AGU PUBLICATIONS

Space Weather

RESEARCH ARTICLE

10.1002/2014SW001067

Key Points:
- The coming solar minimum is likely to resemble the Dalton Minimum
- This will result in the lowest HMF flux during the space age
- Lowest solar wind flux and highest cosmic ray intensity for the space age

Correspondence to:
C. W. Smith,
Charles.Smith@unh.edu

Citation:
Smith, C. W., K. G. McCracken, N. A. Schwadron, and M. L. Goelzer (2014), The heliospheric magnetic flux, solar wind proton flux, and cosmic ray intensity during the coming solar minimum, *Space Weather*, *12*, 499–507, doi:10.1002/2014SW001067.

Received 14 MAR 2014
Accepted 7 JUL 2014
Accepted article online 12 JUL 2014
Published online 29 JUL 2014

The heliospheric magnetic flux, solar wind proton flux, and cosmic ray intensity during the coming solar minimum

Charles W. Smith[1,2], K. G. McCracken[3], Nathan A. Schwadron[1,2], and Molly L. Goelzer[2,4]

[1]Physics Department, Space Science Center, University of New Hampshire, Durham, New Hampshire, USA, [2]Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, New Hampshire, USA, [3]Institute of Physical Science and Technology, University of Maryland, College Park, Maryland, USA, [4]Department of Chemical Engineering, University of New Hampshire, Durham, New Hampshire, USA

Abstract Recent papers have linked the heliospheric magnetic flux to the sunspot cycle with good correlation observed between prediction and observation. Other papers have shown a strong correlation between magnetic flux and solar wind proton flux from coronal holes. We combine these efforts with an expectation that the sunspot activity of the approaching solar minimum will resemble the Dalton or Gleissberg Minimum and predict that the magnetic flux and solar wind proton flux over the coming decade will be lower than at any time during the space age. Using these predictions and established theory, we also predict record high galactic cosmic ray intensities over the same years. The analysis shown here is a prediction of global space climate change within which space weather operates. It predicts a new parameter regime for the transient space weather behavior that can be expected during the coming decade.

1. Introduction

The past 10 years of solar and solar wind observations have shown a trend that is unique in the space age. After a relatively normal level of solar activity during the solar maximum of 1998 through 2004, approximately, the Sun entered a protracted solar minimum phase with greatly reduced activity lasting longer than recent solar minima of the past 50 years. *Smith and Balogh* [2008] showed that the heliospheric magnetic field (HMF) reached record low values at both high and low latitudes. *Connick et al.* [2009, 2011] confirmed that the injection of magnetic flux in the form of helical fields was nearly zero during this time and showed that the HMF flux fell steadily during the years 2005 to 2010 until solar activity resumed. *McComas et al.* [2008, 2013] showed that the solar wind proton flux was also greatly reduced during the solar minimum years. While both the solar wind speed and proton density experienced a significant reduction during the recent solar minimum, it was the reduction of the density that dominates the reduced proton flux results. At the same time neutron monitor counting rates hit record levels [*Oh et al.*, 2013]. The resumption of solar activity in the form of coronal mass ejections (CMEs) from 2010 to 2013 was relatively weak, as was the sunspot number, resulting in the weakest solar maximum of the space age. HMF intensities failed to reach the levels of the previous solar maximum.

Barnard et al. [2011] have previously provided an "analogue" prediction for future solar activity and its impacts on space weather. Their approach was to use the paleo-cosmic radiation (^{10}Be and ^{14}C) data of the past to estimate the probability of various levels of solar activity in the future. By way of contrast, this paper provides a "real-time" prediction methodology. Throughout the space age, the observed data have been used to develop several models of the interdependence of solar and heliospheric quantities. Our methodology uses those models to predict three important features of space weather using data inputs up to the present date, together with projected sunspot numbers for the next 10 years. This methodology has the advantage that it yields quantitative estimates of the space weather in the immediate future and that it can be updated on a year-to-year basis.

We contend that the pattern seen in the past 10 years of sunspot and HMF intensity strongly resembles the Dalton (Grand) and Gleissberg Minima [*Clilverd et al.*, 2006; *Watari*, 2008; *Turner*, 2011; *Kamide and Kusano*, 2013; *Goelzer et al.*, 2013; *McCracken and Beer*, 2014]. We compare the recent protracted solar minimum and the relatively weak solar maximum that followed to past epochs of low solar activity levels and use the

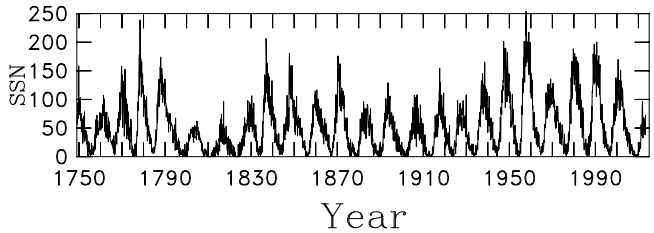

Figure 1. Monthly average sunspot numbers as compiled by the Solar Influences Data Analysis Center (SIDC).

Dalton and Gleissberg Minima as likely proxies for the solar activity that is to come in the next decade. With this assertion and three published theories we can predict the average HMF flux and solar wind proton flux for the coming decade, and from those predictions we can predict the galactic cosmic ray intensity. The first theory [*Schwadron et al.*, 2010] links heliospheric magnetic flux to sunspot number. The Dalton and Gleissberg Minima sunspot numbers then give us the HMF flux. The second theory [*Schwadron and McComas*, 2008] then provides a prediction for the solar wind proton flux in terms of the HMF flux. From these we can use the third theory [*Caballero-Lopez et al.*, 2004; *McCracken*, 2007] to derive a prediction for the galactic cosmic ray intensity over the same period. In the interest of brevity, we present only the results of our methodology as the theories and their tests are already published elsewhere.

