A major solar eruptive event in July 2012: Defining extreme space weather scenarios

D. N. Baker,[1] X. Li,[1] A. Pulkkinen,[2] C. M. Ngwira,[2,3] M. L. Mays,[2,3] A. B. Galvin,[4] and K. D. C. Simunac[4]

Received 9 July 2013; revised 9 September 2013; accepted 12 September 2013; published 9 October 2013.

[1] A key goal for space weather studies is to define severe and extreme conditions that might plausibly afflict human technology. On 23 July 2012, solar active region 1520 (~141°W heliographic longitude) gave rise to a powerful coronal mass ejection (CME) with an initial speed that was determined to be 2500 ± 500 km/s. The eruption was directed away from Earth toward 125°W longitude. STEREO-A sensors detected the CME arrival only about 19 h later and made in situ measurements of the solar wind and interplanetary magnetic field. In this paper, we address the question of what would have happened if this powerful interplanetary event had been Earthward directed. Using a well-proven geomagnetic storm forecast model, we find that the 23–24 July event would certainly have produced a geomagnetic storm that was comparable to the largest events of the twentieth century ($Dst \sim -500$ nT). Using plausible assumptions about seasonal and time-of-day orientation of the Earth's magnetic dipole, the most extreme modeled value of storm-time disturbance would have been $Dst = -1182$ nT. This is considerably larger than estimates for the famous Carrington storm of 1859. This finding has far reaching implications because it demonstrates that extreme space weather conditions such as those during March of 1989 or September of 1859 can happen even during a modest solar activity cycle such as the one presently underway. We argue that this extreme event should immediately be employed by the space weather community to model severe space weather effects on technological systems such as the electric power grid.

Citation: Baker, D. N., X. Li, A. Pulkkinen, C. M. Ngwira, M. L. Mays, A. B. Galvin, and K. D. C. Simunac (2013), A major solar eruptive event in July 2012: Defining extreme space weather scenarios, *Space Weather*, *11*, 585–591, doi:10.1002/swe.20097.

1. Introduction

[2] Recent studies show that spacecraft operational anomalies can occur under a variety of conditions [*Lohmeyer and Cahoy*, 2013] and often are associated with high-speed solar wind streams as the primary space weather driver [e.g., *Lam et al.*, 2012]. But one of the most pressing practical challenges confronting the space physics community is to define plausible "extreme" space weather event scenarios [*North American Electric Reliability Corporation* (*NERC*), 2012; *Baker*, 2012]. Once such severe solar forcing characteristics are specified for the geospace environment, then operators of the bulk power system (BPS), for example, can model with considerable fidelity the likely impacts of solar-induced geomagnetic storms on the complex high-voltage power grid backbone [*Pulkkinen*, 2011; *NERC*, 2012]. Ultimately, operators of electric power utilities, emergency preparedness managers, and policy makers all want to understand how drastically the electric power supply can be affected by so-called "low frequency/high consequence" space weather events [*National Research Council* (*NRC*), 2008; *NERC*, 2010]. This is one very important aspect of severe space weather that joins such things as energetic particle impacts on spacecraft systems, [e.g., *Baker*, 2002].

[3] The largest known solar disturbance to have affected the Earth directly is generally agreed to have been the remarkable solar storm of September 1859. This event was associated with an intense white light solar flare witnessed by astronomer Richard Carrington [*Cliver*, 2006]. A powerful geomagnetic storm commenced 17 h and 40 min following the observed flare [*Green and Boardsen*, 2006]. Some studies [*Tsurutani et al.*, 2003] have shown that the "Carrington" storm event produced a remarkable (~1600nT) depression of the normal geomagnetic field. One presently used measure of such geomagnetic disturbances is the *Dst* index [*Sugiura*, 1964], which measures the globally averaged

[1]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, Colorado, USA.
[2]Space Weather Research Center, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[3]Institute for Astrophysics and Computational Sciences, Catholic University of America, Washington, District of Columbia, USA.
[4]Department of Physics, University of New Hampshire, Durham, New Hampshire, USA.

Corresponding author: D. N. Baker, Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, 3665 Discovery Dr., Boulder, CO 80303-7820 USA. (daniel.baker@lasp.colorado.edu)

