AnGeo Comm., 33, 519–524, 2015
www.ann-geophys.net/33/519/2015/
doi:10.5194/angeocom-33-519-2015

Annales Geophysicae
Open Access

Extremely intense (SML ≤ -2500 nT) substorms: isolated events that are externally triggered?

B. T. Tsurutani[1], R. Hajra[2], E. Echer[2], and J. W. Gjerloev[3,4]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[2]Instituto Nacional de Pesquisas Espaciais, Sao Jose dos Campos, SP, Brazil
[3]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA
[4]Birkeland Center, University of Bergen, Norway

Correspondence to: B. T. Tsurutani (bruce.t.tsurutani@jpl.nasa.gov)

Received: 26 November 2014 – Revised: 7 April 2015 – Accepted: 8 April 2015 – Published: 6 May 2015

Abstract. We examine particularly intense substorms (SML ≤ -2500 nT), hereafter called "supersubstorms" or SSS events, to identify their nature and their magnetic storm dependences. It is found that these intense substorms are typically isolated events and are only loosely related to magnetic storms. SSS events can occur during super (Dst ≤ -250 nT) and intense (-100 nT $\geq$ Dst > -250) magnetic storms. SSS events can also occur during nonstorm (Dst ≥ -50 nT) intervals. SSSs are important because the strongest ionospheric currents will flow during these events, potentially causing power outages on Earth. Several SSS examples are shown. SSS events appear to be externally triggered by small regions of very high density (~ 30 to $50\,\mathrm{cm}^{-3}$) solar wind plasma parcels (PPs) impinging upon the magnetosphere. Precursor southward interplanetary magnetic fields are detected prior to the PPs hitting the magnetosphere. Our hypothesis is that these southward fields input energy into the magnetosphere/magnetotail and the PPs trigger the release of the stored energy.

Keywords. Magnetospheric physics (storms and substorms)

1 Introduction

"Space weather" is the study of phenomena at our Sun causing effects in interplanetary space, in our protective magnetic bubble called the magnetosphere, in our ionosphere, and even at ground. As one extreme example, a flare on the Sun on 1 September 1859 was associated with a coronal mass ejection (CME) that caused the largest magnetic storm in recorded history at Earth, some ~ 17 h and 40 min after the flare occurred (Tsurutani et al., 2003). Loomis (1861) noted that fires and electrical shocks associated with arcing from induced voltages on telegraph lines took place during this magnetic storm. At the time, telegraph communication was the "high technology" of the day. If such a magnetic storm occurred today, it would be much more damaging to society due to the much higher technology (and greater vulnerability) in the space age (Royal Academy of Engineering report, 2013).

Power outages are known to occur during magnetic storms (Kappenman, 1996; Pulkkinen et al., 2012). However the exact nature of the power outages is not well understood. What we do know is that the most intense currents that flow in our ionosphere occur during substorms (Akasofu, 1964). Intense substorms occur repeatedly throughout magnetic storms, but intense substorms (and also power outages: Schrijver and Mitchell, 2013) can occur outside of magnetic storms as well.

Substorm ionospheric currents flow at an altitude of ~ 100 km above the Earth and are associated with intense auroras. It is these currents with amplitudes $> 10^6$ A that induce currents in conductors on the ground and cause overheating and sometimes failures of transformers. In extreme cases, entire power grid outages may occur (Royal Academy of Engineering report, 2013).

Our effort will be to examine extremely intense substorms, which we call "supersubstorms" (SSSs) using a global network of ground magnetic station data called SuperMAG (Newell and Gjerloev, 2011; Gjerloev, 2012). SuperMAG not only contains the standard 12 auroral zone stations used to construct the AE/AL substorm indices but also includes many more ground stations which cover middle latitudes as well. This is particularly important during magnetic storm

