Testing the estimated hypothetical response of a major CME impact on Earth and its implications to space weather

Ramkumar Bala¹, Patricia Reiff¹, and C. T. Russell²

¹Department of Physics and Astronomy, Rice University, Houston, Texas, USA, ²University of California, Los Angeles, California, USA

Abstract The high-speed coronal mass ejection (CME), ejected on 23 July 2012, observed by STEREO-A on the same day as the leading edge of the CME arrived at 1AU was unique both in respect to the observed plasma and magnetic structure and the large solar energetic particle flux that dynamically regulated the shock front. Because of its great intensity, it has been hailed as “Carrington 2” by some, warning that, had that CME been heading toward the Earth, it might have caused a major space weather event. We used the Rice Artificial Neural Network algorithms with the solar wind and interplanetary magnetic field parameters measured in situ by STEREO-A as inputs to infer what the “geoeffectiveness” of that storm might have been. We have also used an MHD model in Open Geospace General Circulation Model to understand the global magnetospheric process in time sequence. We presently show our neural network models of $K_p$ and $D_{st}$ on our real-time prediction site: http://mms.rice.edu/realtime/forecast.html. Running this event through our models showed that, in fact, this would have been an exceptional event. Our results show a prediction resulting in a $K_p$ value of 8+, a $D_{st}$ of nearly $-250$ nT, but when assumptions about maximum dipole angle tilt and density are made, predictions resulting in $K_p$ of 11− and $D_{st}$ dipping close to $-700$ nT are found. Finally, when solar energetic proton flux is included, the $K_p$ and $D_{st}$ predictions drop to 8− and $\approx -625$ nT, respectively.

1. Introduction

Space weather forecasting is the effort to monitor the prevailing conditions at the Sun, the solar wind, and energetic particles of solar origin and to predict changes in fields and particles in the Earth’s magnetosphere and ionosphere. Magnetospheric responses to extreme solar flares and coronal mass ejections (CMEs) can affect both ground and space infrastructure. While CMEs are known to produce the most intense geomagnetic storms occurring at Earth, predicting the onset of a CME or their shape and geometry is a difficult task today. If the field at the leading edge of the CME (or magnetic cloud) is large and southward, magnetospheric storms and accompanying auroral substorms are triggered. On the other hand, if the leading edge has a northward field, the electrical connection and associated geomagnetic activity is significantly less, although plasma can still be loaded on the dayside [Øieroset et al., 2008], leading to a more energetic substorm later when the southward field at the trailing edge of the cloud hits the magnetosphere. Forecasts based simply on optical CME observations may produce false alarms due to the lack of knowledge of the exact magnetic structure of the CMEs.

On 23 July 2012, a major CME outburst on the far side of the Sun was observed by NASA’s STEREO-A (Solar Terrestrial Relations Observatory) [Russell et al., 2013]. The intensity of the solar wind and interplanetary magnetic field (IMF) parameters reported were one of the largest ever ($V > 2300$ km/s; IMF $B_z < -61.4$ nT, with maximum positive dipole tilt of $\approx 31^\circ$ given the impact occurred on 23–24 July when the Sun’s declination is $19.7^\circ$). Fortunately, the Earth was not in the path of the storm, following STEREO-A in its orbit by over 120°. At present, the ACE spacecraft is the best distant upstream monitor, lying approximately 1.5 million km from the Earth on the Sun-Earth line that reliably provides the critical data on the in situ solar wind and IMF conditions; Wind spacecraft is still operating but in a larger orbit that is not quite as useful for space weather predictions. Remarkably, ACE has not seen solar wind and IMF parameters reach such levels in its lifetime; for comparison, the largest solar wind speed and IMF $B_z$, as an hourly average, reported by ACE are $\approx 1200$ km/s and $-50$ nT, respectively. This paper presents an opportunity to study the hypothetical response of this CME impact on Earth by testing some possible scenarios using the Rice artificial neural network (ANN) prediction models of $K_p$ and $D_{st}$ indices [Bala et al., 2009; Bala and Reiff, 2012]. The models
Figure 1. Solar wind and IMF observations from STEREO-A showing (first to fifth panels) the wind speed, IMF $B_r$, $B_t$, $B_n$, and $|B|$ (in RTN coordinates) starting at 22 July 2012 0000 UT leading up to the storm.