1542-7390/13/10.1002/swe.20097

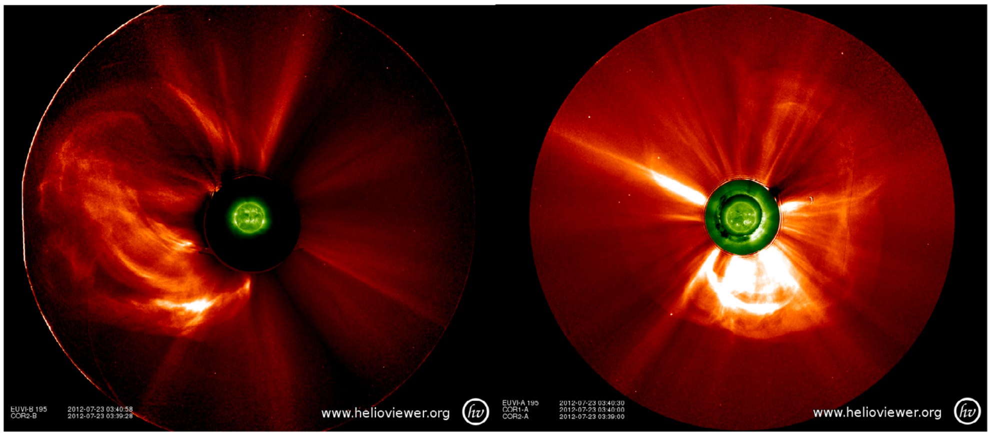

Figure 1. A nested set of images taken by STEREO-A (right) and B (left) spacecraft at ~0340 UT on 23 July 2012. The STEREO-A spacecraft was located at 121° ahead of Earth in its orbit and STEREO-B was located at −115° behind Earth. The outer two concentric rings of the image present coronagraph data showing a large, powerful CME event in progress. Images from Helioviewer [*Müller et al*., 2009].

change in the magnetic field near Earth's equator. *Tsurutani et al*. [2003] suggested that the 1859 Carrington event would have produced disturbances such that *Dst* would have been ~−1760 nT. However, more careful analysis [*Siscoe et al*., 2006] has suggested that an equilibrium solution of the equation describing the solar wind forcing of the magnetosphere would lead to *Dst* ~ −850 nT for the Carrington event. This event of 1859 joins the annals of modern powerful geomagnetic storms such as 4 August 1972 that have had severe impacts on power grids, satellites, and communication systems [*Anderson et al*., 1974].

[4] Since the regular provision of the *Dst* index begin in 1957, the largest measured geomagnetic storm had *Dst* = −589 nT in March 1989 [*Li et al*., 2006]. The March 1989 event produced many space weather effects including failure of the Hydro Quebec power system [*NRC*, 2008]. However, it is well known that even modest space weather disturbances can have important impacts on the present-day power grid [e.g., *Forbes and St. Cyr*, 2012] or on aircraft operations and aircrew health [e.g., *Getley et al*., 2010]. An important question posed by policy makers and operators of space weather-susceptible technology systems is, How severe can space storms become? A related question is, How frequently do storms as severe as March 1989 or September 1859 actually occur? *Riley* [2012] has recently examined several types of severe space weather impacts and estimated their probabilities of occurrence. His conclusion is that extreme events of the Carrington class have an occurrence probability on the order of 10% per decade, thus implying that Carrington storms are somewhat analogous to the "100 year flood" kind of hazard scenario. Given the most extreme space weather conditions, it then becomes an issue of how modern 21st century technologies would fare during such severe storm events.

[5] In this paper, we examine a powerful solar storm that occurred on 23 July 2012. Fortunately, for residents of our planet, this solar storm was focused away from the Earth and was measured most directly by NASA's Solar Terrestrial Relations Observatory (STEREO)-A spacecraft [*Kaiser et al*., 2008]. STEREO-A measurements were able to establish the timing and strength of the solar outputs of the 23 July event. We have been able to use the STEREO-A observations to perform an analysis of what these solar wind drivers would have done had they actually struck Earth. As demonstrated later in this paper, our society narrowly averted—by a margin of perhaps a week or so—a geomagnetic storm almost certainly as large as the March 1989 event. Had the season and time of day for this CME passage been right on striking the Earth, the world would have witnessed a storm larger (possibly much larger) than the 1859 Carrington event. This most likely would have had devastating consequences for many technological systems (see Ngwira C. M., et al., Simulation of the 23 July 2012 extreme space weather event: What if the extremely rare CME was Earth-directed?, submitted to *Geophysical Research Letters*, 2013).

2. Solar and Solar Wind Observations and Modeling

[6] Figure 1 shows a snapshot composite of imaging data taken at ~0340 UT on 23 July 2012 from the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument on the STEREO-A (shown on the right) and STEREO-B (shown on the left) spacecraft. At the center of each "bull's-eye" is a full solar disk 195 Å image taken by each of the STEREO SECCHI EUVI (Extreme Ultraviolet Imager) instruments. The next concentric ring outward for STEREO-A is the COR1 coronagraph covering out to about four solar radii [see *Howard et al*., 2008]; the outermost concentric region (rendered in reddish hues) is the STEREO-A COR2 coronagraph

