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MAGNETIC CLOUDS OBSERVED AT 1 AU DURING THE PERIOD 2000–2003

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Abstract. In this work we have performed a systematic study of all the magnetic clouds identified in the time interval 2000–2003. The study shows that the non force-free model of Hidalgo is a good approximation to the magnetic topology of the MCs in the interplanetary medium. This conclusion is reached based on the good fits obtained with the model for most of the clouds, in spite of the variety of profiles found in the magnetic field strength and in every of its components. The model incorporates the distortion and expansion of the cross-section of the MCs. We have compared, when available, the results obtained with those in literature. The unique published global study of the MCs at the same time interval has been provided by Lepping using the circular cross-section model of Burlaga, and the results are available in his web page. From all the parameters he obtained, only the longitude, ϕ, the latitude, θ, and the distance of maximum approach of the spacecraft to the cloud axis, y_0, may be compared with those obtained by Hidalgo's model. As we show, the main discrepancy between both models refers to the longitude values. Concerning the comparison with other models of literature, only the Bastille day and October 2003 magnetic clouds have been studied by other authors.

1. Introduction

Disturbances of the plasma and magnetic field in the interplanetary medium due to the phenomena occurring at the surface of the Sun are observed during last decades by different spacecrafts (Klein and Burlaga, 1982). Some of these perturbations present well-defined characteristics like a significant elevation in the magnitude of the magnetic field, with a simultaneous rotation in some of their components and a minimum in the thermal velocity or diagonal components of the pressure tensor. All these signatures are associated with the phenomenon of magnetic cloud (MC). This association was first established by Burlaga *et al.* (1981). Simultaneous to these characteristics is the appearance of a linear decrease in the velocity of the solar wind. Even more, a forward-shock is usually related to the movement of the MC in the interplanetary medium.

The MCs are studied in the literature from different points of view: (1) purely theoretical studies, using idealised structures (like spheroidal or toroidal) and trying to understand the behaviour of the different physical magnitudes (Farrugia *et al.*, 1983; Vandas *et al.*, 1993; Romanshets and Vandas, 2001), (2) more realistic approaches using numerical simulations (Hu and Sonnerup, 2001, 2002; Vandas, Odstril, and Watari, 2002), and (3) analytical models which assume simple topologies for the MCs and allow us to fit them to the experimental data (Goldstein, 1983; Marubashi, 1986, 1997; Burlaga, 1988; Lepping, Jones, and Burlaga, 1990; Mulligan and Russell, 2001; Cid *et al.*, 2002; Hidalgo *et al.*, 2002; Hidalgo, 2003).

There is an important aspect of the models to be considered. All the first analytical circular cross-section approaches has been based on the force-free condition (Burlaga, 1988; Marubashi, 1986; Lepping, Jones, and Burlaga, 1990). This implies absence of plasma pressure gradient inside the cloud, i.e., the plasma pressure is constant. However, looking at the experimental data corresponding to the proton or electron pressures, these have a clear structure far to be constant.

Then, more recent models without such force-free restriction have been developed (Mulligan and Russell, 2001; Hidalgo *et al.*, 2002) which makes possible the simultaneous study of the magnetic field topology and the plasma behaviour (Cid *et al.*, 2002).

Most of the analytical models assume a circular cross-section for the MCs. Nevertheless, an exhaustive analysis of the experimental data and the results obtained from numerical simulations (Riley *et al.*, 2003) lead us to consider that the cross-section is distorted in its evolution through the interplanetary medium as a consequence of its interaction with the solar wind. This implies that an analytical model has also to incorporate this deformation. As a first approach, a good starting point is to assume an elliptical cross-section (Mulligan and Russell, 2001; Hidalgo, Nieves-Chinchilla, and Cid, 2002).

We have also mentioned the appearance of a decrease in the solar wind velocity. This is considered a direct consequence of the expansion of the cross-section of the MC and a more realistic model should incorporate it.

In the present work we study all the MCs observed during the time interval 2000–2003 using our elliptical cross-section model (Hidalgo, 2003, 2005) where a distortion and expansion of the cross-section of the cloud is included from first principles. The orientation parameters deduced have been compared with the ones obtained by Lepping, Jones, and Burlaga (1990) with the model of Burlaga. These orientation angles are the common parameters between both models. In several cases we disagree with the MC boundaries he chooses.

In the next section we briefly detail our model. In Section 3 we describe the results we obtain with it, comparing them with other models of the literature.

2. Model

Using the image first established by Goldstein (1983), we consider the MC locally as a cylinder, Figure 1a, but with a deformed cross-section due to its interaction with the solar wind (in several cases the magnetic field strength can be considered as a signature of that distortion). Then, we approach this effect in our model assuming an elliptical geometry in the cross-section of the cloud. Thus, we describe the

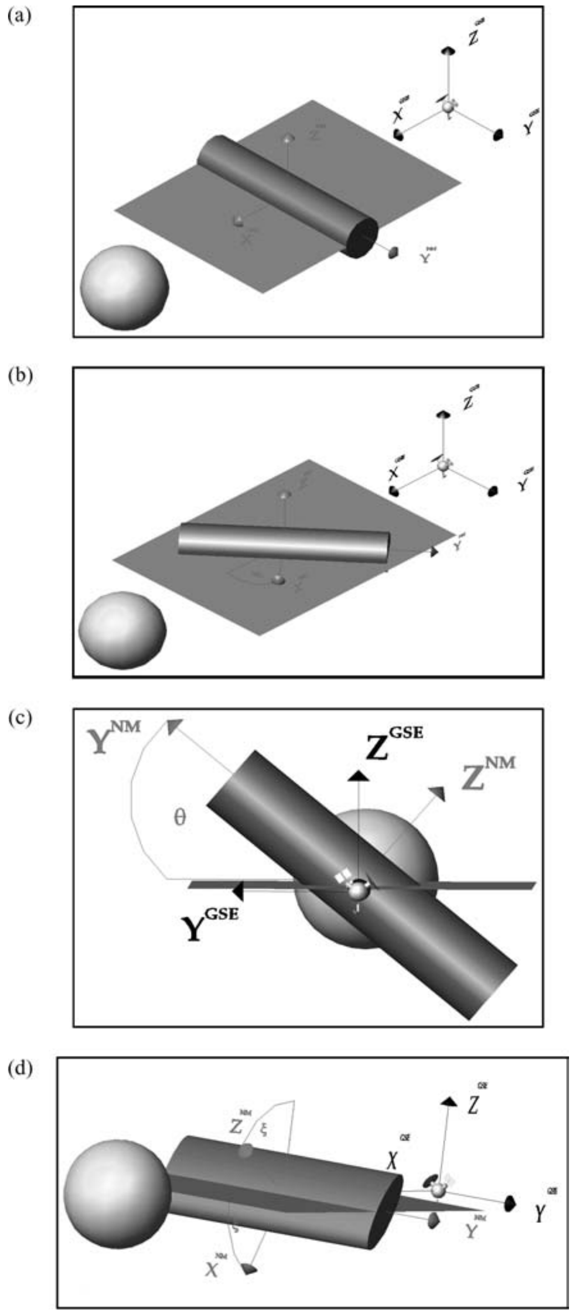


Figure 1. (a) The coordinate systems used in our study and the shape of the MC assumed in our model. We illustrates the three orientation parameters (see text) (b) the longitude (c) the latitude and (d) the angle related to the orientation of the elliptical cross-section of the cloud. In the four figures, X^{NM}, Y^{NM}, and Z^{NM}correspond to the cartesian coordinate system associated to the magnetic cloud and X^{GSE}, Y^{GSE}, and Z^{GSE} to the GSE coordinate system.