2. The Dalton and Gleissberg Minima

We begin with a direct comparison of the sunspot numbers during the recent solar cycles and those of the Dalton and Gleissberg Minima. Figure 1 shows the monthly average sunspot numbers from 1749 to November 2013. There are several intervals when the sunspot numbers associated with solar maximum are lower than is otherwise typical. One such interval is the Dalton Grand Minimum that runs from 1790 to 1830. The solar maximum associated with the start of this interval is typical of other maxima, but the following solar maxima show a series of three maxima with reduced sunspot numbers. The critical point is that such low maxima tend not to occur in isolation but are generally seen as a series of about three such cycles with reduced activity levels. Another period of reduced activity is the Gleissberg Minimum (not usually called a "Grand" Minimum) that runs from 1890 to 1920. Again we see a series of maxima showing reduced activity levels. These intervals form the basis for our prediction of the coming decade of solar activity and its associated HMF flux, solar wind proton flux, and galactic cosmic ray intensity.

Figure 2 (top, left) shows the reported monthly sunspot numbers from 1785 to 1815, the first cycle of the Dalton Minimum. There is another cycle of low sunspot numbers that follows those plotted here. Figure 2 (bottom, left) shows the reported monthly sunspot numbers from 1995 to November of 2013 (black curve). Subsequent sunspot numbers are listed as "provisional" and subject to change, so they are not used here.

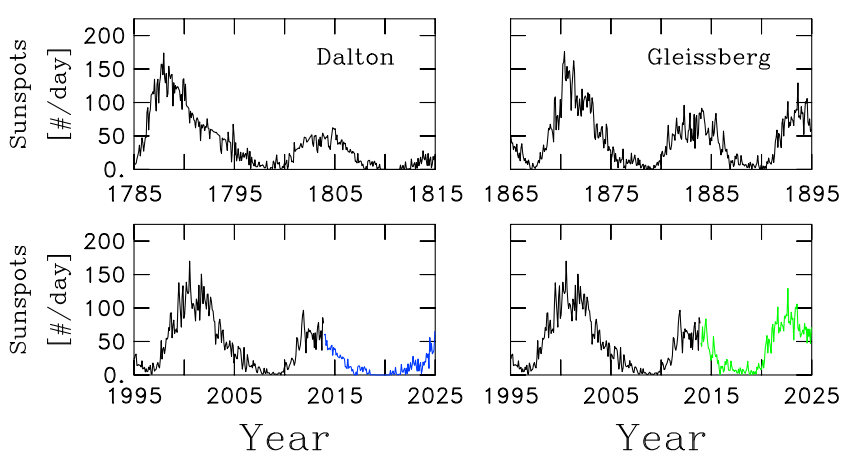

Figure 2. (top, left) Recorded monthly averages of the sunspot numbers from 1785 to 1815 (the start of the Dalton Grand Minimum). (bottom, left) Recorded sunspot numbers from 1995 to 2013 (black curve) followed by a reproduction of the Dalton Minimum values starting in 1805 (shown in blue for the years 2014 onward). (top, right) Recorded monthly averages of the sunspot numbers from 1865 to 1895 (the Gleissberg Minimum). (bottom, right) Recorded sunspot numbers from 1995 to 2013 (black curve) followed by a reproduction of the Gleissberg Minimum values starting in 1885 (shown in green for the years 2014 onward).

Note the "typical" solar maximum from 1998 to 2003 that resembles the maximum from 1785 to 1790. Although slightly different in shape, the two reach comparable levels of intensity with the 1788 values slightly exceeding the 2001 values and both are similar to maxima throughout the space age (1965 onward). When we compare the unusually low sunspot numbers of the maxima for 1804 and 2013, we find that the 1804 values are slightly lower than the 2013 values. Both are uncommonly low for maxima throughout the space age.

Solar maxima peaking at sunspot numbers of 50 are uncommon but are recorded in the sunspot record from 1749 onward. They fall into groupings of two or more and are not seen as isolated events [*Kamide and Kusano*, 2013; *Goelzer et al.*, 2013]. It is therefore likely that we will again see another weak solar maximum after the coming solar minimum. With this in mind, we use the sunspot numbers from December 1804 onward as a prediction for what is coming from December 2013 onward (Figure 2, bottom, left, blue curve). Provisional sunspot numbers in 2014 show a second peak rising to ~100. This is very much uncharacteristic of the last 2 years of sunspot numbers. If these numbers are validated and persist for about a year, it is likely that a better model for the coming solar minimum will be the minimum we experienced most recently. If they are validated but do not persist beyond a few months, they are unlikely to significantly change the predictions shown here as it takes time to accumulate the additional flux that such high sunspot numbers would suggest. Only time will tell if this is true.

Figure 2 (top, right) shows the reported monthly sunspot numbers marking the start of the Gleissberg Minimum from 1865 to 1895. As with Figure 2 (top, left), this represents only the first half of the cycle of reduced sunspot numbers. The solar maximum of 1870 was marginally higher than the maximum of 2001, while the maximum of 1883 is also slightly higher than the maximum of 2013. The Gleissberg Minimum represents a somewhat less extreme reduction in sunspot number relative to the space age than does the Dalton Minimum. As with the Dalton Minimum, we can use the sunspot numbers from 1885 onward as a proxy for the coming solar minimum (2014 onward) which we show in Figure 2 (bottom, right, green curve). The sunspot minima of the Gleissberg Minimum are shorter in duration than those of the Dalton Minimum, but both achieve unusually low sunspot numbers when compared with the space age.

