for almost 50 years. We have solar magnetic records for nearly 100 years and geomagnetic records for 150 years. The solar wind data including the magnetic field are available from the National Space Science Data Center and the geomagnetic data from the World Data Centers for Geomagnetism. A particularly useful book covering historical geomagnetic activity is by Mayaud [2] that contains the aa indices. Sunspot records have been gathered accurately for almost 200 years and with less accuracy for over 400 years. A good collection of solar data can be obtained on Hathaway's NASA website [3]. These measures allow us to judge the present solar activity levels. In this paper we examine the long term trends in these quantities to judge how unprecedented this last solar minimum was. The physical quantities that we need to use in this assessment have only been available continuously since about 1975 whether these are space based or terrestrial based. Thus our examination of the physical measurements such as the solar magnetic
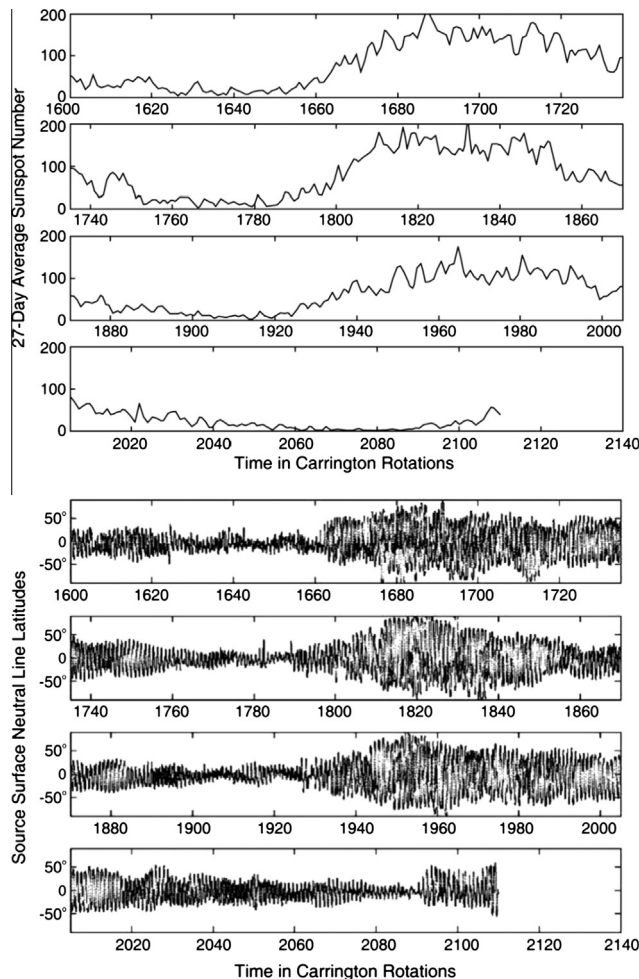
Fig. 3 (Top) Smoothed 27-day average sunspot number over last three solar cycles. Time is given in Carrington rotations which count the number of solar rotations. (Bottom) The evolution of the neutral line of the solar source surface shown over the four intervals shown. The four panels begin on 4/8/73, 5/5/83, 7/4/93 and 2/4/04. Solar maxima occurred on Carrington rotations 1689, 1818 and 1961.

field and the solar wind magnetic field and density will be restricted to the last three solar cycles.

Results

Solar and solar wind magnetic fields

The solar cycle as manifested in the photosphere revolves around the transport of magnetic flux. As shown in Fig. 1, the magnetic flux rises to the photospheric surface in the mid-latitudes of the southern and northern hemispheres of the Sun and from there is transported to the polar regions where it cancels and reverses the existing magnetic flux. This occurred normally in 1980 and 1990, but in 2000, the polar field weakened compared to these two previous cycles, and as we will see below, it has not recovered. A couple of interesting features to note in Fig. 1 are that there was a long gap from about 2005 to 2010 between the end of magnetic flux emergence in the northern hemisphere and the beginning of flux emergence in the northern hemisphere in the next cycle. The southern

behavior has been similar but the southern hemisphere is not in sync with the north at all. Hemispheric asymmetries have been reported for past weak activity cycles, suggesting there may be some relationship between dynamo asymmetry and cycle strength.

The root cause of low sunspot numbers and weak magnetic flux in the photosphere is the weak transport of magnetic flux to the surface from the dynamo below. Since transport from mid-latitudes to the polar caps feeds the open field (coronal hole) regions, and since the magnetic flux from the coronal holes supplies the interplanetary magnetic field [5,6] the field strength in the heliosphere is also expected to be weak. Fig. 2 shows an update of the time history of the averaged solar polar field adapted from the Wilcox observatory website. The asymmetric behavior of the northern and southern hemispheres can be seen in their polar fields, from Fig. 1 with the northern pole nearing reversal of polarity while the southern pole lags behind, as noted above.