physical topology of the cloud through the elliptical coordinates (Hidalgo, Nieves-Chinchilla, and Cid, 2002) whose relations with the cartesian one is given by

$$\begin{aligned} x &= r \cosh \eta \cos \varphi \\ y &= y \\ z &= r \sinh \eta \sin \varphi, \end{aligned} \tag{1}$$

where r is the parameter of the elliptical coordinate system, φ the angular coordinate of the section of the cloud and η the parameter associated with the eccentricity of its cross-section. In this new coordinate system the Maxwell equations for the magnetic field are (Hidalgo, 2003),

$$\frac{\partial B_y}{\partial \varphi} = -\mu_0 j_\eta h, \tag{2}$$

$$\frac{1}{h} r^2 \sinh \eta \cosh \eta B_\varphi + h \frac{\partial B_\varphi}{\partial \eta} = -\mu_0 j_y h^2, \tag{3}$$

$$\frac{\partial B_y}{\partial \eta} = \mu_0 j_\varphi h \tag{4}$$

for the curl of the magnetic field, where $h = r[\cosh^2 \eta - \cos^2 \varphi]^{1/2}$ is the scale factor, and

$$r^2 \sin \varphi \cos \varphi B_\varphi + h^2 \frac{\partial B_\varphi}{\partial \varphi} = 0 \tag{5}$$

for its divergence. In these expressions we have supposed finite axial, B_y, and poloidal, B_φ, components of the magnetic field, but a zero normal component to the cross-section, $B_\eta = 0$. Even more we impose axial symmetry, i.e., $\partial B_y/\partial y = 0$ and $\partial B_\varphi/\partial y = 0$. Additionally to the Maxwell magnetic field equations we take into account the continuity equation in stationary conditions for both basic species of the plasma inside MCs, i.e., $\nabla \cdot (\vec{j}^e + \vec{j}^p) = \nabla \cdot \vec{j} = 0$, which in the elliptical coordinate system looks like

$$r^2 \sin \varphi \cos \varphi \, j_\varphi + h^2 \frac{\partial j_\varphi}{\partial \varphi} + r^2 \sinh \eta \cosh \eta \, j_\eta + h^2 \frac{\partial j_\eta}{\partial \eta} = 0, \tag{6}$$

where we have also assumed $\partial j_y/\partial y = 0$.

On the other hand, the expansion of the cross-section of the cloud is incorporated in the model (Hidalgo, 2003, 2005). This is clearly manifested in the decrease of the velocity of the solar wind at the time interval of the clouds.

Hence, to obtain the equations of the model we solve Equations (2)–(6) simultaneously, deducing the expressions

$$\begin{aligned} B_\eta &= 0, \\ \mathrm{B}_y &= B_y^0 + \mu_0 \alpha (t_0 - t) r \cosh \eta \, \mathrm{SE}(\cos \varphi, 1/(\cosh \eta)) \end{aligned} \tag{7}$$

$$\approx B_y^0 + \mu_o \alpha (t_0 - t) r \ \cosh \eta \, S \cos \varphi,$$

$$B_\varphi = -\frac{\mu_0 r \ \cosh \eta \lambda (t_0 - t)}{[\cosh^2 \eta - \cos^2 \varphi]^{1/2}}$$

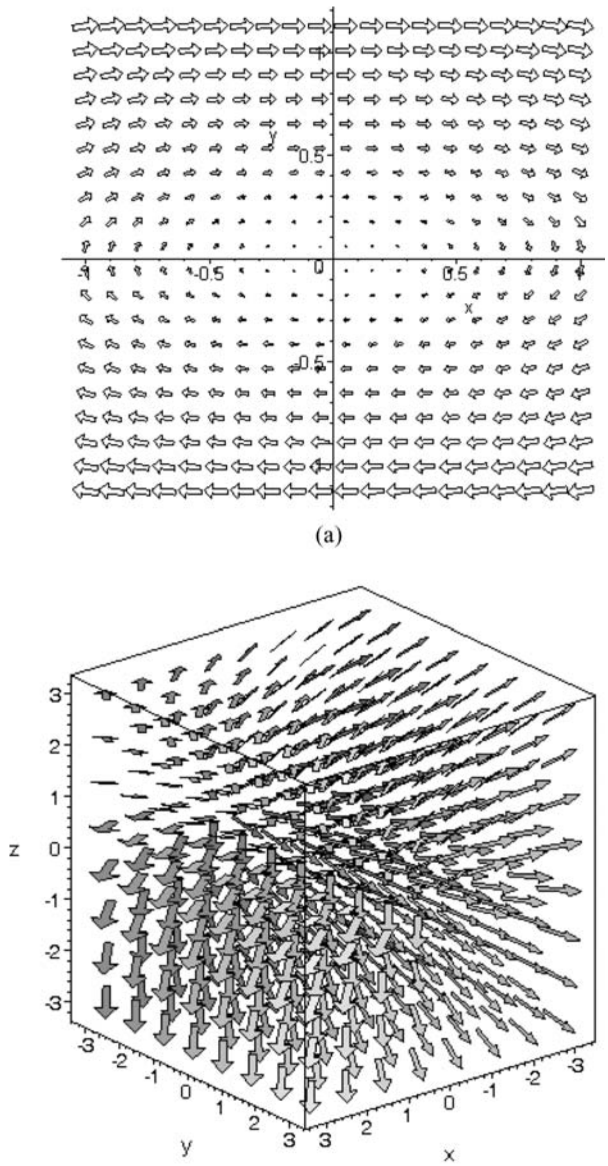
for the magnetic field and

$$\begin{aligned} j_\eta &= \alpha(t_0 - t) \\ j_y &= \frac{\sinh \eta}{[\cosh^2 \eta - \cos^2 \varphi]} \lambda(t_0 - t) \\ j_\varphi &= \frac{\sinh \eta S \cos \varphi}{[\cosh^2 \eta - \cos^2 \varphi]^{1/2}} \alpha(t_0 - t) \end{aligned} \tag{8}$$

for the plasma current density. The y-component, B_y, is approximated considering only the first term in the trigonometric series of the incomplete elliptic integral of second kind. In Figure 2a we show the projection of the magnetic field over the cross-section of the MC (its poloidal component). The elliptical structure of the cross-section clearly appears. In Figure 2b is represented the current density $\vec{j}$ as deduced from Equation (8). We imposed a linear behaviour in its radial component, (Hidalgo, 2003, 2005), depending on two factors: α, which provides information about the expansion of the cross-section of the MC during the passage of the satellite, and $(t_0 - t)$ associated with the expansion rhythm. In Table I we show the values of t_0/t_{sat}, being t_{sat} the time duration of the satellite passage inside the cloud. The bigger the factor is the slower the expansion of the cross-section of the cloud.

Once we have deduced the equations for the magnetic field components, Equation (7), and in order to compare our model with the experimental data, we have to expressed those components in the Geocentric Solar Ecliptic (GSE) coordinates system (Hidalgo, 2003, 2005). This leads us to include in the model the orientation of the cartesian coordinate system related to the MC, (X^{NM}, Y^{NM}, Z^{NM}), with respect to the GSE one, (X^{GSE}, Y^{GSE}, Z^{GSE}). This orientation is determined by three angular parameters: the latitude of the axis of the cloud, θ, its longitude, ϕ, and the angle associated with the orientation of the cross-section of the MC, ξ. In Figure 1b–d we show these angles.