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have been trained using time history of solar wind and IMF inputs using the ACE archival data (http://mms.rice.edu/realtime/forecast.html). Additionally, in order to understand the time evolution of the magnetosphere, we have also simulated the storm using the OpenGGCM MHD model with runs obtained from the Community-Coordinated Modeling Center (CCMC) at NASA's Goddard Space Flight Center (GSFC).

We drive the models using STEREO-A plasma and magnetic data to predict $Kp$ and $Dst$ as a way to study its magnetospheric response. One of the concerns in modeling this event by this approach in its entirety is the absence of reliable observed plasma density. Details concerning the lack of plasma density is discussed in section 2. Fortunately, a few of our models do not require solar wind density. We are also running our other models that are density dependent, hence solar wind dynamic pressure, as an input function; Dynamic pressure ($Dp$): $P_{sw} = m_p n_p v_{sw}^2 (1 + 4 n_a / n_p)$, where $n_p$ is the number density of the protons, $n_a / n_p$ is the alpha to proton ratio, $m_p$ is proton mass, and $v_{sw}$ is the solar wind velocity; $Dst$ is better characterized by the inclusion of solar wind density and subsequent ring current. Our density-independent ($Kp^{BI}$ and $Dst^{BI}$) and density-dependent models ($Kp^{Ram}$ and $Dst^{Ram}$) are described in section 3. In order to make up for the lack of density values, we allow a range of possible density values that resemble similar extreme events from the observed ACE archival data where the result was an extremely severe activity. In addition, we have also derived possible density profiles by running the ENLIL [Xie et al., 2004] with Cone Model (WSA) by choosing parameters for this event.

Another fascinating aspect of this CME is the propagation of solar energetic particles (SEPs), reaching very high flux levels, prior to the impact of the magnetic cloud. During an extreme event like this, SEPs arriving at Earth, where protons have energies $> 10$ MeV, can cause disruptions to HF communication and navigation in polar region [Kress et al., 2010] by penetrating deep down into the ionosphere. High-latitude flight paths, typically near the magnetosphere open-closed boundary in the polar cap, are highly susceptible to radiation exposure [Mertens et al., 2010]. Interestingly, the energetic particle flux, which reached record levels during this interval, may dynamically mitigate the intensity of the storm [Russell et al., 2013] before the magnetic cloud proper reaches the magnetosphere and shields it from the most intense flux. This paper will also test how this affects the resulting magnetospheric activity by exploring the inclusion of SEP flux into the prediction models.

2. Magnetic Field, Plasma, and Energetic Particle Data

We show the in situ STEREO-A solar wind and IMF data from In-situ Measurements of Particles and CME Transients (IMPACT) and PLAsma and SupraThermal Ion Composition (PLASTIC) (http://aten.igpp.ucla.edu/forms/stereo/level2_plasma_and_magnetic_field.html) for the July 2012 event in Figure 1. The magnetic field coordinate system used to depict the data is in RTN (Radial-Tangent-Normal) system, where R is radially outward from Sun, T is tangential to the planetary orbital path, and N is pointing northward. In this study, we have applied the data to represent the GSM system: R as $-X$ being in the Sun-Earth line, N as Z being the north dipole axis, and T to represent $-Y$. Though the neural network models have been developed using the ACE data that were time propagated to the magnetopause, we, however, assume that the in situ STEREO IMF observations are such that it is sufficient and consistent with an upstream L1 monitor and that the CME is Earth bound. Using a complete data set, this study examines a “What if?” case in the context of space weather.
Figure 2. Plot shows the SEP flux measurements using STEREO IMPACT. HET (13.6–100 MeV) flux is the dashed line, and the solid curve represents LET (4–6 MeV) data.

Figure 3. Derived solar wind density profile running the ENLIL-WSA with Cone Model from CCMC.

