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Geomagnetic storms, dependence on solar and interplanetary phenomena: a review

A. Meloni, P. De Michelis and R. Tozzi

Istituto Nazionale di Geofisica e Vulcanologia, I-00143 Roma, Italy; e-mail: meloni@ingv.it

Abstract. Geomagnetic storms are probably the most intensively measured perturbations of the Earth's magnetic field. They are multi-faceted phenomena that result as a final element of a chain of processes that starts on the Sun, affects the solar wind and the interplanetary medium, and ends on the Earth.
At present, one of the key questions in the scientific community is the ability to predict the occurrence of geomagnetic storms on the basis of solar and interplanetary space observations. For these reasons, in recent years a number of investigations have been carried out to understand the solar-terrestrial relationships and to ascertain those factors that are ultimately responsible for geomagnetic storms. Here a brief review of published results on the geomagnetic storm effectiveness from CMEs, solar flares, as well as interplanetary event observations, is presented.

Key words. Geomagnetic storm, Geoeffectiveness of solar phenomena

1. The Geomagnetic Storm: a Brief Descripton

A geomagnetic storm is a multi-faceted phenomenon that owes its origin to physical processes in which energy transfered from the solar wind to the Earth magnetosphere is redistributed in the magnetosphere-ionosphere coupled system in the form of electric currents. There are two distinct categories of geomagnetic storms: i) those that recur with the solar rotation period of 27 days, ii) those that are nonrecurrent. Recurrent storms tend to be moderate and their frequency is anticorrelated with sunspot numbers. In contrast, large storms tend to be nonrecurrent and occur near solar maximum. The solar origin of these two distinct categories of storms is typically different. Recurrent storms are associated with the Earth's crossings of magnetic sectors corresponding to open-field regions (coronal holes) that corotate with the Sun with the 27-day period. For nonrecurrent storms, association with solar flares, coronal mass ejections and more in general with eruptive prominences was found.

The principal manifestation of a geomagnetic storm is the increase of the ring current intensity, a circular current flowing around the Earth at a distance in the range $3 \div 8$ Earth radii (R_E) on the equatorial plane. The increase of this current produces a magnetic field disturbance which, at the equator, is opposite in direction to the Earth's dipole field. This means that on the ground a global decrease of the horizontal component of the geomagnetic field is

Send offprint requests to: A. Meloni

observed. The strength of this perturbation on the Earth's surface is approximately given by the so-called Dessler-Parker-Sckope relationship:

$$\frac{\Delta B}{B_0} = \frac{2}{3}\frac{E}{E_m} \qquad (1)$$

where ΔB is the field decrease at the center of the Earth caused by the ring current, $B_0(\sim 0.3$ gauss) is the average equatorial surface field, E is the total energy of the ring current particles, and $E_m(= 8 \cdot 10^{24}$ erg) is the total magnetic energy of the geomagnetic field outside the Earth.

The standard proxy for the global perturbation field in a geomagnetic storm is the *Dst* index. This geomagnetic index, calculated by averaging the horizontal magnetic deviations observed at four low-/mid-latititude ground stations, is usually considered to reflect the intensity of the symmetric part of the ring current. However nowadays the prevailing idea is that there are other magnetospheric currents (cross tail current, substorm current wedge, magnetopause current, Birkeland field-aligned current), which fluctuating during space storms influence the ground magnetic field and the *Dst* index (Maltsev 2004). So, althought the *Dst* index has long been used as an indirect measure of the ring current intensity, it is now considered as a measurement of the longitudinally averaged ground perturbation at low-latitude magnetometer stations, i.e. a measurement of the effects of many magnetospheric current systems indiscriminately.

The general morphology of a storm-Dst can be seen in Figure 1. Indeed, using the *Dst* index we can see that a typical storm has two phases: the main phase ($dDst/dt < 0$) and the recovery phase ($dDst/dt > 0$). The main phase usually proceeds from 10 to 20 hrs and the field magnitude decreases by 100 (or more) nT, while the recovery phase tipically lasts from 1 to 2 days. Sometimes the storms can be characterized by an initial phase associated with a positive value of *Dst* due to the solar wind dynamic pressure enhancement. Anyway, the initial phase tipically starts suddenly (< 5 min duration) and lasts an indeterminate amount of time. This initial phase is not considered to be a necessary component of the storm. For this reason a geomagnetic storm is defined purely by the growth and subsequent decay of the depression in the H-component of the low latitude magnetic field.