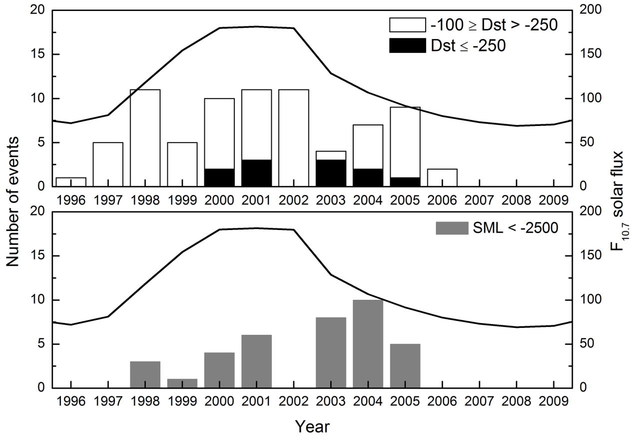

Figure 1. In the upper panel, the open and black histograms show the intense ($-100\,\mathrm{nT} \geq \mathrm{Dst} > -250\,\mathrm{nT}$) and super ($\mathrm{Dst} \leq -250\,\mathrm{nT}$) geomagnetic storms annual occurrence rates for the period 1996 to 2009, respectively. The scale for both is on the left. In the bottom panel, the supersubstorm ($\mathrm{SML} \leq -2500\,\mathrm{nT}$) annual occurrence rate is given in histogram format. The scale is on the left. The solid lines in both the panels show the $F_{10.7}$ solar flux levels. The scale is on the right.

intervals. There are over 100 ground stations used in SuperMAG. The middle-latitude coverage is important during intense magnetic storms or substorms when the auroras and their associated currents move equatorward. It is these instances which can give power grids in the United States and Europe the greatest problems. The SML index is similar to the AL index, but with greater longitudinal and latitudinal coverage. The maximum intensity that we will be using for our study is an SML index of −2500 nT, which is an extremely intense substorm. There were 37 supersubstorms identified in SC23 (1996 to 2009) interval, the interval of study. Their intensities ranged from SML = −2522 to −4418 nT with an average value of −3006 nT.

For reference, the older AE index will be shown in addition to the SML index. Since the SML index uses more ground stations and has better geographical coverage, the AE values will in general be smaller than the SML values. The overall temporal profiles will be almost identical, as one would expect. For this study the peak AE values ranged from 1663 to 4102 nT with an average of 2949 nT.

2 Results

The bottom panel of Fig. 1 shows the solar cycle dependence of $\mathrm{SML} \leq -2500\,\mathrm{nT}$ (supersubstorm) events during solar cycle (SC) 23, from 1996 to 2009. The numbers of SSS events are given in histogram format with the scale on the left. The $F_{10.7}$ solar flux is given as a solid black line with the scale on the right. It is noted that SSS events occurred throughout the solar cycle, except during the two solar/geomagnetic activity minima: 1996–1997 and 2008–2009 (Tsurutani et al., 2011). The neighboring years of the latter minimum, 2006–2007, also did not have any SSS events.

SSS–magnetic storm intensity relationship

The top panel of Fig. 1 shows the intense magnetic storms ($-100\,\mathrm{nT} \geq \mathrm{Dst} > -250\,\mathrm{nT}$) as open boxes and superstorms ($\mathrm{Dst} \leq -250\,\mathrm{nT}$) as black boxes. The $F_{10.7}$ flux is shown in both panels for purposes of context. It is noted that SSS events occur during every year that superstorms occur except in 1998 and 1999. In 2002 near solar maximum, there were no SSS events and also no superstorms. The intense storm ($-100\,\mathrm{nT} \geq \mathrm{Dst} > -250\,\mathrm{nT}$) dependence generally agrees with the SSS dependence, but there are intense storm events in 1996–1997 and 2006 where there are no SSS events. There are also many intense storms that occur during 2002 when there are no SSS or superstorm events. From 2007 through 2009, in the extended solar minimum phase, there are no superstorms, intense storms, or SSS events.

For the SC 23 (1996–1009) interval, 57 % of the SSS events were associated with superstorms and 40 % with intense storms. The remaining 3 % of the SSS events occurred during nonstorm ($\mathrm{Dst} \geq -50\,\mathrm{nT}$) intervals.

We have examined the SSS events from another perspective. We identified all superstorms that occurred during SC23 to determine how often SSS events were related to these events. Eleven superstorms took place during this interval, and nine (∼ 82 %) had associated SSS events. Thus there is some relationship between SSS events and superstorms, but there is not a one-to-one correspondence between the two phenomena.