Figure 1 (first panel) shows the solar wind velocity data beginning to ramp up around 1600 UT on 23 July peaking at 2235 km/s around 2100 UT. We can note the sudden velocity jump ($\Delta v > 1300$ km/s) before gradually decaying back to nominal values over a span of more than 2 days. Similarly, IMF $B_z$ swings rapidly from +83.93 nT to −48.97 nT between 2340 UT on 23 July and 0500 UT on 24 July. IMF $B_x$, in the meantime, changes from +28.8 nT around 2300 UT on 23 July to −73.93 nT around 0240 UT on 24 July. Figure 1 (fifth panel) shows the total magnetic field reaching a high of 102.40 nT. These extremely large fields are capable of delivering adverse space weather effects. Apart from STEREO’s IMF and plasma data, we are also interested in the SEP flux measurements. Flux values from STEREO IMPACT’s SEP instrument suite in the HET (13.6–100 MeV) and LET (4–6 MeV) energy bands are shown in Figure 2. However, we are only studying the effects of the particle flux in the HET energy range in the final $K_p$ and $D_s$ predictions.

One main concern in dealing with STEREO’s PLASTIC data for extreme solar events of this nature is the primary instrument’s limiting factor in measuring the solar wind proton bulk parameters beyond 10.6 keV [Galvin et al., 2008] accurately. This kinetic energy range restricts the upper bound of the bulk velocity measured by the Solar Wind Sector (SWS) Small Channel instrument to approximately 1425 km/s. Therefore, the final velocity profile shown in Figure 1 (first panel) comes from postprocessing of the original data using separate algorithms in the lab.

2.1. ENLIL Density at STEREO-A

For the same reasons stated above, limited by the characteristics of the instruments onboard, determining the density data was even more challenging compared to the velocity data. The density values measured by STEREO PLASTIC were extremely low during the event, possibly due to contamination from strong SEP background flux, returning to nominal values only until after the storm had ended. Instead, we made moderate “guesses” for densities from (a) another high-profile event in April 2001 obtained from ACE and (b) more precisely, by deriving it using the ENLIL Cone Model [Xie et al., 2004], applying WSA [Arge and Pizzo, 2000] for the inner boundary condition, from Community Coordinated Modeling Center at NASA’s GSFC. The model parameters and the properties of the cone clouds used for the run are cone CME initiated (at 21 $R_{\odot}$) at 23 July 2012 at 02:04 UT with 15° latitude, 120° longitude, 1990 km/s cloud velocity, and with a density enhancement factor of 4 compared to fast solar wind.

The density-dependent results discussed in this paper are derived using data from the latter (shown in Figure 3) for the period of interest, however. Figure 4 is a snapshot of the simulated CME right before its leading edge.
A snapshot of the run from the ENLIL-WSA with Cone Model on 24 July 2012 at 10:00 UT showing the CME about to impact STEREO-A. It must be noted, however, because the maximum permissible speed at the inner boundary of the model is less than the true speed, the modeled CME's impact was only felt at STEREO-A's site around 10:00 UT on 24 July, which is much later compared to the actual time reported from in situ measurements. We have, thus, produced density values that are extremely large using maximum allowable input boundary conditions set forth by the ENLIL cone model.

3. Overview of the ANN Prediction Models of $K_p$ and $Dst$

The models used in this paper to simulate the storm are the $K_p$ and $Dst$ 1 h forecast models as discussed in Bala et al. [2009] and Bala and Reiff [2012], which are artificial neural network models. They are written down in terms of their base functions as follows: (i) using the Boyle Index (BI), an empirically derived scalar function that approximates the steady state polar cap potential (PCP), given by $\Phi = 10^{-4}v^2 + 11.7B\sin^3(\theta/2)$ kV, where $v$ is the solar wind velocity in km/s, $B$ is the magnitude of the interplanetary magnetic field (IMF) in nanoteslas, and $\theta = \arccos(B_Z/|B|_{GSM})$ [Boyle et al., 1997]. In that model, the first is the quasi-viscous term and the second term is the merging term. Through the IMF data, the BI can characterize the asymptotic steady state potential drop across the Earth's polar cap. Thus, although the BI was derived only to predict the polar cap potential, it is reasonable to use it as a possible coupling function to forecast other measures of geomagnetic activity (e.g., $K_p$, $Dst$, and $AE$) because geomagnetic indices can be modeled using solar wind derivatives [e.g., Bala et al., 2009; Newell et al., 2007]; and (ii) the “Ram” functions, using the sample inputs as above plus a dynamic pressure term. Note that because of saturation of the polar cap potential, the Boyle index is much larger than the actual measured cross-polar cap potential would be in this event.

