ANALYSIS OF TWO SUCCESSIVE CMES HITTING THE EARTH IN AUGUST 2000

OANA STERE, GEFRY BARAD, LILIANA DUMITRU

Astronomical Institute of Romanian Academy
Str. Cutitul de Argint 5,
040557 Bucharest, Romania
Email: stereoana@yahoo.com

Abstract. The studied event is that of the geomagnetic storm on 12 August 2000, produced by two coronal mass ejections (CMEs) coming from the Sun. The first coronal mass ejection was a partial halo type (PH) observed on 8 August 2000. The second coronal mass ejection was a full halo (FH) observed on 9 August 2000, the source being connected with a solar eruption. In order to find the real speed of propagation of these two CMEs, we have used the sphere model which assumes that a CME is a sphere which expands self-similar in the interplanetary space. The model takes into account as input data the source location, the projection speed on the sky plane and the expansion rate from the image analysis recorded by SOHO/LASCO C2 instrument. Thus we shall estimate the arrival time at the ACE space mission and we can delineate the boundaries of the interplanetary event (front shock, plasma density and back shock). The minimum variance analysis (MVA) shows that it is possible to have multiple magnetic clouds or fragmented structures. This statistical method was performed using 16-sec averages magnetic field data registered by ACE satellite. The coherent rotation of the structure revealed the specific features of magnetic clouds. Finally, we have identified and analysed the solar source of the flare, an active region.

Key words: solar weather – solar-terrestrial relations – coronal mass ejections – flares – interplanetary magnetic fields.

1. INTRODUCTION

Coronal mass ejections (CMEs) are massive expulsions of solar plasma into the interplanetary space. These active phenomena which occur at the surface of solar disk influence the whole dynamic of the heliosphere, and thus, the Earth's magnetosphere. One of the direct effects of interaction with the high atmosphere of our planet could be the generation of geomagnetic storms with an impact on the Earth's atmosphere and surface layers. The geoeffectivity of the CME can have devastating consequences of technology, and of terrestrial life. In the present study, we aimed relationship between these active solar phenomena, their propagation into the interplanetary space (ICME, Interplanetary Coronal Mass Ejection) and the effect on Earth - producing geomagnetic storm, in the opposite direction of their occurrence. We chose this geomagnetic storm due to its peculiarity, namely the two negative peaks of the disturbing storm time (Dst) index (Dst = -235 nT recorded on 12 August, Dst = -106 nT, respectively on 11 August 2000). We believe that there is one geomagnetic storm in steps or, more likely, two consecutive storms, considering the time interval between the two minimum values of Dst. Based on these data, we could identify specific parameters of corresponding ICME (11 August 2000), identifying it as a magnetic cloud (MC), calculating its propagation direction with minimum variance method analysis (MVA) and the detection of the eruptive event at the surface of the Sun and its source. To calculate the propagation velocity of CME, we have used the method of Srivastava *et al.* (2009). The events studied belong to the solar cycle 23, namely from 9 to 12 August 2000.

2. DATA DESCRIPTION

The events were selecting using the following links:

- `http://cdaw.gsfc.nasa.gov/CME_list/` – to identify the halo CMEs and to get their projected speeds
- `http://lasco-www.nrl.navy.mil/daily_mpg/` – to identify the CME source region
- `http://www.solarmonitor.org/` – to get the location of the source region (longitude, latitude)
- `http://omniweb.gsfc.nasa.gov/form/dx1.html` – to find the CME signatures into the interplanetary space
- `http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm` – to compare them with the list of Richardson and Cane
- `http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_MAG.html` – to find the interplanetary magnetic field values
- `http://wdc.kugi.kyoto-u.ac.jp/dstdir/` – for geomagnetic index Dst

  The data were taken from instruments onboard SOHO and ACE. For geomagnetic storms signatures (Dst index) we use various terrestrial geomagnetic stations, whose data are available also at OMNIWeb site.