.1 Supersubstorms on 24 November 2001

Figure 2 shows the interplanetary parameters during two SSS events that occurred on 24 November 2001. The SSS onset times are indicated by vertical red lines. The SML indices are shown in the bottom panel. It is noticed that both SSS events are large, isolated events and are not associated with generally high SML-valued intervals. The first SSS event began at ∼ 07:00 UT and reached a peak SML value of ∼ −3839 nT (a peak AE of 3525 nT). The event ended at ∼ 07:50 UT, giving it a duration of ∼ 50 min. The second SSS event had a peak SML value of ∼ −3312 nT (a peak AE of 3249 nT) and had an onset at ∼ 13:45 UT and lasted until ∼ 14:18 UT, giving it a ∼ 30 min duration.

The SYM-H index in the next to bottom panel of Fig. 2 is equivalent to a high-resolution (1 min) Dst index. Here we use a definition that SYM-H must be ≤ −50 nT for a storm to have occurred (Gonzalez et al., 1994). The storm main phase started at ∼ 06:45 UT when the SYM-H index becomes negative. It reached a local minimum of ∼ −134 nT at ∼ 07:56 UT, recovered, and then reached a deeper minimum

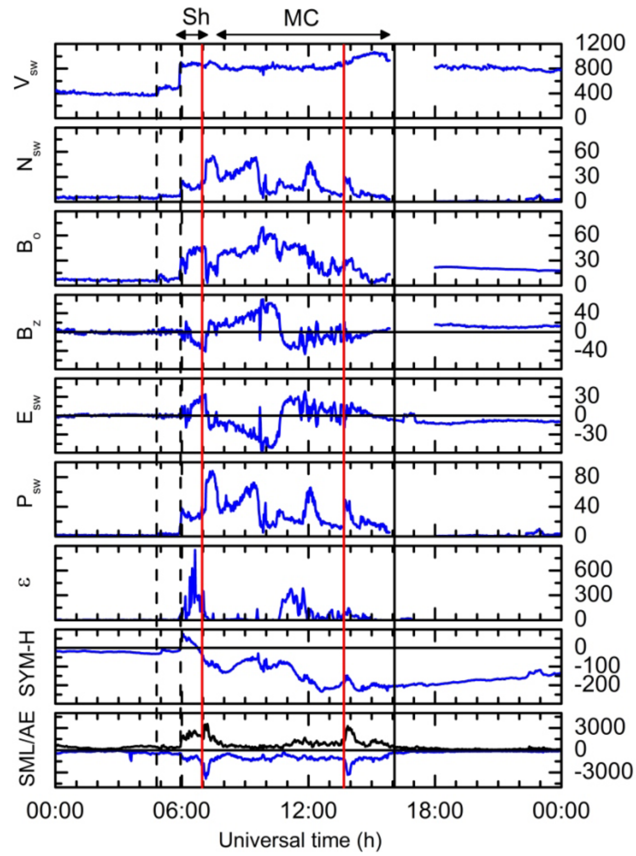

Figure 2. Interplanetary parameters during two SSS events occurring on 24 November 2001. From top to bottom, the panels are the solar wind speed (V_{sw} in $km\,s^{-1}$), the density (N_{sw} in cm^{-3}), the interplanetary magnetic field (IMF) magnitude (B_o in nT), the north–south component of the IMF (B_z in nT), the interplanetary electric field (E_{sw} in $mV\,m^{-1}$), the plasma ram pressure (P_{sw} in nPa), and the interplanetary epsilon parameter (ε in 10^{11} W). The next to the bottom panel contains the SYM-H (nT) indices. The bottom panel contains the ground SML (nT) indices (blue) and the AE indices (black). Onsets of two SSSs are indicated by vertical red lines during the complex magnetic storm on 24 November 2001. Interplanetary shocks are denoted by the dashed vertical black lines. A magnetic cloud (MC: Klein and Burlaga, 1982) is present and is shown bounded by solid vertical black lines. The MC lasted from ~07:50 to ~16:00 UT. It is identified by the northward-then-southward rotation of the IMF B_z component.

of ~ -234 nT at ~12:37 UT. The first storm decrease is caused by the southward interplanetary magnetic field (IMF) in the sheath (Tsurutani et al., 1988), and the second decrease is caused by the southward IMF in the magnetic cloud (MC). The sheath and the MC are indicated by horizontal arrows at the top. Thus using the Fig. 1 definitions of storm intensities, the first storm was an intense storm and the second was a larger intense storm. Both magnetic storms were caused by southward (negative B_z) IMFs, with slight delay times (Gonzalez et al., 1989).