The ANN models are written down in terms of their base functions and input time histories as $K_p^{BI}_{t+1}, Dst^{BI}_{t+1} \equiv f(B_I, B_{I-1}, \ldots, B_{I-8}), K_p^{Ram}_{t+1}, Dst^{Ram}_{t+1} \equiv f(B_I, B_{I-1}, \ldots, B_{I-8}, \sqrt{D_p}, \sqrt{D_{p-1}}, \ldots, \sqrt{D_{p-8}})$, “t” represents the epoch in question while “t – 1” and “t + 1” means 1 h behind and 1 h ahead of t, respectively. $K_p^{BI}_{t+1}, Dst^{BI}_{t+1}, K_p^{Ram}_{t+1},$ and $Dst^{Ram}_{t+1}$ are the forecasted values, and each $B_I, B_{I-1}, \ldots, D_{p-1}$ etc. are hourly averages. The models were trained using ACE IMF and Plasma data covering 1998–2009 (most of solar cycle 23 and the beginning part of solar cycle 24). The data presented to ANNs for training are represented using the GSM coordinate system. Also, note that we have applied formal correction to the $Dst$ index using the Burton-McPherron-Russell (BMR) equation [Burton et al., 1975] in the models and the predicted values are, therefore, corrected for pressure. But pressure correction does not apply to the midlatitude $K_p$ models.

We designed each individual model based on tuning these fundamental quantities: nodes of the neural network and therefore its internal weights, segregating the total available data (from ACE) for testing, training, validation, and lastly the total input time history. Since $K_p$ and $Dst$ represent different geographic latitudes, they respond differently to magnetospheric activities, varying at different time scales. $Dst$ responds slowly to the changes in solar wind conditions compared to the $K_p$ index [Bala and Reiff, 2012]. Roughly 9 h of input time history was sufficient to “generalize” the neural network, i.e., the final optimized
network has neither been overfit nor underfit. We previously determined that adding more inputs (or look-back time) makes the neural network training process computationally more difficult and does not improve the prediction accuracy. The models have been trained by a solar cycle worth of solar wind input and geomagnetic response data. Statistically, each of our models are good for either a 1 h or 3 h prediction to better than one unit in $K_p$ and $\pm 10$ nT in $Dst$.

In estimating the potential of the Carrington 2 storm accurately, one must be mindful of the limitations preexisting in the ANN models. On the one hand, the ANNs have been trained using a handful of high-amplitude spikes, as seen from the ACE data (maximum observed values in the period 1998–2009: $BI \approx 650$ kV; solar wind dynamic pressure $\approx 93$ nPa; $K_p = 9$; $Dst \approx -436$ nT), and the unmodified weights and bias of the models have been applied to this event. But on the other hand, such spikes have only last a few hours or, in many cases, much less. What makes the Carrington 2 storm interesting is its intensity and, most importantly, the unusual duration. Such input values could undermine the network performance, and therefore, the final outputs can be affected. The dynamical behavior of such systems where varying solar wind input signals leading to a wide range of behavior have also been noted previously in the literature [e.g., Horton and Doxas, 1996; Weigel et al., 1999].