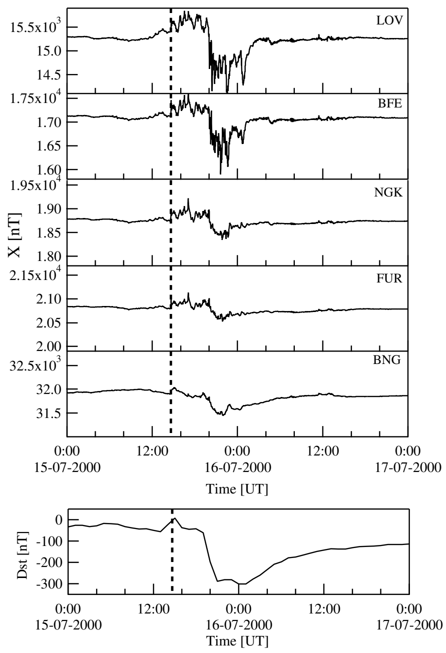

Fig. 1. An example of a geomagnetic storm as observed in the X-component and recorded in 5 different observatories localized approximately at the same geographycal longitude and with a increasing geographycal latitude in the range between 4.43° (BNG) and 59.35° (LOV). Below, the evaluated *Dst* index for the same period.

The three main phases of a geomagnetic storm are associated to different physical phenomena. The sudden and sharp jump in the Earth's field occurring at the onset of the initial phase is generally due to the abrupt increase in the solar wind ram pressure at interplanetary shock. The storm main phase is caused by magnetic interconnection between interplanetary magnetic fields and the Earth's magnetic field, which involves an acceleration of the tail plasma towards the near Earth magnetospheric equatorial regions located near midnight. This process is responsible of the increase of the ring current intensity and of the subsequent decrease of the near-equatorial field. At the end, the storm recovery phase is associated with the loss of the ring current particles from the magnetosphere.

2. The Primary Causes of Magnetic Storms

The primary causes of geomagnetic storms are strong dawn-to-dusk electric fields generated by the interplanetary magnetic field (IMF) transition to a southward direction and lasting for sufficiently long intervals of time. In this configuration the IMF is coupled with the Earth's magnetic field and allows solar wind energy transfer into the Earth's magnetotail/magnetosphere (Gonzalez et al. 1994). The resulting energy input depends on the strength and duration of the southward-directed IMF Bz component, and on the solar wind bulk speed. It has been empirically shown (Gonzalez and Tsurutani 1987) that intense storms ($Dst < -100nT$) are primarly caused by large values of the interplanetary magnetic field ($Bz < -10nT$) maintained for long periods (> 3 hours).

Solar wind usually does not contain long time intervals of southward IMF component since the IMF basically lies in the ecliptic plane. However, sometime, large-scale disturbances propagate in the solar wind, such as interplanetary shocks (IS), which are associated to the occurrence of CMEs on the Sun, magnetic clouds (MC), and corotating interaction region (CIR) that are produced by high speed solar wind streams in the interplanetary medium. These disturbances modify the interplanetary space environment in such a manner that appreciable IMF Bz component can be present in the solar wind for several hours.

The history of solar observations has been developed in such a manner that for a long time all disturbances in the solar wind and in the Earth's magnetosphere were connected with solar flares. Solar flares are explosive phenomena that usually occur in the near Sun atmospheric layers (corona and chromosphere). They occur near sunspots, usually along the neutral line between areas of oppositely directed magnetic fields. Though relatively compacted in size, solar flares are the most intense and energetic phenomena of the solar activity. Some flares are accompanied by an enormous flux of energetic particles with energy up to 10 MeV, which give rise to interplanetary disturbances. Thus is why they have attracted the attention of geomagnetic storm researchers for a long time. With the discovery of coronal mass ejections (CMEs), it gradually became clear that the disturbed solar wind streams associated with the occurrence of CMEs provide a better correlation with large nonrecurrent magnetic storms (Gosling et al. 1991). A working definition of a CME as observed at the Sun has been proposed by Hundhausen (1993): *"an observable change in coronal structure that (1) occurs on a timescale between a few minutes and several hours and (2) involves the appearance of a new discrete, bright white-light features in the coronagraph field view"*. Furthermore, it is important to remark that a CME involves the expulsion of plasma and magnetic field from the solar corona into interplanetary space.

