Analysis of the Energy Transferred from the Solar Wind into the Magnetosphere during the April 11, 2001 Geomagnetic Storm

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Abstract: Coronal mass ejections (CMEs) can have major consequences on Earth's magnetosphere. We investigate here the full halo CME registered by LASCO at 05:30 UT on April 10, 2001. A geomagnetic storm that had a minimum Dst value of -271 nT, on April 11 at 23:00 UT was triggered upon its arrival to Earth.
We focus our study on the energy transfer from the solar wind into the magnetosphere during this geomagnetic storm. We estimate the quantity of energy that is deposited into the magnetosphere during this event using two different formulas by Akasofu (1981) and Wang et al. (2014). We note that the transfer of energy thus calculated does not resume to the main phase of the storm, but lasts much longer. We also discuss the implications of other formulas used in the literature to analyse this kind of transfer.
The chain of events coronal mass ejections – interplanetary coronal mass ejections – geomagnetic storm was tested from a statistical point of view using a model based on logistic regression. We obtained a 100% probability that the April 10, 2001 CME should be geoeffective.

Key words: CME, ICME, geomagnetic storm, energy transfer

1. Introduction

Earth's magnetosphere's shape varies under the influence of solar phenomena sometimes allowing energetic particles to enter our atmosphere or to disturb the geomagnetic field (e.g. Russel, 2001). The energetic particles or the currents induced by the variations in the magnetic field intensity can disturb our space and on ground technologies.

The disturbance of the geomagnetic field is usually referred to as being a geomagnetic storm, and depending on the value of the geomagnetic index Dst the storm can be: small (-30 nT ≤ Dst < -50 nT), moderate (–50 nT ≤ Dst < -100 nT), and intense (Dst ≤ -100 nT) (Gonzalez et al., 1994). Most of the intense geomagnetic storms are related to fast halo coronal mass ejections (CMEs) which have the sources close to the solar disk centre (e.g. Gosling 1993; Richarson et al., 2001; Zhang et al., 2003, 2007; Srivastava and Venkatakrishnan, 2004; Zhao and Webb, 2003; Gopalswamy et al., 2007). Occasionally limb CMEs can also be deflected in such a way that they reach the Earth (Cid et al., 2012) and produce geomagnetic disturbances.

As a consequence of their impact on the terrestrial magnetosphere, the CMEs are intensively studied phenomena (see for e.g. reviews by Schwenn, 2006; Chen, 2011). The main concern while studying these events is whether or not the CME will be geoeffective and to what extent. We can distinguish two different studies: the geoeffectivity of the CME – a simple yes/no answer to the question "Will this CME trigger a geomagnetic storm?" and "how intense will be the geomagnetic storm following this CME?" – usually stated by a prediction of the Dst magnitude (Schwenn et al., 2005; Burton et al., 1975; Temerin and Li, 2006).

Another subject of major interest is the prediction of geomagnetic storms. There are many methods that scientists use to predict such an event, pure statistical ones, empirical ones, some of them include modelling and others are pure CME propagation modelling (for a detailed list please see the review by Zhao and Dryer, 2014). In this paper we chose a semi-empirical model, namely the logistic regression model introduced by Srivastava (2005), in order to predict the triggering of an intense geomagnetic storm on April 11, 2001. The storm was produced by the arrival at the Earth of the CME registered by LASCO/C2 on April 10, 2001, 05:30 UT. The model combines various CME parameters and some interplanetary CME (ICME) measurements to be correlated with the Dst index. The model is described in more detail in Section 2.3.

We also analysed the transfer of energy from the solar wind to the magnetosphere during this geomagnetic storm, as one important factor to explain the geo-effectiveness of the CME resides in this kind of transfer. Early works such as from Chapman and Ferraro (1931), Crooker et al. (1977), considered that the solar wind density and velocity should be key parameters for the energy transfer. Future works were based on combining the speed and density with other solar wind parameters and/or the southern component of the interplanetary magnetic field (IMF), i.e. B_Z. Scientists tried to estimate this transfer through different methods based on theoretical approaches (Vasyliunas et al., 1982; Finch and Lockwood, 2007) or empirical considerations (Svalgaard, 1977; Perrault and Akasofu, 1978). Kan and Lee (1979) calculated the power delivered by the solar wind dynamo to the open magnetosphere based on the concept of field line reconnection, and showed that the calculated power is proportional to the Akasofu-Perrault energy coupling function.