4. Discussion

Our $K_p$ and $Dst$ prediction models assume finite magnetic dipole angle tilt for an Earth-bound impact. This is because our models have been developed using ACE archival data (http://cdaweb.gsfc.nasa.gov) that were time propagated to the bow shock to account for the orientation of the IMF and the location of the instrument ahead of the magnetopause. We know that the Earth's rotation angle ($23.5^\circ$), with respect to the ecliptic plane, in addition to the magnetic dipole angle tilt ($\approx 11^\circ$), with respect to the Earth's axis of rotation, brings an extra factor that will alter the final predicted values. In this paper, we mean the dipole tilt angle to be the combined measure of the magnetic dipole axis and the axis of rotation of Earth. We have, therefore, made few assumptions on the magnetic dipole angle tilt, keeping them unmodified initially and rotating the vectors over $8.7^\circ$, $10^\circ$, $20^\circ$, $30.7^\circ$, and $35^\circ$ angles. The values include Sun's declination of $\approx 19.7^\circ$ on 24 July $\pm 11^\circ$ that will represent the worst case situations for this event. Accordingly, Figures 5 and 6 show the unmodified and modified 10 min average values of $B_z$ and $BI$, respectively. We can note that $B_z$ dips deeper to $-64.5$ nT at $35^\circ$ (from $-48.8$ nT at $0^\circ$ tilt) while the resulting $BI$ jumps from $\approx 550$ kV to 650 nT, making the interplay between the IMF and magnetosphere even stronger.
Our ANN models predict an extreme response to the storm. The BI (at 35° tilt) goes from 79.5 kV to 252.8 kV between 2040 UT and 2050 UT on 23 July, reaching its maximum strength of ≈ 640 kV at 0040 UT on 24 July. The dual peak seen in Figure 6 is as a result of $B_Z$ briefly exhibiting fluctuations, though it remains largely negative. The unprecedented aspect of the storm is the strength and the remarkably long and extended period of severe activity seen inside the magnetosphere. As the BI continues to remain at least 200 kV for more than 14 h, the $Kp$ reaches 10—and the $Dst$ index drops to almost −250 nT (Figures 7, top, and 8, top). In the meanwhile, the solar wind dynamic pressure jumps from 45.5 nPa to 147.3 nPa during the period between 2040 UT and 2050 UT on 23 July reaching a peak pressure of 295.0 nPa at 2100 UT, 23 July. Now having included the dynamic pressure in our models, the level of activity increases furthermore as shown in Figures 7 (bottom) and 8 (bottom); $Kp$ rises to 11—while the $Dst$ index drops below −700 nT. However, the predictions taper off quickly in response to the density drop (please see Figure 3). Table 1 summaries the $Kp$ and $Dst$ predictions for different input representations applied over various dipole angle tilts. In another study, Baker et al. [2013] found a minimum $Dst$ of −480 nT for 0° tilt and a value of −1182 nT with 34.5° tilt for the Earth’s magnetic dipole.

The BI is a good predictor of the cross polar cap potential (CPCP) under steady state conditions. The CPCP saturates for sufficiently large and long periods of solar wind electric fields [e.g., Siscoe et al., 2002; Hairston et al., 2005], but the BI itself does not because it does not contain a saturation term. As a result, the BI will generally overestimate the true polar cap potential for major storms. However, since certain measures of geomagnetic activity do not saturate (e.g., $Dst$ and $AE$), a BI of 300 kV does imply a stronger storm than a BI of 200 kV, even though the actual polar cap potential may turn out to be about the same because of saturation. The likelihood of a storm, having a $Kp$ index of 5 or higher, exceeds 95% when the average BI over the previous 3 h is over 110 kV [Bala, 2010]. Though the BI was derived using steady state conditions, one of the emphasis in using nonlinear techniques such as neural networks to compare $Kp$ and $Dst$ with the solar wind plasma and IMF is to explore the effects of time variability, including preconditioning, which may be nonlinear. As expected, the neural network predictions from the BI model (Figure 7, top), showing values of $Kp$ 6+ and $Dst$ < 130 nT for more than 15 h, correlates well with the extremely high (> 400 kV) BI.