The two SSS events did not occur at the maximum intensities of the two storms. The first SSS event occurred when SYM-H was ~ -85 nT and the second when SYM-H was ~ -148 nT. Thus the first SSS occurred in the main phase of the first intense storm when SYM-H was only at moderate storm ($-50\,\text{nT} \geq \text{Dst} > -100\,\text{nT}$) intensities. The second SSS event occurred in the main phase of the second intense storm when the SYM-H value was only slightly higher than half the peak storm value. At the time of the second SSS event, the SYM-H value was that of an intense storm.

It is useful to show some of the interplanetary features during the day of the two SSS events. There are sudden increases in the solar wind speed (V_{sw}, Fig. 2 top panel), density (N_{sw}, second panel), and the magnetic field magnitude (B_0, third panel) at ~04:49 UT and ~05:52 UT. These sudden increases are indicated by vertical dashed black lines. The jump conditions are consistent with their being fast mode shocks. The characteristics of the shocks have been analyzed but will be given elsewhere.

Is there solar wind priming of the magnetosphere prior to the SSS events?

The IMF B_z component is given in the fourth panel of Fig. 2. The epsilon parameter (ε: Perreault and Akasofu, 1978) is given in the third from the bottom panel. ε is a well-recognized parameter that uses the north–south component of interplanetary magnetic field (IMF B_z) component as a means of identifying solar wind energy transfer to the magnetosphere through magnetic reconnection at the dayside magnetosphere. This energy transfer occurs primarily when the magnetic field is southward (Echer et al., 2008).

Prior to both SSS events, the IMF had southward components (negative B_z) of ~ -28 nT and -21 nT, respectively. The integrated values of IMF B_z for the 1.5 h before the SSS onsets were $-13.2\,\text{nT}\,\text{h}^{-1}$ and $-15.9\,\text{nT}\,\text{h}^{-1}$, respectively. The ε value is high at the same time as the above events, as expected.

Could the SSS events have been triggered?

There is a high-density plasma parcel (PP) of density $\sim 55\,\text{cm}^{-3}$ extending from ~07:00 UT to ~07:50 UT, which is time-coincident with the first SSS event. The PP caused a solar wind ram pressure (P_{sw}) of ~88 nPa. This PP is part of the coronal mass ejection (CME) which came outward from the Sun. It could be either a solar coronal loop (Tsurutani et al., 1998) or a coronal sheath (DeForest et al., 2013).

There is a PP which is well-correlated with the second SSS onset. The PP had a density of $\sim 32\,\text{cm}^{-3}$ and caused a ram pressure increase to ~50 nPa. It is unknown what this density plug might be in the overall structure of the Interplanetary Coronal Mass Ejection (ICME) at this time.

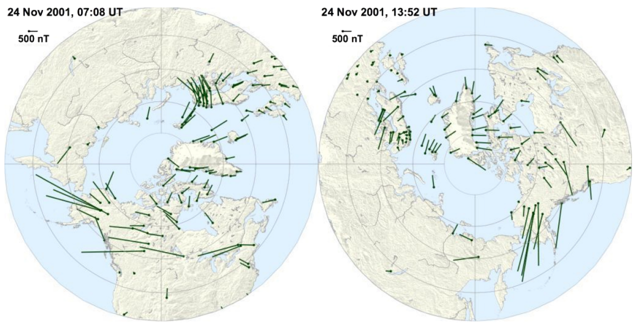

Figure 3. Polar images during two SSS events shown in Fig. 2. The green lines show the magnetic perturbations over the Northern Hemisphere during the two SSS events. These are taken from the SuperMAG data sets from individual ground magnetometer stations.