Gonzalez (1990) showed that most of the widely used coupling functions are particular cases of more general expressions of the electric field and energy transferred into the magnetopause due to the large scale reconnection. Newell et al. (2007) have introduced another coupling function (that combines v, BT and the interplanetary magnetic field clock angle) representing "the rate magnetic flux is opened at the magnetopause", which was correlated best with nine out of ten magnetospheric indices. Among the indices they used were Dst, Kp, AE, AU, AL etc.

In order to calculate the amount of energy input during the geomagnetic storm of April 11, 2001 we used the coupling function deduced empirically introduced by Akasofu (1981) and the improved coupling function introduced by Wang et al. (2014) using a neural network method. We chose the Akasofu parameter because it proved that in spite of its empirical nature it gives a remarkably good estimate for the total energy input into the inner magnetosphere in substorm and storm timescales (see e.g. Koshinen and Tanskanen, 2002). Then, Wang et al. (2014) coupling function was chosen because they used a neural network method (a method which statistically best correlates the observed parameters with their consequences) to establish the relationship between variables which are all included in coupling functions studied so far (in Akasofu coupling function as well). Whether coupling functions have been empirically or theoretically established, they are usually based on the same variables: solar wind speed, IMF intensity and IMF clock angle.

The paper is structured as following: Section 2 describes the CME on April 10, 2001, its interplanetary counterpart on April 11, 2001 and the geomagnetic storm produced by this CME, on April 11, 2001; Section 3 describes the methods and their application to our event (by event we mean the whole chain: CME – ICME – geomagnetic storm); Section 4 summarises our findings with few discussions.

2. Data Analysis

2.1 CME/ICME

A full halo CME was observed by LASCO/C2 at 05:30 UT on April 10, 2001 (http://cdaw.gsfc.nasa.gov/CME_list/halo/halo.html; Yashiro et al. 2004). This CME had a linear speed of 2411 km/s and an acceleration of 211 m/s^2. Its speed at 20 solar radii was 2974 km/s making this CME one of the fastest CMEs of solar cycle 23.

The CME was associated with a X2.3 solar flare that started at 05:06 UT, had its maximum at 05:26 and ended at 05:42 UT, in the active region NOAA 9415. This region had an βγδ magnetic classification and it was situated at S22W21. The CME was directed towards the Earth and it arrived at ACE on April 11 at 22:00 UT (http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm, Richardson and Cane, 2010). The related shock was registered by ACE on April 11, 15:27 (see http://www.ssg.sr.unh.edu/mag/ace/ACElists/obs_list.html#shocks). Two small preceding shocks were also observed on April 11, 2001, 13:14 UT and 14:52 UT (http://www.ipshocks.fi/). The shock was seen as a sudden concomitant increase in solar wind speed, density and magnetic field (see Figure 1). To make the distinction between different parts of the ICME observed by ACE, we adopt here the definition of ICME as given by Rouillard (2011), in which he includes the shock and the sheath as being parts of the ICME itself: "An ICME is defined as the entire solar wind region altered by a solar transient, it includes the shock, sheath, solar wind pile-up, compression regions, driver gas, ejecta wake and/or the legs of magnetic loops." The shock is the first one which arrives to the spacecraft, seen as a concomitant jump in different plasma parameters (in our case the shock arrived at 15:27 UT on April 11, 2001), followed immediately by the sheath (a turbulent and heated region of the solar wind characterised by high fluctuations in magnetic and plasma parameters) and by the ejecta (which in general is referred to as the ICME as defined by various authors: e.g. Jian et al. 2006). In our case, the ejecta arrived at ACE at 22:00, on April 11, 2001.

