SOLAR WIND-MAGNETOSPHERE ENERGY TRANSFER MECHANISMS

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Abstract: Magnetic reconnection has been considered as the unique physical mechanism involved in energy transference from solar wind to magnetosphere. However, theoretical models of geomagnetic indices based on reconnection do not forecast properly geomagnetic activity suggesting that other mechanisms are implicated. The joint analysis of interplanetary data and geomagnetic activity data evidence the existence of an extra mechanism implicated in Sun-Earth interaction, which operates when the frequency of southern interplanetary magnetic field is of the order of 10^{-3} to 10^{-4} Hz.

1 Introduction

The term 'Space Weather', which was introduced in 1994, involves the study of Sun-Earth interaction, that is, of those events that, having taken place in the Sun, and traveling through the interplanetary medium, are related in any way to the magnetic topology of our environment. Then, Space Weather involves different aspects: technological, economics, social, all of them related to a forecasting aspect. This last side is the aim of the present work.

The first interaction between solar wind and terrestrial magnetic field arises because of the so-called 'quiet' solar wind. When this 'quiet wind' (about 5 particles per cubic centimeter, traveling away from the Sun with a velocity close to 350 km/s) reaches the terrestrial environment, the expected dipolar magnetic field topology transforms into a different topology (Figure 1): a bow shock and a tail appear. Also the radiation belts and a ring current inside around terrestrial equator arise.

Eruptive events that take place in the Sun (flares, CMEs, etc.) release huge amounts of plasma and energy which travel through the interplanetary medium evolving as good-organized magnetic field topologies, as flux ropes, which sometimes develop interplanetary shocks ahead itself. When these perturbed conditions arise terrestrial magnetosphere, several changes appear in our environment:

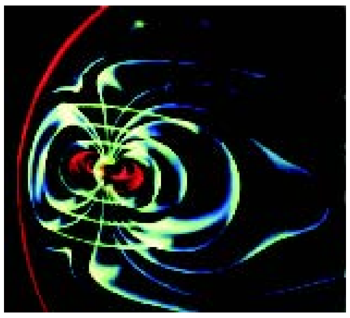

Figure 1: A cartoon of terrestrial magnetosphere.

- Bow shock compression
- Solar wind particles coming in through the polar cusps, producing intense auroras
- Magnetic reconnection between interplanetary magnetic field and terrestrial magnetic field
- Particle injection through the magnetotail to the ring current because of intense convective electric fields
- Enhancement of the ring current encircling the Earth in the westward direction
- Depression in the H component of the magnetic field at terrestrial equator

The Dst index represents the most commonly used proxy of geomagnetic activity. It measures the deviation of the H component at mid-latitude ground stations from their quiet day values. This index is considered as a proxy of the current system flowing around the Earth known as ring current [1, 2, 3], or a proxy of the energy stored in the ring current [4, 5, 6]. Having into account the lowest value of Dst reached (or peak value), the geomagnetic storms can be classified as small (-30nT > Dst > -50nT), moderate (-50nT > Dst > -100nT) and intense storms (Dst < -100 nT) [2].

At Dst index data, a typical geomagnetic storm appears as illustrated in Figure 2. In every storm event a sudden decrease appears (known as main phase) and after the Dst index reaches the 'peak value', we can find the recovery phase. Sometimes there is a previous phase, known as storm sudden commencement (SSC), where the index makes more positive. Each one of these phases is related to a different physical mechanism. The sudden commencement used to be related

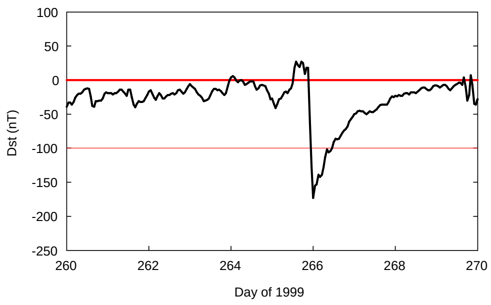

Figure 2: Dst index experimental data from Kyoto during days 260-270 of year 1999 showing a typical geomagnetic storm event.

to a compression of the bow shock because of the arrival of the interplanetary shock. The main phase is related to the energy transfer from the solar wind to the magnetosphere, which is assumed to be due to magnetic reconnection. During the recovery phase there is a decay in the ring current because of charge exchange [2, 7], Coulomb scattering [8] and resonant interactions [9].

