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Solar wind and IMF parameters associated with geomagnetic storms with Dst < -50 nT

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Abstract
A correlative study between the intensity of a geomagnetic storm (given by the Dst index) and the peak value reached by some solar wind parameters (velocity and density) and the southward component of the interplanetary magnetic field (IMF) is made. This study has been performed by using hourly values of the Dst index and measurements taken by the ACE spacecraft in the period 2000–2005, for which 72 geomagnetic storms were considered. It is confirmed that peak Dst is correlated to the maximum negative component B_z of the IMF better than the maxima of n and V (solar wind number density and speed, respectively). By considering all the storms, the correlation coefficient was found to be 0.88. If we consider the geomagnetic storms for which -200 nT $<$ peak Dst < -60 nT, a lower correlation coefficient of 0.63 is obtained.

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1. Introduction

It is well known that a continuous flow of plasma comes out of the Sun, the solar wind. The quiescent solar wind consists of primarily hot electrons and protons with a minor fraction (~3–5%) of He^{++} ions. Proton and electron number densities are typically near 5–7 particles cm^{-3}. In these conditions, solar wind speed varies between 250 and 400 km s^{-1}. The solar wind carries with it the magnetic field of the Sun of intensity ~5 nT. This magnetic field or the interplanetary magnetic field (IMF) has a northward or southward orientation.

If the IMF is directed southward, B_z is negative and the pressure is raised (due to coronal mass ejections (CMEs) or solar flares), geomagnetic storms can be expected.

The southward field causes magnetic reconnection of the dayside magnetopause, rapidly injecting energetic particles into the Earth's nightside magnetosphere, which are also subjected to forces due to the magnetic field curvature and gradient as well as forces due to gyration effects. For charges of the same sign, these forces act in unison, with the net effect of the protons drifting from midnight toward dusk and the electrons drifting from midnight toward dawn. This oppositely directed drift comprises a ring of current around the Earth (Gonzalez *et al* 1994). An enhanced ring current is the prime indicator of a magnetic storm. The initial feature of a geomagnetic disturbance is a sudden increase in the horizontal component of the geomagnetic field H observed in many stations. The geomagnetic index Dst is used to monitor the worldwide magnetic storm level. It is constructed by averaging H from mid-latitude and equatorial magnetograms from all over the world. Negative Dst values indicate that a magnetic storm is in progress, the more negative Dst being indicative of the intensity of the magnetic storm. These negative deflections in the Dst index are caused by the ring current intensification, which flows around the Earth from east to west in the equatorial plane.

Geomagnetic storms are usually classified by the Dst index as intense storms (peak Dst of -100 nT or less), moderate storms (-100 nT $<$ peak Dst < -50 nT) and weak storms (peak Dst $\geqslant -50$ nT). In terms of time sequence, a magnetic storm can be described in three phases: the initial phase, the main phase and the recovery phase (e.g. Gonzalez *et al* 1994). The main phase of a storm is characterized by the large decrease of the Dst index.

Prediction of magnetic storms is becoming more and more important in space weather issues, since they may disturb trans-ionospheric radio communications, cause power blackouts and affect the lifespan of satellites.

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Table 1. Percentage of storms with corresponding time delay.

Delay (h)	Percentage of storms (%)
1	24
2	19
3	17
4	14
5	11
6	9
7	6

The aim of this paper is to show the correlation between the peak value reached by some parameters of the solar wind (velocity and proton density) and the southward component of the IMF B_z with the intensity of the geomagnetic storm (given by the minimum Dst) for geomagnetic storms that occurred in the period 2000–2005. This study has been performed by using ACE spacecraft measurements for 72 geomagnetic storms. ACE orbits at the L1 libration point, which is a point of the Earth–Sun gravitational equilibrium about 1.5 million km from the Earth and 148.5 million km from the Sun with a semi-major axis of approximately 200 000 km. Although the results are presented in this paper are based on a too limited dataset, they serve to corroborate and generalize the previous statement by Kane and Echer (2007) who wrote that 'larger negative B_z seems to give stronger geomagnetic storms'. This statement was based on table 1 of Kane and Echer (2007), where data are listed pertaining to 10 storms.

The solar and interplanetary causes of the solar wind disturbances are beyond the scope of this paper, and the reader is referred to detailed papers, e.g. Tsurutani *et al* (1992), Gonzalez *et al* (1994), Tsurutani and Gonzalez (1997), Tsurutani *et al* (2006) and Gonzalez *et al* (2007).