Figure 1 shows the evolution of the interplanetary magnetic field components B_x, B_y and B_z, the magnitude (B) of the IMF and solar wind parameters (the velocity and density), along with the Dst index (last row). We used the Geocentric Solar Magnetospheric (GSM) – coordinate system where the X axis is aligned with the Earth-Sun line, the Z axis is the projection of the Earth's magnetic dipole axis (positive North) on to the plane perpendicular to the X axis and Y axis supplements the right three, towards the dusk. Except for the Dst, all variables are plotted using high resolution data – 1 minute cadence – in black, and one hour resolution data – in red. The main phase of the geomagnetic storm is marked by vertical dash-dotted lines and the ICME start and stop times are marked by vertical solid lines. Note that the geomagnetic storm's main phase starts slightly after the shock was registered by ACE. The time of the flare start is shown by a vertical dashed line. It is clear from this graphic that the main phase of the storm basically coincides with the sheath of the ICME, i.e. with the region of high variation in all parameters (magnetic field intensity, solar wind speed and density). The total magnetic field shows an increase in the absolute value by a factor of seven compared to the pre-disturbed condition (in the low resolution data), and by a factor of almost ten in the high resolution data. This is related to the variations in its components namely a sudden increase in the B_x values during the first hours of the main phase, followed by a rapid decrease to negative values towards the end of the main phase, interrupted by a sudden jump back to positive values for about 30 minutes; the B_y component decreases from values around 0 nT to values around -30 nT in two steps sepa-

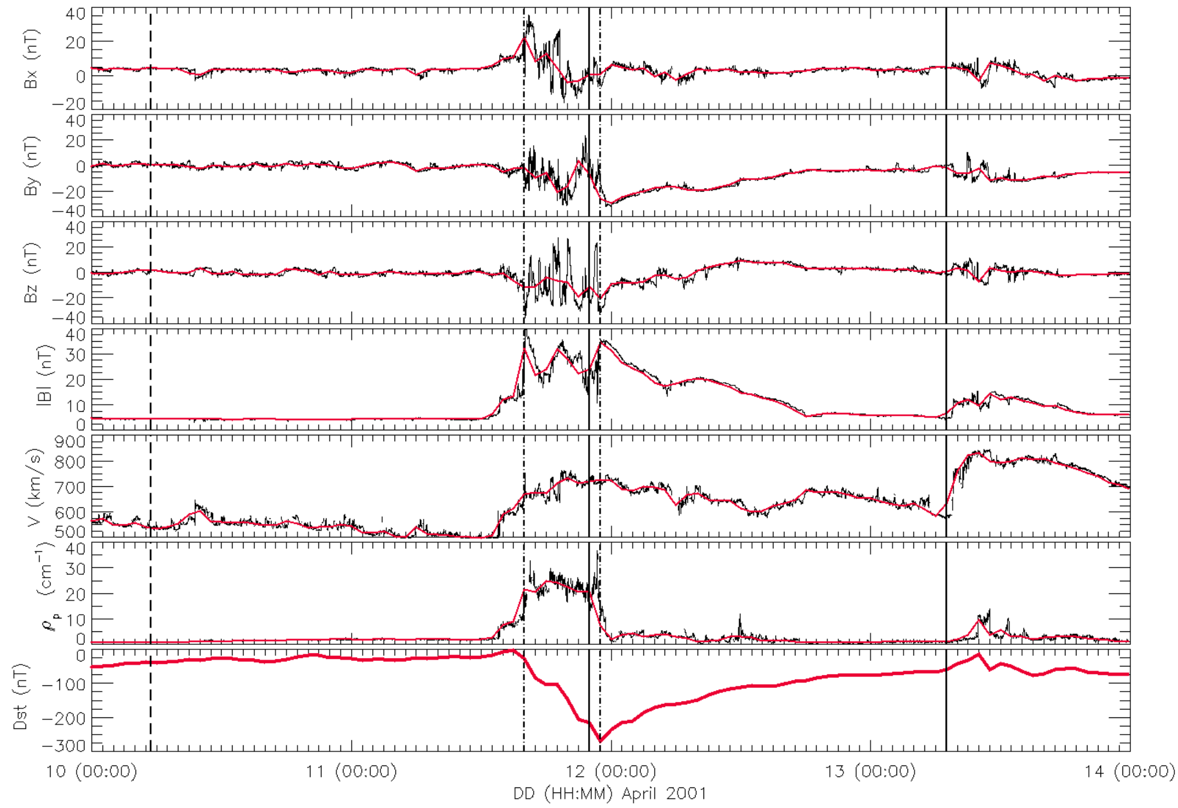

Figure 1: Various solar wind parameters during April 10-14, 2001. Vertical dashed line – start time of the solar flare; Vertical dash-dotted lines – geomagnetic storm main phase limits; Vertical solid lines – ICME start and end time.

rated by a large increase. The B_z component of the interplanetary magnetic field remains negative throughout the entire main phase in the low resolution data, with three different minimums. We can observe in the high resolution data of B_z that it has seven jumps to positive values during the main phase of the geomagnetic storm.