2 Reconnection as coupling mechanism

Magnetic reconnection has been assumed as the mechanism responsible of energy transfer from solar wind to magnetosphere. When interplanetary magnetic field (IMF) is directed southward, this magnetic field and that of magnetosphere are in opposite direction and this mechanism works in a more effective way [10] (Figure 3).

Moreover, southward IMF experimental data and high solar wind velocity (that is, intense duskward electric fields) used to be associated to a decrease in Dst index experimental data, supporting the reconnection mechanism (Figure 4).

The first model to forecast the Dst index was that of [11]. They propose that variation of Dst with time can be modeled assuming that the energy of the ring current is a combination of a source and a proportional loss, then Dst is commonly described by the following first order differential equation:

$$\frac{dDst}{dt} = Q(t) - \frac{Dst}{\tau} \quad (1)$$

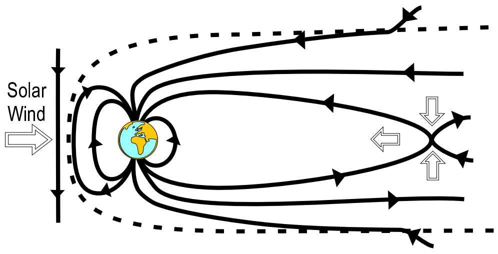

Figure 3: A sketch of reconnection between solar wind and terrestrial magnetosphere.

where τ is the relaxation time and Q is the injection function. Then, considering reconnection as the physical mechanism responsible for energy transfer from solar wind to magnetosphere, the injection function was proposed to be proportional to the product of southern IMF component and solar wind velocity, that is, to the interplanetary duskward electric field. Following them, others have attempted to improve the prediction using the same physical mechanism [12, 3, 13, 22]. Figure 5 includes the expression used for the injection function and the decay time for some of these models related to reconnection. Nevertheless, although these models reproduce properly the Dst index in quiet time, the theoretical values obtained for Dst peak at intense storms can be further than 50 % of experimental value.

Trying to check the goodness of models based on reconnection we have compared the Dst experimental data and the theoretical predictions obtained from the model of [11] and that of [3]. Dst hourly experimental data are from Kyoto World Data Center, and have been obtained through the web site http://swdcwww.kugi.kyoto-u.ac.jp/dstdir/index.html. We have determined theoretical Dst index from both models using magnetic field and solar wind plasma hourly data from ACE spacecraft, during years 1998-2002, at Space Environment Center (http://www.srl.caltech.edu/ACE/ASC/). Then, we have calculated half day mean deviation and Dst mean variation with the following expressions:

$$< \sigma >= \frac{\sum_{i=0}^{halfday} \mid Dst_{theoretical} - Dst_{experimental} \mid}{N_{data}} \quad (2)$$

$$< \Delta Dst >= \frac{\sum_{i=0}^{halfday} \mid Dst_{i+1}^{experimental} - Dst_{i}^{experimental} \mid}{N_{data}} \quad (3)$$

In Figure 6 we have plotted the half day mean deviation versus the mean variation

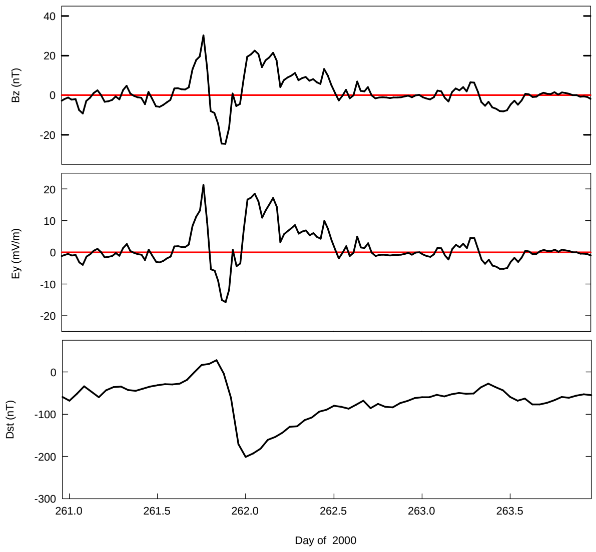

Figure 4: From top to bottom: Z component of interplanetary magnetic field, dawn-dusk electric field component and Dst index during the days 261-264 of year 2000. Interplanetary data are from ACE spacecraft and geomagnetic data from Kyoto data center.

of Dst index. It illustrates clearly the fact that reconnection mechanism is not enough to explain the interaction between solar wind and magnetosphere for great ΔDst. Although the model of [3] improves theoretical predictions, mean deviations over 80 nT remain for $< \Delta Dst >$ over 20 nT.

