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Journal of Atmospheric and Solar-Terrestrial Physics 66 (2004) 161–165

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

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Prediction of peak-*Dst* from halo CME/magnetic cloud-speed observations

W.D. Gonzalez[a,*], A. Dal Lago[a], A.L. Clúa de Gonzalez[a], L.E.A. Vieira[a], B.T. Tsurutani[b]

[a] *Instituto Nacional Pesquisas Espaciais, CP 515, São José dos Campos, São Paulo 12201-970, Brazil*
[b] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA*

Abstract

From the analysis of different sets of magnetic clouds and focusing on the most probable value found for the peak amplitude of their negative B_z fields, we present an estimate for the peak intensity of the associated geomagnetic storms (peak *Dst*).

Since the key parameter for this prediction scheme turns out to be the peak amplitude of the solar wind speed, we extend this prediction to halo CME events observed near the Sun and associated with the magnetic clouds.

Thus, a prediction scheme for peak *Dst*, based on halo CME-expansion speed observation near the Sun and associated with magnetic clouds, is suggested for the first time.

Furthermore, the relationship between the cloud's total magnetic field and its B_s component, empirically found for the two sets of the studied clouds, is consistently supported by the results obtained from a numerical study of magnetic clouds.

Keywords: Magnetic storms; ICMEs; *Dst* predictions; Solar wind speeds

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1. Introduction

For the purpose of predicting the peak amplitude of a geomagnetic storm it has been usually claimed that a key parameter is the peak value of the negative B_z component (B_s) of the IMF associated with the interplanetary structure responsible for the storm (e.g. Gonzalez et al., 1994; Tsurutani and Gonzalez, 1997). Therefore, any attempt to forecast B_s is of prime importance for such a purpose as well as for the benefit of space weather research and applications.

It is also of practical importance for the anticipated knowledge of geomagnetic storm intensification (forecasting) to get some simple scheme that could relate a key observational parameter of CMEs near the Sun with the peak amplitude of the emerging geomagnetic storm (peak *Dst*).

It is the purpose of this paper to present prediction schemes for these two topics of interest.

2. Prediction scheme

The response of the inner magnetosphere to solar wind energization events has been currently measured by the storm–time geomagnetic index *Dst*, as governed by the energy balance equation (e.g. Burton et al., 1975; Gonzalez et al., 1994)

$$\frac{\mathrm{d}Dst}{\mathrm{d}t} = Q(t) - \frac{Dst}{\tau} \tag{1}$$

with Q being the solar wind energy input function, typically represented by the rectified interplanetary electric field, dvB_s, where v is the solar wind speed, B_s the southward component of the IMF and d a dimensionality parameter given by Burton et al. (1975) as 1.5×10^{-3} nT(mV/m)$^{-1}$ s^{-1}, with vB_s given in mV/m and *Dst* in nT. In this equation, τ

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* Corresponding author. Fax: +55-12-394-56810.
E-mail address: gonzalez@dge.inpe.br (W.D. Gonzalez).

1364-6826/$ - see front matter © 2003 Published by Elsevier Ltd.
doi:10.1016/j.jastp.2003.09.006

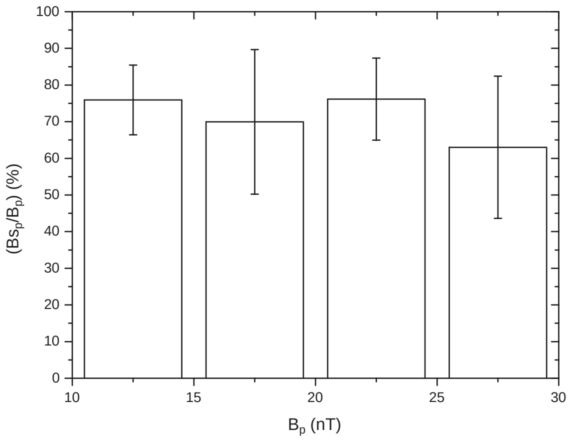

Fig. 1. Percentual fraction of $(B_s)_p/B_p$ as a function of B_p for the magnetic clouds studied by Gonzalez et al. (1998) and Dal Lago et al. (2001).

is the decay time, associated with loss processes in the inner magnetosphere.