2.2 Geomagnetic Storm

We describe the geomagnetic storm by Dst evolution such as defined by Gonzalez et al. (1994) "an interval of time when a sufficiently intense and long-lasting interplanetary convection electric field leads … an intensified ring current strong enough to exceed some key threshold of the quantifying storm time Dst index". The storm comprises three phases – the initial, the main and the recovery phases. The initial phase can start with a sudden commencement for strong storms (such as our case) and lasts until Dst starts to continuously decrease. The period when Dst decreases is called the main phase. The recovery phase starts immediately after the minimum Dst value is reached.

The Dst index used in this paper is based on 1-minute cadence measurements taken from 4 low-latitude observatories, and given in OMNI data base as one value per hour (data used in this paper).

The geomagnetic storm produced by the April 10 full halo CME begun with a sudden commencement recorded at 13:43 UT on April 11 (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUDDEN_COMMENCEMENTS) marked by a sudden jump in the Dst time profile of around 20 nT.

This storm's main phase lasted seven hours (from 16:00 UT to 23:00 UT). The Dst temporal profile shows a small increase around 19:00 UT, and change in the decreasing slope towards its minimum value of -271 nT at 23:00 UT. In the high resolution B_z data we can observe that the Dst middle jump is related to the longest interval (around 20 minutes) of B_z positive values. The recovery phase lasts a bit more than a day and Dst reaches pre-storm values approximately in the same time as the magnitude of the interplanetary magnetic field (B) recovers back to its pre-disturbed values.

3. Method description and results

3.1 Probability of the April 10, 2001 CME to have triggered an intense geomagnetic storm

Srivastava (2005) used a logistic regression model to compute the probability of intense geomagnetic storms to be triggered by CMEs. We applied this model, with different sets of independent variables, to our event. Srivastava's independent variables were: halo-bin, flare-bin, location-bin, initial speed of the CME, total value of the IMF, southward component of the IMF (B_z), ram pressure. Our set of variables are: CME projected speed, acceleration, neutral line orientation, flare importance, position (heliographic latitude and longitude), magnetic classification of AR, average interplanetary magnetic field and the B_z component of

Table 1: List of the events used in the regression model. In bold are shown the events used for validation.