The ground magnetic perturbations

The SML indices shown in Fig. 2 gave an envelope of the largest negative deviation of the horizontal component of the magnetic fields (Gjerloev, 2012). The individual vector components over the Northern Hemisphere are shown in the two panels of Fig. 3. On the left is the ∼ 07:00 UT SSS event and on the right is the ∼ 13:45 UT SSS event. One can note the very large magnetic deviations over Alaska, northern Canada, and northern Europe. Magnetic deviations are also noted in more southern regions as well.

.2 Supersubstorms on 24 August 2005

Figure 4 displays the same format of interplanetary data and ground indices as in Fig. 2 for 12 h of 24 August 2005. The initiations of two SSS events are denoted by the red vertical lines in the figure. The SSS events occur consecutively but are large and distinct from each other. The peak SML intensities are −4143 nT (AE = 3708 nT) at 10:18 UT and −4017 nT (AE = 3608 nT) at 10:37 UT, respectively. The durations of the two SSS events lasted from ∼ 10:05 UT to 10:23 UT and 10:23 UT to 10:49 UT, giving durations of ∼ 17 and 26 min, respectively.

The MC is identified by the variations in the IMF B_x, B_y, and B_z components. The MC extends from 09:02 UT to 12:49 UT and is denoted by a solid horizontal black line. Both SSS events occurred within the interval when the MC had impinged upon the magnetosphere.

The storm main phase began at 09:53 UT and reached a peak intensity of SYM-H −173 nT at ∼ 11:13 UT. This storm was thus an intense magnetic storm. It was caused by the southward component of the MC.

During the SSS events the SYM-H values were −58 nT and −84 nT, respectively. Both SSS events occurred in the storm main phase prior to storm maximum intensity. Both SSS events occurred when the SYM-H level was at a moderate storm intensity level.

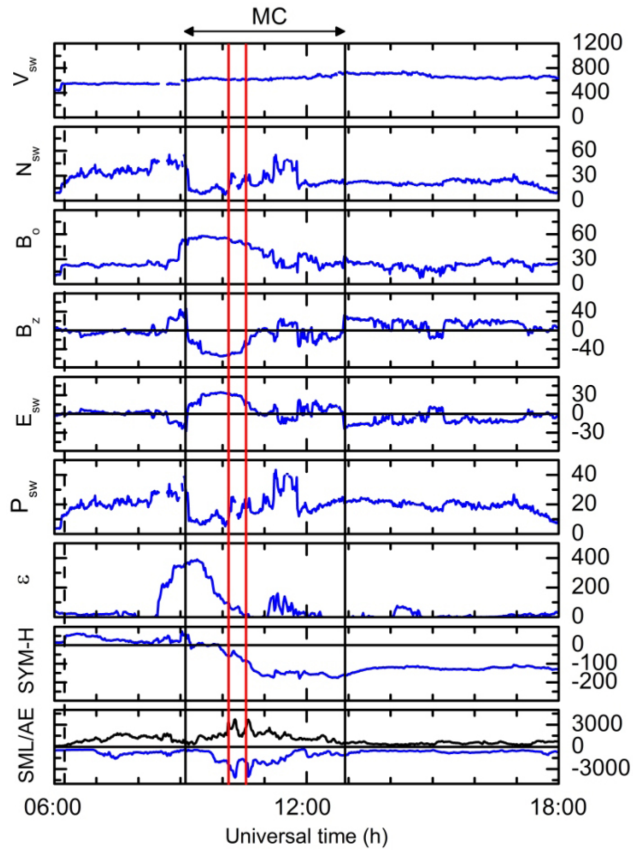

Figure 4. Interplanetary parameters during two SSSs occurring on 24 August 2005. The format is the same as in Fig. 2.

The IMF prior to both SSS events was southward. The 1.5 h IMF Bz-integrated values were $-42.2\,\mathrm{nT\,h^{-1}}$ and $-58.2\,\mathrm{nT\,h^{-1}}$, respectively.

Both SSS events were associated with solar wind pressure pulses. The first had a peak magnitude of 25 nPa and the second of 24 nPa. The solar wind density increases causing the pressure pulses were ∼ 32 and 31 $\mathrm{cm^{-3}}$ (second panel from the top). The solar wind velocity was more or less constant.

