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Dynamical evolution of magnetic flux ropes in the solar wind

M. S. Nakwacki[1*], S. Dasso[1,2], P. Démoulin[3] and C. H. Mandrini[1]

[1] *Instituto de Astronomía y Física del Espacio, Consejo Nacional de Investigaciones Científicas y Técnicas-Universidad de Buenos Aires, Buenos Aires, Argentina*

[2] *Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Buenos Aires, Argentina*

[3] *Observatoire de Paris, Laboratorie d'Etudes Spatiales et d'Instrumentation en Astrophysique, France*

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Resumen

La conservación del flujo magnético en sistemas de baja disipación, como el medio interplanetario, es usada para analizar nubes magnéticas en expansión. En particular analizamos el evento rápido y de gran tamaño observado a una unidad astronómica en el viento solar, el 9-10 de noviembre de 2004. Comparamos las observaciones magnéticas y de velocidad con dos modelos de expansión libre y autosimilar que permiten corregir la combinación de variación espacial y evolución temporal observada in situ por las sondas. Como las nubes magnéticas son objetos astrofísicos que transportan una importante cantidad de flujo magnético y helicidad desde el Sol hacia el medio interplanetario, comparamos los valores de estas magnitudes obtenidas usando los modelos mencionados con aquellos que se obtienen usando el modelo estático de Lundquist.

Palabras clave: Eyecciones de masa coronal, interplanetario, campos magnéticos, reconexión magnética, características observacionales, viento solar, perturbaciones.

Abstract

The conservation of magnetic flux in systems of very low dissipation, as the interplanetary medium, is used to analyze magnetic clouds in significant expansion. In particular, we analyze the fast and huge event observed at one astronomical unit in the solar wind on Nov. 9-10, 2004. We compare magnetic and velocity observations to two self-similar and free expansion models that allow us to correct the mixing spatial-variation/time-evolution observed in situ by the spacecrafts. As magnetic clouds are astrophysical objects that transport a very important amount of magnetic flux and helicity from the Sun to the interplanetary medium, we compare the values of these global quantities obtained using the present models with those values coming from the commonly used static Lundquist's model.

Key words: Coronal mass ejections, interplanetary, magnetic fields, magnetic reconnection, observational signatures, solar wind, disturbances.

Introduction

A subset of interplanetary coronal mass ejections (ICMEs) is formed by magnetic clouds (MCs). They are twisted magnetic flux tubes that can carry a large amount of magnetic helicity, magnetic flux, mass, and energy from the Sun to the interplanetary medium. When observed in the heliosphere they present: (i) an enhanced magnetic field, (ii) a smooth rotation of the magnetic field vector through a large angle (near to 180 degrees), and (iii) a low proton temperature (Klein & Burlaga, 1982) .

The magnetic field in MCs can be modeled by a static and axially-symmetric linear force free field, using the so called Lundquist's model (Lundquist 1950), as in e.g.: Goldstein *et al.* (1983), Burlaga (1988), Lepping *et al.* (1990), Burlaga (1995), and Lynch *et al.* (2003). However, some MCs present characteristics of expansion (e.g. larger velocity in their front than in their back), thus other models considering expansion effects on the magnetic field evolution have been used (e.g., Shimazu & Vandas, 2002; Berdichevsky *et al.*, 2003). These models take into account the decay of the magnetic field (as a consequence of the expansion of magnetized parcels of fluid and the conservation of the magnetic flux in ideal scenarios) as the spacecraft crosses the MC, and try to correct the effect of mixing spatial-variation/time-evolution in the observations to get a better determination of the distribution of the magnetic field. From these models, values for physical quantities can be estimated, such as magnetic fluxes and magnetic helicity. Quantification of magnetic helicity (H_m) in MCs is one of the keys for linking them to their solar sources (Luoni et al., 2005) and tracking them along the heliosphere (Rodriguez *et al.*, 2008). We focus our study in the calculation of H_m. In particular, in this work we study a very fast and huge MC observed in the solar wind, near Earth, on Nov. 9-10, 2004. This event and other related aspects were studied by several authors (e.g., Harra *et al.* 2007; Dasso *et al.*, 2007). This cloud is modeled using three different models: one static that considers the MC as a rigid body, and two dynamical that consider the MC in a self-similar expansion. We calculate and compare magnetic fluxes (Dasso *et al*., 2007) and estimate its magnetic helicity, showing its robustness when the different models are applied.