From the fitting of the model to the experimental data we get nine parameters: related to the orientation of the clouds and the geometry of their cross-section (θ, ϕ, ξ, η, y_0); the behaviour of the plasma (α, λ); the magnetic field at the cloud axis, B_y^0; and t_0, the parameter associated with the expansion of the cloud. In Table I we show the values obtained for these parameters for all the clouds considered in the present work. Instead of η we detail the factor $\varepsilon = \sin \eta / \cos \eta$, expressed in %, directly related to the eccentricity of the cross-section (Hidalgo, 2003). Additionally, for every cloud we give the helicity of the magnetic field lines, H, and the χ^2 function. Finally, at the last column, the most likely coronal mass ejection (CME) associated with every event is given.



(a)

(b)

Figure 2. (a) Poloidal component of the magnetic field over the cross-section of the MC. The elliptical structure of its cross-section clearly appears. (b) Shape of the current density $\vec{j}$ as deduced from Equation (8).

During the fitting process the nine parameters were kept free. As deduced from the magnetic field components, Equation (7), the parameters α, λ, t_0 and $\cosh\eta$ are all grouped, what causes strong dependencies between them. Thus, we have to consider carefully the values obtained for them. The only way to reduce this

TABLE I

Different parameters of the model.

MC (yy/mm/dd)	START Doy (hh)	END Doy (hh)	v_{sw} (km s^{-1})	α (10^{-19} C m^{-2}s^{-2})	λ (10^{-19} C m^{-2}s^{-2})	B_y^0 (nT)	ε (%)	ϕ^a (°)	θ (°)	ξ (°)	y_0 (UA)	t_0/t_{sat}	H	χ^2	CME
000212	43 (12.3)	44 (01)	547	590	32.8	4.8	41	143	7	−9	0.194	1.00	+	0.0016	2000/02/10 02:30:05
000221	52 (21)	22 (12)	441	≈0	4.66	10.9	49	152	34	7	0.066	13.8	−	0.0018	2000/02/17 20:06:05
000608	160 (19)	161 (21)	604	0.07	12.9	4.8	14	27	−77	65	0.040	1.53	−	0.0010	2000/06/06 15:54:05
000715	197 (06)	197 (13)	650	9,2	2.97	19.0	60	20	39	2	0.138	26.7	+	0.0005	2000/07/11 13:27:23
000715	197 (19)	198 (09)	990	7.3	15.1	6.7	40	144	24	90	0.286	3.89	+	0.0056	2000/07/14 10:54:07
000728	210 (19)	211 (09)	459	280	249	18.5	97	278	5	130	0,094	1.69	+	0.0002	2000/07/27 07:31:53 (PH)
000731	213 (22)	214 (15)	456	≈0	1.31	3.25	53	31	−3	111	0.223	16.1	+	0.0018	2000/07/28 18:30:05 (PH)
000812	225 (05)	226 (00)	576	0.33	0.59	6.2	41	158	4	123	0.112	88.3	+	0.0049	2000/08/09 16:30:05
000918	262 (02)	262 (15)	772	7.85	6.49	19.7	21	103	−31	172	0.007	6.10	+	0.0010	2000/09/16 05:18:14
001003	277 (18)	278 (06)	409	0.13	18.3	6.0	45	175	21	22	0.091	5.56	+	0.0005	2000/09/30 18:06:05 (PH)

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TABLE I
(*Continued*)

MC (yy/mm/dd)	START Doy (hh)	END Doy (hh)	v_{sw} (km s^{-1})	α (10^{-19} C m^{-2}s^{-2})	λ (10^{-19} C m^{-2}s^{-2})	B_y^0 (nT)	ε (%)	ϕ^a (°)	θ (°)	ξ (°)	y_0 (UA)	t_0/t_{sat}	H	χ^2	CME
001013	287 (19)	288 (18)	401	0.006	2.76	4.5	70	49	−34	54	0.145	13.6	−	0.0011	2000/10/09 23:26:06
001029	303 (02)	303 (23)	375	3.92	3.16	13.2	45	33	−8	146	0.191	6.11	+	0.0008	2000/10/25 08:26:05
001106	311 (23)	312 (19)	535	1.87	23.4	4.02	27	357	−0.4	128	0.044	3.99	+	0.0031	2000/11/03 18:26:06
010319	78 (21)	79 (13)	423	50.3	41.8	12.3	70	179	6	19	0.024	11.04	−	0.0010	2001/03/16 3:50:05 (PH)
010320	79 (18)	80 (23)	343	34.4	121	1.7	95	39	−8	59	0.098	1.48	+	0.0004	2001/03/18 02:26:05
010404	94 (21.2)	95 (08)	740	31.8	120	7.1	62	314	11	179	0.039	1.51	+	0.0006	2001/04/02 12:50:05 (PH)
010411	102 (23.2)	102 (16)	660	128	320	8.4	38	166	−6	176	0.024	1.19	−	0.0016	2001/04/10 05:30:00
010422	112 (02)	113 (00)	325	0.63	3.4	0.6	32	359	−1	52	0.015	48.7	+	0.0005	2001/04/20 10:06:05
010429	119 (02)	119 (15)	631	≈0	0.84	2.3	39	211	−16	102	0.272	16.8	+	0.0011	2001/04/26 12:30.05

(*Continued on next page*).

TABLE I
(*Continued*)

MC (yy/mm/dd)	START Doy (hh)	END Doy (hh)	v_{sw} (km s^{-1})	α (10^{-19} C m^{-2}s^{-2})	λ (10^{-19} C m^{-2}s^{-2})	B_y^0 (nT)	ε (%)	ϕ^a (°)	θ (°)	ξ (°)	y_0 (UA)	t_0/t_{sat}	H	χ^2	CME
010528	148 (12)	149 (07)	412	4×10^{-6}	1.44	2.77	47	154	−14	99	0.184	11.2	+	0.0024	2001/05/25 17:26:06 (PH)
010710	191 (17)	192 (19)	352	24.6	39.6	3.6	42	182	1	123	0.011	3.67	+	0.0010	2001/07/05 03:54:05
011031	304 (23)	306 (02)	354	2.91	104	3.0	44	5	−3	77	0.011	2.26	+	0.0011	2001/10/28 00:24:05 (PH)
011124	328 (18)	329 (13)	725	16.2	3.33	10.6	6	179	11	111	0.262	1.15	+	0.0023	2001/11/21 14:06:05
020319	78 (23)	79 (13)	369	0.37	4.55	5.79	21	178	2	115	0.095	6.52	+	0.0006	2002/03/18 02:54:06
020324	83 (04)	83 (22)	431	11.9	13.8	5.9	45	136	8	153	0.033	4.31	+	0.0022	2002/03/20 23:54:05 (PH)
020325	84 (06)	84 (23)	449	79.9	95.0	4.1	29	173	−15	145	0.039	1.26	+	0.0009	2002/03/22 11:06:05
020420	110 (14)	111 (14)	497	573	7.96	7.4	27	313	1	87	0.0006	1.30	−	0.0006	2002/04/17 08:26:05
020519	139 (06)	140 (04)	457	1.22	1.40	6.0	25	90	37	18	0.163	5.96	+	0.0004	2002/05/16 00:50:05
020523	143 (23)	144 (20)	701	10.3	8.96	6.2	62	290	−17	14	0.307	1.58	+	0.0003	2002/05/22 03:50:05

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TABLE I
(*Continued*)

