Interplanetary Aspects of the Sun-Earth Connection Events on April 1999 and February 2000

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Abstract. *There are basically two types of interplanetary ejecta: magnetic clouds (MC) and complex ejecta (CE). In this work we analyze the geoeffectiveness and the interplanetary aspects of a MC (April 1999, Dst peak = -91 nT) and a CE (February 2000, Dst peak = -133 nT). Interplanetary propagation conditions, shock strength, ICME axis orientations, and magnetic field strengths, as well as the total energy transferred by the interplanetary structures to the Earth's magnetosphere are described and compared. The magnetic storm profiles are different: smooth and one step for the April 1999 event and complex, with two steps, for the February 2000 event. The energy injection into the magnetosphere is also of different nature for these events, with higher power and lower integrated values for the February 2000 as compared to the April 1999 event. These results reflect the B_z profiles, being smooth in the MC and irregular/fluctuating during the CE.*

Keywords: Sun-Earth interaction; geomagnetic indices; magnetic storms; solar wind.
PACS: 94.30.-d**;** 94.30.Lr; 96.25.Qr.

INTRODUCTION

Solar wind plasma and magnetic field observations are by now routinely used for identification of material in the interplanetary medium that could be the interplanetary counterparts of coronal mass ejections (CMEs) at the Sun. Virtually all geomagnetic storms are caused by CMEs or high speed solar wind streams. We can assume that, in general, there are two classes of interplanetary remnants of coronal mass ejections (ICMEs): magnetic clouds (MC) and non-magnetic cloud [1, 2]. MCs are identified in the solar wind at ~ 1 AU by the passage of a region with dimensions around 0.2-0.3 AU crossing the spacecraft or the Earth in ~ 24h. Their main signatures identifiable in solar wind/interplanetary data are: enhanced magnetic field strengths; smooth rotation in the magnetic field direction through a large angle; low proton temperature and low plasma beta [3]. The non-MCs are sometimes called complex ejecta (CE) [4], due to their disordered magnetic field structure. However this name has also been used for the interaction of two or more ICMEs. Here we will use CE for the magnetic structures resulting of the interaction of two ICMEs and presenting disordered magnetic field structures.

In this paper we present a comparative analysis between 2 particular events: a typical MC passing Earth during April 16-17, 1999, from now on referred as MC1999, and a complex ejecta, resulting of the interaction of 2 ICMEs and lacking a well-ordered magnetic field structure, passing by Earth on February 11-12, 2000, identified from here as CE2000. The storms caused by these structures are comparable in intensity as measured by the Dst index, reaching peak values of Dst ~ -100 and -130 nT, respectively. It was also possible to trace their solar origin, interplanetary propagation conditions and magnetospheric impacts. Their solar origins have been described previously [5]. Here we present the solar wind plasma and magnetic field data, the characteristics of the ICMEs, and an analysis of the shocks driven by them. An assessment of the energy transferred to the magnetosphere during the two events is also presented. This study is a contribution for improving our understanding of the complex Sun-Earth chain and also of the space weather variability.

DESCRIPTION OF THE EVENTS

Figure 1 presents the solar wind plasma and magnetic field data for the April 16-18, 1999 period. Panels are, from top to bottom: proton temperature T_p, solar wind speed V_{sw}, proton density N_p, magnetic field azimuth (*phi*) and inclination (*theta*) angles, the magnetic field magnitude *B,* and GSM (Geocentric Solar Magnetospheric) magnetic field components, B_x, B_y, and B_z, and β. The continuous vertical line delimits the interplanetary shock 'S', driven by the MC. The MC boundaries are delimited by the vertical dotted lines, based on the available signatures of the magnetic structure. The region between the shock and the first MC boundary is the sheath, where the plasma is highly turbulent due to shock compression effects. The interplanetary shock was detected at 10:30 UT on April 16, by ACE. The MC started around ~ 18:00 UT on April 16, lasting until ~19:00 UT on April 17, with duration of ~ 25 h. The solar wind velocity increased, due to the arrival of the shock, from ~ 380 to 470 km/s. B_z deflection was up to -13 nT and a brief particle density enhancement is also seen, reaching ~ 68 cm^{-3} within the sheath. The transit speed of CME (between the solar source and the ACE spacecraft) was estimated in V_T ~ 520 km/s, with ICME average speed of V_{sw} ~ 400 km/s and maximum pos-shock speed (ICME+sheath) of V_{sw} ~ 450 km/s [6].