Observations

We analyze in situ measurements of the magnetic field components obtained by the Magnetic Field Instrument, MFI (Lepping *et al*., 1995), and plasma magnitudes obtained by the Solar Wind Experiment, SWE (Ogilvie *et al*., 1995), both aboard Wind. The observations analyzed are in GSE (Geocentric Solar Ecliptic) coordinates. The MC was observed from 09 Nov (20:30 UT) to 10 Nov (08:15 UT) (for details of the structure of the MC and its environment, see Harra *et al*., 2007 and Dasso *et al*., 2007). The cloud has a very strong magnetic field (> 40 nT) (see Fig. 1) and is in strong expansion, with a difference of 150 km/s in the observed time range (15 hours) between the front and the back region (an expansion of 10 km/s per hour, Fig. 1 shows the cloud frame). This is one of the largest velocity differences ever observed (Nakwacki *et al*., 2007). The observed magnetic field profile presents a North-West-South rotation with time; thus, the MC is formed by a left-handed flux rope with its main axis pointing roughly toward the West. We define the orientation of the cloud axis giving the latitude angle θ between the ecliptic plane and the axis, and the longitude angle φ between the projection of the axis on the ecliptic plane and the Earth-Sun direction x_{GSE} measured counterclockwise.

Models

We compare magnetic and bulk velocity observations with the three models that describe the MC magnetic field configuration and its time evolution. We use the classical linear force-free static Lundquist model (Lundquist 1950) and two models that assume an isotropic self-similar expansion of the MC, as done in Dasso *et al.* (2007). These two last models take into account the expansion of the MC due to effects of the surrounding medium while traveling along the heliosphere. The basic idea is that the cross section of the structure remains with the same shape but with a size increasing as it expands; this produces a decay of the observed MC magnetic field, which is reproduced by the models. Thus, the plasma velocity with respect to the cloud axis (V), the radius (R), the length of the cylinder (L), the azimuthal (B_φ) and the axial (B_z) components of the magnetic field are described as:

$$V(r,t) = \frac{r}{T\mathrm{f}};\ R(t) = R_{in}\,\mathrm{f};\ L(t) = L_{in}\,\mathrm{f};$$

$$B_\varphi(r,t) = B_{in\varphi}\,\mathrm{f}^{-2}\,J_1(\alpha_{in}\,r/\mathrm{f});\ B_z(r,t) = B_{inz}\,\mathrm{f}^{-2}\,J_0(\alpha_{in}\,r/\mathrm{f});$$

