Extreme solar wind conditions and their related geomagnetic responses: observations and estimates

A. Dal Lago, L. E. A. Vieira, E. Echer, L. A. Balmaceda, R. Rawat and W. D. Gonzalez.
(National Institute for Space Research - INPE, São Jose dos Campos, SP, Brazil)

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Abstract

Extreme solar wind conditions are those in which the earth magnetosphere is heavily stressed both by very intense interplanetary magnetic fields and solar wind velocities. These scenarios, although very rare, are observed to be related to the passage of interplanetary coronal mass ejections (ICMEs). Storm-time geomagnetic index (Dst) in such conditions reaches -400 nT or less. We present 2 case studies, one geomagnetic storm observed in 2003 and another estimated geomagnetic storm which did not happened because the ICME occurred in 2012 missed the earth. Had this 2012 event hit the earth, it would have caused the strongest geomagnetic storm in space era, nearly twice as strong as the strongest storm ever observed.

Introduction

Geomagnetic storms were found to be closely related to prolonged periods of southward interplanetary magnetic fields (Gonzalez et al., 1987, Gonzalez et al. 1994). The interplanetary counterparts of coronal mass ejections (ICMEs) are among of the most important sources of such magnetic fields. The more the storm intensity increases, the more the ICMEs become important. For example, it was found that 79% of intense storms (Dst<-100nT) and 95% of very intense storms (Dst<-250nT) are cause by ICMEs or by their associated shock (Gonzalez et al., 2007; Echer et al., 2008 and Gonzalez et al., 2011). In the same direction, Szajko et al. (2013) found that all Dst<-200nT geomagnetic storms of solar cycle 23 were related to ICMEs or their associated shocks. Extreme storms (Dst <-400nT) are found to occur nearly once every 11 year solar cycle. Only 5 of such events occurred during the space era (Gonzalez et al., 2011). The March 1989 event was the most intense ever registered by the Dst index, with a peak value of ~ -600nT. A complete coverage of geomagnetic and interplanetary observations, however, is available only for the November 2003 extreme storm, in which the peak Dst reached ~-422 nT. More recently, in July 2012, a very energetic CME was observed which did not head the earth. It was, however, ejected towards the STEREO A satellite, which was 120 degrees away from the Sun-Earth line. STEREO A in situ observations of this event at 1 AU indicate a extreme scenario in which IMF peak surpassed 100nT, with considerable southward component. The aim of this work is to estimate the intensity of a hypothetic geomagnetic storm had this ICME hit the earth. To do so, we use the Burton et al. (1975) formula for the Dst estimate, which requires only interplanetary observations as input. Since extreme events are expected to have different model parameters as those derived by Burton et al. (1975) for intense storms, first we apply it to the November 2003 extreme event. After that, we estimate the peak Dst for a hypothetical scenario in which the July 2012 ICME hit the earth. The results suggest that such event would have been the strongest geomagnetic storm in space era.

Method

Geomagnetic storms are quantified by the Dst index, which measures the average horizontal component of the geomagnetic field measured by mid-latitude and equatorial stations around the world. Negative Dst values indicate enhanced ring current, and therefore a more intense magnetic storm. An alternative way to estimate the quantitative geomagnetic response of an interplanetary structure was shown by Burton et al. (1975), using only interplanetary observations to estimate the Dst index. This method estimates the Dst index as follow:

$dDst/dt = F(E) - aDst$ (1)

where

$F(E) = 0$, $Ey<0.5$ mV/m (2)

$F(E) = d(Ey - 0.5)$, $Ey>0.5$ mV/m (3)

With

$a = 3.6x10{-}3\ s{-}1$

$d = -1.5 \times 10{-}3\ nT/(smV/m)$

In the above equations, *F(E)* is the ring current injection rate and it depends only on the interplanetary electric field which is given by –(**VxB**), **V** being the solar wind velocity and B the solar wind magnetic field. Burton et al. (1975) formula assumes a ring current decay time of the order of 7.7 hours (*a= 3.6x10-3 s-1*). Fenrich and Luhmann (1998) found that for intense and very intense storms (-80>Dst>-300 nT) decay times ranging from 3 to 5 hours are more adequate for correctly estimate the observed Dst index. In the following session we shall verify whether this decay time is appropriate for extreme events (Dst<-400nT).