Figure 2 presents the plasma and magnetic field interplanetary data for the ICMEs/complex ejecta observed on February 10-14, 2000. Panels present the parameters in the same sequence as in Figure 1. The continuous vertical lines delimit the interplanetary shocks 'S1' and 'S2'. The boundaries of the two ICMEs, 'ICME1' and 'ICME2', are indicated by the vertical dotted lines. The ICME1 is abruptly interrupted by the arrival of the second shock 'S2'. Two CME-related shock fronts passed the ACE spacecraft on February 11. The first shock, S1, occurred at ~02:14 UT on February 11, accompanied by abrupt changes in V_{sw} and N_p, peaks of ~ 580 km/s and ~14 cm^{-3}, respectively, and a brief southward IMF with maximum deflection of ~ -7 nT. The second shock front, S2, passed the spacecraft at ~23:20 UT, February 11, accompanied by a sudden increase in V_{sw} (up to 640 km/s), in N_p (up to 30 cm^{-3}) and in B_z (~ -18 nT). The beginning of ICME1 was identified at ~16:00 UT, February 11, and abruptly ending at ~20:00 UT, February 11, due to the arrival of shock S2. Its average properties are V_{sw}~ 420 km/s, $|B|$ ~ 7 nT and transit speed V_T ~ 630 km/s [13]. The ICME2 began around 12:00 on February 12 and lasted until 00:00 UT on February 13. Its average properties were: V_{sw} ~ 540 km/s; $|B|$~*13* nT; and transit speed ~ 900 km/s [6].

ANALYSIS OF THE EVENTS

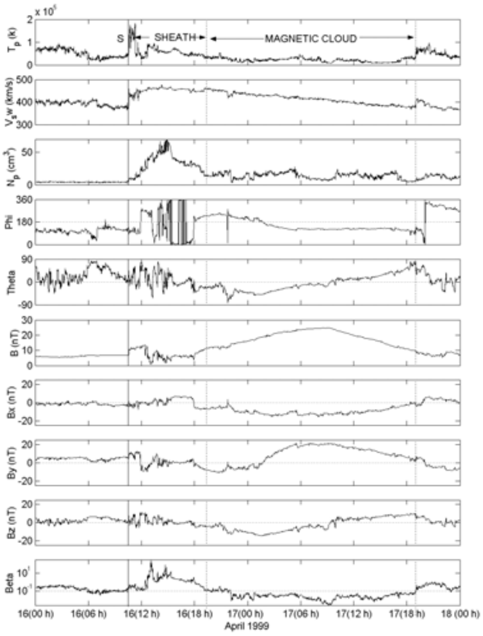
Interplanetary shock parameters were determined following the procedure adopted in a previous work [7]. Plasma and magnetic field parameters are averaged in the upstream and downstream regions, and the differences or ratio between the averaged values are taken as a measure of the shock strength, represented by the density ratio (r_N) and magnetic field ratio (r_B). We have also calculated the shock normal (n_{GSE}), the magnetosonic number (M_{MS}) using the Abraham-Shrauner mixed mode [8], the Alfvén number (M_A), and the angle between the shock and the magnetic field (θ_{Bn}). U_S and SI are, respectively, the shock velocity and the sudden impulse observed within the Dst profile. Shock parameters are summarized in Table 1 for the MC1999 shock and for the two CE2000 shocks.

TABLE 1. Interplanetary shock parameters.

Shock/parameter	April 16, 1999 (10:30 UT)	February 11, 2000 (02:00 UT)	February 11, 2000 (23:00 UT)
r_N	2.0	2.6	3.7
r_B	1.7	1.8	3.1
U_s	486 km/s	510 km/s	630 km/s
M_A	1.63	1.42	3.1
$\boldsymbol{n}_{GSE}$	(0.96;-0.11;-0.26)	(0.96; -0.13; -0.23)	(0.76; 0.38; -0.53)
θ_{Bn}	56^o	11^o	86^o
M_{MS}	1.32	1.22	2.35
SI	15 nT	18 nT	45 nT

The source of the energy that drives magnetospheric processes is the solar wind. Quantifying the transfer of energy from the solar wind to the magnetosphere is a fundamental problem in space physics. At present, there are no direct observational means of determining the energy transfer from the solar wind to the magnetosphere. Reconnection plays a major role in the energy transfer process, and the simplest coupling function, the solar wind speed times the southward component of the IMF, the dawn-dusk electric field given by $E_y=VB_s$ (mV/m), has proved to be an effective measure of energy transfer [9]. Another widely used coupling measurements are the

Akasofu epsilon parameter, $\varepsilon = VB^2 l_0^2 \sin^4(\theta/2)$ [10], which essentially represents the rectified Poynting flux in the solar wind, and the Burton's energy function $F(E_y) = d(E_y\text{-}0.5)$, for $E_y \geq 0.50$ mV/m and $F(E_y) = 0$, for $E_y < 0.50$ mV/m, with $d = 1.5 \times 10^{-3}$ nT/(mv-m^{-1}-s). [11]. On the Akasofu epsilon parameter V is the solar wind velocity, B is the IMF, l_o is an empirical scaling parameter equal to 7 RE, and $\theta = \tan^{-1}(B_Y/B_Z)$ the IMF clock angle.