It has been suggested (Gosling 1993) that CMEs, not flares, are probably the critical element for large geomagnetic storms, interplanetary shocks, and major solar energetic particle events. The geoeffectiveness of the CMEs is a consequence of the fact that they can contain long periods many hours) of southward interplanetary magnetic field, which enhances the transfer of energy from the solar wind to the magnetosphere. Their outward motion can cause a great distortion of the IMF. Moreover, if the differential speed between the remnants of the coronal ejecta and the slow upstream solar wind is greater than the magnetosonic wave speed ($50 - 70$ km/s) a forward shock occurs.

Figure 2 shows the case of an intense geomagnetic storm caused by the arrival on the Earth of a fast CME as observed by ACE (http://www.srl.caltech.edu/ACE/) during the period 6th - 9th April, 2000. From a comparison between the interplanetary and geomagnetic observations it is possible to notice that soon after the schock, B_z is intensified remaning like that for approximately 18 hours.While pointing southward, it causes a very intense

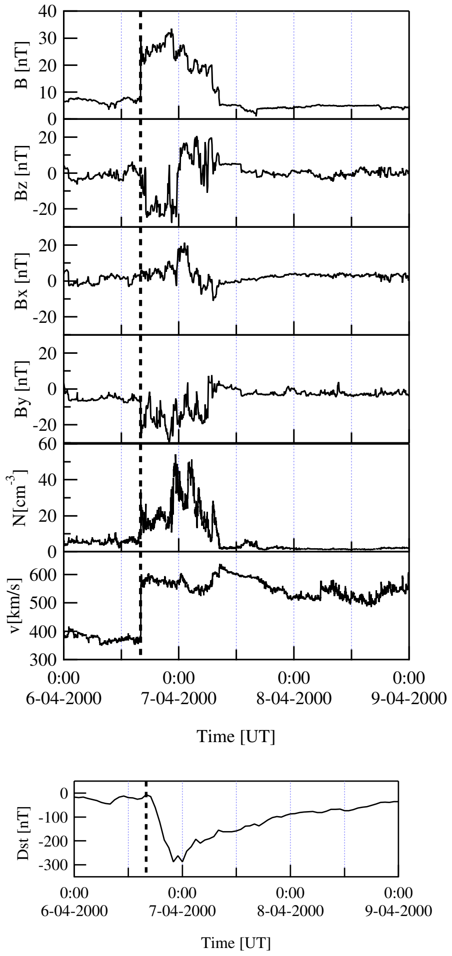

Fig. 2. From th top to bottom: interplanetary magnetic field and its 3 components, B, B_z, B_x, B_y and plasma parameters (velocity v and density N) observed by ACE together with the *Dst* index for the period of April 6th to April 9th, 2000.

fall in the *Dst* index, reaching its minimum of -321 nT.

Approximately 1/3 of the interplanetary manifestations of solar ejecta is represented by magnetic clouds (MCs). The magnetic cloud is a region of slowly varying and strong magnetic fields with exceptionally low proton temperature and plasma beta (Burlaga et al. 1981). Roughly 30-40% of ICMEs are magnetic clouds, and their importance from the point of view of space weather is relevant, since the smoothly changing magnetic field often leads to a southward IMF for many hours.

However, the interplanetary manifestations of fast CMEs are the dominant interplanetary phenomena causing intense magnetic storms essentially around the solar maximum. On the contrary during the declining phase of solar cycle, corotating high-speed streams emanating from coronal holes dominate geomagnetic activity. These fast streams (with velocities of 750-800 km/s) cause the $\sim$ 27 day recurrence of small geomagnetic storms and recurrences of High Intensity Long Duration Continuous AE Activity (HILDCAA) events.