One of the characteristic changes in the solar magnetic field over the course of a solar cycle is the variation in the
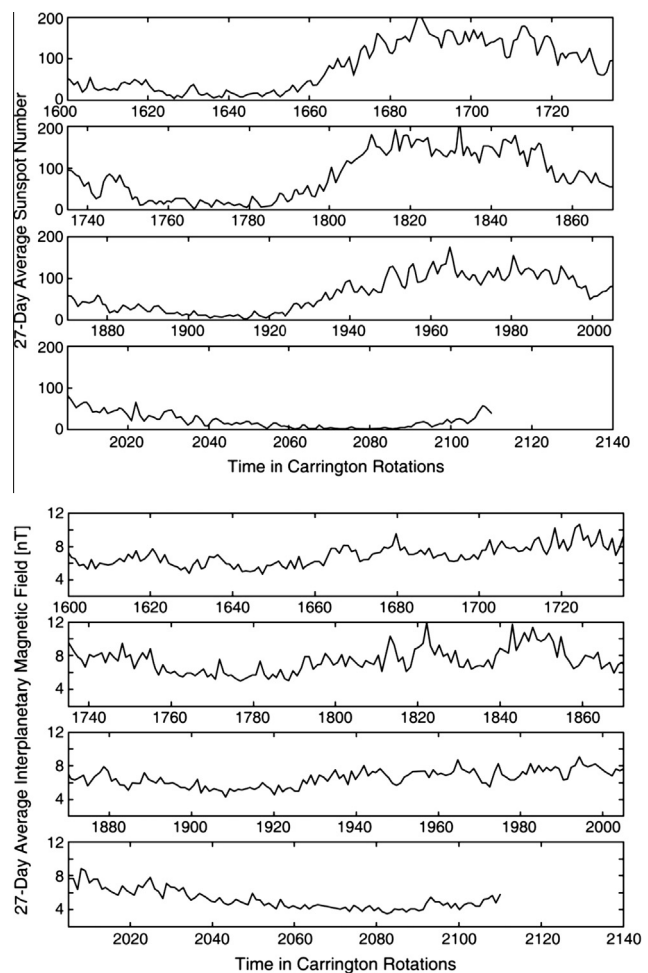