2. Results

For this study, measurements of the solar wind velocity, proton density and southward component B_z of the IMF taken by the ACE spacecraft for the observational period 2000–2005 were considered.

The solar wind plasma and field measurements with 1 h time resolution were obtained from the OMNI website: http://omniweb.gsfc.nasa.gov/. Hourly Dst indices were obtained from the World Data Center at the University of Kyoto database: http://swdc.kugi.kyoto-u.ac.jp/dstdir.

The number of storms with sudden commencements for 2000–2005 was 187, but the real number of all storms is higher. However, in the period considered, for 72 geomagnetic storms ACE spacecraft measurements were available, and in some storm periods only measurements of B_z were available. For all these events the minimum Dst values reached during the main phase of the geomagnetic storms, the maxima of the southward component B_z of the IMF, the speed and density of the solar wind when available, and the time delay between the maximum negative B_z and Dst were determined.

As an example of the behaviour of solar wind velocity, density, B_z and Dst during solar events, figure 1 illustrates the 20 November 2003 event. From the top to the bottom, the panels are: the geomagnetic index Dst for the 20–24 November 2003 storm period, the B_z component (in geocentric solar magnetospheric (GSM) coordinates), the plasma density and the solar wind speed. The abrupt decrease in Dst indicates the onset of the storm main phase. At about 21 UT on November 20, Dst reaches a peak negative value of −422 nT (the end of the main phase). Note that the fast forward shock is identified by the abrupt increase in velocity from ∼460 to ∼670 km s^{-1} and in magnetic field magnitude from ∼5 to ∼50 nT. As can be seen from these hourly values, the maximum negative Dst is lagging behind the maximum B_z value by about 3 h for this storm. In general, peak values of the solar wind speed or density do not necessarily occur before the maximum negative Dst.

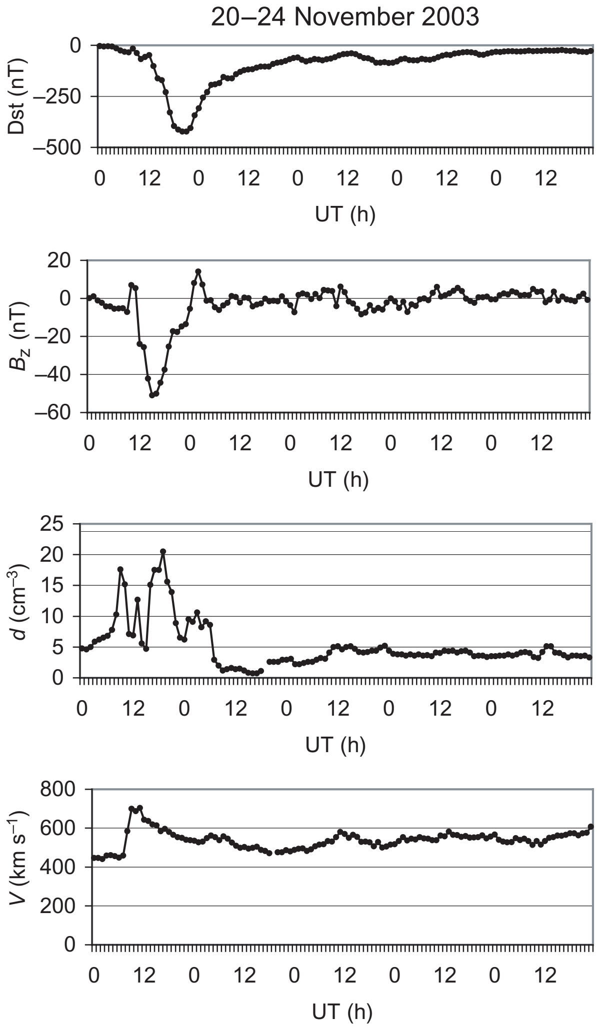

Figure 1. From top to bottom: hourly values of the Dst geomagnetic index (the magnetic storm onset occurs at ∼08 UT on November 20; peak = −422 nT), the B_z component (in GSM coordinates), the protons density and the solar wind speed for the 20–24 November 2003 storm period.

Figure 2 presents the maximum of interplanetary negative B_z (southward) versus the maximum of negative Dst. Statistically, the occurrence of more intense geomagnetic storms (negative Dst magnitudes ∼250 nT or less) is lower (∼10% of the storms considered). In this figure, a linear correlation between B_z and Dst can be seen; that is, the strength of the geomagnetic storm is strongly dependent on the southward component B_z. The correlation coefficient has been found to be reasonably high (0.88).

