GEOMAGNETIC STORMS: THEIR SOURCES AND A MODEL TO FORECAST THE DST INDEX

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Abstract: One of the applications of space weather is to forecast storm events. With this aim, a great effort has to be made in the development of models that let us to predict the Dst index, as indicator of geomagnetic storms. We propose a new model that determines the Dst index from the current induced over the ring current that flows around the Earth, assuming that solar wind electric field is the responsible of these variations. We also study which are the triggers of intense geomagnetic storms both at interplanetary space and at the Sun, and their dependence with solar cycle.

1 Introduction

The study of magnetic storms is one of the main topics of space weather. During a geomagnetic storm, the Sun and the magnetosphere are *connected*, giving rise severe changes both in interplanetary space and terrestrial environment. Some examples are the acceleration of charged particles, enhancement of electric currents, auroras and magnetic field variations on the Earth surface. These changes can produce important damages in electric power supplier, radio communications and spacecrafts.

It is assumed that Sun-Earth interaction depends on solar wind. In fact, intense geomagnetic storms seem to be related to intense interplanetary magnetic field (IMF) with a southern component for a long time [1, 2]. Several papers about geomagnetic storms [3, 4, 5, 6, 7] have pointed out the reconnection between a southern IMF and the magnetospheric magnetic field as the physical mechanism responsible of Sun-Earth connection. Although several aspects on this mechanism are still open questions, it is accepted that reconnection in the day-side of magnetosphere produces a transference of magnetic flux to the magnetotail [8]. Then energetic particles of solar wind can go into the magnetosphere, along magnetic field lines, yielding an injection of plasma in the night-side of the magnetosphere.

The radiation belts are regions of terrestrial environment where charged particles become trapped on closed geomagnetic field lines. These particles show drifts due to magnetic field gradient and curvature as well as to gyration orbit effects. As drifts depend on the sign of charge, ions travel to west and electrons to east, giving rise a ring current (RC) which extents from 4 to 8 terrestrial radii. Variations on this current produce variations into the magnetic field on the Earth surface.

All processes explained above involve energy transference from the solar wind to magnetosphere-ionosphere system, which modify plasma and magnetic field of magnetosphere. This perturbation can develop into a geomagnetic storm. Efficiency of process seems to depend on the southern component of magnetic field (a negative B_z value) and on the solar wind speed (v_x), that is, on the dawn-dusk component of solar wind electric field [9].

When the electric field is intense enough as to enhance the current of the RC above a value, a geomagnetic storm is produced. The Dst index is considered to be an indicator of the current of the RC [10, 11]. This hourly index is calculated as the horizontal variation of geomagnetic field measured at four different observatories distributed in longitude and near Earth equator. Then, if Dst index reaches -50 nT the event is considered as a geomagnetic storm and if it passes -100 nT the storm is considered as intense. Major geomagnetic storms can reach more that -300 nT.

Although the current of the RC is one of the major current systems of the magnetosphere [12, 13, 14], other low latitude currents also contribute to Dst index: magnetotail currents, substorms induced currents, and induced currents in the solid Earth [15, 16, 17]. All these currents can affect the magnetic field on the Earth surface and then, they have to be considered in those periods of intense geomagnetic activity to calculate the Dst index.

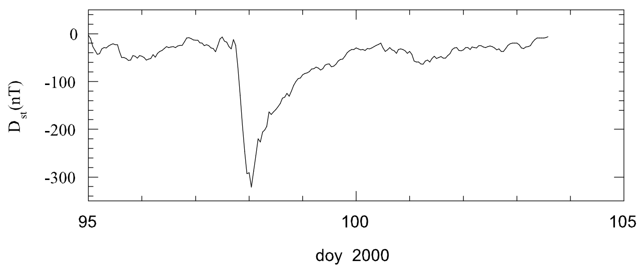

Figure 1: Hourly Dst values for a storm event.

In a geomagnetic storm can usually be distinguished two phases (Figure 1). The first one, the main phase, when energy passes from solar wind to magnetosphere enhancing the current of the RC and producing a strong decrease of Dst index. After, a recovery phase, when the magnetic field on the Earth surface goes back to the value of quiet time because of a decay of the current of the RC. This decay is due basically to loss processes as exchange of charge [9, 18], Coulomb interaction [19], and particle-wave interaction [20]. Each process is sensitive to ions energy, composition, pitch angle, distribution, etc. Then, decay time is a mean value in the RC as a whole that includes all these contributions.