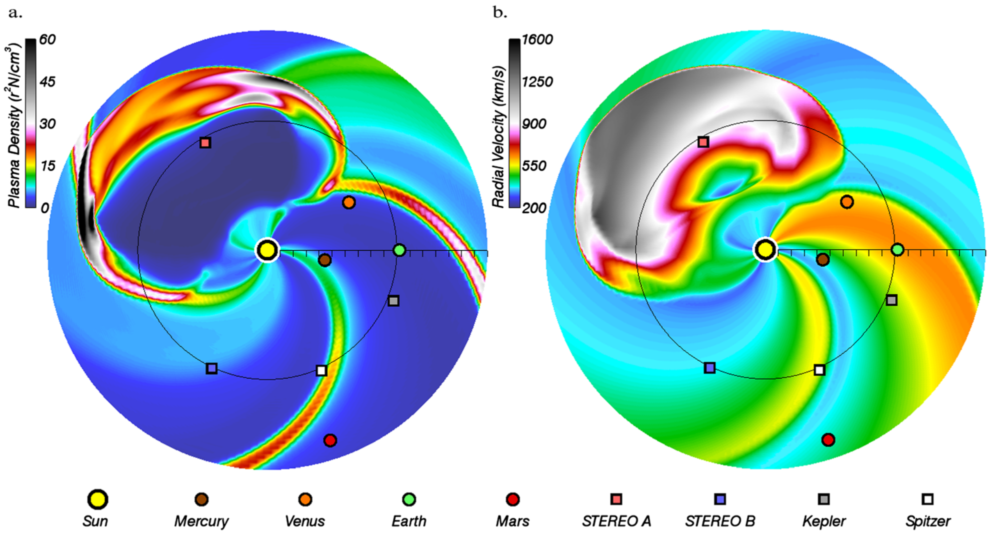

Figure 2. Model outputs from the Wang-Sheeley-Arge (WSA)-ENLIL model for the period around 1200 UT on 24 July 2012. (a) The map of inner heliosphere density from WSA-ENLIL showing a large CME toward the upper left of the figure. (b) Similar to Figure 2a but showing solar wind speed. The small dots and squares show the location of Earth, other planets, and various NASA spacecraft (as labeled) (model run and figure courtesy of George Millward, NOAA/Space Weather Prediction Center).

showing coronal features out to ~15 R_s. The CME erupted after ~0205 UT from Active Region (AR) 1520, which is visible in the lower right quadrant of the STEREO-A EUVI central image. The full extent and configuration of the outer loops and structure of the CME are evident in COR2.

[7] Triangulation measurements were performed using observations made by the STEREO-B COR2 and SOHO (Solar Heliospheric Observatory) LASCO C2 and C3 coronagraphs using the Interactive Data Language routine in SolarSoft, scc_measure [*Thompson*, 2009]. The CME was determined to have a three-dimensional speed of 2500 ± 500 km/s in the direction of 125°+15°−5° longitude and 2° ± 10° latitude (in HEEQ coordinates), and a full angular width of 140° ± 30°. The propagation of this CME was modeled in near real time by the NASA Goddard Space Weather Research Center at the Community Coordinated Modeling Center using the Wang-Sheeley-Arge (WSA) ENLIL + Cone model [see *Arge and Pizzo*, 2000; *Odstrcil et al.*, 2004]. Hence, the model run used here included the "cone" extension [*Xie et al.*, 2004] to give both the ambient solar wind conditions as well as the modeled CME propagation through the inner heliosphere.

[8] Figure 2 shows snapshots of the WSA-ENLIL + Cone model results for the period around 1200 UT on 24 July 2012. Figure 2a is the ENLIL-calculated density, and Figure 2b is the computed solar wind speed. The CME was initiated at the model inner boundary of 21.5 R_s at 23 July 2012 03:30 UT using parameters derived in near real time (with only STEREO-A and SOHO images available) with a speed of 3435 km/s, 144° longitude, −15° latitude, and full width of 160°. By the time shown in this frame, the model results suggest that the leading edge of the interplanetary CME had already passed over the STEREO-A location and had spread to fill the entire sector from ~80°W to beyond 180°W longitude. Note that only STEREO-A was in this quadrant of the heliosphere. The Earth, Venus, Mercury, and Mars happened to be in the opposite quadrant as were NASA spacecraft such as Kepler and Spitzer. The STEREO-B spacecraft was at about −115° longitude and, therefore, was also far from any direct interaction with the outward propagating CME on 23–24 July.

[9] Since the STEREO pair of spacecraft is part of NASA's Heliophysics System Observatory, they have space weather "beacon" transmitters on board. These beacons broadcast real-time data to the Earth to help provide alerts and warnings of important space weather disturbances. Figure 3 shows the STEREO-A beacon magnetic field data in the top three panels in Radial-Tangential-Normal coordinates. These are such that R (~X in third panel) points to the center of the Sun (from STEREO-A), T (~Y in the second panel) is the cross-product between the solar spin axis and R (so T lies in the solar equatorial plane), and N is the cross-product of R and T. For our purposes here, R is identical to the x axis, T is close to the y axis, and N is essentially the same as the z axis in Geocentric Solar Magnetospheric (GSM) coordinates. Hence, the top three panels of Figure 3 are, respectively, the (close to GSM) interplanetary magnetic field z, y, and x components obtained from the In situ Measurements of Particles and CME Transients instrument suite [see *Luhmann et al.*, 2008]. The fourth and fifth panels from the top of Figure 3 shown as solid curves are the beacon version of the solar wind speed and solar density, respectively, as was transmitted from the Plasma and Suprathermal Ion Composition (PLASTIC) investigation [see *Galvin et al.*, 2008].