CME	ICME - start	ICME - stop	GS (Dst min)	Results
May 02, 1998 14:06	May 04, 1998 10:00	May 07, 1998 23:00	May 04, 1998 05:00, -205	1.0000
Sep 20, 1999 06:06	**Sep 22, 1999 19:00**	**Sep 24, 1999 03:00**	**Sep 22, 1999 23:00, -173**	**1.0000**
Oct 18, 1999 00:06	Oct 21, 1999 08:00	Oct 22, 1999 07:00	Oct 22, 1999 06:00, -237	1.0000
Apr 04, 2000 16:32	Apr 07, 2000 06:00	Apr 08, 2000 06:00	Apr 07, 2000 00:00, -288	1.0000
Jul 14, 2000 10:54	Jul 15, 2000 19:00	Jul 17, 2000 08:00	Jul 16, 2000 00:00, -301	1.0000
Aug 08, 2000 16:30	Aug 12, 2000 05:00	Aug 13, 2000 22:00	Aug 12, 2000 09:00, -235	1.0000
Sep 16, 2000 05:18	Sep 17, 2000 21:00	Sep 21, 2000 00:00	Sep 17, 2000 23:00, -201	1.0000
Oct 02, 2000 03:50	Oct 05, 2000 13:00	Oct 07, 2000 11:00	Oct 05, 2000 17:00, -182	1.0000
Nov 03, 2000 18:26	Nov 06, 2000 17:00	Nov 08, 2000 03:00	Nov 06, 2000 21:00, -159	1.0000
Mar 29, 2001 10:26	Mar 31, 2000 05:00	Mar 31, 2000 22:00	Mar 31, 2000 08:00, -387	1.00000
Apr 10, 2001 05:30	**Apr 11, 2001 22:00**	**Apr 13, 2001 07:00**	**Apr 11, 2001 23:00, -271**	**0.9992**
Sep 29, 2001 11:54	Oct 02, 2001 14:00	Oct 03, 2001 16:00	Oct 03, 2001 14:00, -166	1.0000
Nov 19, 2001 16:50	Nov 21, 2001 20:00	Nov 25, 2001 10:00	Nov 21, 2001 21:00, -187	1.0000
Nov 25, 2001 15:26	Nov 29, 2001 22:00	Nov 31, 2001 13:00	Nov 28, 2001 11:00, -157	0.9999
Nov 04, 2001 16:35	Nov 06, 2001 12:00	Nov 09, 2001 03:00	Nov 06, 2001 06:00, -292	0.9999
Nov 22, 2001 23:30	Nov 24, 2001 14:00	Nov 25, 2001 20:00	Nov 24, 2001 16:00, -221	1.0000
Sep 05, 2002 16:54	Sep 08, 2002 04:00	Sep 08, 2002 20:00	Sep 08, 2002 00:00, -181	1.0000
Oct 28, 2003 11:30	Oct 29, 2001 11:00	Oct 30, 2003 03:00	Oct 30, 2003 00:00, -353	0.9999
Oct 29, 2003 20:54	Oct 31, 2003 02:00	Nov 02, 2003 00:00	Oct 30, 2003 22:00, -383	0.9999
Nov 18, 2003 08:50	Nov 20, 2003 10:00	Nov 21, 2003 08:00	Nov 20, 2003 20:00, -422	1.0000
Jul 25, 2004 14:54	**Jul 27, 2004 02:00**	**Jul 27, 2003 22:00**	**Jul 27, 2003 13:00, -197**	**1.0000**
Nov 04, 2004 23:30	Nov 07, 2004 22:00	Nov 09, 2004 10:00	Nov 08, 2004 06:00, -373	1.0000
Nov 07, 2004 16:54	Nov 09, 2004 20:00	Nov 11, 2004 23:00	Nov 10, 2004 09:00, -289	0.9999
May 13, 2005 17:12	May 15, 2005 06:00	May 19, 2005 00:00	May 15, 2005 08:00, -263	1.0000
Aug 22, 2005 01:31	**Aug 24, 2005 00:00**	**Aug 24, 2005 11:00**	**Aug 24, 2005 11:00, -216**	**1.0000**

Table 2: Logistic regression coefficients and their corresponding variables values for the April 10-11, 2001 event

	Regression Coefficient Value	Variables Value
(b_0)	-5.4547	-
CME Proj Speed (b_1)	0.0315	**2876**
CME Acceleration (b_2)	-0.1789	**211.6**
Neutral Line Orientation (b_3)	-11.2480	**4**
Flare importance (b_4)	0.0371	**4.5 · 2.3**
Position (latitude) (b_5)	0.4963	**-22**
Position (longitude) (b_6)	-0.8004	**20**
magnetic classification of AR (b_7)	-0.3025	**7**
B (b_8)	2.5140	**13.7**
Bz (b_9)	0.5499	**-20.5**

the interplanetary magnetic field, and one dependent variable, the Dst index. The choice of the variables is justified by the previous works. Cane et al. (2000) stated that the southward magnetic field component embedded in the ICME is the most important factor in the relationship between CMEs and geomagnetic storms. Wu and Lundstedt (1997) stated that two basic combinations of solar wind parameters would give accurate predictions of geomagnetic storms: (B_s, n, V) and (B_z, n, V) (**B_s** = $|B_z|$ for $B_z < 0$ and **B_s** = 0 for $B_z > 0$). Our parameters include these considerations.

The formula introduced by Srivastava (2005) is

$$\Pi_i = \frac{1}{1+e^{-Z_i}} \quad \text{with } Z_i = b_0 + b_1 \times x_{i1} + ... + b_j \times x_{ij} \quad (1)$$

where Π_i is the probability of the occurrence of intense geomagnetic storm given by the i-th observation of the solar variable (in our case we used 25 observations of intense geomagnetic storms), b_j are the model parameters, to be derived (known as regression coefficients)– there are 9 values in our case (corresponding to the independent variables listed above); x_{ij} (with i=0 to I and j=0 to J, I being 25 and J being 9 in our model) are the independent variables that we listed above. The regression coefficients are estimated through an iterative method. Z is estimated as a natural logarithm of the odds of the occurrence of an intense geomagnetic storm.