From Eq. (1), in order to estimate peak $Dst(D_p)$, we consider $dDst/dt = 0$ and get the following relation:

$$D_p = (dvB_s)_p\tau_p, \tag{2}$$

where $(dvB_s)_p$ is the magnetospheric electric field driving D_p, and τ_p is the decay time at D_p. Thus, with vB_s in mV/m, v in km/s, B_s in nT and τ_p hours, we have

$$D_p(\mathrm{nT}) = 5.4 \times 10^{-3}\tau_p\ (\mathrm{h})v_p\ (\mathrm{km/s})(B_s)_p(\mathrm{nT}). \tag{2a}$$

Gonzalez et al. (1998) presented a relationship between the peak values of the solar wind speed and magnetic field intensity for magnetic clouds at 1 AU:

$$B_p(\mathrm{nT}) = 0.047v_p\ (\mathrm{km/s}) - 1.1. \tag{3}$$

Using 54 magnetic clouds observed and identified during the interval of 1965–1997, Dal Lago et al. (2001), found a similar relationship between B_p and v_p.

For the same set of magnetic clouds, we studied the distribution of peak B_s, as a function of peak B. This distribution is shown in Fig. 1, in which one can see, within the error bars, a fairly constant ratio of $(B_s/B)_{\mathrm{peak}}$, with a most probable value of about 0.7, namely

$$(B_s)_p \approx 0.7B_p. \tag{4}$$

A similar result is also obtained for a different set of magnetic clouds, given in Table 1 and discussed below. The $(B_s/B)_{\mathrm{peak}}$ distribution for this second set of magnetic clouds is shown in Fig. 2.

Thus, from Eqs. (3) and (4), and neglecting in Eq. (3) the small last term, we have for Eq. (2a):

$$D_p(\mathrm{nT}) \approx 1.8 \times 10^{-4}\tau_p\ (\mathrm{h})v_p^2\ (\mathrm{km/s}). \tag{5}$$

From this equation we can estimate peak Dst with the knowledge of the peak value of the solar wind speed near the Earth (such as at the L_1 region). However, we need to use some value of τ_p which could be representative of the peak Dst situation.

Cliver et al. (1990) have expressed the solar wind speed near the Earth, v_p, as a function of the average transit speed of the solar wind, from the Sun to near Earth regions, $\bar{v}$, as given by

$$v_p = 0.775\bar{v} - 40. \tag{6}$$

Thus, from Eqs. (5) and (6) one gets

$$D_p(\mathrm{nT}) \approx 1.1 \times 10^{-4}\tau_p\ (\mathrm{h})\bar{v}^2\ (\mathrm{km/s}). \tag{5a}$$

(Note that in this expression we have neglected the term corresponding to the constant value 40 of Eq. (6), since its contribution is fairly small when compared to the first term of this equation.)

Eq. (5) allows us to estimate peak Dst from the knowledge of the observed interplanetary speed near 1 AU, whereas Eq. (5a) does it using the knowledge of the propagation speed of the ejecta, as compared from the travel time of the observed CME at the Sun and the observed response at 1 AU.

Thus, Eqs (5) and (5a) allow a prediction of peak Dst only for a short interval before the occurrence of the storm, which can be just about 1 h if the arrival of the solar/interplanetary structure is measured at L_1.

For the purpose of extending this forecasting time as much as possible, one could try to relate the interplanetary speed (v_p) near 1 AU with the CME speed near the Sun, such as the expansion speed (v_e) of halo CMEs.