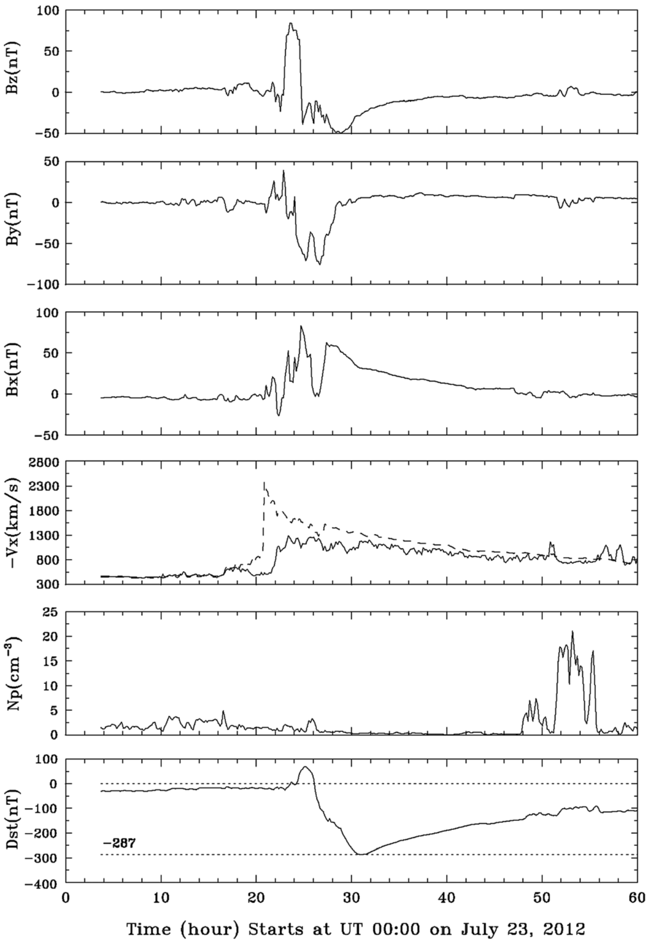

Figure 3. (top three panels) STEREO-A magnetic field, (fourth panel) solar wind speed, and (fifth panel) solar wind density for 23–25 July 2012. The data come from the STEREO real-time "beacon" data set. In Figure 3 (fourth panel), the solid curve is the original beacon data while the dashed curve is the true solar wind speed profile determined by ground-based analysis of the PLASTIC data. (sixth panel) Modeled *Dst* index values (assuming this CME event directly impacted the Earth) using the beacon data.

[10] The STEREO-A magnetic field data in the top three panels of Figure 3 show that, indeed, the first hint of the CME arrival was seen just prior to 2100 UT on 23 July. (Note that magnetic field, plasma, and energetic particle aspects of this event at STEREO-A have recently been studied by *Russell et al*. [2013]). Large interplanetary magnetic field (IMF) component deflections were observed in the By (Figure 3b) and Bx (Figure 3c) components beginning at ~2100 UT. A strong northward deflection of the IMF Bz component was evident beginning at ~2220 UT, reaching a maximum value of Bz = +84 nT just before 2400 UT. A rapid reversal of the Bz component then occurred leading to an hours-long period of strong southward IMF accompanied by large negative By and often large positive Bx. Together, these IMF field changes would represent immensely strong drivers of geomagnetic activity if this CME structure were to have hit Earth's magnetosphere (see brief discussion of this point in *Russell et al*. [2013]).

[11] In Figure 3 (fourth panel), the solid trace shows the nominal real-time (beacon) value of the solar wind speed provided from STEREO-A. As can be seen in the figure, the value of |Vx| started to rise rapidly at ~2130 UT and it rose to peak values of 1100–1200 km/s (at ~2400 UT) before gradually falling downward to ~800 km/s over the course of the next 40 h. The beacon values of Vx were the data values that were supplied promptly to support the space weather user community. Similarly, Figure 3 (fifth panel) provides the beacon values of the solar wind proton density (Np) for the interval under study. As can be seen, these preliminary (real-time) density values never were computed to rise above a few cm^{-3} until early on 25 July. As will be discussed below, the beacon solar wind parameters were very low estimates of the real conditions for the CME.

[12] The space weather user community is increasingly attuned to space weather alerts and warnings [e.g., *NERC*, 2010, 2012]. A convenient and relatively simple index to help scale geomagnetic storm warnings is provided by the *Dst* index discussed in section 1. Negative *Dst* values of less than −300 nT signal to the user community that a powerful geomagnetic storm is underway. The best, most well-proven model to use interplanetary magnetic field and solar wind data to compute empirically the expected *Dst* value is that of *Temerin and Li* [2006]. This model utilizes measured values of the IMF components, plus terms that involve solar wind speed, density, and ring current decay properties. In extensive validation analyses, the *Temerin and Li* [2006] model has been shown to "predict" the ultimately measured *Dst* values with extraordinarily high efficiency (≥91%). We use the *Temerin and Li* [2006] model here (without changes or further tuning of the published version) to estimate what *Dst* would have been had the 23–24 July 2012 CME actually hit the Earth.