Though the actual plasma and IMF parameters were obtained as 10 min samples, our ANN models use 1 h time-averaged (time scalings denoted by the end of the integrated time)
Table 1. Table Showing the Prediction Summary of the Models for Different Tilt Angles

<table>
<thead>
<tr>
<th>Tilt Angle</th>
<th>Min(Bz)</th>
<th>Max(Kp)</th>
<th>Min(Kp)</th>
<th>Max(Dst)</th>
<th>Min(Dst)</th>
</tr>
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<tbody>
<tr>
<td>0°</td>
<td>-48.8 nT</td>
<td>9.6</td>
<td>10.8</td>
<td>-251 nT</td>
<td>-707 nT</td>
</tr>
<tr>
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<td>-48.7 nT</td>
<td>8.8</td>
<td>10.4</td>
<td>-251 nT</td>
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<td>8.7</td>
<td>10.4</td>
<td>-251 nT</td>
<td>-693 nT</td>
</tr>
<tr>
<td>20°</td>
<td>-54.0 nT</td>
<td>8.7</td>
<td>10.0</td>
<td>-250 nT</td>
<td>-688 nT</td>
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<td>8.9</td>
<td>9.7</td>
<td>-251 nT</td>
<td>-696 nT</td>
</tr>
<tr>
<td>35°</td>
<td>-64.5 nT</td>
<td>8.9</td>
<td>9.6</td>
<td>-252 nT</td>
<td>-700 nT</td>
</tr>
</tbody>
</table>

The dipole tilt angle shown here is the combined measure of the magnetic dipole axis and the axis of rotation. The values in boldface indicate the worst case extrema: Sun’s declination of ≈ 19.7° ± 11°.

input values sliding an hourly window after each prediction, as discussed in section 3. Therefore, the predicted values come out as 1 h values. It will be interesting to see the predicted intensities at a higher resolution, at least at “30 min per prediction” rate. However, with the current provisions within the traditional method of keeping the Kp and Dst indices this is not feasible. Additionally, isolated storms of this nature are extremely rare, exhibiting a large deviation from the training data. Large amplitudes (seen in Figures 7 and 8) in addition to the duration of the intensity have been abnormally high. One of the limitations of this approach is the propensity of the neural network models to overestimate or underestimate the outputs at their threshold extrema, and the forecast accuracies can decline as a result.

4.1. Comparison With MHD Simulations

We used the OpenGGCM model framework, developed at the University of New Hampshire, through CCMC service request to study the storm. Figures 9–12 show simulated global magnetospheric and ionospheric response to the storm taken at two instances (0212 UT and 1200 UT on 24 July 2014). A very strong X line appears around 0212 UT prenoon, and the bow shock is well compressed to come within 5 $R_E$ (Figure 9); the OpenGGCM model is very robust allowing the subsolar inner magnetopause boundary close to 3 $R_E$. Later, during the recovery period, the X lines form around postnoon at 1200 UT on 24 July approximately past 6 $R_E$ (Figure 12).

A strong two-cell polar cap convection pattern with irregular polar cap boundaries (not shown here) in the Northern Hemisphere indicative of large negative IMF Bz can be seen in Figure 10 (observed potential extrema are +178 kV and −155 kV and Δcpcp > 300 kV). We have chosen this instance (as in other cases) to demonstrate the brunt of the storm where the 10 min averaged BI in the preceding 5 h has been over 250 kV approximately. The conjugal southern hemispherical pattern is shown to its right. The northern polar convection pattern observed here is large asymmetric lobe and convection cells indicative of large negative By and negative Bz, leading up to the observed time; IMF Bz remained well below −37 nT for nearly 2 h between 0020 UT and 02210 UT while the IMF By went from being strongly northward to strongly southward during the same time interval (recalling the IMF traces from Figure 1).
Figure 10. Plot showing the polar cap ionosphere at the time instant corresponding to Figure 9. Observed convection potential contours are color coded with extremes at +178 kV and -155 kV. We can see a very strong convection pattern indicating large negative $B_z$. Simplified northern polar cap convection patterns (from Reiff and Burch, 1985) are shown here for strong southward $B_z$ when $B_y < 0$. Red and black loops are merging cells, and the dashed loop is lobe cell.