In last decade great efforts have been made to develop models to predict the Dst index from solar wind data. The aim of these models is double: to know the physical mechanisms of RC dynamics and to study the influence of solar wind in the terrestrial environment. These models can be summarized into three groups: those based in a first order differential equation, those with linear filters [21] and those developed from neural networks [22]. In the first group outstands the work of [23], where the time evolution of Dst is modeled as a difference between an injection function, $Q(t)$,and a recovery term of the RC with a characteristic time τ. The injection function is associated to the energy coming by reconnection. Although the expression for $Q(t)$ has been discussed in many papers (see as an example [24]), it is accepted that magnetospheric injection is directly related to dawn-dusk component of solar wind electric field [25, 9, 26]. On the other hand, the recovery term is associated to the decay due to any loss process in the RC and it is proportional to the own Dst index.

Several corrections to the model proposed by [23] for Dst have been introduced trying to consider the contributions the dynamic pressure effect and the contribution of other currents (tail and magnetopause currents) that can also affect the magnetic field on the Earth surface [7, 17]. But a substantial modification was that of McPherron and O'Brien [26]. They assumed that the parameters involved in the model of Burton et al. have not a constant value, but depended on the dawn-dusk component of solar wind electric field. About the value of the decay time, it has varied from 7.7 hours (assumed by [23]) to a value which decreases in an exponential way as geomagnetic activity increases, varying nearly from the order of 15 hour for low geomagnetic activity to 5 hours for high level of activity.

Predictions on growing and decay of geomagnetic storms from solar wind conditions follow on improving. Nowadays, it is possible to reproduce roughly the hourly variation of the index Dst from solar wind data by several techniques (linear and non-linear). The problem arises when a storm is made of several substorms nearly in time. Then, the main phase of Dst index is not properly reproduced by any technique. Moreover, the relative importance of storms and substorms in building of RC is still an open problem.

2 Modeling the Dst index

We have developed a model to calculate the Dst index based only on the response of the RC to movement of IMF. The starting point of our model is considering the RC as if it would be an electrical circuit and solar wind as a power supplier. Although the dynamics of the RC is very complex, we will only consider global effects. Then, this approach does not let us to analyze those phenomena which are taking place inside the RC, but it let analyze in a simple way the effect of this current in the magnetic field measured on the Earth surface.

The energy by unit of charge that feeds this circuit at every time t depends on the dawn-dusk solar wind electric field and can be determined by the expression $v_x B_z l$, being l the longitude of the circuit. By separating the contribution of quiet solar wind and that of disturbed solar wind, we can represent the power of that circuit as two batteries serial connected: a *quiet* battery and an *extra* one. In this scenario, the first one would be related to the current of the RC in quiet time (I_{quiet}) and then to H component measured at the equator on quiet days (H_{quiet}).

When a disturbation occurs in the solar wind, the *extra* battery connects, supplying more electromotive force and enhancing the current of the RC. This current induced will produce a variation in the magnetic field measured on the Earth surface which is identified as the value of Dst index, and can be easily calculated, considering the magnetic field in the center of a ring:

$$Dst = H_{disturbed} - H_{quiet} = \mu_0 \frac{I_{quiet} + I_{extra}}{2R_{RC}} - \mu_0 \frac{I_{quiet}}{2R_{RC}} \tag{1}$$

In order to obtain I_{extra}, we have to take into account that at storm events, sudden variations in the current induced are produced. Then autoinduction cannot be negglected. Assuming a resistance R and an autoinduction coefficient L for the circuit, and having into account the initial conditions, I_{extra} can be determined from:

$$\xi_{extra} = RI_{extra} + L\frac{dI_{extra}}{dt} \tag{2}$$

Up to now, our model has been undiscriminating with the sign of the dawn-dusk electric field, that is, with the orientation of B_z. However, as has been said before, reconnection between the magnetospheric magnetic field and a southern IMF favors the entrance of energy into the magnetosphere. This fact is outstanding in fast changes of B_z. Experimental data show that when changes in electromotive force are due to an increase in southern component of IMF, the response of the magnetosphere is very fast. On the other hand, if changes are due to an increase in northern component, the response is slower and we can neglect autoinduction term.

Two different cases are considered that let us to simplify the general model in order to calculate R and L: a purely resistive case and a case with a sudden increase in *extra* battery electromotive force (or in dawn-dusk electric field), followed by a disconnection of that battery.