Schwenn et al. (2001) and Dal Lago et al. (2002) have used solar and interplanetary observations from January 1997 to April 2001 to correlate v_p with v_e. Solar observations from the large angle and spectroscopic coronograph (LASCO) combined with the extreme ultra-violet image telescope (EIT), both onboard SOHO, provided the set of frontal halo coronal mass ejections during this period. The interplanetary plasma and magnetic field data were obtained from the observations made by the ACE solar wind electron, proton and alpha monitor (SWEPAM) and magnetic fields investigation (MFI). It was possible to identify over 200 side halo CMEs at the Sun, of which 99 had a univocal correspondence to a single interplanetary shock at 1 AU. Ninety two of these CMEs were clear enough to enable measurements of their lateral expansion speeds, which, according to Schwenn et al. (2001), is the lateral growth speed of the CME perpendicular to its largest plane-of-sky speed direction. These same authors have proposed this CME expansion speed as a proxy of the Sun–Earth line speed, providing better prediction of the CME travel time to Earth as compared to a plane of sky speed. From these 92 interplanetary events, 18 were identified as magnetic cloud structures, according to the criterion of Burlaga et al.

Table 1
Halo CMEs and their corresponding magnetic clouds at 1 AU, with rotations across the ecliptic plane, observed from January 1997 to April 2001

Halo CME date/time	Halo CME expansion speed (km/s)[a]	Shock date/time at 1 AU (cloud follows)[b]	Travel time time to 1 AU (h)	Peak *Dst* index (nT)
1997/01/06 15:10	284	1997/01/10 00:22	81	−78
1997/05/12 06:30	577	1997/05/15 00:56	66	−115
1997/10/07 13:30	358	1997/10/10 15:48	74	−130
1997/11/04 06:10	1156	1997/11/06 22:07	64	−110
1998/10/15 10:04	367	1998/10/18 19:00	81	−112
1998/11/05 20:44	1116	1998/11/08 04:20	56	−142
1999/04/13 03:30	478	1999/04/16 10:47	79	−90
2000/07/14 10:54	2178	2000/07/15 14:18	27	−300
2000/08/09 16:30	897	2000/08/11 18:19	50	−237
2000/11/02 16:26	668	2000/11/06 09:08	89	−159
2001/03/16 03:50	543	2001/03/19 10:12	78	−163
2001/03/29 10:26	1511	2001/03/31 00:14	38	−285
2001/04/09 15:54	1905	2001/04/11 13:03	45	−251

[a] Schwenn et al. (2001).

[b] From http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_publ.html.

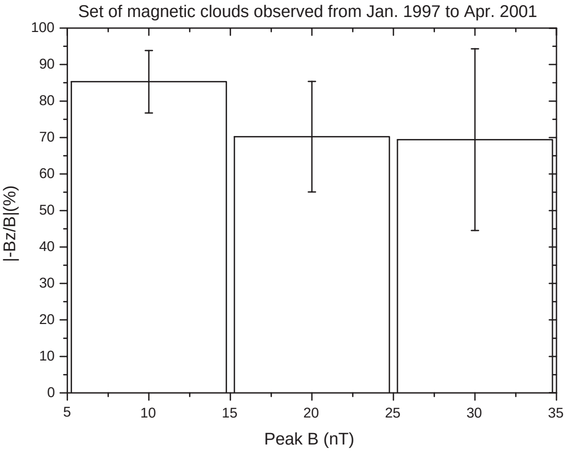

Fig. 2. Percentual fraction of $(B_s)_p/B_p$ as a function of B_p for the magnetic clouds listed in Table 1.

(1981). From these clouds, 11 had rotations of their magnetic field across the ecliptic plane, thus providing strong negative B_z fields. For those events, listed in Table 1, the peak *Dst* values of the corresponding geomagnetic storms had values between about −80 and −300 nT. For those magnetic clouds, Dal Lago et al. (2002) obtained a linear relationship between the halo expansion speed (v_e) of their originating CMEs and the magnetic cloud speed (v_p) at 1 AU. The linear best fit had a correlation coefficient of 0.78 and the relationship is given by

$$v_p = 0.22 v_e + 340. \tag{7}$$

Thus, using expression (7) in Eq. (5) one gets

$$D_p(\mathrm{nT}) \approx 1.8 \times 10^{-4} \tau_p\ (\mathrm{h})[0.22 v_e\ (\mathrm{km/s}) + 340]^2. \tag{5b}$$

Fig. 3 gives peak *Dst* for the selected 11 magnetic clouds for the three expressions (5), (5a) and (5b), namely, using the measured peak speed of the magnetic cloud at 1 AU, the magnetic cloud propagation speed from Sun to Earth, and the measured CME-halo expansion speed, respectively.