3. Geomagnetic Storms and Solar Wind Parameters

After departing from the Sun the CMEs travel into the interplanetary medium and, if Earth directed, reach the Earth in 1-4 days depending on their speed. For this reason, in order to predict the geoeffectiveness of CMEs, it is necessary to analyse solar data from the moment the disturbance is generated on the Sun until the CME effects arrive on Earth. This requires an examination of ground-based and space-based multi-instrument data sets. As a matter of fact, analysing solar data it is possible to notice that the frequency of CME emission depends on the solar cycle. For example during the 23^{th} solar cycle the rate of CME occurrence has been about 0.6 CME per day during the solar minimum and 4.5 CME per day during the maximum. This means that the average rate of occurrence of CMEs increases by a factor around 7.5 from solar minimum to maximum. Nevertheless, the average rate of occurrence of intense geomagnetic storms near solar maxima is two or three times that observed in the ascending phases of the solar cycle near the minimum. This suggests that only a small percentage of all CMEs is directed Earth-ward, and only a few of them succeed in producing intense geomagnetic activity. It has been found that among all the CMEs those characterized by a full halo (i.e. CMEs for which the angular extent of the emission is approximately $> 360°$) are potential sources of intense geomagnetic storms. In particular, this is true in the case of the superintense storms ($Dst < -200nT$) that are all associated with full halo CMEs. The situation is lightly different in the case of intense storms ($-100nT < Dst < -200nT$), among these ~ 58% is associated with full halos, while ~ 25% is associated with partial halos (emission seen in an angular span greater than 140° in LASCO images) and for the remaining 17 % either the LASCO data are not available or the localizations of sources are too close to the limb to observe a full or a partial halo (Srivastava & Venkatakrishnan 2004). It is clear, however, that to predict the geoeffectiveness of a CME the identification of a CME with a full or partial halo is not sufficient, because not all full halo CMEs produce intense geomagnetic storms. During the period between 1996 and 2002 there have been 64 intense geomagnetic storms ($Dst < -100nT$). This means that during a period of 7 years there have been only 64 geoeffective CMEs while their total number was around 600, 235 of which characterized by a full halo. Thus, only 10% of all CMEs (with halo> 140°) emitted from the Sun produced intense geomagnetic storms.

The geoeffectiveness of CMEs strongly depend on the location of their origin. Indeed, few studies have shown that the geoeffective CMEs are generally confined to the active region belt present at low and moderate latitude (Gonzalez et al. 1996, Wang et al. 2002, Zhang et al. 2003, Srivastava & Venkatakrishnan 2004). Another useful parameter can be the initial speed of the CME. It has been found that the superintense geomagnetic storms are caused by fast CMEs moving at speeds higher than 1500 km/s even if the converse may not always be true (Srivastava & Venkatakrishnan 2004). At the end the intensity of geomagnetic storm can also depend on the ram pressure of the geoeffective CME, i.e., on the pressure exerted by the disturbed solar wind on the Earth's magnetosphere. Indeed a high ram pressure leads to the compression of the magnetic cloud and intensifies the southward component of Bz. All these studies clearly evidence that we are far from being able to quantitatively relate Earth-directed CMEs and magnetic storms. However, the study of the geoeffectiveness of the solar and interplanetary phenomena is one of the key points to predict the occurrence of geomagnetic storms on the basis of solar and interplanetary space observations.

At present, the number of publications on this theme has steadily grown. However, the problem is that these publications contain strongly diverging estimations of geoeffectiveness of the solar phenomena. For example, estimations of CME geoeffectiveness change from 35% up to 70% (Plunkett et al. 2001, Wang et al. 2002, Zhang et al. 2003, Webb et al. 1996). Similarly magnetic cloud (MC) geoeffectiveness ranges from 25% up to 82% (Vennerstroem 2001, Wu & Lepping 2002, Yermolaev & Yermolaev 2002, Cane & Richerdson 2003). These discrepancies are essentially consequence both of different methods of data analysis and of the direction of analysis process.

To study the geoeffectiveness of the solar and interplanetary phenomena it is necessary originally to select the phenomenon, respectively on the Sun or in the solar wind and then to compare the phenomenon with the event at the following step of the chain. Thus for example, the estimation of CME influence on the storm can be done considering both the direct process (CME → Storm) and the indirect process (CME → Magnetic cloud, Ejecta and Magnetic cloud, Ejecta → Storm). Of course, in the latter case the estimation of the entire process (CME → Storm) must be obtained as the product of probabilities of each process (Yermolaev et al. 2005). If we take into account the different studies in this field it is possible to conclude that the geoeffectiveness of the Earth-directed CMEs for magnetic storms with $Kp > 5$ ($Dst < -50nT$) is about 40-50% (Yermolaev et al. 2005). Conversely, studing the possible correlation between the storms and the CMEs we do not obtain the geoeffectiveness of CME rather than the probability to find the appropriate candidates among CMEs for magnetic storms. Furthermore, the results of a two-step process for back tracing substantially differ from the results of a one-step process.This suggests that the data analysis techniques must be improved. At the end, it is interesting to remark that the values relative to the CME geoeffectiveness (40-50 %) exceed only slightly the estimations of geoeffectiveness of solar flares (30-40 %) (Parker et al. 2001, Yermolaev & Yermolaev 2002, 2003).

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