The November 2003 event

On November 18th (2003), a M3.9 flare was observed from AR 10501 (N03E08), at 08h31. The Large Angle and Spectrometric Coronagraph (LASCO) C2, aboard the Solar and Heliospheric Observatory (SOHO), observed a halo coronal mass ejection in association to this flare, starting at 08h50 of the same day. Plane of sky velocity was measured to be 1645 km/s with a CME expansion at 2900 km/s. On the 20th of November 2003, the Advanced Composition Explorer (ACE) satellite observed a shock, followed by an interplanetary magnetic cloud, according to the definition of Burlaga et al. (1981). Figure 1 shows this magnetic cloud and its geomagnetic response, in terms of the Dst index. From top to bottom, it is presented the interplanetary magnetic field, its Bz component, plasma velocity, interplanetary electric field and the geomagnetic Dst index, both observed and estimated using Burton et al. (1975) formula. It is important to note that the >50nT magnetic field intensity of this event was considerably high, as compared to the average solar wind magnetic field, typically of the order of 5nT. The magnetic field profile, with a strong Bz component throughout nearly the entire structure, indicate that the magnetic cloud was highly inclined, with a negative pointing axial flux rope field. This Bz field, combined with the high velocity, peaking above 700 km/s, produced the interplanetary electric field shown in Figure 1, peaking at 30 mV/m. According to Gonzalez and Tsurutani (1987), an electric field higher than 5 mV/m, lasting for 3 hours or more is sufficient to drive an intense geomagnetic storm (Dst <-100nT). Given the intensities, this event originated a peak Dst of the order of -420 nT, making this geomagnetic storm the most intense of the entire solar cycle 23.

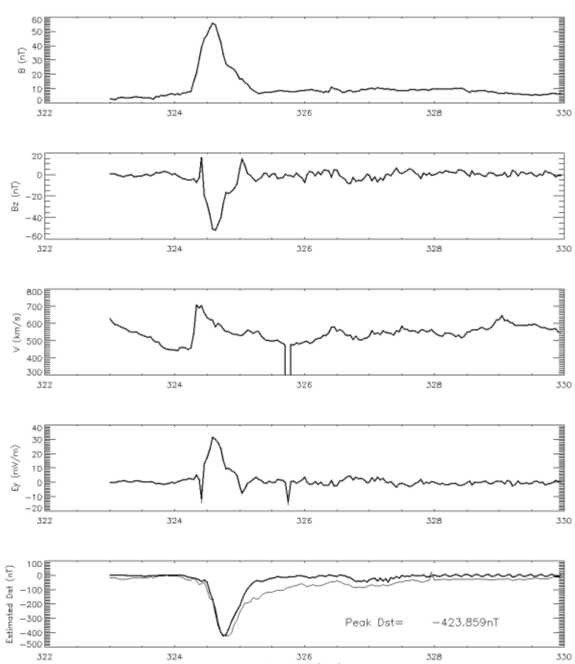

Figure 1: From top to bottom, the interplanetary magnetic field, its Bz component, plasma velocity, interplanetary electric field and the geomagnetic Dst index, both observer and estimated using Burton et al. (1975) model, considering a ring current decay time of 4.5 hours.

Burton at al. (1975) formula was used to reproduce the Dst index of this event, and the result is presented in the last pannel of Figure 1, thick curve. A ring current decay time of 4.5 hours was used, in order to correctly reproduce the peak intensity of the storm. Similar decay times have been used by Fenrich and Luhmann (1998) to study very intense storms. It is also evident, from Figure 1, that the recovery phase of the storm is not well reproduced by the model. Nevertheless, the model is appropriate to estimate the main phase and peak intensity of the storm. Similar conclusions were found by other authors (Fenrich and Luhmann, 1998).

