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A non force-free model for the magnetic field and plasma studies of magnetic clouds

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Abstract. In this work we present an improvement of a previous non force-free model for the study of the magnetic topology of the magnetic clouds (MCs) which now incorporates an analysed of the behaviour of the pressure of plasma inside the MCs. The model is fitted to the experimental data of the three components of the magnetic field in the GSE cartesian reference system and the plasma pressure measured by the spacecraft.

1 Introduction

Burlaga et al. (1981) introduced the term magnetic cloud (MC) for a structure in the solar wind that follows an interplanetary shock and shows a smooth rotation of the magnetic field. Other features of these events are low temperature and a relatively high magnetic field strength. Nowadays, the analysis of spacecraft data reveals that these events are common in the solar wind, Bothmer and Schwenn (1998) and are considered a subset of interplanetary ejecta or Coronal Mass Ejections (CMEs) in the solar wind. About 1/3 of CMEs observed in the solar wind exhibit internal field rotations, characteristic of magnetic flux ropes Gosling (1990). At present it is unclear how the flux rope topology associated with the MC arises, but there is evidence that MCs are magnetic flux ropes with helical field lines (see the review by Burlaga (1991)).

Goldstein (1983) proposed that a MC could be explained as a flux rope with a force-free configuration. Based on the force-free cylinder approach, Lepping et al. (1990) developed an algorithm that fits magnetic field. Their procedure provides the local orientation of the axis of the MC (q, f); the closest distance of approach of the spacecraft trajectory to the MC's symmetry axis (y_0); the center time (t_0); the helicity of the cloud (H); the amplitude (B_0); and the parameter a (related to the size of the cloud). Given the observed average bulk speed, the radius of the MC could be determined. The fits made with this procedure usually reproduce the observed magnetic field direction accurately, but fit only qualitatively well the magnetic field strength for most of the clouds.

Chen (1996) gave a different focus studying a flux rope formed near the Sun, which moves to the interplanetary medium. In this case the field was only due to the current inside the loop and it did not need to be force-free.

We present an improvement of a previous non force-free model which we developed for the magnetic field configuration of a magnetic cloud, Hidalgo et al. (2000) and Cid et al. (2001). Basing us on this non force-free character we calculate the pressure inside the cloud analyzing the theoretical profile obtained and comparing with the corresponding experimental data.

2 Topology for the magnetic field

We assume that we can represent a MC as a flux rope that locally is a cylinder with circular cross section. Thus, it is convenient to describe it with a cylindrical reference system. In this scenario the magnetic field lines have only two components: one along the cloud axis and the other one around it. Hence, we decompose the magnetic field into an axial component B_y and a poloidal one, B_j, (Figure 1). For the topology we assume there is no radial component, B_r=0

To obtain the mathematical expressions for those non-zero components of the magnetic field we develop the

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Maxwell equations considering a current density vector $\left(0, j_j, j_y\right)$, where we suppose j_y to be constant and the poloidal component of the current density $j_j = a\ r$, i.e., linearly dependent of the distance to the cloud axis inside the cloud, where a is a parameter of the model. This last assumption is the main difference with the work presented in Hidalgo et al. (2000) and Cid et al. (2001). Therein we assumed a constant value for the poloidal component of the current density, also one of the parameters of the fitting.

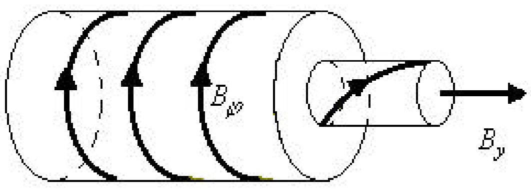

Figure 1: Magnetic field lines for the configuration assume in the developing the model.

Then, under those conditions, the solutions of the Maxwell equations are given by the expressions

$$B_j = \frac{m_0}{2} j_y r$$
$$B_y = \frac{m_0}{2} a\left(R^2 - r^2\right) \tag{1}$$

where m_0 is the vacuum permeability and R the radius of the cloud. Thus, we find that the poloidal component of the magnetic field is a consequence of the toroidal component of the current density and, reciprocally, the toroidal component of the magnetic field is due to the poloidal component of the current density.