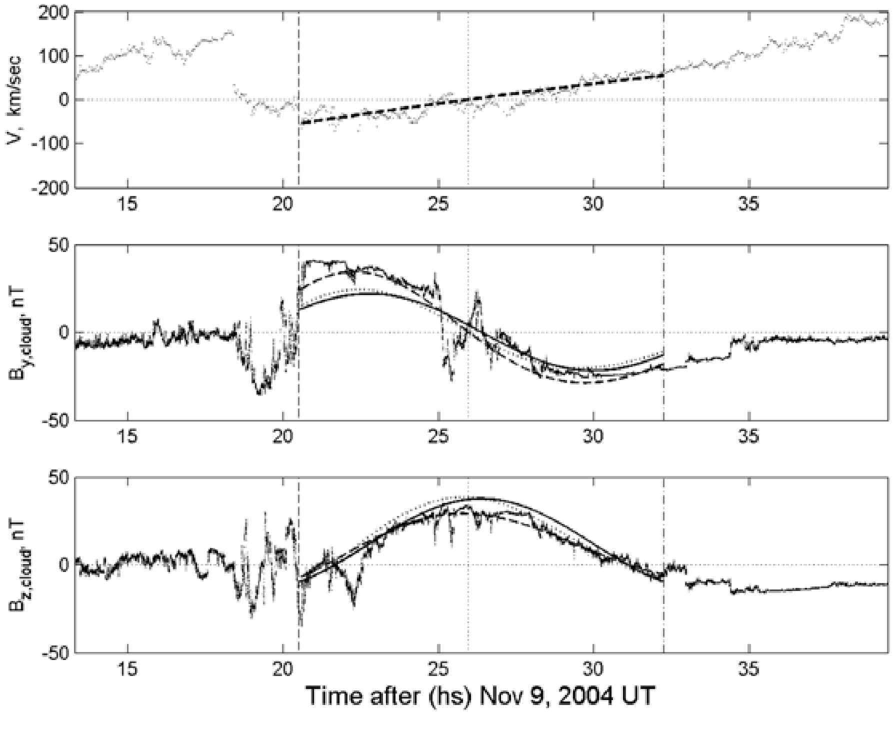

Fig. 1. Upper panel shows the velocity profile in the cloud coordinate reference frame, observations are marked with points, and fitting curve is shown in dashed line. Middle and lower panels show the magnetic field components (azimuthal and axial, respectively), observations are marked with points and models A, B, and C are shown with straight, dotted, and dashed lines, respectively.

where t_{in} is the time when the spacecraft observes the MC axis, T can be interpreted as the cloud age (i.e. the duration of the self-similar expansion prior to the start of Wind observations at 1 AU), and f is 1 for Lundquist's model (model A) and $f = 1+(t-t_{in})/T$ for the two expanding models (for a justification of this equation see Section 4.1 in Dasso *et al.*, 2007). The difference between these two models is that one of the expansion models (model B) uses the same decaying amplitudes for both magnetic field components (we force $B_{in\varphi} = B_{inz}$ which means that the configuration remains being that of Lundquist's model during the expansion, with a decay of its magnetic field intensity and of its twist α_{in}/f), while the other (model C) allows different amplitudes (we keep three degrees of freedom: α_{in}, $B_{in\varphi}$, and B_{inz}, allowing for different magnetic amplitudes in the two components, this represents a possible lack of cylindrical symmetry of the configuration, i.e., a possible oblate cross section of the MC, for an exact oblate solution see Vandas & Romashets, 2003).

We derive theoretical expressions for the magnetic fluxes (Φ_z: the magnetic flux crossing a surface perpendicular to the main axis of the MC, and Φ_φ: magnetic flux crossing a surface formed by the main axis and the direction of the spacecraft trajectory, for a deeper explanation on magnetic fluxes expressions see Dasso *et al.* (2007)). We obtain a general expression for the magnetic helicity (H_m), which includes the three models according to their degrees of freedom. Note that, as expected because all these quantities are constants of motion in an ideal medium, the time dependence is cancelled.

$$\Phi_z = \frac{2\pi}{\alpha_{in}} R_{in} B_{inz} J_1(\alpha_{in} R_{in})$$

$$\Phi_\varphi = \frac{B_{in\varphi}}{\alpha_{in}} (1 - J_0(\alpha_{in} R_{in})) L_{in}$$

$$H_m = \frac{2\pi}{\alpha_{in}} R_{in}^2 B_{inz} B_{in\varphi} (J_1^2(\alpha_{in} R_{in}) - J_0(\alpha_{in} R_{in}) J_2(\alpha_{in} R_{in})) L_{in}$$