The July 2012 event

The UVI instrument, aboard the STEREO A satellite, observed a solar eruption on the 23rd of July (2012), around 02h30 UT. From the earth perspective, it was a behind the limb event. The AIA instrument, aboard the SDO satellite observed a filament eruption over the limb, at this same time. A CME was observed by SOHO/LASCO nearly the same time, with a first detection in the LASCO C2 instrument on July 23rd (2012) at 02:36. SECCHI/COR1 instrument, aboard STEREO A, also observed this CME, starting at 02:30UT. Latter on, SECCHI/COR 2 A observed a full halo CME, starting at 02:54UT. On the 23rd of July, the in situ plasma instrument aboard the STEREO A spacecraft detected an extreme event, with magnetic field intensity higher than 100 nT, 20 times stronger than the average solar wind magnetic field. Russell et al. (2013) reported very high solar wind velocities, above 2000 km/s. Figure 2 shows, from top to bottom, the interplanetary magnetic field, its Bz component, plasma velocity, interplanetary electric field. The bottom panel shows a hypothetical Dst index estimated using Burton et al. (1975) model, had this event hit the earth. In the model estimate, a ring current decay time of 4.5 hours was considered. The estimate peak Dst value reached -1113.2 nT. This means that, had this event hit the earth, it would have caused the strongest geomagnetic storm in space era, nearly twice as strong as the strongest storm observed in 1989. As stated before, we consider that the Burton et al. (1975) formula is suitable for the main phase and peak intensity of a geomagnetic storm at such extreme conditions.

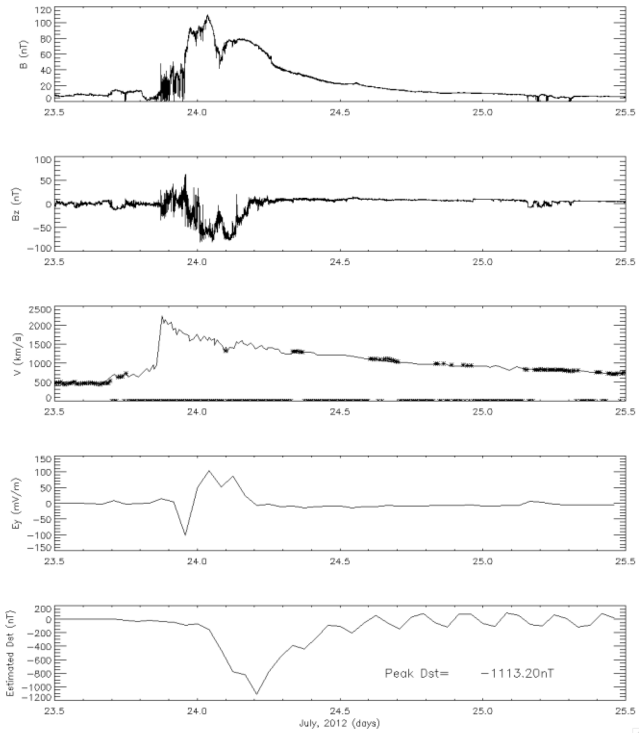

Figure 2: From top to bottom, the interplanetary magnetic field, its Bz component, plasma velocity, interplanetary electric field and the hypothetical geomagnetic Dst index estimated using Burton et al. (1975) model, considering a ring current decay time of 4.5 hours.

Conclusion

In this work, we investigate the geomagnetic response to extreme solar wind conditions using observations and modeling. In particular, 2 events were studied, one occurred in November 2003 and another in July 2012. The former was related to a CME ejected towards the earth, which originated an extreme geomagnetic storm, with peak Dst = -420nT. It was possible to correctly estimate this peak value using the formula derived by Burton et al. (1975), assuming a ring current decay time of 4.5 hours. The second event was a CME not directed towards the earth, but towards the STEREO A spacecraft. In situ observations of the related ICME indicate that this interplanetary conditions, had it been ejected towards the earth, would give rise to strongest geomagnetic storm in space era. Estimates using Burton et al. (1975) formula, with similar ring current decay time as those from the 2003 event (4.5 hours), indicate peak Dst values of -1113.20 nT.

Acknowledgments

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