3. THE GEOMAGNETIC SIGNATURE

A geomagnetic storm is characterized by decreasing geomagnetic Dst index, which gives an assessment of the total energy content of the particles forming the ring current. Depending on the value of Dst index, geomagnetic storms are classified into four categories (Gonzalez *et al.*, 1994). According to them, the storm from 12 August 2000 is an intense geomagnetic storm (Fig.1):

Fig. 1 – The geomagnetic storm on May 11 and 12 August 2000 revealed by the Dst index values (source: http://wdc.kugi.kyoto-u.ac.jp/).

It is seen from the Fig.1 that there are two minimum values of Dst index (Dst = -235 nT recorded on 12 August, at 09:00 UT, Dst = -106 nT respectively on 11 August 2000, at 06:00 UT), at an interval of 27 hours. This may indicate that there were two consecutive interplanetary events, possibility that we will further study.

We have identified the associated interplanetary coronal mass ejection (ICME) using as source the table `http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm/`. In Fig.2 there are displayed its main characteristics: the proton temperature (K) rated to the expected temperature, the plasma beta, the magnetic field components in the RTN system, the proton density and speed. We have identified the ICME boundaries, expressed in day of the year (DOY) as follows: t1=224.75, t2=225.20, t3=226.10, t4=226.30.

As the following are observed: high intensity of the magnetic field, low proton temperature, plasma β (plasma beta represents the ratio of plasma to magnetic pressure) subunit, we see that the characteristics of a magnetic cloud (MC) are met. According to Gosling (2000) and Mulligan, Russell, and Luhmann (2000), magnetic clouds are manifestations of interplanetary coronal mass ejections, where a continuous rotation of the magnetic field has been observed, this one being a characteristic of a helical structure (flux rope).

The cylindrical structure increases its size with variable acceleration from the moment it leaves the solar surface. A spaceship takes more than six hours to cross