Results

We use the minimum variance (MV, Sonnerup & Cahill, 1967) method to estimate the orientation of the MC (see e.g., Bothmer & Schwenn, 1998; Gulisano *et al.*, 2005). We apply the MV technique to the normalized magnetic field (B/|B|) to decrease the cloud 'aging' consequences. We obtain $\theta = -23°$ and $\varphi = 274°$, this result is in agreement with that found using a different method (e.g., Qui *et al.*, 2007). The observed components of the velocity (rotated to a frame oriented as the MC) are used to fit the free parameters of the expansion model (Equation 10 of Dasso et al., 2007). We get $\langle V_{x,cloud} \rangle = -794$ km/s from the observations, from the fitting we obtain T = 79hs (approx. 3.3 days), and the modeled cloud center corresponds to Nov. 10 at 01:58UT, before the central observing time for the full structure, as expected for an spatially symmetric expanding object. We find that the MC expands in a factor ~1.2, with its radius varying from R_{in} = 0.10AU to a final value of 0.12AU.

Fig. 1 shows the magnetic field profiles (axial and azimuthal components) and the radial velocity in the cloud reference frame. The velocity fitting is marked with a dashed line and the observations with points. For each magnetic field component we show the observations with points and the fitted curves for models A, B, and C with straight, dotted and dashed lines, respectively. For both components the best fitting is obtained using model C which reproduces the asymmetry caused by the expansion.

From the fitted parameters of each magnetic model, we quantify the global magnetic quantities and we respectively obtain for models A, B, and C: Φ_z = [7.4,7.4,6.4] x 10^{20} Mx, Φ_φ = [60,64,91] x 10^{20} Mx, and H_m = [-7.6,-8.2,-9.6] x 10^{42} Mx^2, where we have assumed a length (L_{in}) of 1.5AU for the cloud. Thus, these results show that taking into account the expansion effects only changes slightly the computed fluxes (with a larger change in Φ_φ), while decoupling the fits of B_φ and B_z has the largest effect. For the magnetic helicity we also find that changing the model affects slightly the results. We calculate the mean value between the three models (M = -8.5 x10^{42} Mx^2), and compare the relative difference between two of them (e.g. (H_m (A)-H_m (B))/M). We find that the main change occurs between A and C (24%), and the smallest change is between A and B (7%), while for the relative difference between both expansion models B and C it is 16%.

Conclusions

We have used three models that are based on Lundquist's solution. The first one is the classical static solution, the second one includes a self-similar expansion with the same rate in the axial and radial directions, and the third one also includes an isotropic expansion but decouples the fit of the azimuthal and the axial components of the field to take into account the observed strong azimuthal component (a possible signature of a flat cross section). The expansion rate is obtained fitting the model to the observed plasma velocity. We derive theoretical expressions to calculate global magnetic quantities from the fitted parameters for each model. From these expressions and the fitted parameters, we find Φ_z = [6.4-7.4] x 10^{20} Mx, Φ_φ = [60-91] x 10^{20} Mx, and $|H_m|$ = [7.6-9.6] x 10^{42} Mx^2. The main limitations on the flux computations are: the unknown shape of the cross section for the axial flux (Φ_z) and the distribution of the flux along the MC axis for the azimuthal flux (Φ_φ). For the helicity (H_m), the limitation is provided by both (H_m can be obtained from an integral of B_φ weighted with the accumulative axial flux, see equation 7 in Dasso *et al.*, 2006). We find that taking into account the expansion effects only changes slightly the computed fluxes and helicity, while decoupling the fits of B_φ and B_z has the largest effect. However, in this paper we show the robustness in the calculation of these quantities using both static and expansion models. For the studied case we find a relative change for H_m between ~10% and 20%.

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M. S. Nakwacki[1*], S. Dasso[1,2], P. Démoulin[3] and C. H. Mandrini[1]
[1]Instituto de Astronomía y Física del Espacio, Consejo Nacional de Investigaciones Científicas y Técnicas-Universidad de Buenos Aires, Buenos Aires, Argentina
[2]Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Buenos Aires, Argentina
[3]Observatoire de Paris, Laboratorie d'Etudes Spatiales et d'Instrumentation en Astrophysique, F-92195 Meudon Principal Cedex, France
E-mail: sdasso@iafe.uba.ar
mandrini@iafe.uba.ar
**Corresponding author: sole@iafe.uba.ar*