3 Magnetic field oscillations as a feature of storms

The facts of previous sections describe a scenario which has guided to forecast using neural networks models [14], where a historical training code is used to forecast geomagnetic activity. However, scientific community should look for other physical mechanisms involved in solar wind-magnetosphere interaction. These

Model	$Q(t)$ (nT/hour)	τ (hours^{-1})
Burton *et al.* [7]	$\begin{cases} -5.4(-VB_z - 0.5) & VB_z < 0.5mV/m \\ 0 & VB_z \geq 0.5mV/m \end{cases}$	7.7
Fenrich and Luhmann [8]	$\begin{cases} -4.32(-VB_z - 0.49)P_{dyn}^{1/3} & VB_z < 0.5mV/m \\ 0 & VB_z \geq 0.5mV/m \end{cases}$	$\begin{cases} 3 & VB_z < 4mV/m \\ 7.7 & VB_z \geq 4mV/m \end{cases}$
O'Brien and McPherron [3]	$\begin{cases} -4.4(-VB_z - 0.49) & VB_z < 0.49mV/m \\ 0 & VB_z \geq 0.49mV/m \end{cases}$	$\begin{cases} 2.4e^{\frac{9.74}{4.69-VBz}}, & B_z < 0 \\ 2.4e^{\frac{9.74}{4.69}}, & B_z \geq 0 \end{cases}$
Maltsev and Rezhenov [9]	$\begin{cases} 1.05 - 4.0VB_z - V/243), & B_z < 0 \\ 1.05 - V/243), & B_z \geq 0 \end{cases}$	$\begin{cases} \frac{15.4}{1-0.326VB_z} & B_z < 0 \\ 15.4, & B_z \geq 0 \end{cases}$

Figure 5: A summary of proposed injection functions and recovery time for different models. See text for details.

mechanisms shall be related to the features that appear at interplanetary experimental data associated to intense geomagnetic storms.

Having into account reconnection, alerts of geomagnetic storms used to be determined following the criteria of [15] or [16]. Using ISEE-3 field and plasma data, [15] found that duskward interplanetary electric fields greater than 5 mV/m over periods exceeding 3 hours were related to intense storms. [16] found that this electric field condition is approximately equivalent to $B_z < -10$ nT, which evidence that the triggering probability for storms is high during the southward IMF passage [17, 18, 19]. These features in interplanetary electric and magnetic field data support magnetic reconnection as the mechanism involved in solar wind-magnetosphere interaction. However, in several intense storms of this solar cycle, these features do not appear.

As an example, we present an event of 24 November 2001 (Figure 7). Although Dst reaches -221 nT, the duskward electric field arises over 5 mV/m only from 6:23 UT to 6:59 UT, and between 10:16 UT and 11:23 UT. The total duration of these intervals is lower than 3 hours.

These results suggest that another feature shall appear at interplanetary data which gets light about the physical mechanisms involved. Comparing Figure 4 with Figure 7, it is easy to observe a common feature: an oscillation appears at B_z and E_y data at the main phase of both storms. Moreover, after analyzing all intense storm events of present solar cycle, we have found that every sharp discontinuity of Dst is related to an oscillation in B_z (and then in E_y) of the

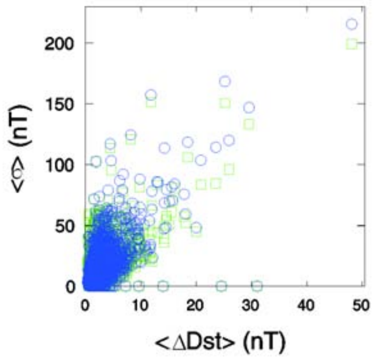

Figure 6: Half day mean deviation versus the mean variation of Dst index for the model of [11] (circles) and that of [3] (squares).