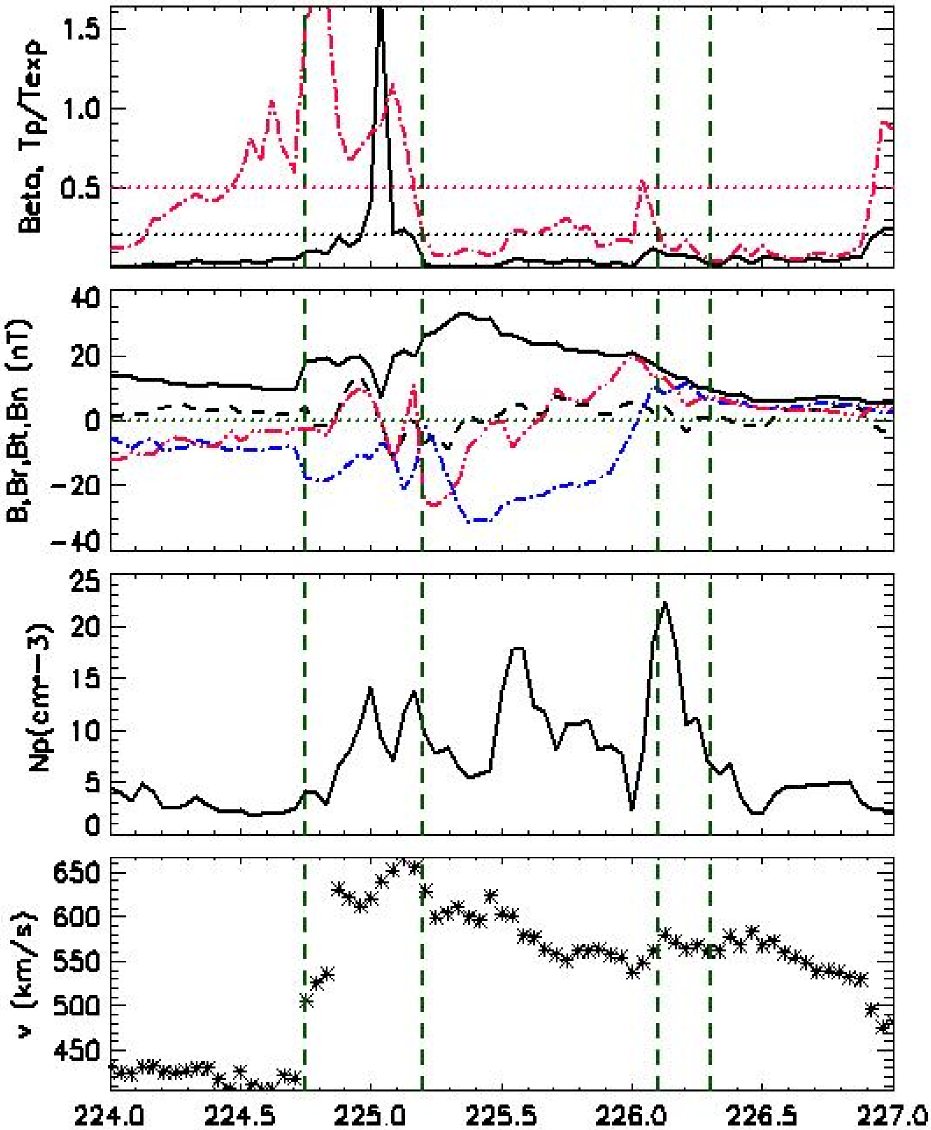

Fig. 2 – ICME registered at ACE on 11.08.2000 (day of year DOY=223). From top: First panel: proton beta (thick line), Tp/T_{exp} (dash-dotted line); Second panel: magnetic field components and magnitude: B (thick line), Br (dashed line), Bt (lower dash-dotted line), Bn (dash-dotted line); Third panel: proton density; Fourth panel: plasma speed. The vertical lines denote the ICME boundaries at t1=224.75, t2=225.20, t3=226.10, t4=226.30.

this magnetic structure (Burlaga, Hundhausen, and Zhao, 1981; Klein and Burlaga, 1982; Bothmer and Schwenn, 1998).

4. MINIMUM VARIANCE ANALYSIS OF THE MC ON 11 AUGUST 2000

Minimum variance analysis (MVA) was used for the first time by Sonnerup and Cahill (1967) to identify and describe rotational configurations of the magnetic field in the solar wind and magnetopause. This statistical method is used to approximate the true orientation of the magnetic clouds after their rotation at the satellite encounter. In several articles (Burlaga, Lepping, and Jones, 1990; Vandas, Fischer, and Geranios, 1999; Osherovich *et al.*, 2002), it was observed that the magnetic field describes a half-circle in the maximum variance plane. In most cases (magnetic clouds from 1967-1978), the axis of the cloud is the intermediate variance direction (Sonnerup and Scheible, 1998).

Our analyzed magnetic cloud satisfies this general property. A particular feature of this cloud is that it is likely to contain several substructures, or it is composed by two flux ropes of different origins or his initial flux rope structure is fragmented into multiple ones. For our study, we have performed the MVA for the 4862 points of normalized, 16-sec averages, magnetic field data registered by ACE satellite (Fig.3), *i.e.* between the t2 and t3 MC boundaries.

The solution of the equation: :

$$H = \frac{2\pi R^2 B_0^2}{\alpha}\left[J_0(\alpha R)^2 + \alpha R J_1(\alpha R)^2 - \frac{2J_0\alpha R}{\alpha R}J_1\alpha R\right] \quad (1)$$

for a cylindrically symmetric force-free field with constant was given by Lundquist (1950). Thus, the three components of the magnetic field modelled after Lundquist solution are as follows: $B_R = 0,\ B_\theta = HB_0J_1(\alpha R),\ B_z = B_0J_0(\alpha R)$, where R = the distance to the cloud's axis, (R, θ, Z) = the cylindrical coordinates, B_0 = the axial field value, J_0 and J_1 = the zeroth and first order Bessel functions, α = const. H stands for helicity and it can be plus or minus one.