To determine the regression coefficients and from here the probability of the occurrence of intense storm, we used a set of 25 ICMEs which produced intense geomagnetic storms (Dst < -150 nT) in solar cycle 23. We have trained the logistic model with 21 events, and used the remaining four for validation. The list of the events used in this model is shown in Table 1. The four events used in validation are shown in bold. Column 1 lists the time when the CME was first observed in LASCO (as taken from the CME catalogue), column 2 and 3: start and end of the ICME, as taken from the Richardson and Cane catalogue. Note that the catalogue shows the beginning of the ejecta as we defined it in this paper, and not the beginning of the shock. Column 4: time of the minimum value of the Dst index, together with the value of the Dst index. Column 5: the probability that the CME produced an intense geomagnetic storm.

The coefficients obtained running the regression model are shown in Table 2. We chose the neutral line orientation (b_3) to be a number describing the possible orientations (NS – 1, NE-SW – 2, EW – 3, NW-SE – 4). We defined the flare importance (b_4) a factor scaling the classification of the X-ray solar flare associated with the CME. Each class (B, C, M, X) was dived into two resulting nine factors that were multiplied with the strength of the flare (for example in our case the flare importance for the X2.3 event was 4.5 · 2.3). We chose the magnetic classification (b_7) of the active region (AR) as a number where lowest value – 1 – was associated to alpha-type ARs and 8 with gamma-delta configuration. All other coefficients being the parameters specified in the first column.

By applying the regression model explained above, we obtained a 100% probability that April 10, 2001 halo CME should have triggered an intense geomagnetic storm.

3.2 Energy transfer from the solar wind into the magnetosphere

Using the parameter introduced by Akasofu (1981) we computed the energy transferred from the solar wind into the magnetosphere during the geomagnetic storm of April 11, 2001.

From the Akasofu parameter

$$\varepsilon = 10^7 \, V \, B^2 \, l_0^2 \, \sin^4(\theta/2) \ \text{(J/s)} \qquad (2)$$

we calculated this energy as $W_\varepsilon = \int_{t0}^{tf} \varepsilon dt$ (J), where tf to t_0 is the time interval of the geomagnetic storm main phase. The variables in the ε formula are V – the solar wind velocity (m/s), B – the intensity of the interplanetary magnetic field (T), l_0 – a constant equal to 7 Earth radii (RE) (m), and θ – the angle between the two components of the interplanetary magnetic field – B_y and B_z. The factor l_0 was empirically determined and represents the "effective cross-sectional area" (Akasofu, 1981) of the solar wind-magnetosphere interaction and was added to fit the energy input to the total estimated output. Some authors argue that this factor is rather low (Lu et al., 1998; Knipp et al., 1998; Koskinen and Tanskanen, 2002; Østgaard and Tanskanen, 2003; Tanskanen et al., 2002) because this scaling factor (l_0) was computed assuming that the energy input equals the estimated energy dissipation (the joule heating and auroral precipitation in the ionosphere) and the ring current dissipation. In this study, we chose the initial value of $l_0=7R_E$ of the parameter.

Using the function obtained by Wang et al. (2014)

$$E_{IN} = 3.78 \times 10^7 \, n_{SW}^{0.24} \, V_{SW}^{1.47} \, B_T^{0.86} \, (\sin^{2.7}(\theta/2) + 0.25) \ [\text{J/s}] \quad (3)$$

we also calculated the energy $W_{E_{IN}} = \int_{t0}^{tf} E_{IN} dt$ (J). In this formula the variables are the same as for formula (3), except for the n_{sw} – the density of the solar wind and $B_T = (B_y^2+B_z^2)^{1/2}$ – the transversal interplanetary magnetic field used instead of B. In this formula the scaling factor is computed such that the parameter units no longer need transformations from their OMNI units to international system of units when computing the numerical values.

Figure 2 shows the temporal profiles obtained using formulas (2) and (3) defined here. In black are shown the values obtained by using the high resolution data and in red the values derived by using the low resolution data. The two vertical lines (dash-dotted) show the duration of the storm's main phase. The third and fourth row show two parameters commonly used in the literature to estimate the energy transferred from the solar wind into the magnetosphere, namely PC (polar cap index) and Ey (y-component of the interplanetary electric field). They were both downloaded from the OMNI database. For an easy comparison we plotted on the last row the Dst profile.