When the cloud is observed in the solar wind its axis makes an angle q (latitude) with respect to the ecliptic plane, it has a longitude, f, in the ecliptic plane, and the spacecraft does not pass through the cloud axis. Then, in order to fit Eq. (1) to the experimental data we have to incorporate in the model this attitude of the cloud axis and the spacecraft path, transforming the equations of the magnetic field Eq. (1), determined in the cloud reference system, to the cartesian GSE coordinate system and also expressing the trajectory of the satellite as a function of this parameters. Then, we can make the fit. Once we have fixed the boundaries of the cloud, its radius is not a parameter of the model but it is determined by these boundaries and the attitude of the cloud.

Hence, at this stage, the model has five parameters: the two corresponding current density components, the longitude, latitude and the minimum distance between the spacecraft and the cloud axis, y_0. It is important to pay attention that the current density components we obtain from the fitting, assuming that the concentration of electrons and protons, n, are the same in the plasma, correspond to

$$j_j = en\left(v_j^{protons} - v_j^{electrons}\right)$$
$$j_y = en\left(v_y^{protons} - v_y^{electrons}\right)$$

where

$$\bar{v}^{electrons} = \left(0, v_j^{electrons}, v_y^{electrons}\right)$$

$$\bar{v}^{protons} = \left(0, v_j^{protons}, v_y^{protonss}\right)$$

are the vector velocity of electrons and protons, respectively.

In Figure 2 we show the fitting obtained for the cloud measured the 10 January 1997. The cloud corresponds to the interval between the two dash lines. It is shown the amplitude of the magnetic field, its three cartesian GSE components and the thermal velocity of protons, this to verify that all the criteria fixed by Burlaga (1981) to define a magnetic cloud encounter are satisfied. As it is seen, the fitting provide a very good profile for each components of the magnetic field and reproduce the behavior of magnetic cloud although the magnetic field strength is not very accurate at the beginning of the cloud. It means, our model seem to reproduce the magnetic field topology.

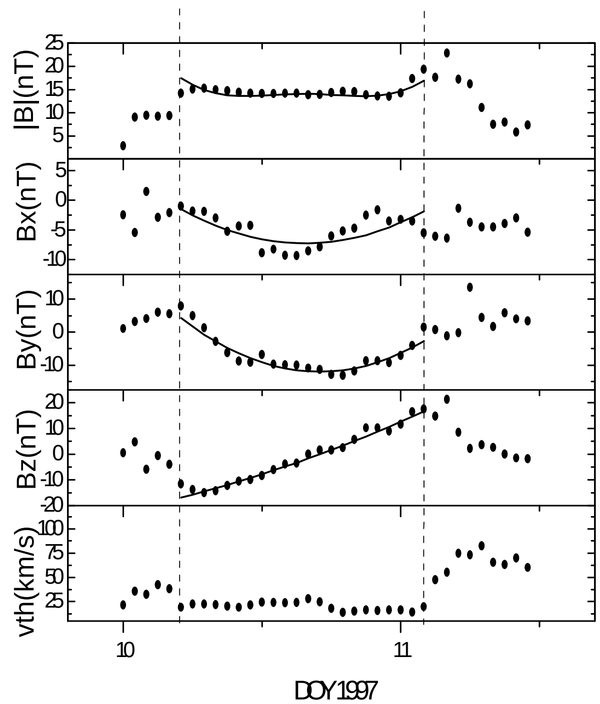

Figure 2: Magnetic field strength (B), cartesian components (Bx, By, Bz) together with thermal velocity (vth) surrounding the 10 January 1997 event observed by WIND. Dots represent the experimental data, hourly average. The solid lines are the fitted components of our modeled magnetic cloud structure. The vertical dash line represent the start and end time of the cloud.

Actually, we have fitted several clouds measured by WIND spacecraft and, in general, we find a very good fitting. In the next table is detailed the fitting parameters obtained for the different clouds analyzed, besides the start and end times.

The Helicity has not been incorporated in this table since, in this model, this is inferred of the sing of the current density components. In the analysis of this events, the helicity is positive.

Table 1: In the table is shown the five parameters obtained in the fitting of three magnetic cloud and the radius of the cloud inferred.

