Solar cycle 24: Implications for energetic particles and long-term space climate change

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[1] The recent solar minimum was the longest and deepest of the space age, with the lowest average sunspot numbers for nearly a century. The Sun appears to be exiting a grand solar maximum (GSM) of activity which has persisted throughout the space age, and is headed into a significantly quieter period. Indeed, initial observations of solar cycle 24 (SC24) continue to show a relatively low heliospheric magnetic field strength and sunspot number (R), despite the average latitude of sunspots and the inclination of the heliospheric current sheet showing the rise to solar maximum is well underway. We extrapolate the available SC24 observations forward in time by assuming R will continue to follow a similar form to previous cycles, despite the end of the GSM, and predict a very weak cycle 24, with R peaking at ~65–75 around the middle/end of 2012. Similarly, we estimate the heliospheric magnetic field strength will peak around 6nT. We estimate that average galactic cosmic ray fluxes above 1GV rigidity will be ~10% higher in SC24 than SC23 and that the probability of a large SEP event during this cycle is 0.8, compared to 0.5 for SC23. Comparison of the SC24 R estimates with previous ends of GSMs inferred from 9300 years of cosmogenic isotope data places the current evolution of the Sun and heliosphere in the lowest 5% of cases, suggesting Maunder Minimum conditions are likely within the next 40 years. Citation: Owens, M. J., M. Lockwood, L. Barnard, and C. J. Davis (2011), Solar cycle 24: Implications for energetic particles and long-term space climate change, Geophys. Res. Lett., 38, L19106, doi:10.1029/2011GL049328.

1. Introduction

[2] The recent solar minimum, the end of solar cycle 23 (SC23), has been longest and deepest of the space age, with the weakest heliospheric magnetic field, B [Lockwood et al., 2009a, 2009b] and a significant reduction in the solar wind speed and density [McComas et al., 2008]. At the photosphere, this minimum has resulted in the largest number of consecutive sunspot-free days since 1913 and the lowest polar magnetic field strength since routine observations began in 1975 [Wang et al., 2009]. The magnitude of the delayed cycle 24 is of major interest not only for space weather concerns during the remainder of SC24 [e.g., Barnard and Lockwood, 2011; McCracken, 2007; Hapgood, 2011], but also long-term space climate change [Barnard et al., 2011]. [3] Average solar activity, as quantified by a variety of parameters, has been declining since about 1985 [Lockwood and Fröhlich, 2007] and the recent exceptionally low minimum is part of this decline [Lockwood, 2010]. From a study of the durations of Grand Solar Maxima (GSMs) during the past 9300 years, as detected in cosmogenic isotope data, Abreu et al. [2008] deduced that the current GSM was uniquely long-lived and due to end soon. This was supported by extrapolations of recent trends in heliospheric parameters [e.g., Lockwood et al., 2009b]. This decline has potential implications for predictions of winter climate in Europe [Lockwood et al., 2011] and of hazardous particles in Earth environments [McCracken, 2007; Barnard et al., 2011], specifically galactic cosmic rays (GCRs) and solar energetic particles (SEPs).

2. Predicting Solar Cycle 24

[5] Figure 1 shows time series of various solar parameters since 1975, when routine photospheric magnetic field measurements began. All data have been averaged to 27 days. Observed monthly sunspot number (R) is shown in blue: The peak amplitude of R has been declining through much of the space age [Lockwood et al., 2009b; Lockwood and Fröhlich, 2007], and the recent solar minimum was particularly low, with R essentially zero for much of 2009. The black line shows the average latitude (θ, in degrees) of sunspots, scaled up by a factor 5: The sudden increase at solar minimum is due to the emergence of high latitude sunspot pairs of new cycle polarity, which results in the classic butterfly diagram. The red line shows the HCS inclination index i (which is the HCS length perpendicular to the solar rotation direction [Owens et al., 2011]), computed from potential-field source-surface reconstructions of Wilcox Solar Observatory magnetograms: this has been scaled by 1800 to fit on the same y-axis scale.