3. Heliospheric Magnetic Field

The first theory that we employ here is an extension of the idea that CMEs inject magnetic field lines into interplanetary space and then magnetic reconnection in the low solar atmosphere releases those field lines [*McComas et al.*, 1992; *Solanki et al.*, 2000; *Low*, 2001; *Owens and Crooker*, 2006, 2007; *Owens et al.*, 2008, 2011a; *Lockwood et al.*, 2009; *Schwadron et al.*, 2010; *Owens and Lockwood*, 2012]. While attached to the Sun these newly injected field lines are drawn out to match the spiral configuration predicted by *Parker* [1958, 1963]. Once released, presumably by reconnection low in the solar atmosphere, they are free to be ejected from heliospheric space by the solar wind. We use the theory of *Schwadron et al.* [2010] to predict the HMF flux based on sunspot number. *Smith et al.* [2013] applied this theory to the Omni2 data set [*King and Papitashvili*, 2005] with favorable results. *Goelzer et al.* [2013] employed the same parameter choices in a comparison with HMF analyses derived from ^{10}Be observations going back to 1749 and also obtained favorable results. We employ the exact same formulation of the theory here.

Figure 3 (top) shows the monthly sunspot number (black curve), followed by the predicted sunspot numbers derived from the Dalton Minimum postulate (blue curve) and the Gleissberg Minimum postulate (green curve) which are used as predictions for the coming decade of solar activity. Figure 3 (middle) shows the predicted value of $\langle |B_R| \rangle$ as derived from the above theory (red curve) and the average value of $\langle |B_R| \rangle$ as computed from the Omni2 data set (black circles). There is good agreement between the predicted and measured HMF flux densities. This is consistent with the results of *Smith et al.* [2013] and *Goelzer et al.* [2013].

Beginning with the year 2014, the sunspot numbers are assumed to follow the reported observations of the Dalton and Gleissberg Minima as described above. The predicted sunspot numbers are then used as input to the above theory to obtain a prediction for the HMF flux density $\langle |B_R| \rangle$ for the years 2014 and beyond. These are also shown in the figure where use of the Dalton Minima (blue curve) and Gleissberg Minima (green curve) yield consistent results until 2019. The only significant question is "When will the minimum end and the rise to the new maximum begin?" Note that the adoption of the Dalton and Gleissberg Minima sunspot numbers is not exactly the same as reproducing the predicted or observed HMF flux for the Dalton or Gleissberg Minima as there is a significant hysteresis effect within the theory, but it is similar.

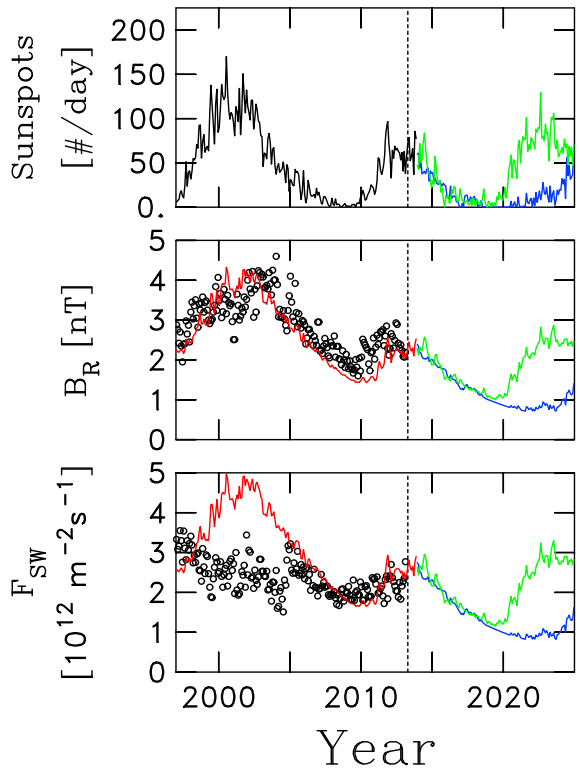

Figure 3. (top) Monthly averaged sunspot number leading to December 2013 (black curve) with extension using Dalton Grand Minimum (blue curve) and Gleissberg Minimum extension (green curve). (middle) Predicted value of HMF flux density $\langle|B_R|\rangle$ using the observed sunspot numbers (red curve) leading up to the start of 2014 with the predicted level derived from the Dalton Minimum extension and the *Schwadron and McComas* [2008] theory as applied by *Smith et al.* [2013] and *Goelzer et al.* [2013] (blue curve) and Gleissberg Minimum extension (green curve), as well as the measured value of $\langle|B_R|\rangle$ obtained from Omni2 data set (black circles). (bottom) Predicted value of F_{SW} as obtained by the theory of *Schwadron and McComas* [2008] and related papers using the observed sunspot numbers (red curve) followed by the prediction using the Dalton postulate (blue curve) and Gleissberg postulate (green curve).