A schematic representation of IMF-dependent northern polar cap convection models [Reiff and Burch, 1985] has been overlaid in Figures 10 and 12 for strong southward $B_z$ for $B_y > 0$ and $B_y < 0$, respectively. Here the red loop is a merging cell indicative of strong southward IMF $B_z$, dashed line is a lobe cell (where Earth’s open field lines connect to the IMF), and the black loop shows nested viscous cells that are independent of IMF. Another snapshot of the convection pattern during recovery phase is shown in Figure 12 where the duskside lobe cell in the Northern Hemisphere grows as $B_y$ becomes positive (convection patterns are also more pronounced in the south polar cap region). The polar cap potential drops as IMF $B_z$ gradually turns less negative, and the BI goes down below 200 kV. In this time, the IMF $B_y$ has turned positive while the $B_z$ still remains negative.

Figure 13 shows the magnetospheric standoff distance for the entire duration starting at 0000 UT 23 July. The magnetopause nose clearly stands off within $5 R_E$ for nearly 12 h, even reaching $3 R_E$ for a few hours starting around 0100 UT on 24 July. These numerical results are consistent with the extremely strong $Kp$ and $Dst$ values between 2300 UT 23 July and 0500 UT 24 July predicted by the ANN models. However, it is important to note that any compressions observed below 4 Earth radii is within the limits allowed by global MHD models (model’s inner boundary is $3 R_E$). Though the general trend is indicative...
of a very strong event, the validity of the results closer to the boundary at the nose of the magnetopause may not be truly accurate.

In situ measurements and results from the analysis evoke new challenges and raises new questions. A likely question is what defines a "worst" case situation? It has allowed that the space weather user community and science teams involved in designing instruments for future science missions identify and redefine worst possible scenarios to augment the success of the mission. For example, the Magnetospheric Multiscale (MMS) Mission, set for launch in March 2015, has a goal of measuring electron diffusion regions at X lines in the dayside magnetopause and in the magnetotail, so spacecraft operations must allow for extreme events. It is not too likely that an event like this will head toward Earth in the next few years given the declining solar cycle, yet one cannot rule out the possibility. Fortunately, giant sunspots like this do generally live more than one solar cycle, so we might be able to give some statistical predictions of activity and increase MMS operations times based on this study.

4.2. Effect of Solar Energetic Particles

Finally, the SEP fluxes in the HET and LET band range registered by STEREO-A are also extremely large (aggregate proton flux > 32,888/square cm s sr) and have reached
abnormal levels. For comparison, the strongest proton flux measured by the GOES satellite during the ACE era (1998 to the present) has never exceeded 6300/sq cm s sr (October 2003 storm). While such events are rare fortunately, it gives us an opportunity to study them in detail, as their effects can be dramatic and dangerous. As seen in Figure 2 earlier, the SEP intensity, and hence its activity, lasts a few days.

SEP events occur when there several large Earth-directed flares occur in a sequence or after a major CME. When the polar cap flux is opened equatorward, they can send SEP’s potentially dangerous fluxes to unusually low latitudes. This kind of situation is not common, requiring two or more flares within a few days or a powerful CME, pushing the cutoff latitude equatorward. Cutoff latitude is the lowest latitude to which an energetic ion can penetrate [e.g., Kress et al., 2010]. A familiar example is one that occurred in March 1989 where stronger CME shocks continued to accelerate protons (> 500 MeV) out to 1 AU. More recently, another major SEP event happened in January 2012, when a second M class flare and an Earth-directed CME occurred (on 23 January) after the impact of a previous CME (erupted on 19 January). An event like this has several implications to space weather.

Thus far, the Rice models have been driven by solar wind-magnetosphere coupling functions, representing the dayside merging rates, as basis functions to artificial neural networks, to give about 1–6 h of lead time. We suspect that since the ionospheric conductivity can be enhanced from SEPs, it is possible that a given solar wind energy input becomes more geoeffective in times of SEPs. Here we introduce a set of model that takes into account the SEP flux enhancements in addition to the functions discussed in section 3. Specifically, we have revised our algorithms to take input fluxes with energies over 10 MeV. For the purposes of training and validation, we have used the ACE IMF, plasma, and Solar Isotope Spectrometer (SIS) instrument compiled over a solar cycle. The new models are written down as

\[
\begin{align*}
Kp_{t+1}^P & \equiv f(B_{t}, B_{t-1}, \ldots, B_{t-8}, P_{t}, P_{t-1}, \ldots, P_{t-8}) \\
D_{t+1}^P & \equiv f(B_{t}, B_{t-1}, \ldots, B_{t-8}, P_{t}, P_{t-1}, \ldots, P_{t-8})
\end{align*}
\]

where Pf is the SEP flux, e.g., from STEREO-A High Energy Telescope (HET) or ACE/SIS. In essence, an extra input term for ion flux has been added to the Ram functions. Like the other models, we time average the input data to 1 h.