Fig. 3 displays the results of the MVA analysis, performed for the interval between t2 and t3, that corresponds to 4862 data points, starting with the moment 06:00 UT, on 12 August 2000 (1 hour has 225 points on the x-axis). As results of the MVA, we obtained the following eigenvalues for the direction of maximum variance, intermediate variance and minimum variance, respectively: $\lambda_1 = 0.013493$, $\lambda_2 = 0.006613$, $\lambda_3 = 0.000957$.

The variance directions are well determined because the ratio between the eigenvalues for the intermediate and minimum variances is 4.46, the criterion of $\lambda_2/\lambda_3 > 2$ being fulfilled (Bothmer and Schwenn, 1998). Written as columns, the three eigenvectors $\mathbf{e_1}$, $\mathbf{e_2}$, $\mathbf{e_3}$, of the direction of maximum variance, intermediate variance and minimum variance, respectively, are presented in Table 1.

The elevation angle and azimuthal angle are: $\phi = [19.5, -80.5, 0]$ and $\theta = [14.8, -85.1, 90]$.

Table 1

The eigenvectors (columns) of magnetic cloud position

$\mathbf{e_1}$	$\mathbf{e_2}$	$\mathbf{e_3}$
0.254823	0.94542	0.203093
−0.00179	0.210487	−0.9776
−0.96699	0.248751	0.055327

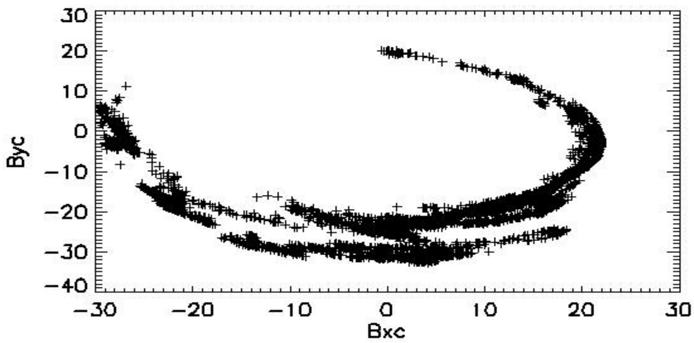

Fig. 3 – The hodogram of the magnetic field components (Br, Bt, Bn) in the maximum-intermediate variance plane.

The data set represents rotational profile of a negative helicity (left-handed).

The hodogram of the magnetic field components in the maximum-intermediate variance plane, as presented in Fig.3, reveals that the MC displays a negative helicity and it is of South-East-North type (Bothmer and Schwenn, 1998).

5. THE CME PROPAGATION TO EARTH AND THE TIME ESTIMATION

Generally, the speeds we measure on LASCO images are projected speeds (V_{proj}). From one view direction only, it is difficult to infer the real speeds, unless some assumptions are employed. In this study we assume that the CME is a sphere which propagates self-similar into the interplanetary space, as in the model described by Srivastava *et al.* (2009). The speed towards the observer (V_{tt}) is derived from the equations (Mierla *et al.* , 2012):

$$V_{\mathrm{tt}} = \left[V_{\mathrm{cent}} \cos\alpha + \sqrt{V_{\mathrm{exp}}^2 - V_{\mathrm{cent}}^2 \sin\alpha}\right] \cos\beta \quad (2)$$

$$V_{\mathrm{proj}} \cos\beta = V_{\mathrm{cent}} \sin\alpha + V_{\mathrm{exp}} \quad (3)$$

We couldn't find the actual speed of the first CME from our study using the sphere model of a CME, since we have obtained non-real value.

For the second CME we could not use the sphere model in order to find the true speed of propagation of the CME, because the source is unknown. In a previous study Srivastava *et al.* (2009) has shown that this model gave solutions only for the CMEs with symmetry brightness. Our event shows asymmetry brightness.

If we calculate a simple linear propagation of the two CMEs, we obtain the arrival times ta1=223.64 and ta2=225.14. The second CME has an arrival time very closed to the MC's starting boundary, *i.e.* t2=225.20. Between t1 and t2 it is the MC forward shock, while the t3 and t4 is the reverse shock. The first CME, that actually was a partial halo, seems to hit tangentially the Earth.