In the first case the current induced presents a smooth variation, or which is the same, there are not sharp changes in solar wind dawn-dusk electric field. Then the second term can be neglected in eq 2 and

$$Dst = -\frac{\mu_0 \pi}{R} v_x B_z \tag{3}$$

By fitting equation 3 to experimental data (Figure 2), our results indicate that $R = 0.12\Omega$.

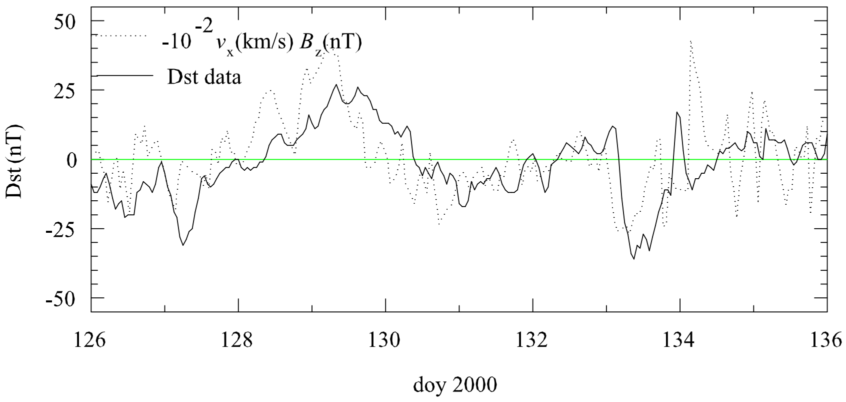

Figure 2: Figure shows one of the intervals in experimental data analyzed in order to determine the resistance of the RC.

In the second case, in order to obtain the value of L, it is necessary to analyze cases where we can consider that the *extra* battery has been disconnected after providing a sudden enhancement of the current of the RC. That is, we have to observe in the solar wind dawn-dusk electric field data a sharp discontinuity (at $t = t_0$) followed by a nearly zero value (Figure 3). In this case equation 2 is reduced to $I_{extra} = -\frac{L}{R}\frac{dI_{extra}}{dt}$, for the interval where $\xi_{extra} = 0$, which solution is $I_{extra} = I_0 e^{(t_0 - t)\frac{R}{L}}$. Then we obtain that

$$Dst = C_0 e^{(t_0 - t)\frac{R}{L}}, C_0 = \frac{\mu_0 I_0}{2R_{RC}} \tag{4}$$

Although C_0 and t_0 depend on the interval analyzed, the value of $\frac{R}{L}$ that we have obtained in all cases is always $1.1 day^{-1}$(see bottom panel of Figure 3 as an example). This indicates that $L = 9425H$, having into account the value of the resistance obtained before.

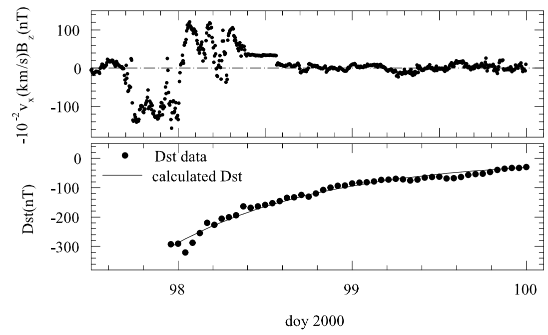

Figure 3: An interval in experimental data used for calculation of autoinduction coefficient of the RC.

With the values of the resistance and autoinduction coefficient calculated above, we can obtain a solution at intervals for equation 2. The number of intervals is determined by the number of sharp changes at dawn-dusk electric field. The function Dst for the interval $t_i < t < t_{i+1}$ can be expressed as follows:

$$Dst = -\frac{\mu_0 \pi}{R} v_x(t) B_z(t) + C_i e^{(t_i - t)\frac{R}{L}} \tag{5}$$

where t_i is the time where the sharp change number i happens, and C_i is a constant for every interval. Figure 4 shows Dst data (solid line) and Dst calculated with our model (dotted line) for a complex event, only using solar wind speed and IMF experimental data and values of R and L, obtained from simpler events. Although the value of C_i coefficients seems to be related to the magnitude of change in dawn-dusk electric field, it also depends of how quick changes. Anyway, a study that includes a great number of events is needed in order to conclude anything about this.