order of $10^{-3} - 10^{-4}$ Hz. This feature guides us to think about an energy transfer mechanism related to oscillations. In this case, the peak value of Dst shall be related to the amplitude and to the frequency of the oscillation [20]

4 Forecasting with different physical mechanisms

We have checked the alerts of intense storms that will produce every physical mechanism described above: reconnection and resonant response of magnetosphere to dawn-dusk electric field oscillation. In the first case, we have looked for long intervals of southern interplanetary magnetic field. Then, following [15], we select every interval longer than 3 hours where the duskward electric field exceeds 5 mV/m. In the second case, the feature looked for has been the IMF oscillation of a frequency about $10^{-3} - 10^{-4}$ Hz and an amplitude exceeding 10 nT.

In both cases we have used magnetic field and solar wind velocity 64 s resolution data from ACE spacecraft during years 2000 and 2001 (maximum solar activity period) as real-time data. Three different situations appear in our analysis:

- HIT: The feature at interplanetary data forecasts an intense storm event, and the storm happens.

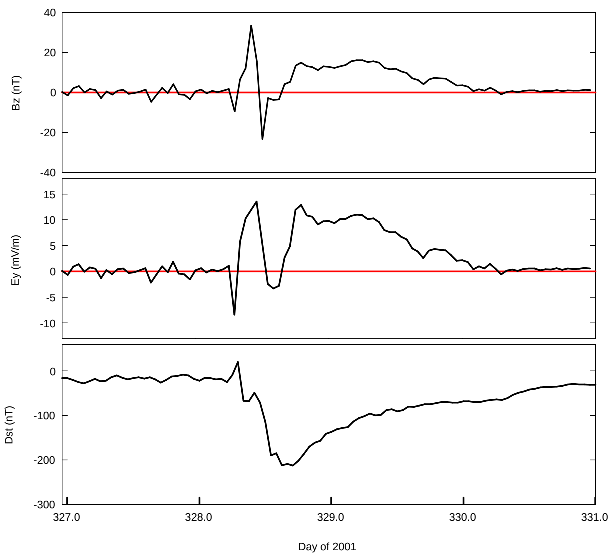

Figure 7: From top to bottom: Z component of interplanetary magnetic field, dawn-duskward electric field component and Dst index during the days 327-331 of year 2001. Interplanetary data are from Wind spacecraft and geomagnetic data from Kyoto data center.

- FALSE ALERT: The feature at interplanetary data forecasts an intense storm event, and the storm does not happen.
- FAIL: The feature at interplanetary data does not forecast an intense storm event, but a storm happens.

The results of alerts produced in both cases, published in [21], are illustrated in Figure 8. While for year 2000 the results are good and coincident for both approaches (11 hits,1 fail and 2 false alerts), in 2001 the hits of reconnection reduce to 26 % (5 events) and the hits of oscillations are again over 70 % (11 events), even reducing the number of false alerts (3 events), which is also an valuable characteristic for the operational performance of these physical mechanisms.

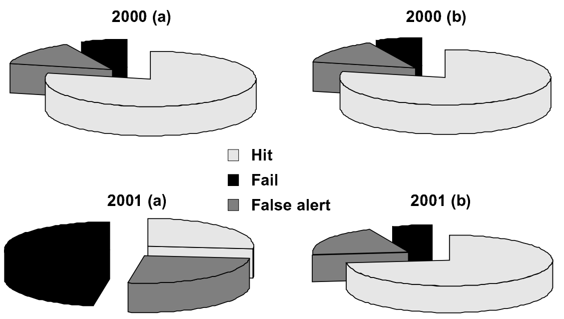

Figure 8: The graphs show the results of alerts produced using ACE data from years 2000 and 2001 as real-time data in both cases: (a) magnetic reconnection and (b) oscillations.

5 Conclusions

The interaction between solar wind and terrestrial magnetosphere involves different physical mechanisms operating in a coordinated way. Although reconnection is always present, the appearance of an oscillation in convective electric field causes a very effective energy transfer. While this last mechanism is the most efficient for great variations of terrestrial magnetic field, the two interplanetary features and corresponding geomagnetic responses can be thought of as being complementary in nature.

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