Figure 3 shows the peak proton density versus the maximum Dst (negative). No definite relationship between

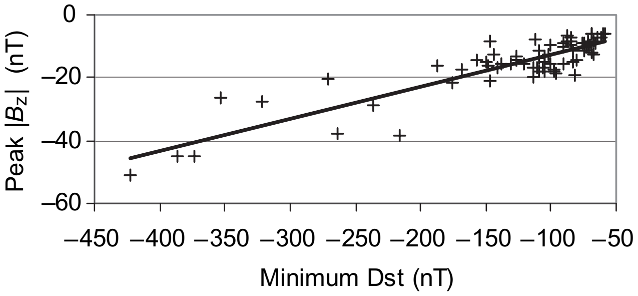

Figure 2. Negative B_z (max) at the ACE location versus peak Dst values for some storms that occurred in the period 2000–2005.

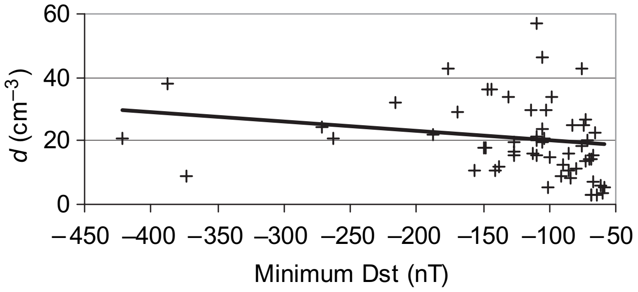

Figure 3. Peak proton density versus peak Dst values for some storms that occurred in the period 2000–2005.

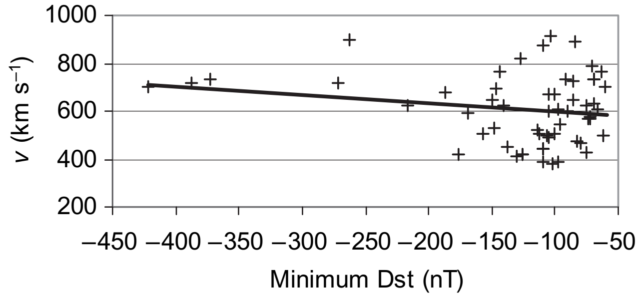

Figure 4. Peak solar wind speed versus peak Dst values for some storms that occurred in the period 2000–2005.

both these parameters is found. It can be seen that the greater intensity geomagnetic storms are not necessarily associated with greater values of solar wind density. This means that there is a high probability that intensity of a geomagnetic storm is not determined by the increased density. The correlation coefficient between both these parameters is 0.17. This result may be obvious. Solar wind density has significant growth mainly during (or before) the initial phase of geomagnetic storm (not during the main phase, tested here). Absence of high linear correlation between density and Dst during the main phase does not mean that solar wind density is not a geoeffective parameter, which is considered below.

Figure 4 presents maximum values reached by the solar wind speed V versus negative Dst (max). The scatter is larger, with a wide range of velocities varying between 400 and 900 km s^{-1}. The more intense geomagnetic storms (peak Dst < -350 nT) are not associated with greater values of solar wind velocities. The correlation coefficient between V and peak Dst has been found to be 0.19. Previous results on the correlation between Dst and V showed also that V is disappointing (e.g. Crooker and Gringauz 1993, Papitashvili *et al* 2000).

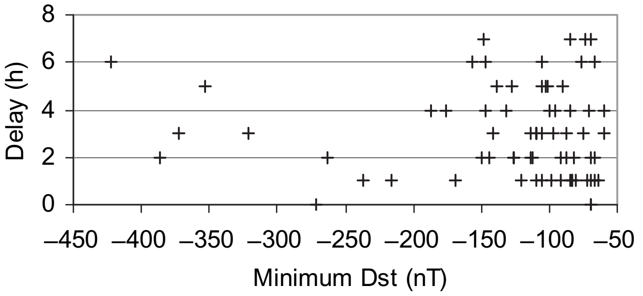

Figure 5. Time delay between the peak negative B_z and the negative Dst (peak) for storms that occurred in the period 2000–2005.

Figure 5 shows the delay between the peak negative B_z and the negative Dst (peak). As can be seen, great storms (peak Dst < -300 nT) present a time delay between 3 and 6 h, while moderate and weak storms between 1 h (or less) and 7 h. Table 1 shows the percentage of storms with the corresponding time delay Δt. It can be seen that 50% of the total geomagnetic storms present lags between 1 and 3 h and a minor percentage of storms (15%) present delays in the range 6–7 h.