For the geoeffective magnetic clouds of Fig. 3c, the best fit to the data gave a value of 2.9 h for the ring current–time decay τ_p, which is smaller than typical values (e.g. Gonzalez et al., 1994) because this value refers to the peak stage of the storm main phase and probably also because the range of storms covered by the selected events is fairly intense. Further, since τ_p most probably corresponds to the ring current-loss time still during the asymmetric stage (e.g. Kozyra et al., 2002), such a time constant could well represent the flowout-time of partial ring current particles during intense events.

If we use this fit value of 2.9 h for τ_p from Fig. 3c in Eq. (5b) we could write a halo *CME/magnetic cloud-forecasted peak Dst* expression, using only the measured expansion speed of the halo CME, as

$$D_p(\mathrm{nT}) = 5.2 \times 10^{-4}[0.22 v_e\ (\mathrm{km/s}) + 340]^2. \tag{8}$$

Notice that this expression is restricted to halo CMEs with associated interplanetary structures that are magnetic clouds with rotations across the ecliptic plane.

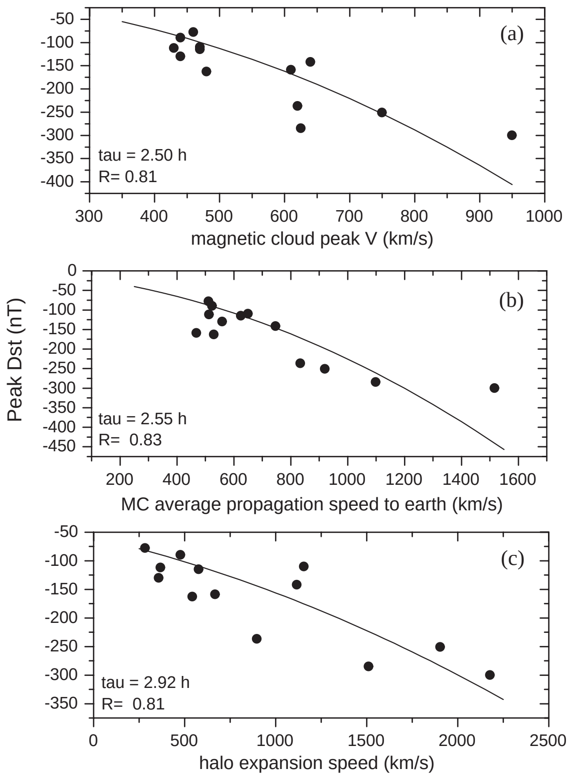

Fig. 3. Peak *Dst* values for the 13 magnetic clouds selected for the present study as a function of (a) the peak solar wind speed of the observed magnetic cloud at 1 AU, (b) the average CME propagation speed from Sun to 1 AU, (c) the halo CME expansion speed measured from SOHO/LASCO observations.