6. THE SOLAR SIGNATURE

6.1. CMES IDENTIFICATION

Through fixed time window technique we search the eruptive events for 30-120 h in the past. We took into account two possible CMEs events:

- The first CME was recorded on 9 August 2000 at 16:30 UT, with the speed value V_{proj}= 731 km s^{-1}. It was a full halo type CME associated with a C2.3 class flare (recorded at 15:19 UT). The corresponding solar source was the active region AR 09114 (N11;W15).

- The second CME was recorded on 08 August 2000 at 15:54 UT, being a partial halo type with a C2 class flare associated and the source unknown. The recorded speed value was V_{proj}= 733 km s^{-1}.

We have focused on the magnetic field twist in the active region NOAA09114, as derived from the non-linear force-free field extrapolations.

A dipole magnetic field is defined in the 3D, x, y, z Cartesian coordinates, as:

$$\mathbf{B}_x = B_0\left(\frac{3xz}{r^5}\right) \tag{4}$$

$$\mathbf{B}_y = B_0\left(\frac{3yz}{r^5}\right) \tag{5}$$

$$\mathbf{B}_z = -B_0\left[\frac{\left(1-3z^2/r^2\right)}{r^3}\right] \tag{6}$$

where $r=\sqrt{(x^2+y^2+z^2)}$ and B_0 is the strength of the magnetic field.

Using this dipole model, we have extrapolated the coronal magnetic field from the photospheric magnetic field measured by SOHO/MDI instrument, by a technique described by Lee (2002). We have performed computations at three moments near the flare occurrence time and we the estimated the force free field parameter α.

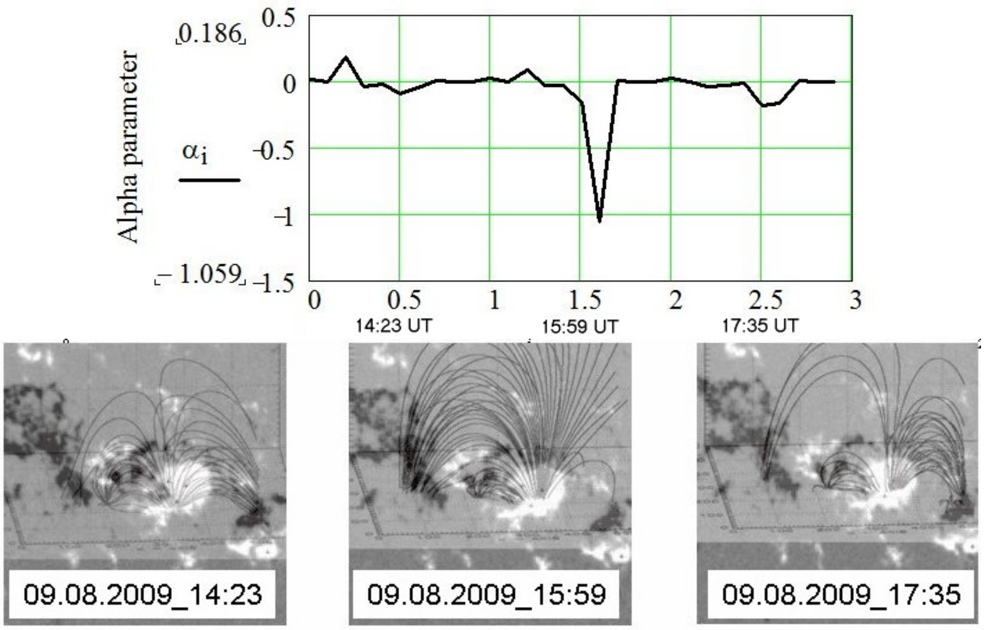

Fig. 4 – Top: Results of alpha force-free field parameter computations for 9 August 2000 at the moments 14:23 UT, 15:59 UT and 17:35 UT. Bottom: The coronal magnetic field extrapolation using the MDI data at the same moments, ı.e before, during and after the flare occurrence.