3 The Triggers of Geomagnetic Storms

The objectives of space weather cannot be only modeling the response of the terrestrial environment to solar wind. A special effort should be made in order to know which are the solar phenomena that trigger a geomagnetic storm and the way to forecast its occurrence in advance. Although magnetic storms can be triggered by other solar phenomena, the most intense storms have been associated to coronal mass ejections (CMEs). These solar events are large-scale eruptions of plasma, which are observed with coronagraphs. As these instruments only provide images of the sky plane, it is

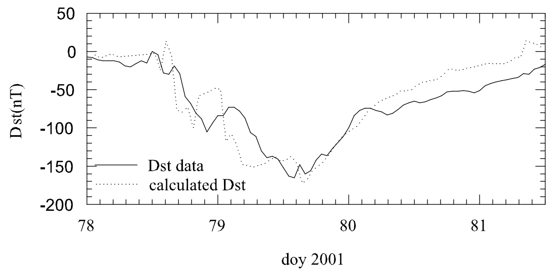

Figure 4: Dst index experimental data and theoretical results for a complex storm event.

difficult to determine if the material ejected from the Sun is directed to Earth. CMEs known as *halo* are those which extend 360 around the disk of the coronagraph. This kind of CMEs are thought to be ejections along the Sun Earth line [27]. But an event from the visible side of the Sun, seen by a coronagraph, provides the same image as another event on the opposite side. Then, in order to determine if a halo CME goes towards the Earth (front-side event) or goes away from it (back-side event), observations from solar disk are necessary. Front-side halo CMEs are more likely to affect the magnetosphere than other CMEs, but not all of them drive intense geomagnetic storms. As the number of CMEs varies with the solar cycle [28], intense geomagnetic activity triggered by CMEs is expected at solar maximum. A different kind of storms are those recurrent. These storms have been associated to coronal holes (CHs) and it is assumed that they are less intense than those considered before [2]. As the holes are largest and extend toward the helioequator during the declining phase of the solar cycle, at this stage the number of recurrent storms is expected to increase.

Anyway, a geomagnetic storm is the response of the magnetosphere to the interplanetary phenomena, which arises as a consequence of the solar event. Then, it is necessary to identify first the interplanetary event and after relating it to the solar activity. As mentioned above, intense dawn-dusk interplanetary electric field during a long time are the true triggers of geomagnetic storms. There are four kinds of interplanetary events that are associated to these intense electric fields: ejecta, corotating interaction regions (CIRs), alfvenic IMF fluctuations and Russell-McPherron effect [29]. However, the two last events cannot produce any storm if they are not together either to a ejecta to a CIR. Then, ejecta and CIRs are the primary interplanetary triggers of any storm.

The signatures in the solar wind of ejecta and CIRs are reasonably well defined and have been described in a number of previous works (see for example [30] for ejecta and vol. 89 of *Space Science Reviews* for CIRs). It can be summarized as follows: in an ejecta the magnetic field direction varies slowly, the magnetic field strength increases, and plasma proton temperature and thermal pressure decrease, that is, the ejecta is a low-β plasma. On the other hand, a CIR is a region of compressed plasma formed by the interaction of a high-speed flow with a preceding slow solar wind. Within the boundaries of a CIR, the proton temperature and the magnetic field strength are high.

A common association between solar and interplanetary event guides us to assume as starting point that ejecta are ICMEs (interplanetary CMEs) and CIRs are the result of interaction of a high speed stream from a CH with the slow solar wind. With the exception of some particular events, previous works have studied either the interplanetary or the solar sources of geomagnetic storms, but not the whole solar-terrestrial event. In order to study the solar triggers of geomagnetic storms, we have first identified all geomagnetic storms with an index Dst< -100 nT (intense storms) since 1995 to 2001. We have considered this period because it includes minimum and maximum solar activity. Then, we have determined the interplanetary medium event related to every storm. Finally, we have inspected solar data trying to determine the whole solar-terrestrial event.