3. Discussion and conclusions

It is widely recognized that solar and interplanetary causes produce geomagnetic disturbances. In general, there are two kinds of solar sources of geomagnetic storms: CMEs and co-rotating interaction regions (CIRs) (Wang 2007). The main source of most of the intense geomagnetic storms is CME (Vennerstroem 2001, Webb *et al* 2000, Khabarova *et al* 2006). However, storms are also produced either by recurrent streams or by streams of mixed origin (Yermolaev *et al* 2005, Khabarova *et al* 2006). The current paradigm of solar wind geoeffectiveness is as follows: ‘For intense magnetic storms the solar wind speed and the IMF intensity must be substantially higher than their ‘average’ values, the field must also be southwardly directed for a substantial length of time’ (Gonzalez *et al* 1999).

Taking that into account, in this paper the relative importance of the peak value reached by some parameters of the solar wind (velocity and proton density) and the southward component of the IMF B_z for determining the intensity of the geomagnetic storm is studied and then confirmed using measurements taken onboard the ACE spacecraft for the observational period 2000–2005.

It has been verified that geomagnetic storm intensity is correlated well with the southward component B_z of the IMF better than density and solar wind velocity. If we consider all the storms, the correlation coefficient has been found to be 0.88. If we consider the geomagnetic storms for which -200 nT $<$ peak Dst < -60 nT, a lower correlation coefficient of 0.63 is obtained. Although the idea that the IMF B_z component is essential for determining magnetospheric activity is not new (e.g. Wu and Lundstedt 1997, Jurac *et al* 2002, Wu and Lepping 2002), this result confirms the assumption by Kane and Echer (2007): for the intense storms, the larger negative B_z gives the stronger negative Dst and suggests that solar wind velocity possibly does not play a more significant geoeffective role.

However, a sharp density increase may work as a trigger, and the combination of density increase with consequent negative B_z can produce weak, moderate and even strong magnetic storms without any significant changes of the solar wind velocity (Khabarova *et al* 2006).

Thus, the previous result suggests it could be possible to obtain a linear relationship connecting the peak B_z and the minimum Dst.

The time delay between the arrival of solar wind disturbances at the ACE location at the L1 point and the growth of the ring current varies in a wide range from one geomagnetic storm to another: between 1 h (or possibly a shorter time period) and 8 h. Since the range is very wide, predictions of timings for any intensity of geomagnetic storm could be very uncertain. About 19% of the number of storms with a negative Dst magnitude of $\sim$150 nT or less for which $\Delta t = 1$ h. In general, the average delay between the peak B_z and the peak Dst values is $\sim$3.2 h. The order of magnitude for this value is similar to that obtained by other authors (Kane and Echer 2007).

Severe geomagnetic storms cause damage to electrical installations and communication systems mainly at high latitudes, and moderate storms often produce much higher increases of relativistic electron fluxes near the geosynchronous orbits than do intense storms (O'Brien *et al* 2001) and can lead to satellite anomalies and failures (Romanova *et al* 2005). Therefore, a warning of the likely occurrence must be expanded to the whole body of storms, not only the intense ones (Khabarova and Yermolaev 2008).

Khabarova (2007) proposed that the minimum Dst value during the main phase may be successfully derived from the maximum value of solar wind density before storm onset, the minimum IMF B_z value during the geomagnetic storm, and the time lag between the density maximum and the B_z minimum. Difference to the above mentioned, this simple conclusion presented could be of practical use in space weather forecasting, because from the report of the solar wind information of ACE spacecraft it could be possible to estimate the strength of a geomagnetic storm at least 1 h in advance (not forecast the occurrence of a geomagnetic storm) and to take necessary precautions. Another possibility is to infer the IMF B_z component from the observation of Dst minima. In order to obtain a relatively accurate relationship to predict the intensity of a geomagnetic storm from the observation of a minimum of B_z at L1 (e.g. by ACE), a greater observational period of measurements is required.

Although the correlations of Dst with the maxima of n and V (solar wind number density and speed), and the IMF B_z component have been extensively studied (e.g. Wu and Lundstedt 1997), the result of this study is important because it is essentially based on 72 events and generalizes the statement made by Kane and Echer (2007), where data are listed pertaining to 10 storms with $-490\,\text{nT} < \text{Dst} < -200\,\text{nT}$, by considering geomagnetic storms of different intensities.

However, it is clear that the present analysis should be considered preliminary, mainly because of the uncertainty in time delay, which should be investigated in detail for prediction purposes.

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