Figures 14 and 15 show the results from these models. The results highlight the importance of SEP precipitation as a precursor to magnetospheric activities.
Interestingly, in spite of elevated SEP flux levels, the peak $Kp$ and $Dst$ values have been reduced to a small extent; $Kp$ reaches a maximum value of $8^-$ while staying at least $5$ for more than $20\ h$ and $Dst$ remains below $-100\ nT$ for more than a day reaching a minimum value of $-623\ nT$. The net effect of the SEP flux is that it mitigates the storm intensity. Russell et al. [2013], in their analysis, observe that highly energetic particles in the strong CME could have altered the plasma properties in a manner that would have lessened the overall space weather danger.

From a space weather perspective, if the SEP was still strong during the time of major magnetopause compression (less than $5\ R_E$, Figure 13), like it is during this event, the risk to aircraft would be severe. Although the SEP flux peaks are observed earlier (Figure 2), it is only later, as the polar cap flux starts to open up, when it becomes easier for them to penetrate to lower latitudes. We can readily observe this in Figure 16 (0356 UTC, 24 July) where the open-closed field boundary in the Northern Hemisphere moves closer to $50^\circ$ latitudes and, though distorted. In the Southern Hemisphere, it is apparent that the polar cap boundary has been pushed down to even lower latitudes (below $50^\circ$) around local noon. At such levels, for example, International Space Station that is at an inclined orbit of $52^\circ$ with respect to the equator can be susceptible to SEP fluxes.

It must be noted that our efforts to train the ANNs rely on the ACE/SIS data (being upstream at L1) but the energy bands available for use in order to train the network were insufficient. For example, SEP data from GOES complements well but it is not an upstream monitor. As a result, we are disadvantaged in that we could not use all of the energetic particle data from STEREO-A, besides the LET range, to investigate the Carrington 2 storm. Therefore, though our finding here aligns with Russell et al. [2013] in that it supports role of the cloud in shielding the most intense flux from the Earth, it is very difficult to say definitively based on this work alone. Perhaps, a future study will help us investigate this topic further.

5. Conclusions

This paper demonstrates that the 23 July 2012 CME erupting from the farside of the Sun is clearly the worst ever, coming in the ranks of the famous 1859 Carrington storm, observed in the spacecraft era and is consistent with the finding of Freed and Russell [2014] that the 23 July 2012 storm was similar in strength to the Carrington event. The instruments onboard STEREO-A in the space weather beacon mode was put to test by the CME, forcing their limits. Nevertheless, they were successful in registering the IMF and plasma parameters that are usable and having a reasonable level of certainty. Density measurements were poor,
however. Having STEREO-A (real-time Space Weather Beacon instruments) align with the CME at the right location and at the right time has been critical in studying the timing of the IMF and plasma flow, and with the help of the Rice ANN models we were able to estimate a few common measures of geoeffectiveness associated with its impact. Had it been Earth-bound, the CME would have produced a kp of 9 andDst of ~250 nT, at the minimum. But when assumptions for plasma density and magnetic dipole tilt were made, their effects were even stronger, resulting in a kp of 11—andDst of ~700 nT. We were also able to demonstrate its extreme nature by running the OpenGGCM MHD model to see the magnetospheric and ionospheric polar cap response as a function of time, giving a standoff distance inside 3 R_E. Finally, when we analyzed the SEP flux, we predict a slightly lowered kp andDst peaks compared to what was observed without including it. Quite certainly, the plasma properties, magnetic structure, and the strong SEP flux observed in this CME makes it one of the strongest ever known to the space weather community, and testing our models with these parameters affirms that.

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