Our calculations predict that if the coming solar cycle follows the form of the Dalton Minimum the HMF flux density circa 2020 will decrease to ~60% of that during 2009. The cosmogenic radionuclide ^{10}Be provides a record of the cosmic ray intensity in the past, and *McCracken* [2007] used it to estimate the annual HMF intensity at Earth since 1420. Those estimates decreased by a factor of 70% between the solar minima of 1798 and 1810 [see *Goelzer et al.*, 2013, Figure 1], these being the analogous minima to 2009 and 2020. The annual average of the HMF intensity near Earth was ~3.9 nT in 2009. Our predictions, based on sunspot number during the Dalton Minimum, indicate that $\langle|B_R|\rangle$ will reach down to almost 0.7 nT. If in situ comparisons hold with regard to the component of the HMF perpendicular to the Parker field, which is all that is predicted by the *Schwadron et al.* [2010] theory, the HMF near Earth will decline to ~2.5 nT in 2021 if the coming solar minimum follows the Dalton Minimum. If the coming solar minimum follows the Gleissberg Minimum, then $\langle|B_R|\rangle$ falls to ~1 nT in 2019 and then begins to recover earlier than in the Dalton Minimum postulate. This suggests a minimum HMF intensity of ~3 nT. Note that in either instance the next solar minimum will be weak compared with any minimum of the space age.

4. Solar Wind Proton Flux

We now use this prediction for the HMF flux to obtain a prediction for the solar wind proton flux during the same years. *Schwadron and McComas* [2008] derive a prediction for the solar wind proton flux based on a linear scaling with the HMF flux and demonstrate that it holds for high-speed winds (> 750 km s^{-1}) observed by the Ulysses spacecraft. In an attempt to simplify the expressions used by *Schwadron and McComas* [2008] we make the following assertion:

$$F_{SW}^{Th} = 1.15 \times 10^{12} \langle|B_R|\rangle. \quad (1)$$

This proportionality constant will be justified below by the results, but it is approximately equivalent to the analysis of *Schwadron and McComas* [2008].

Returning to Figure 3 (bottom), we take the predicted value of $\langle|B_R|\rangle$ derived from the theory of *Schwadron et al.* [2010] and the recorded sunspot numbers and predict the solar wind proton flux (red curve) using the above scaling. We also reproduce the observed solar wind proton flux from the Omni2 data set (black circles). As seen in the figure, the agreement is poor before 2005 but good from 2005 onward. The prediction also works well during the solar maximum of 2013 when solar activity was relatively low.

There are good reasons why this simple scaling may not work well in times of high solar activity, but we are unprepared at the present time to provide a defensible explanation. Efforts to understand this and modify

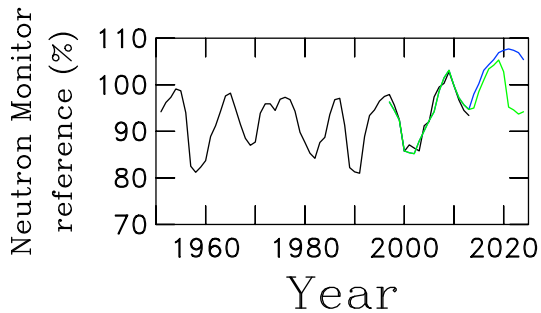

Figure 4. (black curve) Neutron monitor observations derived from Climax instrument (years 1951–1964), *Oh et al.* [2013] (years 1965–2010), and Oulu instrument (2011–2013). Numbers follow the normalization prescription of *Oh et al.* [2013] with the monthly counting rate during February 1987 being defined as 100%. (blue curve) Predicted neutron monitor values derived from the theoretical prediction for the HMF intensity using the Dalton Minimum prediction. (green curve) Same using the Gleissberg Minimum prediction.

the theory are ongoing. The years from 2005 onward are times of low solar activity that correspond to the years when Ulysses observed the high wind speeds used in the *Schwadron and McComas* [2008] study. We surmise that this theory works well during times of low solar activity for reasons that probably have to do with there being a more stable flow configuration close to the Sun. Therefore, it seems reasonable that we should be able to take the predictions for the HMF flux based on the Dalton and Gleissberg Minima and use them to predict the solar wind proton flux during the coming decade. Figure 3 (bottom) does exactly this. The blue curve derives from the Dalton Minimum, while the green curve is obtained from the Gleissberg Minimum. The resulting predictions are that the solar wind proton flux will reach an all-time low from 2017 onward as a result of the HMF failing to recover "normal" solar maximum intensities during the relatively weak activity levels of 2013 and surrounding years. Only the recovery times differ significantly.

5. Cosmic Ray Intensity at Earth

The intensity of the galactic cosmic rays reaching Earth is largely determined by the strength of the HMF and the speed of the solar wind [*Parker*, 1965]. For example, (a) during the past 50 years the ~4.0 nT 11 year cycle in the HMF intensity has resulted in a ~20% decrease in the cosmic ray intensities observed by high-latitude neutron monitors (NM) and (b) the ~1.2 nT decrease in the annual average HMF between the sunspot minima of 1996 and 2009 was accompanied by a 5.3% increase in the annual average counting rates of high-latitude NM [*Oh et al.*, 2013]. Consequently, it is to be expected that the low HMF intensity predicted for 2020 will result in higher cosmic ray intensities than in 2009, which were, in turn, the highest intensities observed since the commencement of the NM record in 1951.