[6] While R is a good proxy for the rate of photospheric flux emergence and hence the production of new open solar flux [e.g., Solanki et al., 2000; Vieira and Solanki, 2010; Krivova et al., 2007], i may serve as an indicator of the rate at which open solar flux is destroyed [Sheeley et al., 2001; Owens et al., 2011]. Indeed, the HCS did not flatten as quickly at the end of cycle 23, which may be responsible for the associated drop in B in the recent solar minimum [Owens et al., 2011].
cycles 12 to 23 to the average variation in significantly from the average behaviour. We therefore scale

<table>
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<th>$R$</th>
<th>$B$</th>
<th>$F$</th>
<th>$N$</th>
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<tr>
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<td>0.75</td>
<td>0.70</td>
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</table>

3. Implications for Energetic Particles

We now apply the same composite scaling procedure to the space-age observations of heliospheric magnetic field strength, $B$, total unsigned heliospheric magnetic flux, $F$, and neutron monitor counting rate, $N$. We note that all the space-age cycles have all been part of a Grand Solar Maximum, whereas SC24 is predicted to return to lower, more nominal activity levels. Thus we have to assume, without any direct observations, that the heliospheric properties of SC24 follow the same statistical behaviour as the previous GSM cycles. The red lines in Figure 3 (left) show the variations in $B$, $F$ and $N$ since SC20–23 using OMNI data [King and Papitashvili, 2005] and neutron monitor counting rate, in 100s counts per hour, from the McMurdo station in Antarctica, superimposing both odd and even solar magnetic polarity cycles [e.g., Usoskin, 2008, and references therein].

These are then scaled to the mean values using the factors shown in Table 1. Figure 3 (right) shows the mean-scaled variation further linearly adjusted to the available SC24 observations, shown in black. $B$ is expected to peak at the start of 2014 at around 6 nT, while $F$ should peak around $8 \times 10^{14}$ Wb. Neutron monitor counting rates at McMurdo should stay above 9000 throughout the cycle. This results in a GCR intensity $\sim 10\%$ higher in SC24 than SC23.
higher than SC23). Using observed values of $B$ and $R$, we find that the integrated value of $P_{SEP}$ for SC23 (from minimum to minimum) was 0.5, whereas the predictions for SC24 yield 0.8. Thus a large SEP event is 60% more likely during the current solar cycle than it was in the previous one. This is due to the predicted $B$ decrease, which reduces heliospheric Alfvén speed, increasing the shock strength. We note, however, that such low values of $B$ are outside the range used to empirically characterise the $P_{SEP}$ algorithm and that additional factors may become important in this new parameter regime. Additionally, the occurrence of moderate SEP events is likely to decline with the weaker solar activity cycle [Barnard and Lockwood, 2011; Barnard et al., 2011].

4. Implications for Long-Term Solar Variability

[11] Assuming SC24 continues to follow the average $R$ variation from SC12–23 and peaks around $R = 65 – 75$, then the end of the space-age grand solar maximum (GSM) occurred during the recent minimum [Usoskin et al., 2003; Solanki et al., 2004; Abreu et al., 2008]. Using $^{10}$Be cosmogenic isotope data, extended to overlap with modern neutron monitor data by means of the heliospheric modulation formalism [Steinhilber et al., 2008, 2010], Barnard et al. [2011] characterised solar activity following the end of 24 GSMS which occurred over the last 9300 years [Lockwood, 2010; Lockwood et al., 2011]. However, note that $^{14}$C data only show 19 GSMS during a similar time period [e.g., Usoskin, 2008, and references therein]. Two of the 24 $^{10}$Be GSM ends resulted in Maunder minimum-like conditions within 40 years. Lacking information about the magnitude of cycle 24, Barnard et al. [2011] concluded there is an 8% probability of Maunder minimum-like conditions within the next 40 years. Here, we use our estimate

Figure 2. A comparison of solar cycle 24 (black), with SC21–23 (coloured lines). The variation in (top left) the average sunspot latitude and (top middle) the HCS inclination is very similar for the rise phase of all four cycles, despite (top right) the large difference in sunspot number between cycles. A comparison of SC24 with a composite of (bottom left) $\theta$ and (bottom middle) $R$ for SC12 through SC23. (bottom right) A linear scaling of $R$ used to predict a maximum $R$ for SC24 of 65–75 around the end of 2012.