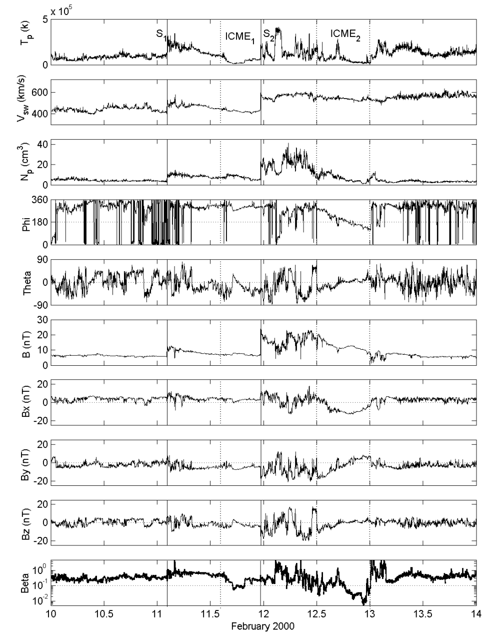


FIGURE 1. (Rigth) Plasma and magnetic field ACE interplanetary data for the April 16-18, 1999 period. Panels are, from top to bottom: proton temperature T_p [K], solar wind speed V [km/s], solar wind proton density N_p [cm^{-3}], IMF azimuth, *Phi,* and inclination, *Theta,* angles, magnetic field strength B and GSM magnetic field components Bx, By, Bz [nT], and the β plasma parameter. The continuous line indicates the interplanetary shock 'S'; the MC boundaries are delimited by the dotted lines. The region between the shock 'S and the MC is identified as the sheath.

FIGURE 2. (Left) the Plasma and magnetic field ACE interplanetary data for the February 10-14 2000 period. Panels are presented in the same sequence as Figure 1. The continuous lines indicate the interplanetary shocks S1 and S2. The ICME1 and ICME2 boundaries are delimited by the dotted lines.

The geoeffectiveness parameters described previously are summarized in Table 2. Although it is not shown here, the B_z profiles determine in part the profiles of the coupling parameters; they are in general smoother for the MC1999 and more fluctuating/irregular for the CE 2000 event.

TABLE 2. Geoeffectiveness parameters.

Parameters	April 16, 1999	February 11, 2000
B_s peak	-14.0 nT	-16.4 nT
E_y peak	6 mV/m	9.5 mV/m
duration Bs <-10 nT	5 hours	3 hours
$\int E_y$ (during Bs<-10)	130 (mV/m)h	73 (mV/m)h
Perc. Bs peak	74%	82%
F(E) peak	-30 nT/h	-49 nT/h
$\varepsilon_{Akasofu}$	2.6×10^{19} W	7.2×10^{19}W
Dst peak	-91 nT	-133 nT

The minimum variance analysis (MVA) method [12] is widely used to identify and describe planar magnetic field configurations associated with thin current sheets in the solar wind and in planetary magnetopauses. The knowledge of the magnetic field topology and structure within ICMEs is very important to understand the solar wind-magnetosphere coupling process. Of special interest is the southward component of the interplanetary magnetic field, B_s, configuration.. The MVA was applied to the MC/ICMEs 5-min GSE data in order to determine their axial orientation [13]. The MC1999 event had its MV axis with an inclination of -16.5^o, while the cloud axis (intermediate variance) had an inclination of 73.5^o relative to the ecliptic plane, and an azimuth of 8^o in relation to the Sun-Earth line. This result is in excellent agreement with reference [14] (inclination of 72^o and azimuth of 4^o). The ICME1 of CE2000 had an inclination around -5^o and an azimuth of -72^o, but it had a too short duration to allow a clear identification of its structure. The ICME2 of CE2000 had an axis inclination of ~18^o and azimuth of ~ 152^o to the Sun-Earth line; this indicates that its axis could be close to the ecliptic plane.

CONCLUSIONS

In this work we presented the interplanetary aspects of two different, contrasting Sun-Earth events. The first of these events was caused by a MC with an intense but smooth and long duration B_s field. The other one was caused by the interaction of two ICMEs, with intense but irregular and fluctuating B_s fields. The solar wind-magnetosphere energy coupling, and the resulting geomagnetic storms, as recorded by the Dst index, were of a different nature, although they had similar intensity. Peak values of energy functions are higher for the complex event, while the total (integrated) energy deposited in the magnetosphere was higher for the MC event, as shown in Table 2. These differences between these two events indicate the complexity of the solar wind-magnetosphere coupling and the need of analyzing the interplanetary structure leading to a magnetic storm to better understand an event. Future studies should encompass a larger number of events for a better understanding of the basic physics of geomagnetic storms origin.

ACKNOWLEDGMENTS

This study was partially supported by research fellowship from CNPq (303343/2004-4). Thanks to Brazilian government agency CAPES for doctoral fellowship and to FAPESP , project number: 02/12723-2, 02/14150-0, 04/14784-4, and 2005/03501-4. Thanks to World Data Center for Geomagnetism-Kyoto for the Dst index, to the International Solar Terrestrial Physics Project, through WIND, SOHO and ACE teams for high-resolution solar wind data and to the National Space Science Data Center (NASA/Goddard) for the OMNI data set.

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