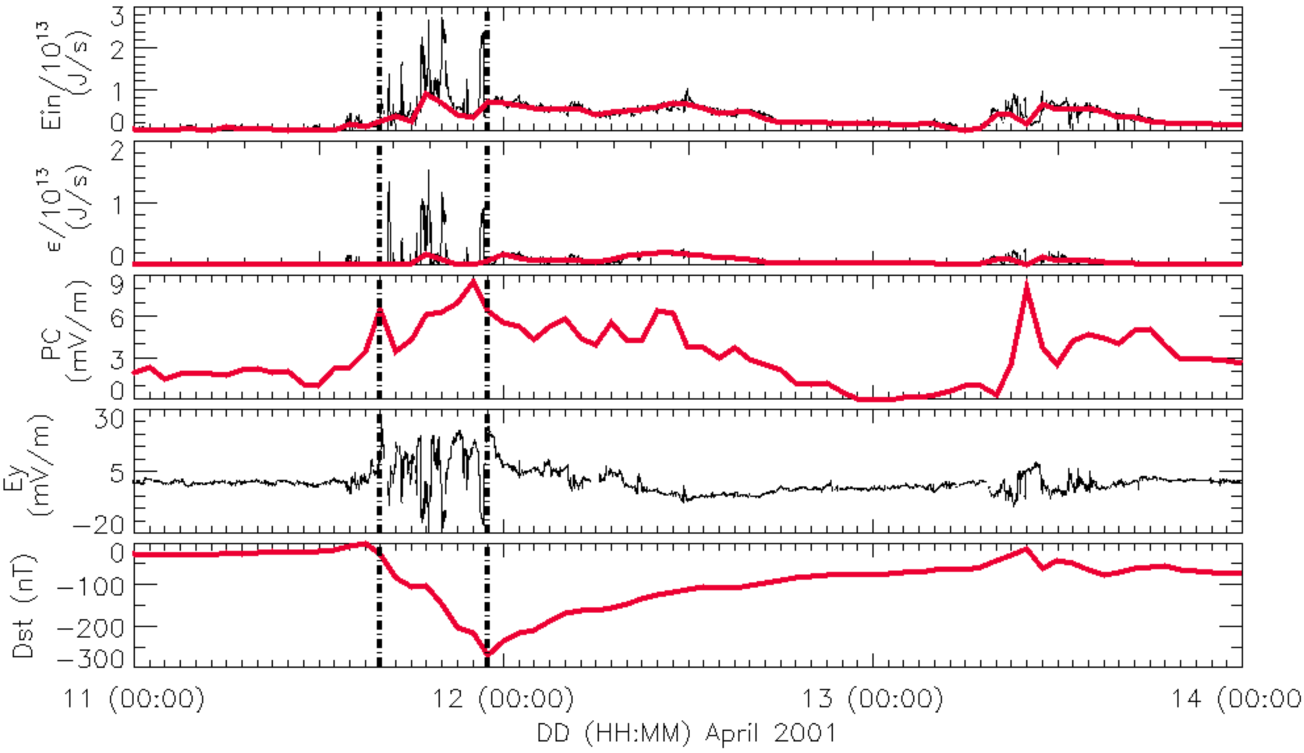

Figure 2: Temporal profiles of ε and EIN during April 11 – 13, 2001 (black lines results using high resolution data; red lines results using low resolution data). For comparison, PC, Ey and Dst profiles taken from OMNI data. Date format in this figure is day (hour:min.).

Even though the high resolution data (when available) show higher variability during the main phase of the geomagnetic storm, it is clear that the energy is transferred not only during this phase, but much longer (almost 24 hours of continuous energy input, energy that has values about four to six times the non-storm ones). During the main phase of the storm we observe the highest values of the energy injected per second (in the ε and E_{IN} evolution). The epsilon parameter has another peak comparable as magnitude with the one during the main phase, that coincides with the last minimum B_z value from the high resolution data (00:00 on April 12, 2001 – one hour after the end of the storm's main phase). As general profiles ε and E_{IN} are similar, but differ in magnitude. The difference in magnitude comes from the different evaluation method of the scaling factor. This is in accordance with remarks made by authors such as Palmroth et al. (2003) or Koskinen and Tanskanen (2002) that the scaling factor should include plasma sheet heating and the energy carried by the plasmoids in the magnetotail.