The results are displayed in Fig.4. The top image shows the force-free field parameter at 14:23 UT, 15:59 UT and 17:35 UT. We observe a negative peak at the 15:59 UT, corresponding to the magnetic field lines opening during the flare, as displayed in the bottom image. The bottom image in Fig.4 presents the 3D coronal magnetic field extrapolation, superposed on the MDI magnetograms.

7. SUMMARY

In this paper we studied the geomagnetic storm developed on 12 August 2000, that displayed two minimum negative values in a time interval of 27 hours. We considered that there are two geomagnetic storms after we have analyzed the associated interplanetary and solar associated events.

We have found two ICMEs events registered by ACE spacecraft, one of them being a magnetic cloud. We have performed an MVA for 4862 data and proved that it is a MC. We found that the MC has a negative helicity and it is of South-East-North type (the magnetic field that moves from south to north passing through east). As the source of the CME we found the AR 09114 with the flare class C2 at 15:19 UT and we highlighted the magnetic reconnection of this active region, a condition in the occurrence of eruptive phenomena. A negative peak is also displayed by the force-free field parameter α, as calculated from non-linear magnetic field extrapolations of the 3D magnetic field components of the solar source (the active region NOAA09114, at the moment of the field lines opening at the solar flare occurrence (the source of the CME). We applied the sphere model of a CME in order to obtain the real propagation speed of the CME recorded on 9 August 2000, but we didn't find any solution. A possible answer could be the asymmetry brightness of the studied CME.

Acknowledgements. This paper was presented at the International Symposium "The Astronomer Nicolae Donici – 140 years after the birth", Bucharest , 8th September 2014.

REFERENCES

Bothmer, V. and Schwenn, R.: 1998, *Annales Geophysicae* **16**, 1.
Burlaga, L.F., Hundhausen, A.J., and Zhao, X.-P.: 1981, *J. Geophys. Res.* **86**, 8893.
Burlaga, L.F., Lepping, R.P., and Jones, J.A.: 1990, *Washington DC American Geophysical Union Geophysical Monograph Series* **58**, 373.
Gonzalez, W.D., Joselyn, J.A., Kamide, Y., Kroehl, H.W., Rostoker, G., Tsurutani, B.T., and Vasyliunas, V.M.: 1994, *Journal of Geophysical Research* **99**, 5771.
Gosling, J.T.: 2000, *26th International Cosmic Ray Conference, ICRC XXVI* **516**, 59.
Klein, L.W. and Burlaga, L.F.: 1982, *J. Geophys. Res.* **87**, 613.
Lee, J.K.: 2002, *Coronal Loop Identification*, Master Thesis, University of Alabama in Huntsville.
Lundquist, S.: 2012, *Ark. Fys.* **2**, 361.
Mierla, M., Besliu-Ionescu, D., Chiricuta, O., Maris, G.: 2012, *Sun and Geosphere* **7**(1), 13.
Mulligan, T., Russell, C.T., and Luhmann, J.G.: 2000, *Advances in Space Research* **26**, 801.
Osherovich, V.A., Fainberg, J., Vinas, A.F., Fitzenreiter, R.: 2002, *AGU Spring Meeting Abstracts*, 1.
Sonnerup, B.U.O. and Cahill, L.J., Jr.: 1967, *Journal of Geophysical Research* **72**, 171.
Sonnerup, B.U.Ö. and Scheible, M.: 1998, *ISSI Scientific Reports Series* **1**, 185.
Srivastava, N., Inhester, B., Mierla, M., and Podlipnik, B.: 2009, *Solar Phys.* **259**, 213.
Stere, O. , Oprea, C., Maris-Muntean, G., Mierla, M., Besliu-Ionescu, D.: 2012, *Ninth European Space Weather Week* Conference.
Vandas, M., Fischer, S., and Geranios, A.: 1999, *AIP Conference Series* **471**, 127.

Received on 12 September 2015