Caballero-Lopez et al. [2004] used the cosmic ray propagation equation to determine the dependence of cosmic ray intensity upon the intensity of the HMF at Earth for a three-dimensional heliosphere. *McCracken* [2007] extended that methodology, and we have used it to predict the high-latitude NM counting rates up to 2025. Using the predicted decrease in HMF flux density in Figure 3 along with equation (3) and Figure 2 of *McCracken* [2007] (with the value of $\alpha = 1.5$), we can predict the cosmic ray intensity during the coming solar minimum. Figure 4 reproduces the observed neutron monitor annual counting rates together with the predicted annual counting rates derived from the HMF model for both the Dalton and Gleissberg postulates. We compute that the high-latitude annual average NM counting rates will be ~4.5 ± 1.3% above that observed in 2009 and ~9.0 ± 1.3% above the average of the values observed during the solar minima of 1954–1996 (97.7% of the scale in Figure 4). For the Gleissberg postulate, we compute that there will be a short-lived maximum in 2019, the counting rate being 2.5 ± 1.3% above that in 2009 and ~7.0 ± 1.3% compared to the sunspot minima of 1954–1996. Recent calculations based on the paleo-cosmic ray record (^{10}Be and ^{14}C) estimate that the highest NM counting rate would have been 12% above the latter average during the Dalton Minimum and ~6% higher during the Schwabe Minimum of 1902 within the Gleissberg Minimum [*McCracken and Beer*, 2014]. That is, our estimates of the HMF during the next solar minimum yield predictions that are consistent with those recorded by the paleo-cosmic ray data in the past.

The modulation of the cosmic ray intensity is a strong function of particle energy. Using the predictions in Figure 3, we have estimated the modulation functions [*Gleeson and Axford*, 1968] for 2019 that are appropriate to the Dalton and Gleissberg postulates and then used them to compute the cosmic ray spectra in the vicinity of Earth. These are given in Figure 5 for both the Dalton and Gleissberg postulates, together with those for the sunspot minima of 1965–1996 and an estimate for the highest intensity phase of the

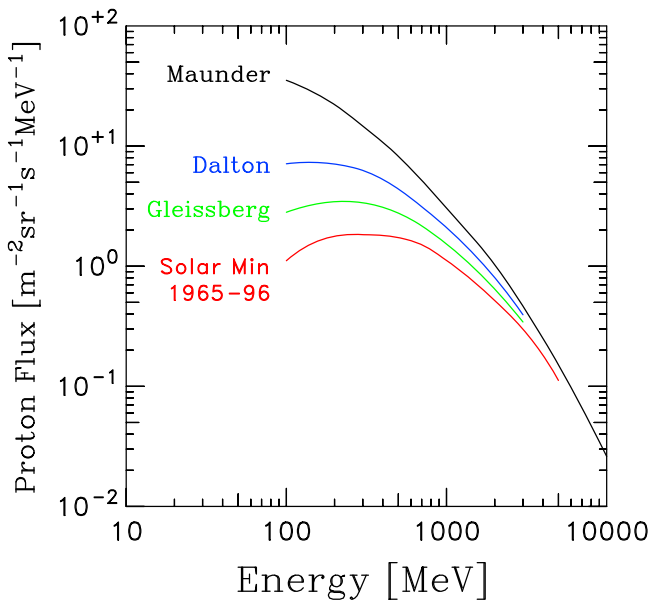

Figure 5. Predicted GCR spectrum for the Maunder Minimum (black curve), Dalton Minimum (blue curve), Gleissberg Minimum (green curve), and solar minimum spectrum of 1965–1996 (red curve).

Maunder Minimum in 1700 [*McCracken et al.*, 2004]. *Barnard et al.* [2011] have estimated the "integral" cosmic ray intensity >1 GeV for three different estimates of future solar activity. The "differential" spectra given here are broadly consistent with those estimates while emphasizing the very substantial energy dependence of the intensities relative to those observed during the space age.

6. Uncertainties

We have provided predictions for the coming decade without uncertainties attached to the values. By no means do we claim that significant uncertainties in the predictions do not exist. Let us focus first on the predictions for the HMF flux. Our purpose is simply to demonstrate how the concept of flux injection and decay during sequential, weak solar cycles result in depressed HMF flux levels. We do not know how to properly assess the uncertainty given that the solar activity driving the model is only a replication of the historical record. We can assess the accuracy of the model during past sunspot cycles. If we define

$$\Delta \equiv \sqrt{\frac{1}{N}\sum \frac{\left(\left\langle |B_R^{\mathrm{OMNI}}|\right\rangle - \left\langle |B_R^{\mathrm{NS}}|\right\rangle\right)^2}{\left\langle |B_R^{\mathrm{OMNI}}|\right\rangle^2}}, \tag{2}$$

where $\left\langle |B_R^{\mathrm{OMNI}}|\right\rangle$ is the monthly average of the absolute value of the radial component of the HMF as recorded by the Omni2 data set and $\left\langle |B_R^{\mathrm{NS}}|\right\rangle$ is the associated prediction for the radial component derived from the *Schwadron et al.* [2010] theory above, then Δ is a measure of the average fractional difference between observation and theory. When we apply this measure to the data from 1975 to 2013, we get $\Delta = 0.22$ indicating a 22% difference, on average, between observation and theory. When we apply this measure to the data from 1998 onward (the time interval shown in Figure 3), $\Delta = 0.19$. We hope that ongoing efforts to compare the theory to multiple data sets will improve the agreement. Of course, this does not address the accuracy of our assumption for the coming solar cycle sunspot numbers, so it is not a valid assessment of the predictions here. It is only a measure of the past performance of the model. The uncertainty in the predicted solar wind proton flux is comparable when that theory works, which appears at present to be times of low solar activity.

As stated in the previous section, the estimated NM intensity has a standard error of 1.3% for a given estimate of the HMF. As such, the estimated NM intensities for both postulates are higher than those observed during 2008, and both are comparable with those estimated using the cosmogenic data for the Gleissberg and Dalton Minima.