On the third row of Figure 2 we plotted the PC index (Troshichev and Andrezen, 1985) as a reliable proxy for characterising the solar wind energy that entered the magnetosphere (Troshichev et al., 2011). PC also shows energy being transferred for about the same period as ε and E_{IN}. Troshichev et al. (2011) suggested PC = 2 mV/m as a threshold for the solar wind energy input. As clearly seen in Figure 2 (third row) this limit is valid from April 11, 2001, 13:00 UT until April 12, 2001, 18:00 UT. This interval is consistent with the interval of excess energy deposition as calculated by the two formulas used in this study.

In the fourth row of Figure 2 we plotted the interplanetary E_y calculated by OMNI as $E_y = -V_x \cdot B_z$. The E_y's significant variations limit to the main phase duration of the storm.

Gosling et al. (1990) as well as Khotyaintsev et al. (2004) found proof of reconnections happening during strong (negative) B_y. For the analysed storm, B_y has a second minimum, the lowest minimum during the entire storm, just after the moment the minimum Dst value is reached (Figure 1, second row). This could explain the second major peak in ε and E_{IN} that is visible in Figure 2.

Therefore, using the "classical" consideration that the energy is input into the magnetosphere during the main phase of the storm (Akasofu, 1981), which in our case lasts for seven hours (the interval marked by dash-dotted vertical lines in Figures 1 and 2), we obtained the total input energy during this time: $W(\varepsilon) = 1.35 \times 10^{17}$ (J) and $W(E_{IN}) = 1.33 \times 10^{18}$ (J). $W(E_{IN})$ is one order of magnitude larger than $W(\varepsilon)$. This is a larger discrepancy as compared to the results obtained by Wang et al. (2014) – where the difference was by a factor of 2 only.

Integrating over the entire period in which both ε and E_{IN} show a significant increase as compared to a background level – in this case from April 11 at 13:00 UT to April 12 at 18:00 UT – we obtained $W(\varepsilon) = 2.88 \times 10^{18}$ (J) and $W(E_{IN}) = 1.48 \times 10^{19}$ (J).

However, we should acknowledge that none of these methods is testified to have correctly estimated the total quantity of energy transferred from the solar wind into the magnetosphere. We only use them (as well as any other coupling formula) to make estimations of the amount of energy which would have been transferred during the storm. A better understanding of all the processes involved will improve these estimations.

Therefore the errors that the formulas imply may be qualitative (physical processes not considered) or quantitative (up to 4% depending of the OMNI database quality data).

4. Summary and Discussion

We presented the characteristics of the geo-effective CME driven by a solar flare on April 10. The CME arrived to Earth where it induced an increase in the ring current, associated with a minimum Dst value of -271 nT reached almost 34 hours later. By applying a logistic regression based model we obtained a 100% probability that the April 10, 2001 CME should be geoeffective. We analysed the evolution of the geomagnetic storm and we estimated the amount of energy deposited into the magnetosphere during this storm.

One of the most important remarks of this work is that the energy transferred into the magnetosphere does not resume to the main phase of the geomagnetic storm. This may be related to the different definition of some geomagnetic storms as stated by Troshichev et al. (2011). They consider the main phase to start at the sudden commencement and ends after the minimum Dst value is reached, including a damping phase of several hours (the damping phase would be previously be considered as part of the recovery phase).

Palmroth et al. (2003) have studied the energy transfer in MHD simulation. Their results show that the total energy flux through the surface has values exceeding the pre-storm ones over a period longer than the geomagnetic storm's main phase, namely energy being transferred during the recovery phase.

We also observed that the two formulas used to calculate this energy transfer have similar temporal profiles, but one order of magnitude difference in intensity, confirming observations made by authors cited here. Part of the energy is transferred even while B_Z is positive (short intervals of 3 to 18 minutes) suggesting other possible locations for the transfer (polar cusps, magnetosphere tail) or other mechanisms different than magnetic reconnection.

In a future work we are aiming in including estimations of how each parameter variation (included in the coupling formulas) is affecting the energy transfer from the solar wind into the magnetosphere, by applying it to a bigger data set.

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