3 Summary

We have shown that superintense substorms (SSSs) with SML ≤ −2500 nT are isolated and distinct events and are not simply parts of generally intense SML intervals which might occur during maximum storm intensities. For the detailed studies shown in Figs. 2 through 4, three of the SSS events occurred when the SYM-H values were of moderate (−50 nT ≥ Dst > −100 nT) intensity and one occurred when SYM-H was at an intense (−100 nT ≥ Dst > −250 nT) level. None of the four SSS events occurred when SYM-H was at superstorm (Dst ≤ −250 nT) intensity level. It was noted that SSS events could occur during all levels of storm intensity. Some events even occurred outside of magnetic storms.

The detailed examples showed evidence of magnetospheric/magnetotail priming. The average IMF B_z 1.5 h prior to the high-density regions was negative (southward), and the integrated IMF Bz was large and negative. Geomagnetic activity was ongoing prior to all four SSS events.

Evidence for external triggering by solar wind pressure pulses was noted for all four SSS events. The solar-wind-convected densities range from ~ 30 to $55\,\mathrm{cm}^{-3}$. These pressure pulse durations ranged from 17 to 50 min.

4 Discussion and conclusions

It had been previously noted by Heppner (1955) (and many references afterwards) that interplanetary shocks can trigger substorms. It was shown that precursor southward IMF B_z was a criterion for shock triggering of substorms to occur (Zhou and Tsurutani, 2001). The amount of precursor time was empirically determined to be ~ 1.5 h. Tsurutani and Zhou (2003) postulated the idea that the stored energy was always being dissipated away, and ~ 1.5 h was the approximate time constant for this dissipation.

The 1.5 h time-integrated IMF B_z values for the four SSS events shown in this paper were -13.2, -15.9, -42.2 and $-58.2\,\mathrm{nT\,h}^{-1}$, respectively. To put this into context, the typical IMF magnetic field intensity in the slow solar wind upstream of shocks is ~ 5 nT. If this upstream field were totally southwardly directed, the 1.5 h time-integrated IMF B_z would be $-7.5\,\mathrm{nT\,h}^{-1}$. Thus the precursor IMF B_z events for the four SSS events were ~ 2 to 7 times larger than those for typical shock cases.

Quiet time solar wind densities are typically 3–5 cm^{-3}. Interplanetary shocks have downstream density increases typically ~ 1 to 3 times and only moderate velocity increases, so the ram pressure increases are usually a maximum of ~ 3. Thus the maximum densities downstream of shocks are typically $\sim$ 9–15 cm^{-3}. The plasma densities for the four PPs triggering the SSS events were ~ 55, ~ 30, ~ 32, and $\sim 31\,\mathrm{cm}^{-3}$. Thus the PP events were ~ 2 to 6 times larger than the typical interplanetary shock downstream densities (Tsurutani and Lin, 1985; Echer et al., 2011).

Since SSS events are associated with extreme levels of ionospheric currents, prediction of the occurrence of SSSs could be used to forecast power outages on Earth. Schrijver and Mitchell (2013) concluded that ~ 50 US power grid disturbances in a 19-year US Department of Energy disturbance record could be assignable to geomagnetic activity. Further detailed analyses of the relationship between SSSs and world power grid disturbances are beyond the scope of this paper but will be taken up at a later date. If the SSS events can indeed be related to power grid disturbances, then it is clear that an upstream monitor at the L1 libration point could give ~ 30 min to 1 h warning of impending problems.

At this time we have not shown how often SSS events are triggered and whether solar wind priming is a necessary and sufficient condition. This work needs to be done and we encourage space weather researchers to undertake such efforts.

Finally, we should also mention that not all SSS events will have equal effects on power lines. Those that occur during superstorms will take place at lower geomagnetic latitudes over more populated areas. However if triggers for specific events could be identified in advance, the susceptible geographic locations could be forewarned.

Acknowledgements. Portions of this research were performed by the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA. The work of R. Hajra is financially supported by FAPESP post-doctoral research fellowship at INPE. E. Echer would like to thank to the Brazilian CNPq (301233/2011-0) agency for financial support. The SuperMAG data were collected from the following website: http://supermag.jhuapl.edu/. The solar wind/interplanetary data were collected from the OMNI website: http://omniweb.gsfc.nasa.gov/.

The topical editor G. Balasis thanks one anonymous referee for help in evaluating this paper.

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