MC (yy/mm/dd)	START Doy (hh)	END Doy (hh)	v_{sw} (km s^{-1})	α (10^{-19} C m^{-2}s^{-2})	λ (10^{-19} C m^{-2}s^{-2})	B_y^0 (nT)	ε (%)	ϕ[a] (°)	θ (°)	ξ (°)	y_0 (UA)	t_0/t_{sat}	H	χ^2	CME
020801	213 (10)	213 (21)	454	4.98	12.7	6×10^{-3}	40	342	0	70	0.047	10.3	–	0.0037	2002/07/29 12:07:30
020802	214 (08)	214 (22)	490	1.81	19.7	1.7	55	160	5	67	0.106	3.72	+	0.0005	2002/07/29 23:30:05 (PH)
030127	27 (02)	27 (16)	515	12.4	7.3	9.1	19	185	16	146	0.239	1.4	+	0.0050	2003/01/23 23:30:31 (PH)
030320	79 (13)	79 (22)	669	0.63	20.5	5.4	50	353	−30	167	0.129	3.3	–	0.0010	2003/03/18 13:54:05
031029	302 (11)	302 (23)	1200	≈0	29.4	19	35	125	55	34	0.586	1.43	+	0.0056	2003/10/28 11:30:05
031031	304 (02)	304 (12)	1119	≈0	141	13.5	64	140	−48	161	0.053	1.34	+	0.0022	2003/10/29 20:54:05

The first three columns identify the MC with its corresponding start and end times. The fourth column gives the mean solar wind velocity at the cloud interval. The following columns detail the different parameters of the model obtained for every MC analysed: the normal, α, and axial, λ, factors of the plasma current density; the magnetic field at the cloud axis, B_y^0; the parameter associated with the eccentricity of its cross-section, ε; the attitude (latitude, θ, and longitude, ϕ) of the cloud axis; the orientation of its cross-section, ξ; the closest-approach distance of the spacecraft to the cloud axis, y_0; and the characteristic time ratio, t_0/t_{sat}. In the following columns we show the helicity of the magnetic field lines, the χ^2 function and, finally, the most probable CME each MC is associated with.

[a]The ϕ values detailed in the column refer to the Sun–Earth line.

uncertainty is introducing in the study not only the magnetic field topology but also the plasma behaviour. On the other hand, the parameters associated with the orientation of the clouds are more reliable.

3. Results and Discussion

The data of the magnetic field and plasma used in our analysis have been provided by WIND and ACE spacecrafts. In order to identify the MCs in the solar wind we have needed the list of the halo CMEs given by LASCO, boarded in SOHO, looking for the encounter with the cloud at 1 AU several days after the appearance of a CME at the Sun.

We have studied all the MCs observed by WIND and ACE during the period 2000–2003. Among them only the Bastille day event, and more recently the clouds of October 2003, have been extensively analysed in literature.

However, there is a list of results, corresponding to the orientation parameters and the maximum distance approach to the cloud axis, obtained by Lepping (1990), analysing all these clouds with the circular cross-section model of Burlaga. These results are published in the Lepping's website page *http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub2p.html*. Although he gives the parameters of the fitting, he does not show the figures with the fits, providing only the χ^2 function

$$\chi^2 = \frac{1}{3N - p}\left[\left(B_x^{\exp} - B_x^{\mathrm{teo}}\right)^2 + \left(B_y^{\exp} - B_y^{\mathrm{teo}}\right)^2 + \left(B_z^{\exp} - B_z^{\mathrm{teo}}\right)^2\right],$$

where N is the number of the experimental points considered in the fitting with the model and p its corresponding number of parameters (nine in our case).

One of the main difficulties of the study of MCs (already an open problem) is the choice of their boundaries (Wei *et al.*, 2003). We mentioned above the three signatures that should appear in the experimental data in order to identify a MC, (Burlaga *et al.*, 1981). However, they are not always clearly defined. Although the entrance of the spacecraft into the cloud is in general established after its forward-shock, however, the exit is not usually so well defined, neither in the magnetic field strength nor in the plasma behaviour. Most of the times this cause ambiguity and arbitrariness in the choice of this rear limit. In fact, many of the boundaries we have taken for the MCs are not the same as the Lepping's ones.

In Figures 3–7 the boundaries of the clouds have been marked with dotted vertical lines.

In Figure 3 we show the event of 31 July 2000 measured by ACE. Looking at the velocity of the solar wind, we see that this cloud does not expand significantly during the passage of the spacecraft. This leads us to think that a static

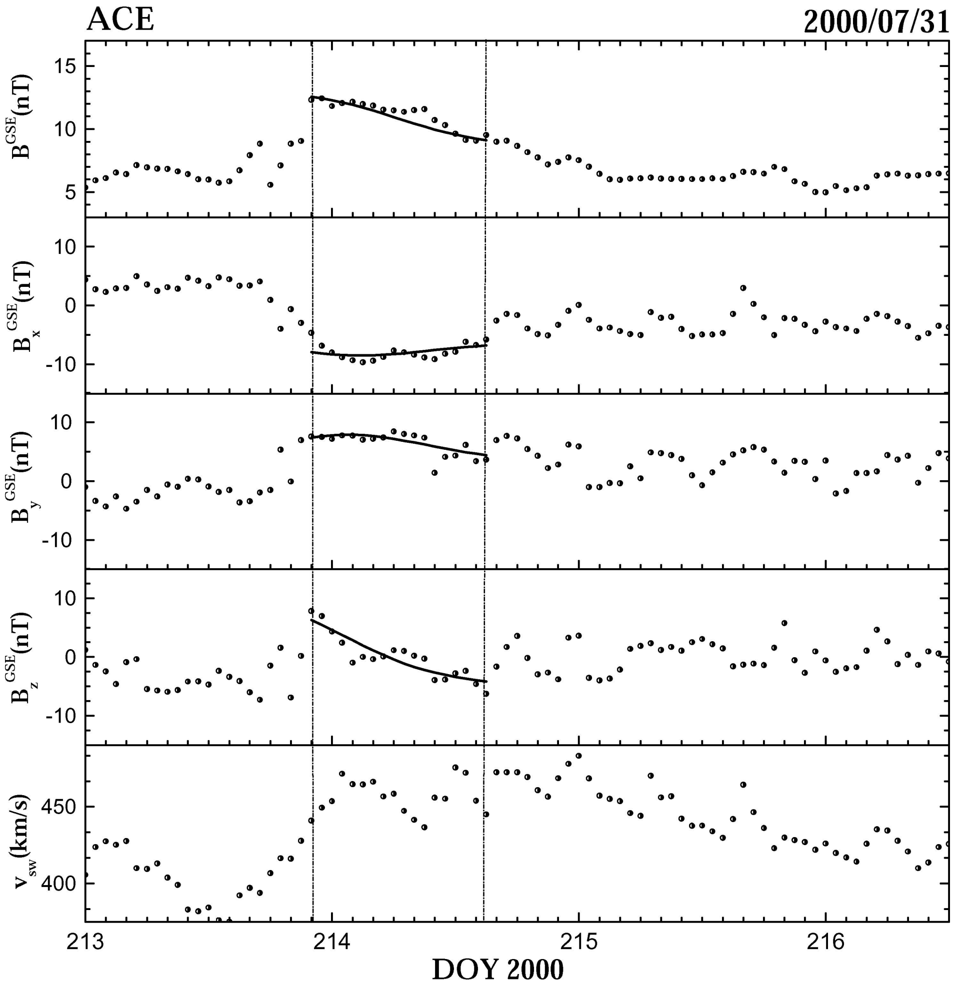


Figure 3. Magnetic cloud of 31 July 2000 as measured by ACE spacecraft. In the graphs are presented the strength of the magnetic field, B, the three GSE components, B_x, B_y, and B_z and, finally, the velocity of the solar wind, v_{SW}. The boundaries of the cloud are marked with *vertical dotted lines*. Superimposed to the experimental data the fit obtained with our model is presented.

model (without expansion) could be a good approximation (Hidalgo *et al.*, 2002). However, the shape of the magnetic field strength, which has not the same value at the entrance of the spacecraft with respect to the exit, implies the presence of a deformation in the cross-section, what makes a circular cross-section model not to be adequate for its analysis. Fitting the GSE magnetic field components, we can see that our elliptical cross-section model (Hidalgo, 2003, 2005) accurately reproduces not only the profile of every component of the magnetic field, but also its strength. In particular the deformation of the cloud is confirmed by the ε value we obtained, which is close to 50%.