What we have done is to attempt to demonstrate a basic aspect of this theory: That the HMF flux must be restored by activity during solar maximum, or the following solar minimum will show a reduced flux relative to the previous minimum. The 2012–2013 solar maximum failed to accomplish this restoration of flux. Therefore, we expect an even lower flux level during the coming minimum. Beyond this, all predictions shown here are for demonstration purposes only and should not be construed as detailed yearly predictions.

7. Discussion

Other authors have made roughly similar predictions to these with different assumptions for the coming solar minimum and different theories for the HMF flux [*Barnard et al.*, 2011; *Owens et al.*, 2011b]. We have taken the relatively conservative association of recent observations with the Dalton and Gleissberg Minima, but at least one paper [*Lockwood et al.*, 2011] has argued that the Sun may be entering conditions similar to the Maunder Minimum. If true, the resulting HMF flux and solar wind proton flux will fall to even lower values than those shown here, while the galactic cosmic ray intensities will reach still higher values.

The consequences of the reduced solar wind pressure will be an expansion of the magnetosphere and contraction of the heliosphere. The absence of typical solar wind transients will reduce magnetospheric storm activity and the relativistic electron intensity in the magnetosphere [*Kataoka and Miyoshi*, 2010]. The radiation belts will be diminished, and the atmosphere will be less effective at removing orbital debris [*Turner*, 2011]. All of these conditions are aligned with a less active space weather environment. However, it has been observed that extreme Carrington-like events can occur during times of low solar activity [*Turner*, 2011; *Riley*, 2012; *Kataoka et al.*, 2012; *Kataoka*, 2013].

At the same time that the magnetosphere will become less active the galactic cosmic ray intensity will increase to record levels for the space age. This means a greater hazard for astronauts and electronics outside the Earth's atmosphere and magnetosphere. Transient events (Forbush decreases and globally merged interaction regions) will become less frequent and perhaps less severe, and the constant bath of galactic cosmic radiation will exceed any past measurements during solar minima.

In this analysis we have omitted the possibility of a floor, or minimum value, in the HMF intensity. The *Schwadron et al.* [2010] theory allows for a floor, but to date we find little if any theoretical or observational motivation for its existence. Should it exist, the predicted HMF flux and associated intensity may be greater during the coming solar minimum, the associated prediction for the solar wind proton flux will increase accordingly, and the predicted cosmic ray intensity will decrease. The coming solar minimum is likely to be an interesting test of the floor concept. We should also note that the standard sunspot numbers used here are now under review. Various estimates place the revised values prior to 1947 at 7% to 20% higher than the values used here (M. Lockwood and L. Svalgaard, private communication, 2014). Since the prediction for the HMF flux scales with sunspot number, the resulting effect on our prediction for 2014 through 2020 is a minimal absolute increase should those revisions hold true.

It appears that the assertion of *Schwadron and McComas* [2008] that the solar wind proton flux scales linearly with the HMF flux is presently limited to times of low solar activity, both solar minimum and weak solar maximum conditions. We do not, as yet, understand how to extend this theory to times of greater solar activity. We have shown that the linear scaling works well at low latitudes during solar minimum and weak solar maximum conditions as a complement to the high-latitude results previously found. Using the *Schwadron et al.* [2010] formulation whereupon HMF flux depends upon CME injection rates and linking this to sunspot number has permitted us to predict solar wind proton flux over the coming decade under the assumption that the present solar cycle will follow the weak and possibly protracted behavior seen in the Dalton and Gleissberg Minima. The period of low CME activity will result in low HMF flux levels which, in turn, lead to a prediction for record low solar wind proton flux levels in the coming years.

As emphasized previously, the *Schwadron and McComas* [2008] scaling appears to be restricted to coronal hole wind at present. The fact that activity has been light in the current "mini" cycle 24 and the apparent fact from past cycles that such mini cycles do not appear in isolation suggests that this scaling will continue to apply through the coming solar minimum. However, even in its most conservative form, the prediction is that in the next minimum between cycles 24 and 25, we should observe a continued decline of the solar wind proton flux to levels never before observed directly. This is because the last solar maximum failed to restore the HMF intensity to typical solar maximum levels and the coming solar minimum activity level is likely to be inadequate to compensate for ongoing flux loss mechanisms.

8. Summary

We have postulated, based on a 264 year history of sunspot activity, that the coming solar minimum will resemble the lows of the Dalton or Gleissberg Minima. Others have suggested the same [*Clilverd et al.*, 2006; *Watari*, 2008; *Turner*, 2011; *Kamide and Kusano*, 2013; *Goelzer et al.*, 2013; *McCracken and Beer*, 2014]. Using

the sunspot number as a measure of CME activity [*Owens*, 2008], together with the theory of *Schwadron et al.* [2010] that predicts the HMF flux based on CME rates, we have made predictions for the HMF during the coming solar minimum. We predict a record low HMF flux for the space age. In turn, we use the theory of *Schwadron and McComas* [2008] that shows a strong correlation between HMF flux and solar wind proton flux to predict the solar wind proton flux for the same years. We also show that the theory works well when using 1 AU data when the sunspot number is lower than traditional solar maximum values. This predicts a record low solar wind proton flux during the coming solar minimum regardless of whether one uses the Dalton or Gleissberg Minima as a model for the coming years. Lastly, we use the predictions for the HMF flux, together with the theories of *Caballero-Lopez et al.* [2004] and *McCracken* [2007], to predict the galactic cosmic ray intensity for the same years. The predicted radiation levels attain record highs beginning ~2017 and lasting through the coming solar minimum. The Gleissberg postulate results in a short-lived intensity maximum, while the Dalton model implies a maximum of duration ~5 years. These increased cosmic ray intensities represent a clear threat to satellites and astronauts, especially those outside the protection of the Earth's magnetosphere. We note that one prescription for a manned mission to Mars uses transients at solar maximum to sweep the galactic cosmic rays from interplanetary space followed by a duck-and-cover approach to solar cosmic radiation [*Turner*, 2006]. The coming decade will be a particularly poor time to attempt this method of survival.