Fig. 4 (Top) Smoothed 27-day average sunspot number over last three solar cycles. Time is given in Carrington rotations which count the number of solar rotations. (Bottom) Smoothed 27-day averages of interplanetary magnetic field strength over last three solar cycles, as observed at 1 AU by the Wind and ACE spacecraft.
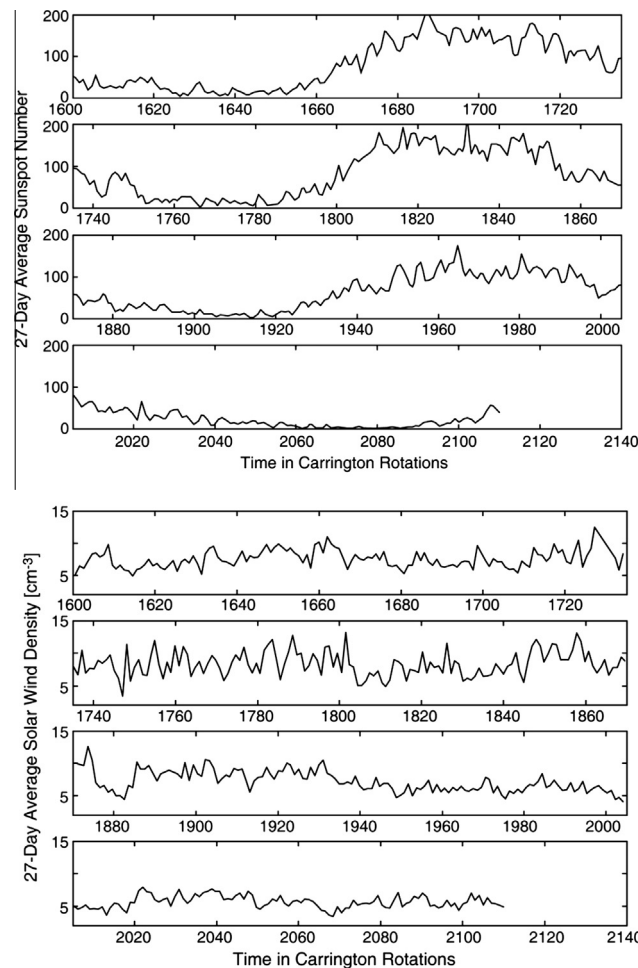
Fig. 5 (Top) Smoothed 27-day average sunspot number over last three solar cycles. Time is given in Carrington rotations which count the number of solar rotations. (Bottom) Smoothed 27-day averages of solar wind proton number density over last three solar cycles, as observed at 1 AU by the Wind and ACE spacecraft.
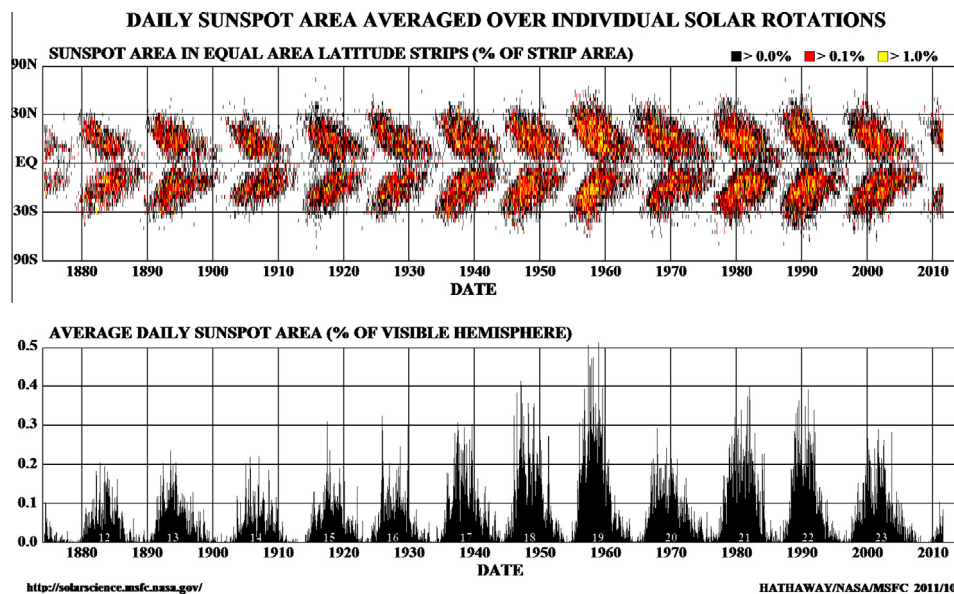
Fig. 6 Butterfly diagram (top) of the frequency of sunspots forming at different solar latitudes. Since 1874, normally these patterns nest so that during solar minimum, sunspots are appearing from both the old and the new cycles at low and high latitudes, respectively. The average sunspot area over the visible hemisphere of the Sun is shown in the bottom panel [3].
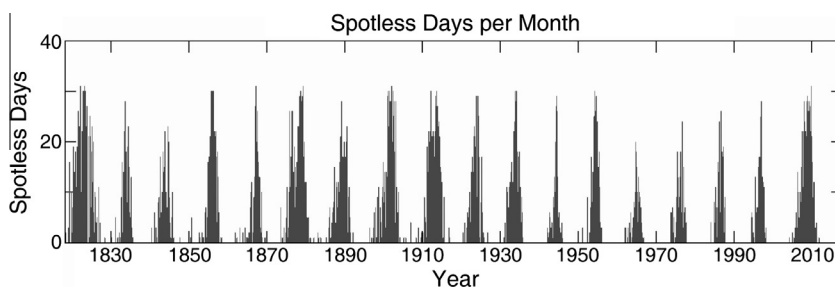

Fig. 7 Number of spotless days per month since 1820 in the Dalton minimum. The past solar minimum had a very significant number of spotless days but not as many as in the Dalton minimum [3].