For the case of a CIR, we inspect sun disk images obtained two or three days before the interplanetary event in order to check if a low latitude CH appears. Then, we associate the fast wind with the wind from that CH. The identification of the solar source of an ejecta requires a more careful analysis. First, we inspect LASCO CME catalog looking for any CME candidate in a time window consistent with the solar wind speed measured for the ejecta. Usually, several CMEs are found and choosing the appropriate candidate for the ejecta is not an easy task. The appearance of a front-side halo CME candidate is widely used as a reliable indicator of the solar source of ejecta [31]. However, a front-side halo CME can be also associated to very bright material ejected far away from the solar central meridian. In this case, the association between the solar ejection and the interplanetary ejecta is far to be sure. Then, we have not considered the angular size of the CME as an indicator for the association of solar and interplanetary events. Instead of that, we take into account the location on the solar disk where the material is ejected. We have checked that this location is near the central solar meridian using Sun disk images, in order to be sure that the ejection reaches the Earth. We have also inspected how the material ejected evolves along the chronograph field of view, and we have tried to relate it with solar wind speed observed at ejecta.

During the period analyzed 48 storm events with Dst less than -100 nT were observed. Our results indicate that the main cause of intense storms are ejecta, but the number of storms related to CIRs is not negligible (29%). Moreover, these storms can be as intense as those from ejecta, as in the case of 22 October 1999. This event was associated previously by Zhang [32] with the CME from S40E05 on October 18, 00:06 UT. By relating interplanetary data and the Dst index, we think that the ejecta related to CME reaches the Earth before starting the storm (at Oct 21, 15:00 UT). In our opinion, the true trigger of this intense storm is the fast wind that appears in interplanetary data after passing the ejecta, that comes from the CH that appears in SXT image on October 20.

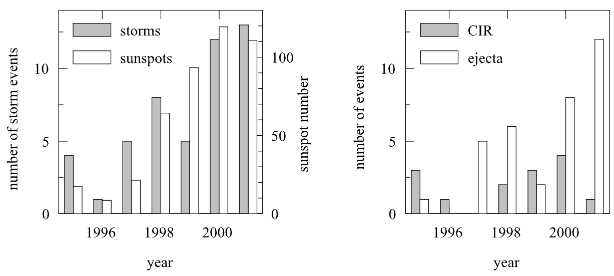

Figure 5: Frecuency histograms along solar cycle.

We have also analyzed if the kind of event that triggers a storm depends on solar cycle. With this aim, we have represented in Figure 5 the yearly sunspot number next to the number of storm events (a) and next to those related to CIRs (b) and ejecta (c). CMEs are considered the origin of intense storms in the increasing side of the solar cycle and coronal holes in the decreasing side [33]. Our results seem to indicate that there is a clear contradiction to those arguments. It can be seen in Figure 5 that the number of storms is closely related to solar cycle, although in year 1999 an anomalous behavior appears. The number of events related to CIRs is almost constant along the solar cycle and those related to ejecta is bigger in years of maximum activity (2000 and 2001) than in those of minimum (1995 and 1996), but the trend does not follow solar cycle.

Several works [32] indicate that most effective CMEs are those full halo and partial halo. Then, trying to check if the angular width of a CME was an indicator of geomagnetic storms, we have make a histogram of the angular width of CMEs related to intense storms (Figure 6a). As figure shows the number of non halo CMEs which trigger an intense storm is not a negligible quantity. Moreover, CMEs with a small angular width can be associated to storms as intense as those halo. Other fact about intense storms is that they are related to fast CMEs. In Figure 6b we show that there is not any relationship, moreover a slower CME can be more geoeffective than a faster one.

Finally, we want to remark that extracting conclusions from the trigger of a storm only from partial information of the whole solar-interplanetary event, can lead us to

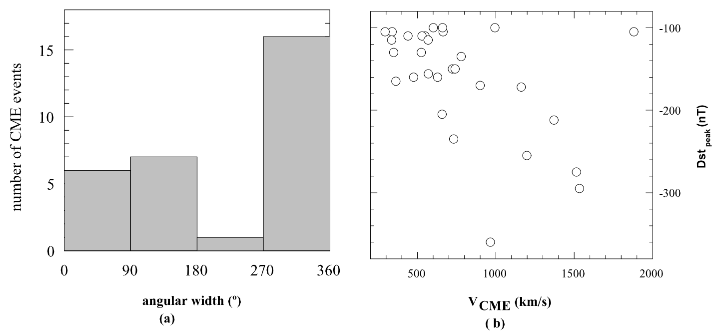

Figure 6: (a) Histogram distribution of the CMEs angular width and (b)the CME speed at 20 R_{SUN} as a function of Dst peak.

obtain wrong conclusions. Usually there is only a part of information available, and moreover, it is difficult to be sure that all the pieces of the time-puzzle from the Sun to 1 AU have been settled properly. We think that a great effort should be made in those events that seem to be well identified.

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