[13] The curve in Figure 3 (sixth panel) is the Temerin-Li (TL06) value of *Dst* computed using the STEREO-A magnetic field (top three panels), the beacon solar wind speed (solid curve, Figure 3 (fourth panel)), and the beacon solar wind density (Figure 3 (fifth panel)). As can be seen, the TL06 value of *Dst* reaches a minimum of −287nT at ~0700 UT on 24 July. The *Dst* computation indicated a sudden commencement (initial phase) right at the beginning of 24 July and showed an extended recovery phase occurring over the latter part of 24 July, 25 July, and well into 26 July. While *Dst* ~ −300 nT would represent a major geomagnetic disturbance, it is certainly not an alarmingly large space weather threat.

[14] An immediate concern about the beacon-derived solar wind properties arose, of course (see Ngwira et al., submitted manuscript, 2013): It was known to the PLASTIC investigator team [*Galvin et al*., 2008] that for very high flow speeds ($V_{sw} \geq 1500$km/s) and with high energetic particle backgrounds [e.g., *Russell et al*., 2013], complete, accurate determinations of the proper solar wind parameters with the

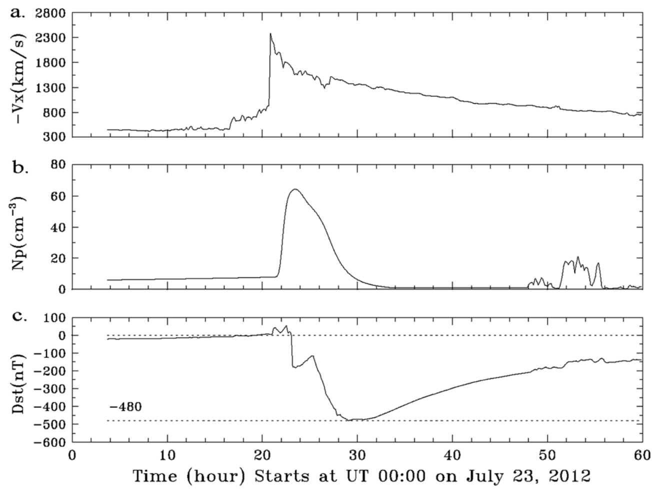

Figure 4. Solar wind and *Dst* data for 23–25 July 2012. (a) The correctly retrieved solar wind speed information derived by the PLASTIC investigation team. (b) Solar wind density from WSA-ENLIL (Ngwira et al., submitted manuscript, 2013). (c) Modeled *Dst* using data shown in Figures 4a and 4b.

onboard beacon algorithms were not possible. Thus, the beacon values of V_{sw} were almost certainly underestimates of the true bulk flow speed (as might also be inferred by the short transit time of the CME from the Sun to 1 AU).

[15] The beacon data calculations are limited by the onboard array sizes available in the data processing unit for the computation of the beacon algorithm. This affects the robustness of the product for an extreme event such as 23–24 July. Although the instrument itself covers an energy-per-charge range extending to about 80 keV/e, and data products with that energy range are brought down in the telemetry, the onboard "real-time" algorithm for the beacon data uses an array that is limited to an upper value of ~13 keV/e (1580 km/s). The bulk speed should be at least a thermal speed below that value to be determined properly by the moment calculation used for the beacon data. In contrast, with the ground processing and full telemetry products, the PLASTIC team has access to various rates that cover the full energy-per-charge range of the instrument. These have been used to determine the proton speed and the oxygen speeds. The oxygen and protons fall into different energy-per-charge ranges of the instrument, as well as different rate bins, with different logic conditions, and therefore provide a cross-check of the derived speeds. These are shown as the dashed curve in Figure 3 (fourth panel) (and also appeared in the *Russell et al*. [2013] paper).

[16] Figure 3 (fourth panel) shows that properly determined STEREO-A solar wind flow speed values throughout the period of interest are higher than the beacon values. Compared with the beacon speeds, we see that the true −Vx values on 23 July rose much more sharply than portrayed in the beacon data. The corrected speeds later fall off comparably quickly to the beacon values. Clearly, the |Vx| values in Figure 3 (fourth panel) are considerably higher than the original beacon values during most of 24 July.

[17] While it has been possible to extract much improved and more accurate Vx values by careful analysis, it has been much more difficult to get good solar wind density determinations. The rate routinely used for the proton processing was impacted by the accompanying SEP event, so the PLASTIC team is using alternative rates, with different logic conditions that are "cleaner." These alternate logic conditions have different electronic dead-times than the default rate. This is in the process of being incorporated. Because of some design features in the entrance system, PLASTIC investigators also have to include a changing geometrical factor, which has been well calibrated for the usual solar wind speed range, but the team is taking care as measurements extend to higher E/Q (i.e., speed values). Consequently, we have adopted the approach of Ngwira et al. (submitted manuscript, 2013) here and used the WSA-ENLIL computed values of Np (see Figure 4b). The ENLIL density values reasonably (and rather expectedly) peak up strongly during the initial CME passage over the STEREO-A location.