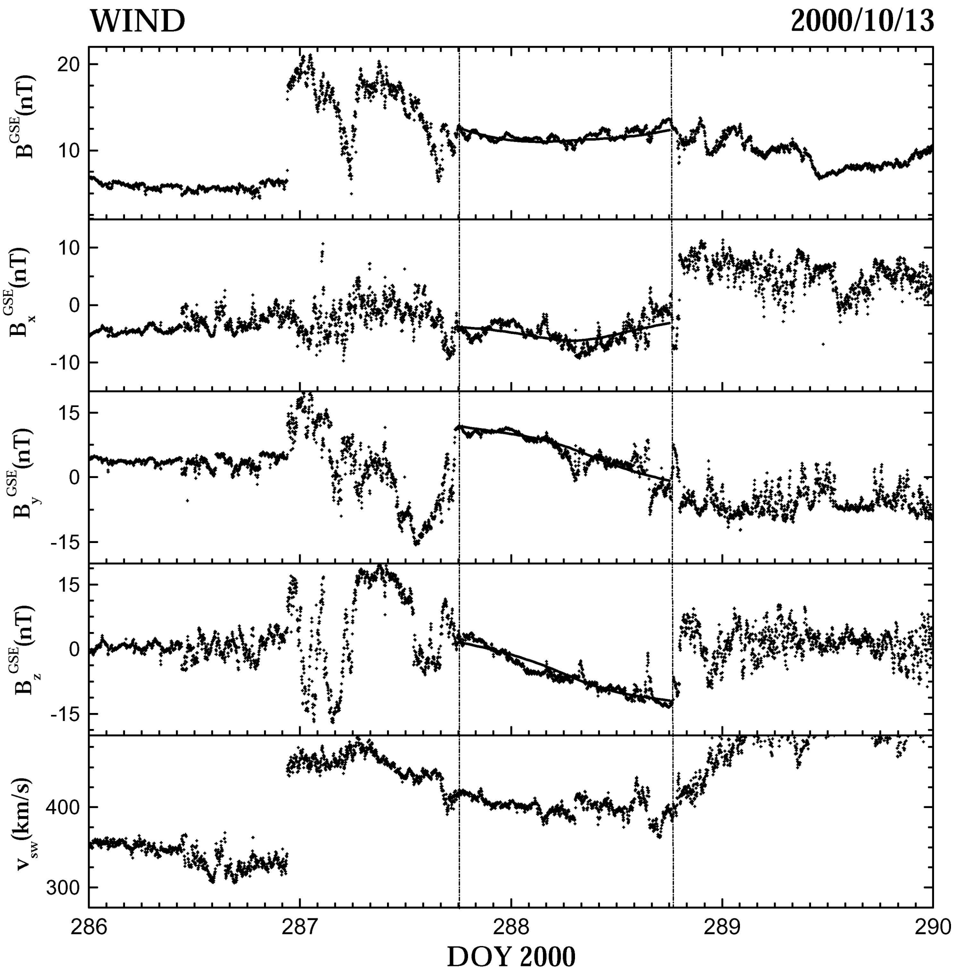
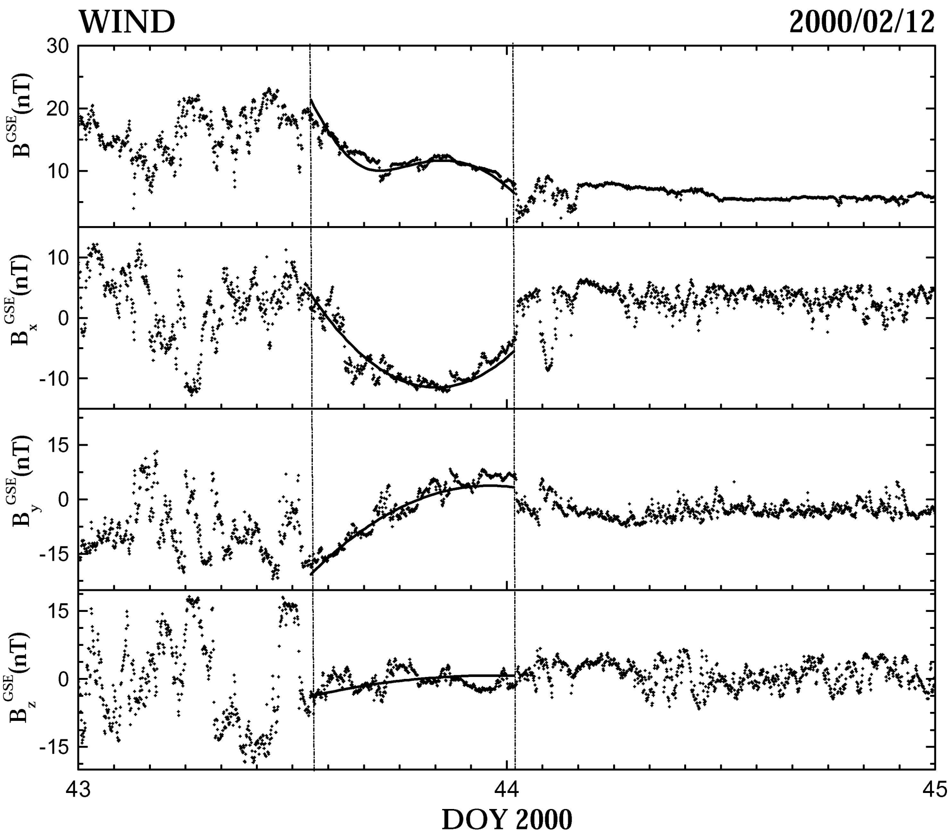


Figure 4. The same data as in Figure 3, now for the cloud of 13 October 2000: B, B_x, B_y, B_z, and v_{SW}. The fit of our model is presented superimposed to the experimental data.

In Figure 4 we show the event on day 13 October 2000 measured by the Wind spacecraft. Looking at the velocity of the solar wind we can assume that the cross-section of the cloud does not expand, or this expansion is not significant. This fact is confirmed by the values obtained for α and t_0. On the other hand, the strength of the magnetic field profile is indicative of a circular cross-section (the model gives a value of ε near 70%).

Figures 5a, b and c show typical fits obtained with our elliptical model for clouds with very different magnetic field strengths. They correspond to events observed on 12 February 2000, (Figure 5a), 22 April 2001, (Figure 5b), and 19 May 2002, (Figure 5c) all of them measured by Wind. For the first event the solar wind velocity is almost constant at the cloud interval while at the second and third clouds it decreases. For the three MCs the fits are excellent.

Concerning the boundaries of the clouds, we have also analysed the effect of these choices over the parameters. In Figure 6 we show the obtained fits of the event on day 18 September 2000 depending on the limits chosen. We have taken two different intervals although in both the beginning of the cloud is the same, delimited by the forward-shock. With respect to the end, one of the common criteria established, the appearance of a minimum in the thermal velocity, is not useful in the present case. We have to look at the diagonal components of the electron tensor pressure (or its trace) where that rear boundary is better defined. Viewing this we have chosen two different cloud intervals. The parameters obtained with the shorter interval are detailed in Table I. In particular for the orientation we find $\phi = 103°$ and $\theta = 31°$. On the other hand for the wider interval we have obtained $\phi = 178°$



(a)

Figure 5. Fittings for the clouds on days (a)12 February of 2000; (b)22 April 2001; (c)19 May 2002. In all the three plots are shown the magnetic field strength and its three GSE components.