MC			a	j_y	q	f	y_0/R	R
EVENT (yy-mm)	STAR (doy-h)	END (doy-h)	(10^{-23} $Cm^{-3}s^{-1}$)	(10^{-12} $Cm^{-2}s^{-1}$)	(º)	(º)		(10^{10}m)
97-01	10-05	11-02	9.00	1.73	-9	246	0.11	1.58
97-10	283-23	285-00	5.53	1.01	-6	251	0.43	1.90
98-11	312-19	314-01	7.20	1.05	72	202	-0.41	1.84

3 Determination of the plasma pressure

From Eq. (1) and the current density assumptions made it is easily seen that the model proposed is non force-free. From this condition the main consequence we can get is the appearance of a plasma pressure gradient. Precisely, if we consider the Euler equation for every particle of the plasma, protons and electrons, imposing stationary conditions, we have to solve the equation

$$(\bar{v}\cdot\nabla)\bar{v} = -\frac{\nabla p}{n} + q(\bar{v}\times\bar{B})$$

where, as before, n is the density of the corresponding particle and we consider $|q|=e$. With the configuration we assume for the magnetic clouds the first term of this equality is zero and we have to solve the following equation for the plasma

$$\nabla p = qn(\bar{v}\times\bar{B}) \quad (2)$$

For the force-free models the second term of this equation is identically zero and then we have

$$\nabla p = 0$$

there is no plasma pressure gradient, i.e., the pressure is constant inside the cloud

$$p = cte$$

However, in our case, the second term of Eq. (2) is not null providing a pressure gradient. Then, solving this equation with the conditions imposed to the current density and the expressions for the magnetic field Eq. (2) we can get immediately the solution for the pressure inside the magnetic cloud

$$p = p_0 + A\left(\frac{R^2 r^2}{2} - \frac{r^4}{4}\right) - B\frac{r^2}{2} \quad (3)$$

where $A = m_0 a^2/2$, $B = m_0 j_y^2/2$ and p_0 is the pressure value at the cloud axis.

From an experimental point of view the magnitudes measured related with the plasma are the three components of the velocity of protons and electrons and the density these particles. Then in order to determine the pressure we have to calculate the temperature. Assuming that the behavior of plasma is closed to the ideal gas, once we have the temperatures of both kind of particles, T_p and T_e, we can obtained the pressure through the expression

$$p = nK(T_{protons} + T_{electrons}) \quad (4)$$

where we have supposed that the density of electrons and protons are the same, n.

However, to determine the temperatures is necessary to obtain the thermal velocity from the data of different components of the velocity, what require to make a strong supposition about the traslational velocity as a whole of the cloud. But, once we have this thermal velocity we can calculate the temperature

$$kT = \frac{1}{2} m\bar{v}_{thermal}^2$$

Next we present a comparison of the experimental data of plasma pressure (figure 3), obtained from Eq. (4) and the theoretical one, Eq. (3). The fitting carried out is independent to the corresponding to the magnetic field

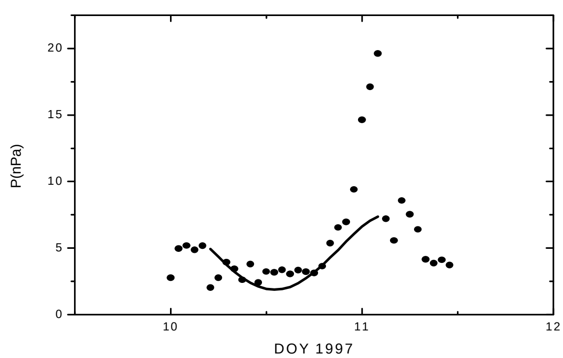

Figure 3: Plasma pressure (p) surrounding the 10 January 1997 event observed by WIND. Dots represent the plasma pressure inferred of the experimental data, hourly average. The solid line is the fitted plasma pressure.

The experimental data of the plasma pressure has been fitted separately of the experimental data of the magnetic field because the measurement time are different. The parameters, in both fitting, are not the same exactly but does not defer too. This lead us to think that same problem in the procedure can be the cause.

The plasma pressure obtained of the experimental data the event happened the 10 January 1997 has been fitted and the value of the parameters related with the attitude orientation are like the Table 1 (magnetic field fitting: θ=191º, ϕ=-4).

In the other hand, the value of the parameter related with the current density components defer in a magnitude order ($j_y=3.17\cdot10^{-13}$ $Cm^{-2}s^{-1}$, $\alpha= 2.6\cdot10^{-22}$ $Cm^{-3}s^{-1}$) of the obtained in the magnetic field fitting.

However, the results obtained give us a linework directed to the detailed pressure analysis.

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