[18] Using the beacon IMF values (top three panels of Figure 3) and using the properly determined Vx values (Figure 4a) along with the ENLIL solar wind density (Figure 4b) give adequate information to do a revised modeling of *Dst* in the TL06 framework. In this modeling, we assumed as a baseline that the Earth's rotation axis and dipole tilt were both 0°. With these assumptions, we get the *Dst* profile shown in Figure 4c. We find that the minimum *Dst* value for 24 July (~0600 UT) would have been ~−480 nT —an impressively strong geomagnetic storm, indeed.

[19] It should be mentioned that the TL06 model was developed based on solar wind and the final *Dst* index from the years 1995–2002, during which the largest storm only has a *Dst* value of close to −400 nT. With the same model applied for out-of-sample large storms in 2003 (the Halloween storm and 21 November) and 2004 (7 November) when the *Dst* values also reached close to −400 nT, the model still achieved a high prediction efficiency of 0.86 and 0.89, respectively, a good validation [*Temerin and Li*, 2006]. However, we have not had events with *Dst* value below −400 nT with both good solar wind and *Dst* measurements, so one needs to keep in mind that for such extreme case, some extrapolation is exercised in applying the TL06 model.

[20] We note that we have assumed 0° tilt for the Earth's magnetic dipole in Figure 4. However, it is known that Earth's rotation axis is tilted 23.5° away from the normal of the ecliptic plane. Moreover, during the optimal part of the day, the magnetic dipole could add another 11° tilt implying that the total magnetic tilt could be as much as 34.5° (i.e., rotating the measured IMF around the *x* axis by 34.5°). Taking appropriate account of the true tilt of the Earth's dipole in July 2012, the size of the *Dst* disturbance would have been considerably greater than the values calculated in Figure 4. Thus, had this event occurred when the Earth

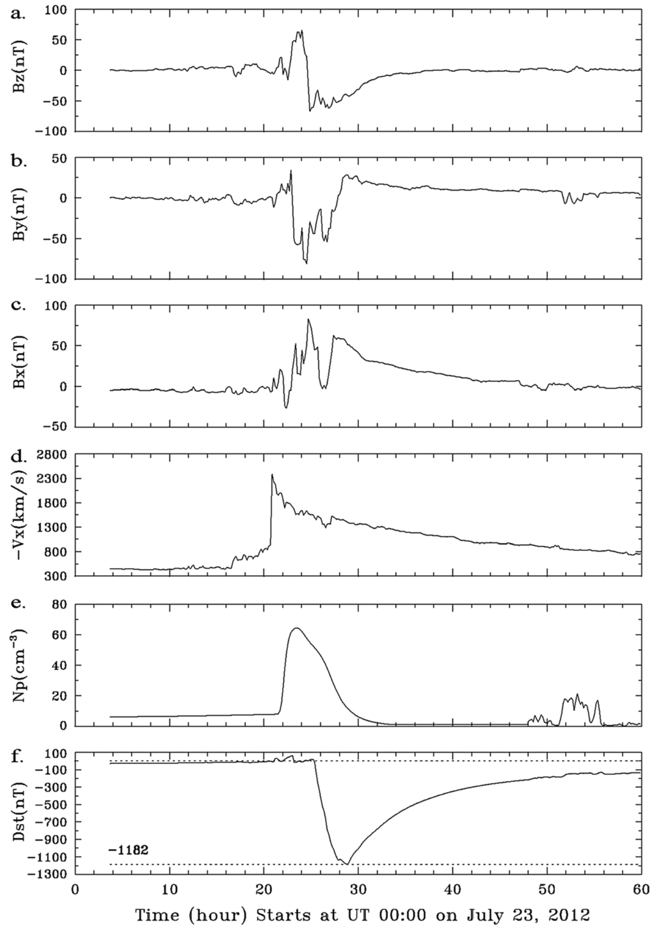

Figure 5. Similar to Figure 3 but using maximum Earth rotation axis and magnetic dipole tilt assumptions for the 23–25 July 2012 CME event (as described in the text).

was in the path of the CME, it is quite likely that the resulting geomagnetic storm would have been as large as any witnessed in the twentieth century and would have been larger than any storm of the past 25 years [see *Siscoe et al.*, 2006].

[21] In Figure 5, we have made a "worst case" assumption for the CME passage period. This modification makes the southward component of the IMF stronger (see Figure 5a) such that the maximum Bz excursion is ~−70nT. The IMF By component is also affected (Figure 5b), while the Bx component is not changed from Figure 3 (third panel). For the extreme forcing scenario, we again used the ENLIL solar wind density profile (Figure 5e) and we used the best experimental values for solar wind speed (Figure 5d). As shown in Figure 5f, this set of maximum (but quite plausible) assumptions lead to the astonishing finding that the 23–24 July CME event—had it occurred on the right day and the right time—could have produced the extraordinary result of *Dst* = −1182 nT! It should be noted that the velocity of the interplanetary shock after the large flare on August 1972 was even larger, ~2850 km/s [*Vaisberg and Zastenker*, 1976] than for this case, but that no such large magnetic storm occurred probably only because the direction of the IMF was northward with a magnitude of ~73 nT [*Tsurutani et al.*, 2003]. Had the magnetic cloud Bz been southward for the August 1972 event, the storm *Dst* intensity would have been even more negative (<−1600 nT) [*Li et al.*, 2006].