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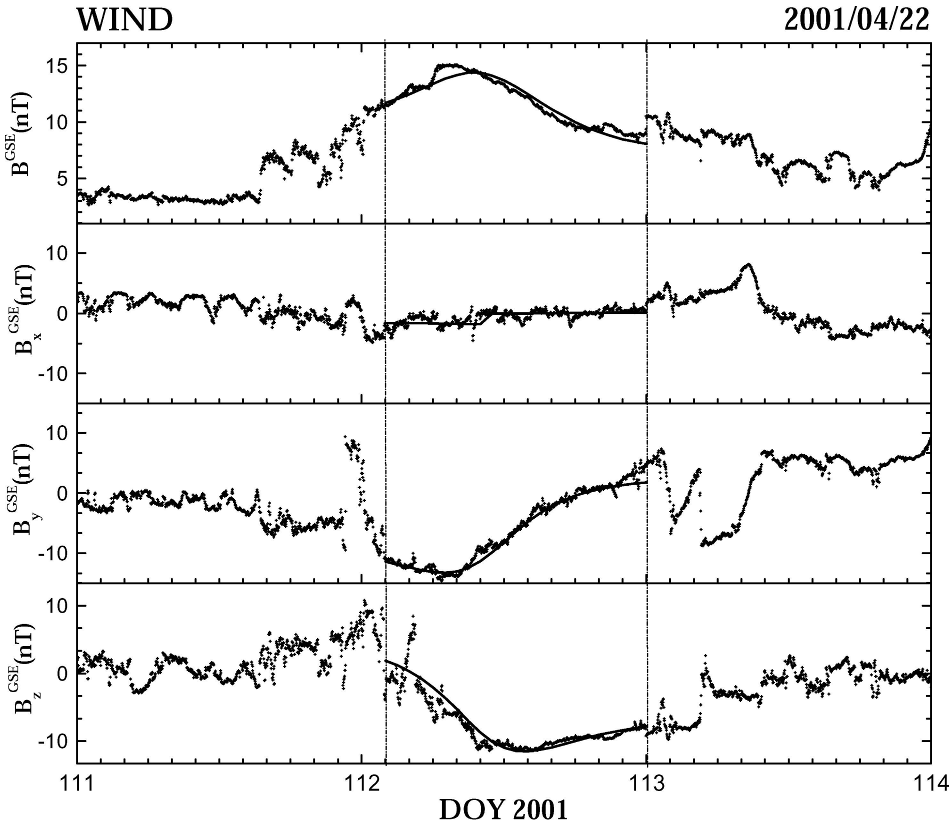


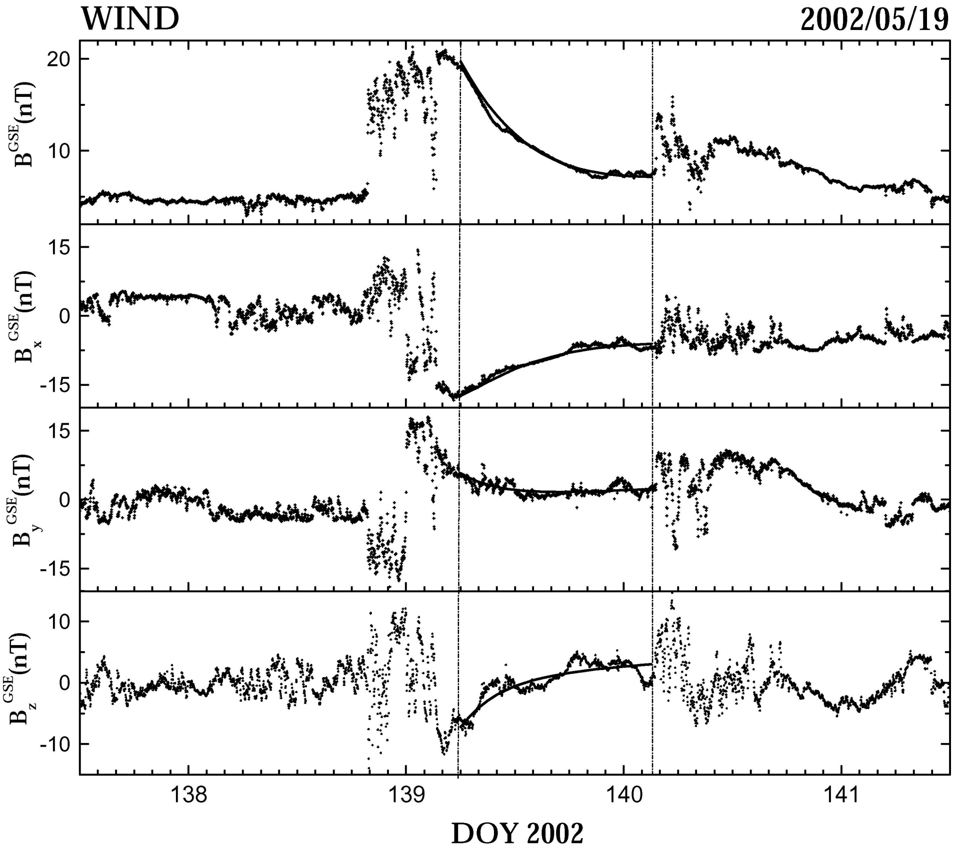
(b)

Figure 5. (*Continued*).

and $\theta = 0°$. Thus, we can see how critical the choice of the boundaries of the MC could be.

Comparing our MCs list with the Lepping one we find some differences. In particular he identifies only one cloud on 19 March 2001. However, from our point of view, that event corresponds to two clouds (whose parameters are detailed in Table I). This fact is confirmed by the behaviour of the plasma and the appearance of two CMEs at the Sun surface which clearly justify the presence of two clouds in the interplanetary medium. On the other hand, to consider only one event would imply a so large cloud (of the order of two days), that the expansion of the cloud during its travel from the Sun should have been extremely fast; but at the light of the behaviour of the solar wind velocity we can conclude that this is not the case.

These two clouds were also analysed in the paper by Hidalgo (2003). For the second one, corresponding to the 20 March 2001, similar orientation parameters are obtained. But there are discrepancies between both fits for the first cloud. This is due to the differences in the MC time interval considered in each work.



(c)

Figure 5. (*Continued*).

A similar problem arises with the event of 24 March 2002. From our point of view it corresponds to two clouds, one on day 24 March and another one on day 25 March. In the solar wind velocity the existence of these two events is clear. Even more, two precursors of halo CMEs appeared at the Sun, associated with the first cloud on 20 March and on 22 March related to the second one.

Another discrepancy we find is related to the event of 30 September 2002. The solar wind velocity increases at the time instead of it, which is a clear evidence of a corotating interaction region (CIR).

On the other hand, we think we have identified two new clouds not included in the Lepping list.