inclination of the neutral line. The neutral line is the series of points around the Sun at 2.5 solar radii in the potential field source surface model where the closed magnetic field lines reach their maximum altitude and return to the solar surface [7]. If the Sun's field were dipolar this line of points would trace out the magnetic equator. It is a good indication of the evolution of the Sun's magnetic structure during the solar cycle. Fig. 3 shows the latitude of the neutral line over the last three solar cycles and the beginning of cycle 24. It is clear from the duration of the period where the neutral line was confined to low to midlatitudes that the solar minimum period was atypically long. The inclination has now increased but seems not to portend a return to the large inclination of cycles past. The high inclination in past cycles was caused by the appearance of strong active regions in the photospheric field, and so this behavior is consistent with the relative infrequency of new cycle active regions whose field strengths are competitive with the previous cycles. The weakness of the solar polar field has also led to weakness in the measured interplanetary magnetic field as shown in Fig. 4. In prior years the increasing solar activity was accompanied by an increase in the long term average strength of the interplanetary field. The field has scarcely increased since the past minimum especially when compared to the ramp-up of the previous three cycles. Fig. 5 shows that
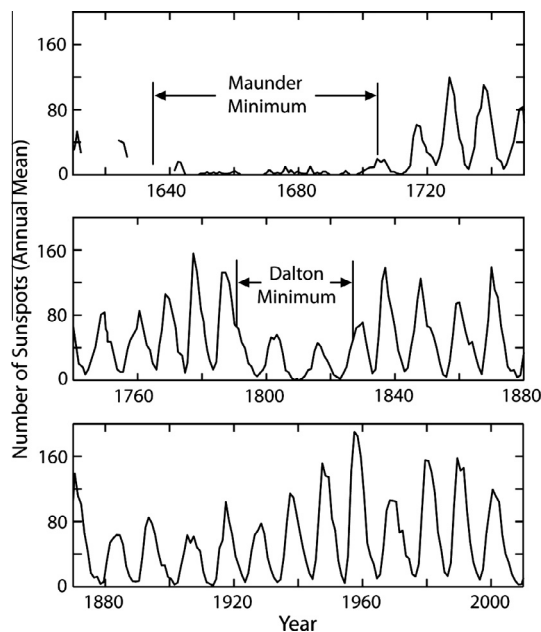
Fig. 8 The smoothed annual sunspot number going back to 1605, illustrating the Maunder minimum and the Dalton minimum.
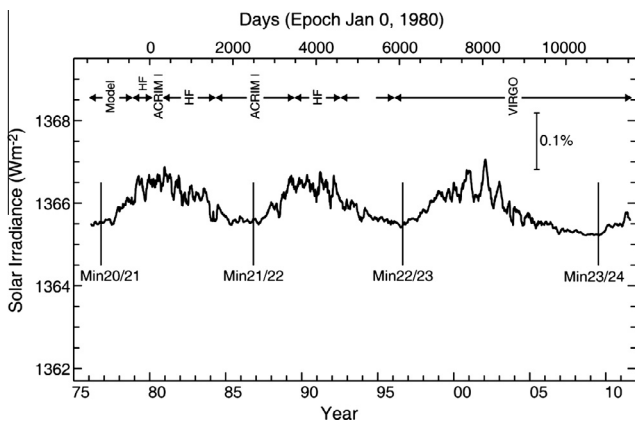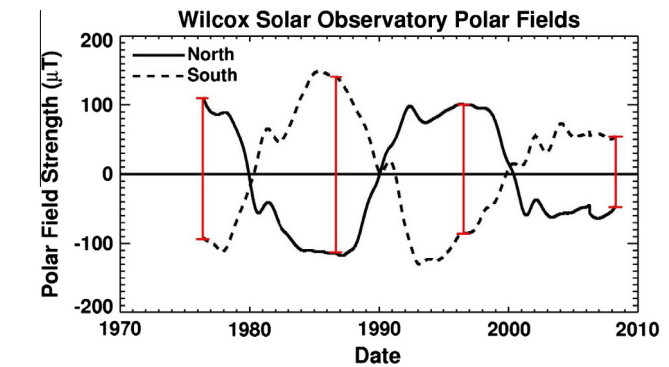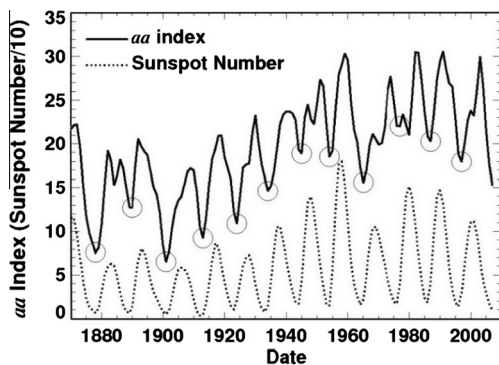
Fig. 9 Total solar irradiance over the last three solar cycles illustrating the recent continued decline of the optical output of the Sun [8].


Fig. 11 The polar magnetic field of the Sun in the north (solid line) and the South (dashed line). The vertical red bar shows the difference between the fields in the two poles at solar minimum. This difference field is used to predict the sunspot maximum of the next solar cycle.

the solar wind proton number density generally is less well correlated with the solar activity than the magnetic field. Nevertheless during the past solar minimum it dropped substantially and has barely changed during the cycle 24 rise.