3. Discussion

[22] As noted in section 1, the operational user community has long been waiting for the space weather research community to define a plausible, defensible "worst case" or extreme solar wind forcing scenario. We believe that nature performed an ideal active experiment on 23–24 July 2012 to meet this end. With one isolated spacecraft standing as the lone sentry, the Sun released a huge CME directly toward STEREO-A. The sensors on board the STEREO spacecraft were certainly stressed when the CME passed over the satellite, but nonetheless good solar wind speed measurements could generally be retrieved. Magnetic field values were accurately determined and solar wind plasma flows could (as described here) be extracted (or estimated in the case of density). It was found that for the day and time of the event—had the Earth then been near the STEREO-A spacecraft location—our planet would have been subjected to a geomagnetic storm of the size often attributed to the Carrington event of 1859. A Carrington-sized storm [*Siscoe et al.*, 2006] coming in at *Dst* ~ −700 or −800 nT would have had devastating effects on human technology [*NRC*, 2008]. Had this same CME struck the Earth at the right time around the equinox period, the *Dst* values would have been much worse (*Dst* ~ −1200nT).

[23] It is the opinion of the authors that our advanced technological society was very fortunate, indeed, that the 23 July solar storm did not occur just a week or so earlier. Had the storm occurred in mid-July 2012, the Earth would have been directly targeted by the CME and an unprecedentedly large space weather event would have resulted. In fact, there is very legitimate question of whether our society would still be "picking up the pieces" from such as severe event [see *NRC*, 2008].

[24] We believe that the 23 July 2012 solar storm was a "shot across the bow" for policy makers and space weather professionals. The event gave a very clear and credible representation of how severe the solar space weather drivers can be; it gave direct observational values for solar wind forcing parameters with in situ STEREO data; and it did this when the Earth, other planets, and most space hardware were in a completely different sector of the heliosphere, so most assets were out of harm's way.

[25] We note with some irony that this solar storm occurred in the course of what many regard as a very weak (compared to recent cycles) solar activity maximum period. This again makes the important point that incredibly powerful—even extreme—space weather events can occur even during times of weak or moderate sunspot cycles.

[26] In conclusion, we would argue that this July 2012 period should be adopted as quickly as possible as the

prototypical extreme event scenario for emergency preparedness purposes. It is our belief that the conditions portrayed in Figure 5 of this paper give power grid operators and emergency preparedness officials the kind of scenario they need to now model how extreme space weather might affect us all. We should waste no time in playing this extreme event through our technological "war game" scenarios [see, e.g., *Baker*, 2012].

[27] **Acknowledgment.** The authors appreciate useful suggestions by L.J. Lanzerotti, H.J. Singer, and R.L. McPherron. Thanks are also extended to G. Millward for modeling support. The authors are thankful for helpful discussions with M. Temerin in applying the TL06 model for this event. The authors also thank B.J. Thompson for useful discussions on the CME analysis. This work was supported by NSF grants including work supported by the Center for Integrated Space Weather Modeling (CISM).

References

Anderson, C. W., L. J. Lanzerotti, and C. G. MacLennan (1974), Outage of the L4 system and the geomagnetic disturbances of 4 August 1972, *Bell Syst. Tech. J.*, *53*(9), 1817–1837.

Arge, C. N., and V. J. Pizzo (2000), Improvement in the prediction of solar wind conditions using near real-time solar magnetic field updates, *J. Geophys. Res.*, *195*(A5), 10,465–10,479, doi:10.1029/1999JA000262.

Baker, D. N. (2002), How to cope with space weather, *Science*, *297*, 1486–1487.

Baker, D. N. (2012), The Third Electric Infrastructure Security World Summit Meeting, *Space Weather*, *10*, S07002, doi:10.1029/2012SW00820.

Cliver, E. W. (2006), The 1859 space weather event: Then and now, *Adv. Space Res.*, *38*, 119–129, doi:10.1016/j.asr.2005.07.077.

Forbes, K. F., and O. C. St. Cyr (2012), Did geomagnetic activity challenge electric power reliability during solar cycle 23? Evidence from the PJM regional transmission organization in North America, *Space Weather*, *10*, S05001, doi:10.1029/2011SW000752.

Galvin, A. B., et al. (2008), The Plasma and Suprathermal Ion Composition (PLASTIC) investigation on the STEREO observatories, *Space Sci. Rev.*, *136*, 437–486, doi:10.1007/s11214-007-9296-x.