The first appears on 8 June 2000, Figure 7a, and is related to a halo CME observed at 15:54 on 6 January 2000. The magnetic field strength has a mean value of the order of 20 nT, with a smooth rotation in its y component (from our fitting we deduce a latitude of 77°). We have used the forward-shock associated with the

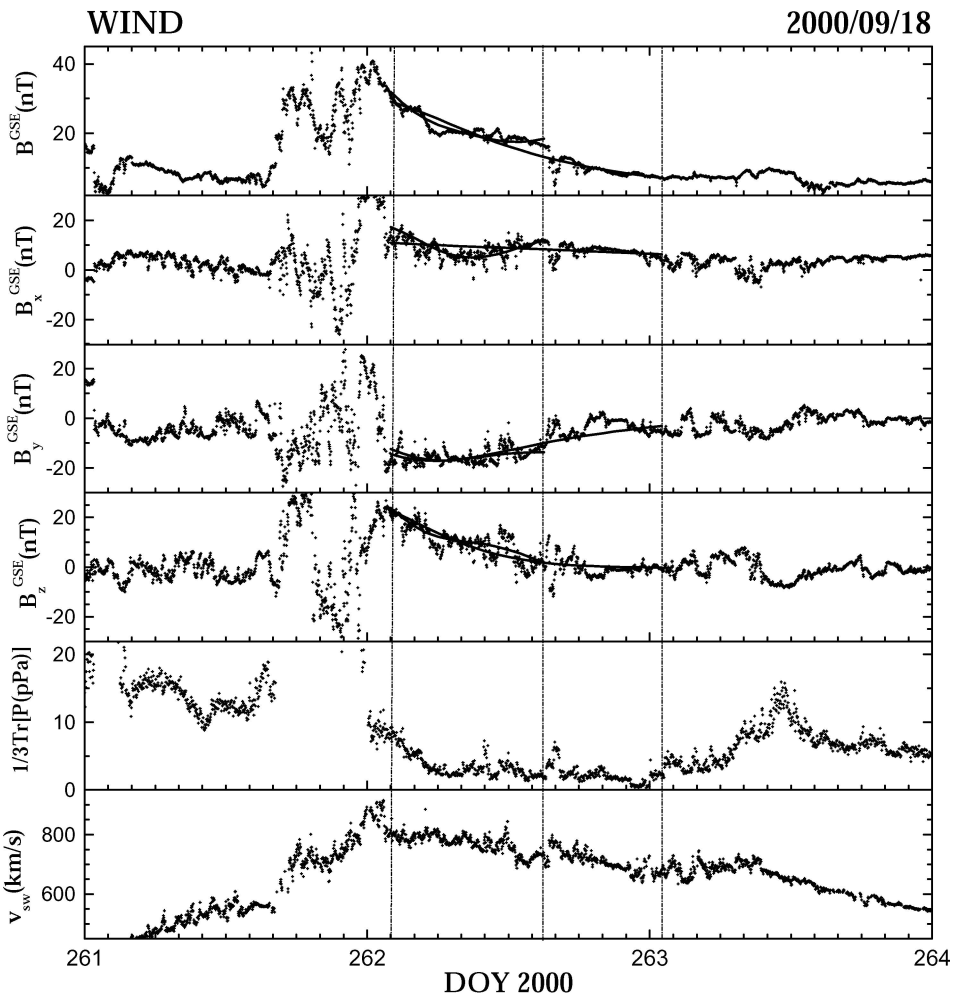


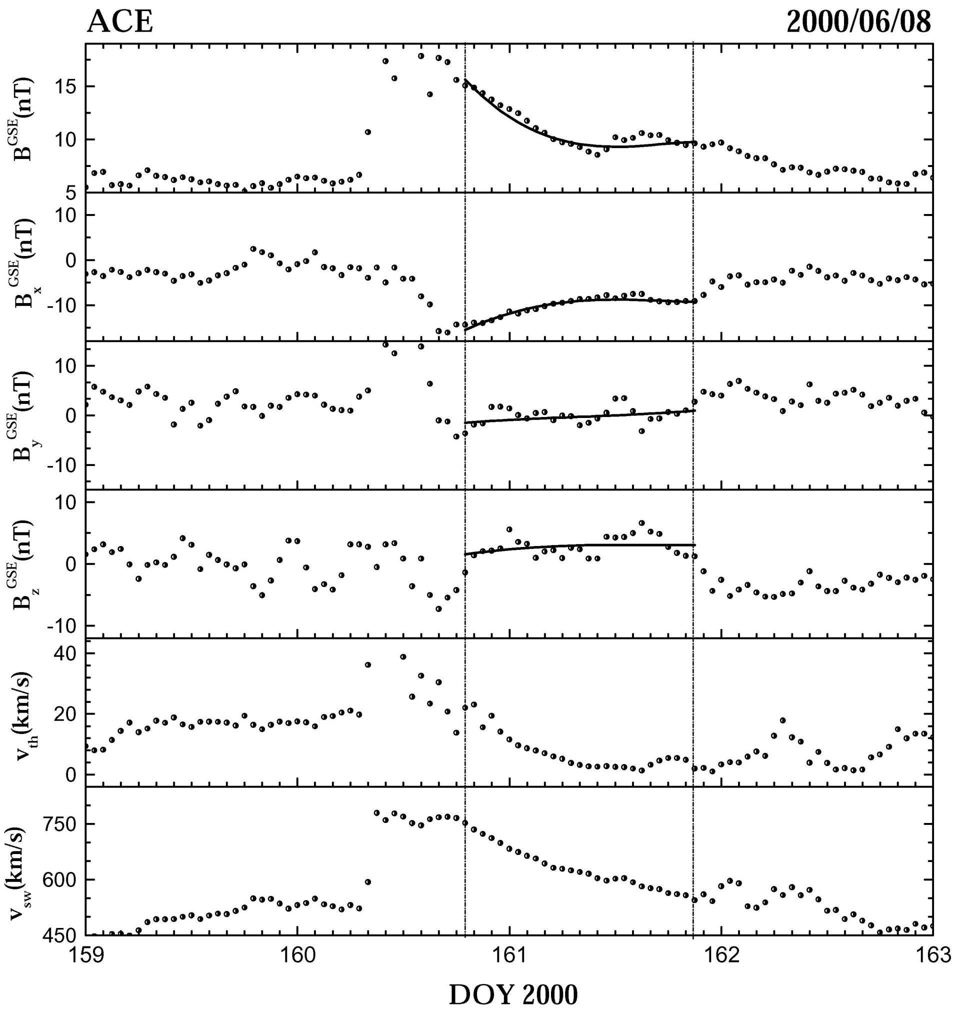
Figure 6. MC on day 18 September 2000. The fit is superimposed to the experimental data which correspond to the magnetic field strength, its three components, the trace of the electron pressure tensor and the velocity of the solar wind velocity.

cloud in order to define the entrance of the spacecraft into it, and the solar wind velocity to establish the rear boundary.

The second new identification corresponds to the event measured on 27 January 2003, Figure 7b. It is related to a partial halo CME on the 23 January 2003 at 23:30. The ions pressure shows a well defined minimum and the solar wind velocity decreases quickly, i.e., the cloud has a fast expansion. The model provides a small value for t_0/t_{sat} and a large value of α. A peculiarity of this cloud, as it appears in the magnetic field strength, is the lack of a forward-shock; this fact is not too usual although is observed in some events (Bothmer and Schwenn, 1998).

Before establishing the comparison of the global results between the model of Lepping and ours we have to take into account the different nature of both models. The first has a force-free character and assumes a circular cross-section; meanwhile ours does not impose the force-free condition and, besides, supposes an elliptical distortion in the cross-section of the MC due to its movement in the interplanetary medium.