While these predictions suggest coming years of relatively low activity levels for space weather, it should be kept in mind that a single, isolated transient can still do great damage to our increasingly technical society. During the last protracted solar minimum we heard colleagues complain that there was little to study in the way of solar transients (interplanetary shocks, CMEs, solar energetic particles, etc.), while we found great opportunities to better understand the fundamental physics behind the solar wind and HMF. We respectfully suggest that times of quiet solar wind conditions may provide interesting insights into the underlying dynamics of the Sun, solar wind, and magnetosphere that will make us better able to predict space weather events in the future.

Acknowledgments
The authors thank the National Space Science Data Center for providing data used in this study. We thank the SIDC for sunspot data used in this study (http://sidc.oma.be/sunspot-data/). C.W.S. is funded by Caltech subcontract 44A-1062037 to the University of New Hampshire in support of the *ACE*/MAG instrument. N.A.S. is funded by EMMREM (grant NNX07AC14G), C-SWEPA (NASA grant NNX07AC14G), and Sun-2-Ice (NSF grant AGS1135432) projects. K.G.McC. is funded by NSF grant 1050002. M.L.G. is an undergraduate student at the University of New Hampshire.

References

Barnard, L., M. Lockwood, M. A. Hapgood, M. J. Owens, C. J. Davis, and F. Steinhilber (2011), Predicting space climate change, *Geophys. Res. Lett.*, *38*, L16103, doi:10.1029/2011GL048489.

Caballero-Lopez, R. A., H. Moraal, K. G. McCracken, and F. B. McDonald (2004), The heliospheric magnetic field from 850 to 2000 AD inferred from ^{10}Be records, *J. Geophys. Res.*, *109*, A12102, doi:10.1029/2004JA010633.

Clilverd, M. A., E. Clarke, T. Ulich, H. Rishbeth, and M. J. Jarvis (2006), Predicting solar cycle 24 and beyond, *Space Weather*, *4*, S09005, doi:10.1029/2005SW000207.

Connick, D. E., C. W. Smith, and N. A. Schwadron (2009), The flux of open and toroidal interplanetary magnetic field as a function of heliolatitude and solar cycle, *Astrophys. J.*, *695*, 357–362.

Connick, D. E., C. W. Smith, and N. A. Schwadron (2011), Interplanetary magnetic flux depletion during protracted solar minima, *Astrophys. J.*, *727*, 8, doi:10.1088/0004-637X/727/1/8.

Gleeson, L. J., and W. I. Axford (1968), Solar modulation of galactic cosmic rays, *Astrophys. J.*, *154*, 1011–1026.

Goelzer, M. L., C. W. Smith, N. A. Schwadron, and K. G. McCracken (2013), An analysis of heliospheric magnetic field flux based on sunspot number from 1749 to today and prediction for the coming solar minimum, *J. Geophys. Res. Space Physics*, *118*, 7525–7531, doi:10.1002/2013JA019404.

Kamide, Y., and K. Kusano (2013), Is something wrong with the present solar maximum?, *Space Weather*, *11*, 140–141, doi:10.1002/swe.20045.

Kataoka, R., and Y. Miyoshi (2010), Why are relativistic electrons persistently quiet at geosynchronous orbit in 2009?, *Space Weather*, *8*, S08002, doi:10.1029/2010SW000571.

Kataoka, R., H. Miyahara, and F. Steinhilber (2012), Anomalous ^{10}Be spikes during the Maunder Minimum: Possible evidence for extreme space weather in the heliosphere, *Space Weather*, *10*, S11001, doi:10.1029/2012SW000835.

Kataoka, R. (2013), Possibility of occurrence of extreme magnetic storms, *Space Weather*, *11*, 214–218, doi:10.1002/swe.20044.

King, J. H., and N. E. Papitashvili (2005), Solar wind spatial scales in and comparisons of hourly Wind and ACE plasma and magnetic field data, *J. Geophys. Res.*, *110*, A02104, doi:10.1029/2004JA010649.

Lockwood, M., A. P. Rouillard, and I. D. Finch (2009), The rise and fall of open solar flux during the current grand solar maximum, *Astrophys. J.*, *700*, 937–944.

Lockwood, M., M. J. Owens, L. Barnard, C. J. Davis, and F. Steinhilber (2011), The persistence of solar activity indicators and the descent of the Sun into Maunder Minimum conditions, *Geophys. Res. Lett.*, *38*, L22105, doi:10.1029/2011GL049811.

Low, B. C. (2001), Coronal mass ejections, magnetic flux ropes, and solar magnetism, *J. Geophys. Res.*, *106*, 25,141–25,163, doi:10.1029/2000JA004015.

McComas, D. J., J. T. Gosling, and J. L. Phillips (1992), Interplanetary magnetic flux: Measurement and balance, *J. Geophys. Res.*, *97*, 171–177.