Getley, I. L., L. G. I. Bennett, B. J. Lewis, B. Bennett, C. S. Dyer, A. D. P. Hands, and M. L. Duldig (2010), Evaluation of new cosmic radiation monitors designed for aircrew exposure assessment, *Space Weather*, *8*, S01001, doi:10.1029/2009SW000492.

Green, J. L., and S. Boardsen (2006), Duration and extent of the great auroral storm of 1859, *Adv. Space Res.*, *38*, 130–135, doi:10.1016/j.asr.2005.08.054.

Howard, R. A., et al. (2008), Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI), *Space Sci. Rev.*, *136*, doi:10.1007/s11214-008-9341-4.

Kaiser, M. L., T. A. Kucera, J. M. Davila, O. C. St. Cyr, M. Guhathakurta, and E. Christian (2008), The STEREO Mission: An introduction, *Space Sci. Rev.*, *136*, 5–16, doi:10.1007/s11214-007-9277-0.

Lam, H.–L., D. H. Boteler, B. Burlton, and J. Evans (2012), Anik-E1 and E2 satellite failures of January 1994 revisited, *Space Weather*, *10*, S10003, doi:10.1029/2012SW000811.

Li, X., M. Temerin, B. T. Tsurutani, and S. Alex (2006), Modeling of 1–2 September 1859 super magnetic storm, *Adv. Space Res.*, *38*, 273–279, doi:10.1016/j.asr.2005.06/070.

Lohmeyer, W. Q., and K. Cahoy (2013), Space weather radiation effects on geostationary satellite solid state power amplifiers, *Space Weather*, *11*, 1–13, doi:10.1002/swe.20071.

Luhmann, J. G., et al. (2008), STEREO IMPACT investigation goals, measurements and data products overview, *Space Sci. Rev.*, *136*, 117–184, doi:10.1007/s11214-007-9170-x.

Müller, D., G. Dimitoglou, B. Caplins, J. Pablo García Ortiz, B. Wamsler, K. Hughitt, A. Alexanderian, J. Ireland, D. Amadigwe, and B. Fleck (2009), Jhelioviewer – Visualizing large sets of solar data using JPEG 2000, *Comput. Sci. Eng.*, *11*, 38.

National Research Council (NRC) (2008), *Severe Space Weather Events – Understanding Societal and Economic Impacts: A Workshop Report*, National Research Council, Space Studies Board, National Academies Press, Washington, D. C.

North American Electric Reliability Corporation (NERC) (2010), High-impact, low frequency event risk to the North American Bulk Power System Report.

North American Electric Reliability Corporation (NERC) (2012), Special reliability assessment interim report: Effects of geomagnetic disturbances on the bulk power system.

Odstrcil, D., V. J. Pizzo, J. A. Linker, P. Riley, R. Lionello, and Z. Mikic (2004), Initial coupling of coronal and heliospheric numerical magnetohydrodynamic codes, *J. Atmos. Sol. Terr. Phys.*, *66*, 1311–1326, doi:10.1016/j.jastp.2004.04.007.

Pulkkinen, A. (2011), Electric fields, GOCC flow, and transformer response, on behalf of EPRI, available at http://ccmc.fsfc.nasa.gov/RoR_WWW/workshops/2012/ Thursday_pdf/lordan_ccmc2012.pdf.

Riley, P. (2012), On the probability of occurrence of extreme space weather events, *Space Weather*, *10*, doi:10.1029/swe.v.10.2/issuetoc.

Russell, C. T., et al. (2013), The very unusual interplanetary coronal mass ejection of 2012 July 23: A blast wave mediated by solar energetic particles, *Astrophys. Jour.*, *770*, 38.

Siscoe, G., N. U. Crooker, and C. R. Clauer (2006), Dst of the Carrington storm of 1859, *Adv. Space Res.*, *38*, 173–179, doi:10.1016/j.asr.2005.02.102.

Sugiura, M. (1964), Hourly values of equatorial Dst for the IGY, in *Ann. Int. Geophys. Year*, vol. 35, pp. 9–45, Pergamon Press, Oxford, U. K.

Temerin, M., and X. Li (2006), Dst model for 1995–2002, *J. Geophys. Res.*, *111*, A04221, doi:10.1029/2005JA011257.

Thompson, W. T. (2009), 3D triangulation of a Sun-grazing comet, *Icarus*, *200*(2), 351–357, doi:10.1016/j.icarus.2008.12.011.

Tsurutani, B. T., W. D. Gonzalez, G. S. Lakhina, and S. Alex (2003), The extreme magnetic storm of 1–2 September 1859. *J. Geophys. Res.*, *108*(A7), 1268, doi:10.1029/2002JA009504.

Vaisberg, O. L., and G. N. Zastenker (1976), Solar wind and magnetosheath observations at Earth during August 1972, *Space Sci. Rev.*, *19*, 687.

Xie, H., L. Ofman, and G. Lawrence (2004), Cone model for halo CMEs: Applications to space weather forecasting, *J. Geophys. Res.*, *109*, A03109, doi:10.1029/2003JA010226.2004.