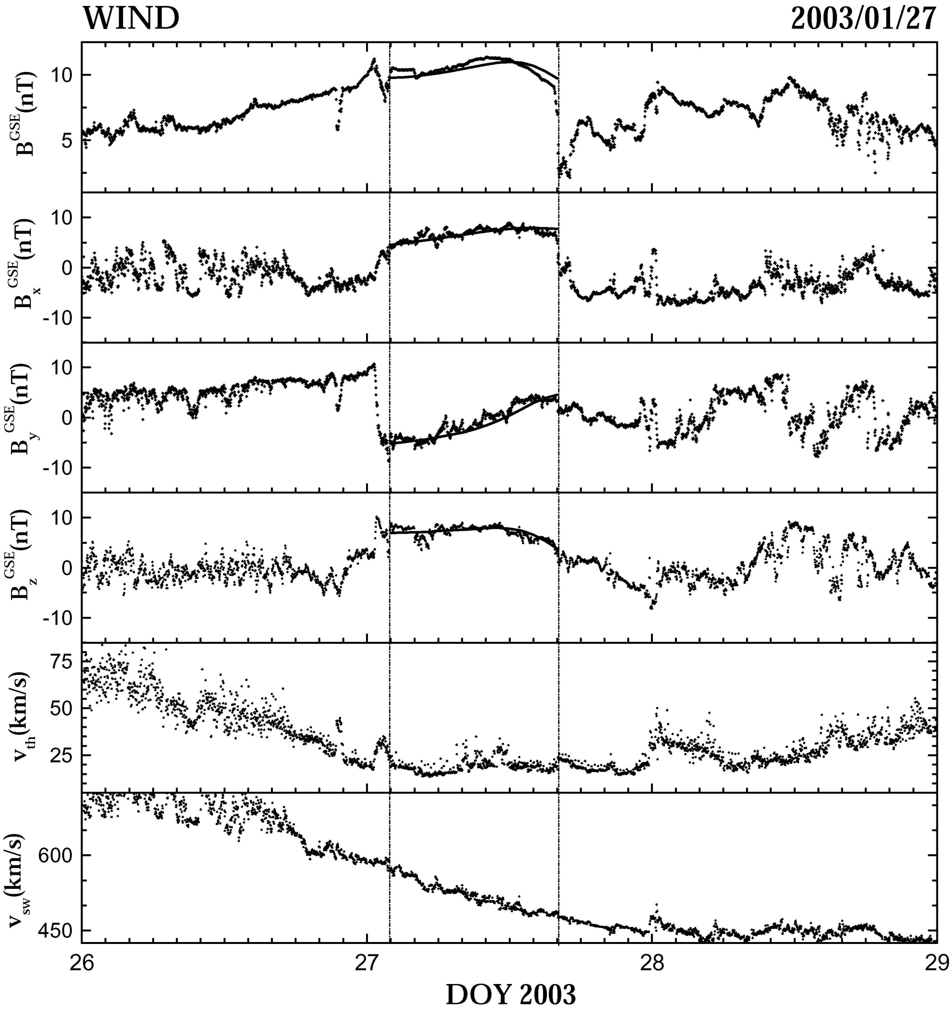
Because both models considered a local cylindrical geometry for the MC, there are three common parameters: the orientation of the cloud axis, i.e., the latitude



(a)

Figure 7. Events on (a) 8 June 2000 and (b) 27 January 2003. The graphs are the same as in Figure 6. The trace of the electron pressure tensor has been changed for the thermal velocity.

(*Continued on next page*)



(b)

Figure 7. (*Continued*).

and the longitude, and the distance of maximum approach to the cloud axis. Additionally, from a physical point of view, they also give the helicity of the magnetic field.

Although we cannot compare the profiles of the fits obtained for the magnetic field components and its strength, the χ^2 function can give us an idea of the degree of optimisation of the fitting. For all events analysed we have found lower values.

In Figure 8 we present two comparative histograms of the results of both models for the longitude (a), and latitude (b), for all the clouds analysed. (We have not included the MCs for which we are in disagreement.)

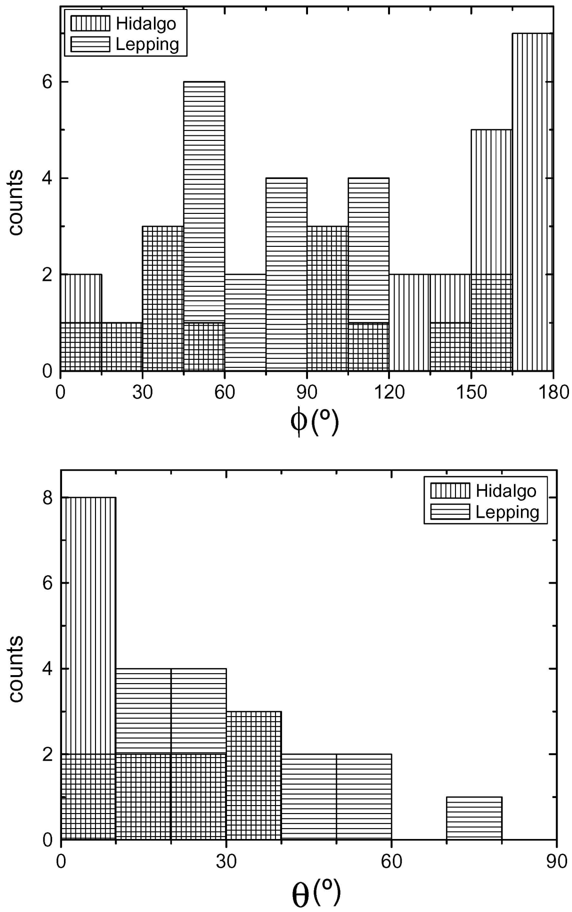


Figure 8. Histograms corresponding to the global results obtained with our model for all the clouds studied in the current work. (a) Longitude and (b) latitude. In both figures are superimposed the results obtained with Burlaga's model by Lepping.

The global results for the latitude are similar with both models. However, there are discrepancies in the longitude. Thus, while Lepping find that most of the clouds passes through the spacecraft with longitudes at the interval 90° or 270°, both respect to the Sun–Earth line, we obtain a distribution of longitudes extended over all the possible longitude interval, finding clouds with values near the Sun–Earth line.

There is an important event which has been a centre of research interest for different groups due to its geomagnetic storm implications. It corresponds to one of the most important clouds recorded in the late years; the Bastille day MC, which took place on 15 July 2000. This event has mainly been analysed in detail by Lepping *et al.* (2001), and Mulligan *et al.* (2001).

The only data available to achieve the study of this cloud correspond to the magnetic field components provided by ACE.

Because for the fitting process we need the mean solar wind velocity at the cloud interval, we have determined it by extrapolating the value corresponding to the velocity of the CME associated with this event. Then, like Lepping *et al.* (2001), we have assumed an approximate mean velocity of $1100\,\mathrm{km\,s^{-1}}$.

Mulligan and Russell's model incorporates the expansion and distortion of the cross-section of the clouds. Then we can compare with ours not only the orientation parameters but also both effects (Hidalgo, Nieves-Chinchilla, Cid, 2002).

The orientation obtained with the two models differs one to the other. Even more, although in some cases the boundaries chosen for the fitting are the same, the profiles of the fits are very different. Lepping *et al.* (2001) obtained a longitude $\phi_L = 46^\circ$ and a latitude $\theta_L = 55^\circ$. Taking the same time interval to analyse the event we got $\phi_H = 144^\circ$ and $\theta_H = 24^\circ$.

Mulligan and Russell (2001), studied this cloud in more detail using data of two spacecraft, ACE and NEAR. The time interval selected by the authors is larger than ours and although the entrance time of the spacecraft is the same, the rear limit is taken at 12:00 on 16 July. From the fitting they obtained $\phi_{\mathrm{MR}} = 88^\circ$ and $\theta_{\mathrm{MR}} = 37^\circ$ (with respect to the GSE system) values closer to ours. Taking into consideration their time interval we get similar results.

The other MCs profusely studied in literature correspond to the October 2003 clouds. Like the Bastille day, they caused one of the most important geomagnetic storm ever recorded. For their intrinsic interest we will analyse it in more detail in a separate work.

Finally, in the papers by Hidalgo, Nieves-Chinchilla, and Cid (2002) and Hidalgo (2003), besides the clouds of 19 March 2001, we also studied with our elliptical model the clouds on 15 July, 12 August, 18 September, 28th October 2000 and 11 March of 2001. In the clouds of 2000 the orientation parameters are quite similar although is not the case for the MC of 2001, where the boundaries were not the same in each study.

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