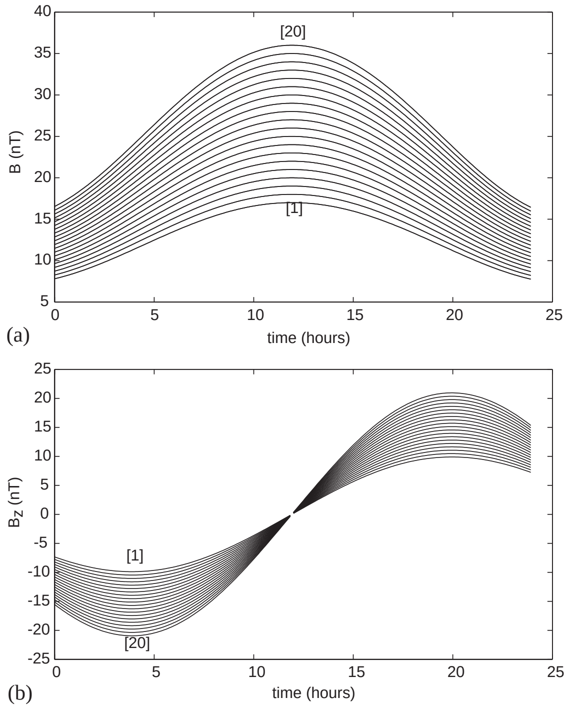

Fig. 4. Constant-alpha force-free field model profiles for magnetic clouds with their axes on the ecliptic: (a) Total magnetic field intensity profiles, (b) B_z field intensity profiles. The curves, numbered from 1 to 20, correspond to the range of B_{p} values 16 nT $< B_{\mathrm{p}} \leqslant 36$ nT.

3. Discussion

One way of checking the validity of Eq. (2a), in order to predict D_{p}, is to use the empirical criteria for intense storms given by Gonzalez and Tsurutani (1987). The lower limit of such criteria gives $D_{\mathrm{p}} = -100$ nT when $v_{\mathrm{p}} = 500$ km/s and $(B_{\mathrm{s}})_{\mathrm{p}} = -10$ nT.

Using $\tau_{\mathrm{p}} \approx 3$ h, as obtained in the present paper, we get, with Eq. (2a), $D_{\mathrm{p}} \approx -80$ nT (which is a fairly reasonable approximation, considering the crude criteria suggested by Gonzalez and Tsurutani).

The dependence of peak *Dst* on v_{p}^2 of Eq. (5) was obtained from Eqs. (3) and (4) inserted in Eq. (2a). The validity of this dependence is restricted to the set of magnetic clouds studied by Gonzalez et al.(1998), although Owens and Cargill (2002) have reported a similar correlation between solar wind velocities and magnetic fields for a larger class of events.

A value for $(B_{\mathrm{s}})_{\mathrm{p}}/B_{\mathrm{p}}$ close to that empirically obtained from the two sets of clouds, shown in Figs. 1 and 2, is also obtained using the magnetic cloud model proposed by Burlaga (1988), which assumes that locally the magnetic cloud has a cylindrically symmetric constant alpha force-free structure given by the Ludquist's solution. Fig. 4 shows: (a) the magnetic field intensities; and (b) the B_z components, both given by the Burlaga's model for the range of peak B values, 16 nT $< B_{\mathrm{p}} \leqslant 36$ nT (numbered from 1 to 20 in this figure). For this model, the relation $(B_{\mathrm{s}})_{\mathrm{p}}/B_{\mathrm{p}}$ is a constant value of approximately 0.6. However, the model does not consider any interaction of the magnetic cloud with the solar wind as it propagates through the inner heliosphere, which can produce internal compressed fields in the front and rear portions of the magnetic cloud Fenrich and Luhmann (1998), affecting more significantly $(B_{\mathrm{s}})_{\mathrm{p}}$ than B_{p}, due to the closer proximity of $(B_{\mathrm{s}})_{\mathrm{p}}$ to the borders of the cloud. Also, the simple model used here does not take into account any variability in the orientation effect, assuming that the cloud-axis lies perfectly in the ecliptic plane.

It is interesting to point out that in the case of a lack of interplanetary observations, Eq. (5a) provides a means of estimating peak *Dst* just from the knowledge of the travel time of an observed solar ejecta and the observed sudden impulse produced by the impinging shock at the magnetopause. For example, Tsurutani et al. (2003) have studied the extreme storm event of September 1–2, 1859, for which we had this type of information, and the results presented by these authors were obtained applying Eq. (5a) to the reported observations.

Acknowledgements

Portions of this work were performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA. One of the authors thanks the support of "Fundaço de Amparo à Pesquisa do Estado de São Paulo" (Project 98/15959-0)

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