McComas, D. J., R. W. Ebert, H. A. Elliott, B. E. Goldstein, J. T. Gosling, N. A. Schwadron, and R. M. Skoug (2008), Weaker solar wind from the polar coronal holes and the whole Sun, *Geophys. Res. Lett.*, *35*, L18103, doi:10.1029/2008GL034896.

McComas, D. J., N. Angold, H. A. Elliott, G. Livadiotis, N. A. Schwadron, R. M. Skoag, and C. W. Smith (2013), Weakest solar wind of the space age and the current "mini" solar maximum, *Astrophys. J.*, *779*, 2, doi:10.1088/0004-637X/779/1/2.

McCracken, K. G. (2007), The heliomagnetic field near Earth, 1428–2005, *J. Geophys. Res.*, *112*, A09106, doi:10.1029/2006JA012119.

McCracken, K. G., and J. Beer (2014), Comparison of the extended solar minimum of 2006–2009 with the Spoerer, Maunder, and Dalton Grand Minima in solar activity in the past, *J. Geophys. Res. Space Physics*, *119*, 2379–2387, doi:10.1002/2013JA019504.

McCracken, K. G., J. Beer, and F. B. McDonald (2004), Variations in the cosmic radiation, 1890–1986, and the solar and terrestrial implications, *Adv. Space Sci.*, *34*, 397–406.

Oh, S., J. W. Bieber, P. Evenson, J. Clem, Y. Yi, and Y. Kim (2013), Record neutron monitor counting rates from galactic cosmic rays, *J. Geophys. Res. Space Physics*, *118*, 5431–5436, doi:10.1002/jgra.50544.

Owens, M. J. (2008), Combining remote and in situ observations of coronal mass ejections to better constrain magnetic cloud reconstruction, *J. Geophys. Res.*, *113*, A12102, doi:10.1029/2008JA013589.

Owens, M. J., and N. U. Crooker (2006), Coronal mass ejections and magnetic flux buildup in the heliosphere, *J. Geophys. Res.*, *111*, A10104, doi:10.1029/2006JA011641.

Owens, M. J., and N. U. Crooker (2007), Reconciling the electron counterstreaming and dropout occurrence rates with the heliospheric flux budget, *J. Geophys. Res.*, *112*, A06106, doi:10.1029/2006JA012159.

Owens, M. J., N. U. Crooker, N. A. Schwadron, T. S. Horbury, S. Yashiro, H. Xie, O. C. St. Cyr, and N. Gopalswamy (2008), Conservation of open solar magnetic flux and the floor in the heliospheric magnetic field, *Geophys. Res. Lett.*, *35*, L20108, doi:10.1029/2008GL035813.

Owens, M. J., N. U. Crooker, and M. Lockwood (2011a), How is open solar magnetic flux lost over the solar cycle?, *J. Geophys. Res.*, *116*, A04111, doi:10.1029/2010JA016039.

Owens, M. J., M. Lockwood, L. Barnard, and C. J. Davis (2011b), Solar cycle 24: Implications for energetic particles and long-term space climate change, *Geophys. Res. Lett.*, *38*, L19106, doi:10.1029/2011GL049328.

Owens, M. J., and M. Lockwood (2012), Cyclic loss of open solar flux since 1868: The link to heliospheric current sheet tilt and implications for the Maunder Minimum, *J. Geophys. Res.*, *117*, A04102, doi:10.1029/2011JA017193.

Parker, E. N. (1958), Dynamics of the interplanetary gas and magnetic fields, *Astrophys. J.*, *128*, 664–676.

Parker, E. N. (1963), *Interplanetary Dynamical Processes*, Wiley-Interscience, New York.

Parker, E. N. (1965), The passage of energetic particles through interplanetary space, *Planet. Space Sci.*, *13*, 9–13.

Riley, P. (2012), On the probability of occurrence of extreme space weather events, *Space Weather*, *10*, S02012, doi:10.1029/2011SW000734.

Schwadron, N. A., and D. J. McComas (2008), The solar wind power from magnetic flux, *Astrophys. J.*, *686*, L33–L36.

Schwadron, N. A., D. E. Connick, and C. W. Smith (2010), Magnetic flux balance in the heliosphere, *Astrophys. J.*, *722*, L132–L136.

Smith, C. W., N. A. Schwadron, and C. E. DeForest (2013), Decline and recovery of the interplanetary magnetic field during the protracted solar minimum, *Astrophys. J.*, *775*, 59, doi:10.1088/0004-637X/775/1/59.

Smith, E. J., and A. Balogh (2008), Decrease in heliospheric magnetic flux in this solar minimum: Recent Ulysses magnetic field observations, *Geophys. Res. Lett.*, *35*, L22103, doi:10.1029/2008GL035345.

Solanki, S. K., M. Schüssler, and M. Fligge (2000), Evolution of the Sun's large-scale magnetic field since the Maunder Minimum, *Nature*, *408*, 445–447, doi:10.1038/35044027.

Turner, R. (2006), Space weather challenges intrinsic to the human exploration of space, in *Solar Eruptions and Energetic Particles*, vol. 165, edited by N. Gopalswamy, R. A. Mewaldt, and J. Torsti, pp. 367–374, AGU, Washington, D. C.

Turner, R. (2011), Solar cycle slow to get going: What does it mean for space weather?, *Space Weather*, *9*, S04004, doi:10.1029/2011SW000671.

Watari, S. (2008), Forecasting solar cycle 24 using the relationship between cycle length and maximum sunspot number, *Space Weather*, *6*, S12003, doi:10.1029/2008SW000397.