What can we learn from sunspots?

Fig. 6 shows a butterfly diagram for sunspot locations as well as the sunspot area index. Besides the fact that sunspot cycle 24 is now underway in both hemispheres, this plot shows that the sunspot area has not built up to historic values for this phase of the solar cycle. This appears to be a result of the weakness of the photospheric magnetic field. If the field becomes too weak, it is possible that no sunspots would be formed, even if active regions are present since weak active regions do not produce sunspots. Solar physicists also keep track of the number of spotless days. This is our best proxy for the solar magnetic field strength before the invention of the solar magnetograph. Fig. 7 shows the plot going back to the Dalton minimum in 1820. The recent number of spotless days certainly exceeds anything in the last 100 years but maybe not in the last 200 years. Thus there have been even weaker cycles in the past. Keeping track of spotless days was not possible before 1820 and may be inaccurate until the 20th century but rudimentary data on sunspots are available to allow us to go back even

further in time with sunspot proxy data. Fig. 8 shows us the Dalton and Maunder minima in this measurement. We have no reason to expect a Maunder minimum based on the current behavior of the Sun. However, since these times coincided or overlapped with cold periods, some are expecting possible changes in climate during this period. Fig. 9 shows the Total Solar Irradiance [8]. Certainly it dropped measurably during the last solar minimum but not so much that it should make a noticeable change in the ambient temperatures on Earth, if the thermal changes are directly proportional solar irradiance changes. However the relationship between climate and solar activity is complex and still under active investigation.

Predicting future solar activity

Since it is clear that the solar magnetic cycle is on average 22 years long, it is reasonable that one could extrapolate at least 11 years. The most popular means of taking advantage of this fact is to use geomagnetic indices to gauge the current solar wind state and use persistence to predict what will happen in the next cycle. Ohl [9] developed one such technique that uses the minimum of geomagnetic activity at solar minimum to predict the maximum sunspot number of the next cycle. This technique seems to be totally empirical. Since it cannot be calculated until solar minimum has occurred, the
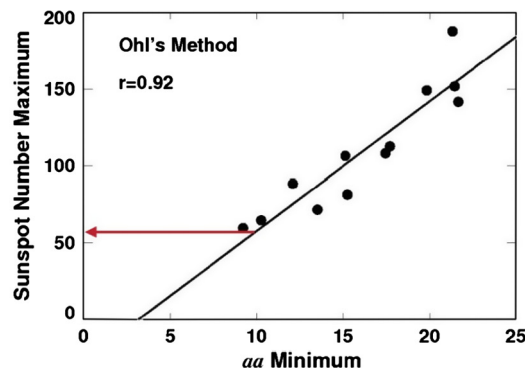
Fig. 10 (Left) The aa index and sunspot number back to 1870 used to calibrate Ohl's formula for the prediction of the coming sunspot maximum [9]. (Right) The Ohl formula is applied to predict the maximum smoothed sunspot number of cycle 24.

prediction for cycle 24 was not available until just recently. Fig. 10 shows how this is calculated and how the value predicted for the next sunspot maximum is about 55. Of course the root cause of the geomagnetic activity cycle is the solar magnetic cycle, and the strength of the photospheric field is the most direct predictor of the coming solar cycle [10]. The red[1] bars in Fig. 11 shows the preceding and current field value for the polar regions and it too points to a weak solar maximum in cycle 24. The expected sunspot number based on these fields and historical records is 75 ± 30.

Discussion and conclusions

We are now far enough into solar cycle 24 to tell it will be a weak solar cycle. This in turn is due to the weakness of the photospheric magnetic field. The reasons for this weakness are poorly understood but may lie in changes in the transport of the flux from the region of generation [11]. Heliospheric scientists have been celebrating the appearance of energetic particle events on STEREO and other spacecraft. These events have been very instructive but more so because they occur in an otherwise quiet background. There is not a confusion of sources. Newspapers and television have brought space weather storm news to their audiences, not so much because of its importance to terrestrial systems but because it has become a rare phenomenon and we observe it as never before. It remains to be seen if the deep minimum we just experienced signals the end of the Sun's anomalous behavior or whether we will experience an equally low period of geomagnetic activity into the next cycle as well. But the Sun is full of surprises and strong activity can arise everyday during otherwise moderate activity periods like the great storm of 1859 observed by Carrington.

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[1] For interpretation of color in Fig. 11, the reader is referred to the web version of this article.