Figure 3. (left) A comparison of the heliospheric magnetic field strength, $B$, the total heliospheric magnetic flux, $F$ and the neutron count at McMurdo in Antarctica, $N$ for solar cycle 24 (black) with SC20–23 (red). (right) SC20–23 scaled to the average, then to SC24 levels. $B$ is expected to peak at the start of 2014 at around 6 nT, while $F$ should peak around $8 \times 10^{14}$ Wb. Neutron counts at McMurdo should stay above 9000 throughout the cycle, approximately 10% higher than SC23.
reach a sunspot maximum of $R_{75}$ around the middle of cycle 22 [Lockwood et al., 2011]. These probabilities are in 10% intervals starting at 5% in mauve, to 95% in red. The black plot shows the observed sunspot number, which transitions to the red prediction for cycle 24. If this SC24 extrapolation is correct, this GSM end is in the lowest 5% in terms of $R$.

for SC24 to better constrain the probability of a period of such low solar activity.

[12] Figure 4 shows past and future variations in $R$. Coloured smooth curves show the values $R_p$ that $R$ will fall below at certain probability levels $P(R<R_p)$ following the exit from a GSM, based on the previous 24 GSM endings [Barnard et al., 2011] and assuming all cycles will be 11 years in duration. These probabilities are in 10% intervals starting at 5% in mauve, to 95% in red. The black plot shows the observed sunspot number, transitioning to the red prediction for cycle 24. If this SC24 extrapolation is correct, the current GSM end is in the lowest 5%, suggesting the Sun is on course for a new Maunder minimum within the next 40 years. Using the higher NOAA prediction of $R \sim 90$ still puts the SC24 in the lowest 35% of GSM endings.

5. Discussion and Conclusions

[13] While peak sunspot number varies considerably from cycle to cycle, the distribution of photospheric magnetic flux, manifest in the average latitude of sunspots (12 solar cycles of data available) and the heliospheric current sheet inclination (only 3 cycles of data available), is remarkably similar during the rise phase of different solar cycles. Defining the start of a solar cycle as the time of the sharp increase in average sunspot latitude allows cycles to be composited to describe an “average” cycle. Linearly scaling all cycles to this average, then further scaling to the available cycle 24 observations gives a prediction of sunspot variation for cycle 24, assuming it continues to follow the average variation. In this manner, we predict the Sun will reach a sunspot maximum of $R \sim 65 - 75$ around the middle/end of 2012. This is lower than the official NOAA prediction of $R \sim 90$ at the middle of 2013.

[14] We performed a similar solar cycle scaling analysis for the heliospheric magnetic field strength, $B$, the total unsigned heliospheric magnetic flux, $F$, and ground-based neutron monitor counting rates, $N$. The uncertainties in these SC24 estimates are higher than for $R$, as data are only available for space-age solar cycles. We predict $B$ to peak around $6 \pm 1$ nT, roughly equal to average minimum conditions over SC20–23, and about a third to a quarter lower than the average maximum value during that interval. $F$ shows very similar trends. The probability of a major SEP event is 60% higher during the current SC than it was during the last one and the GCR flux above 1GV is $\sim 10\%$ higher.

[15] Past work has used cosmogenic isotope data to predict the future evolution of solar activity at various levels of probability based on the ends of past grand solar maxima [Barnard et al., 2011; Lockwood et al., 2011]. In the current paper we have taken this further by studying the evolution of several solar and heliospheric parameters during the current solar cycle and found that they are following trajectories consistent with a rapid descent into Maunder minimum conditions (within about 40 years). However, it must be stressed that this is not based on modelling of the solar dynamo, rather it uses past experience which also shows that declines from one cycle to the next do not always persist. For example, one might have reached the same conclusion when cycle 20 was found to be so much weaker than the exceptional cycle 19 before it; but that trend did not persist, with long-term solar activity rising again to a second peak in the middle of cycle 22 [Lockwood and Fröhlich, 2007; Lockwood et al., 2011]. However, that reversal of the initial decline also resulted in the current grand solar maximum becoming the longest in the 9300-year record [Usoskin et al., 2003; Solanki et al., 2004; Abreu et al., 2008] and that may be related to the unusually rapid descent that is now taking place.

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