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On expansion of magnetic clouds in the solar wind

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Abstract. Magnetic clouds are supposed to be large interplanetary flux ropes propagating away from the Sun. Due to enhanced inner magnetic pressure, they expand during their travel. We have analyzed 21 magnetic clouds from Wind observations and fitted them by our model. Comparison of the time-dependent model with observations is shown for several cases with a detailed discussion. The model describes behavior of compared quantities satisfactorily. In addition to magnetic field vectors, also velocity vectors were modeled and it was found that radial velocity component behaves as expected. Analysis of velocity components put models under a more strict test and yields more confidence into models and derived magnetic cloud parameters.

1 Introduction

Magnetic clouds are supposed to be large interplanetary flux ropes (e.g. Burlaga, 1988). They have been identified by insitu spacecraft observations of the solar wind as special regions with enhanced magnetic field magnitude, smooth magnetic vector rotation through a large angle, and depressed proton temperature (Klein and Burlaga, 1982). Numerous model magnetic field configurations have been proposed to describe observed magnetic field profiles in magnetic clouds (e.g. Goldstein, 1983; Burlaga, 1988; Vandas et al., 1991; Bothmer and Schwenn, 1998; Mulligan and Russell, 2001; Hidalgo et al., 2002; Vandas and Romashets, 2003; Romashets and Vandas, 2003). Burlaga (1988) suggested to use a simplest configuration, a constant-alpha, axially-symmetric force-free field in a cylinder (Lundquist, 1950). This solution is widely accepted as a basic local model for magnetic clouds and yields a fairly good agreement between modeled and observed profiles of magnetic field components.

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2 Model

From the discovery of magnetic clouds it was argued that they expanded during their propagation in the heliosphere (Klein and Burlaga, 1982). This was demonstrated on velocity profiles with declining slopes: at the spacecraft entry into a magnetic cloud its expansion velocity is in direction of the background solar wind, so the total velocity is the highest, contrary to the spacecraft exit. Magnetic cloud models have been extended to include expansion effect (e.g. Osherovich et al., 1993; Hidalgo, 2003,; Vandas et al., 2006; Marubashi and Lepping, 2007). Here we use a model which represents a generalization of the Lundquist solution (Vandas et al., 2006):

$$B_r = 0, \tag{1}$$

$$B_\varphi = \frac{B_0}{(1+t/t_0)^2}\,\mathrm{J}_1\left(\frac{\alpha r}{1+t/t_0}\right), \tag{2}$$

$$B_Z = \frac{B_0}{(1+t/t_0)^2}\,\mathrm{J}_0\left(\frac{\alpha r}{1+t/t_0}\right). \tag{3}$$

Magnetic field components are given in cylindrical coordinate system r, φ, and Z. B_0 scales the magnetic field, α is related to the flux rope radius and chirality, t is the time counted from the spacecraft entry, and J_0 and J_1 are the Bessel functions. It is assumed that the flux rope expands radially only, with velocity

$$V_r = \frac{r}{t+t_0}. \tag{4}$$

The radius r_c of the cloud is increasing due to expansion according to

$$r_c = r_0\left(1+\frac{t}{t_0}\right), \tag{5}$$

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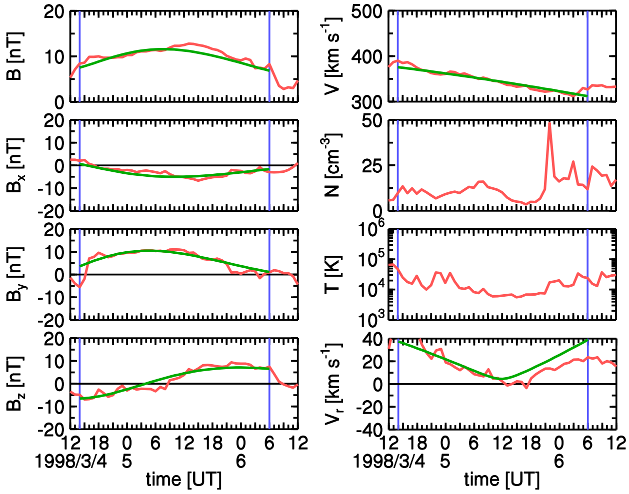

Fig. 1. Magnetic cloud of 5 March 1998. Left panels show the magnetic field magnitude B and GSE components, right panels show the solar wind velocity magnitude V, density N, proton temperature T, and radial velocity V_r (in the cloud's frame). Observations (hourly averages) are plotted in red, model values are displayed in green. The vertical blue lines indicate estimated cloud boundaries.

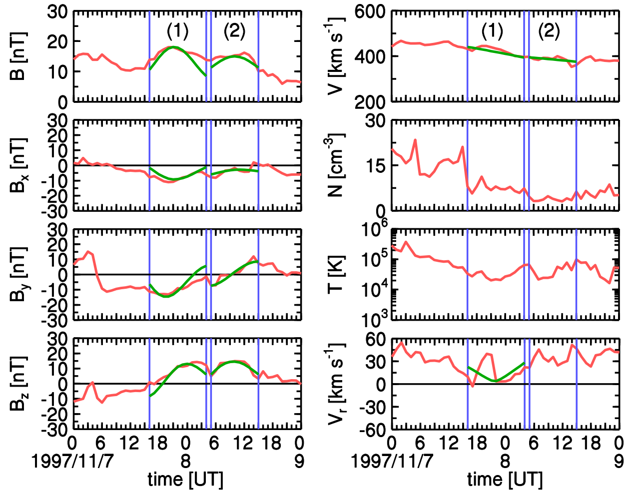

Fig. 2. Magnetic clouds of 8 November 1997. The layout of the figure is similar to Fig. 1, but instead of one event, two clouds are indicated by the labels (1) and (2).

where r_0 is the cloud radius at the spacecraft entry. The field is time dependent but force-free at any instant. The parameter t_0 is related to expansion rate and it is determined from the velocity magnitude slope.

There is an increasing interest in magnetic cloud expansion during recent years (e.g. Hidalgo, 2003; Vandas et al., 2006; Marubashi and Lepping, 2007; Dasso et al., 2007; Lepping et al., 2007, 2008; Démoulin et al., 2008). Understanding of magnetic cloud expansion can help to select among existing models and to predict magnetic cloud evolution during its propagation. The present paper does not deal with causes of magnetic cloud expansion but how well it is described by a model. Expansion has an effect on the observed magnetic field magnitude profiles in magnetic clouds: the profile does not remain symmetric (like in a static case) but its maximum is shifted towards the leading edge of a cloud. The maximum can also be shifted due to cloud interaction with the surrounding solar wind (e.g. if the cloud moves faster) but such an effect is neglected in the present analysis. Majority of papers on magnetic cloud expansion deal with solar wind velocity magnitudes inside magnetic clouds. However, models do not yield only velocity magnitude, but also velocity components and their profiles can be directly compared with observations (if they are available). A satisfactory comparison would yield more confidence into a model used. The first study of velocity vectors in magnetic clouds has been done by Wu et al. (2002). They reported that velocity did not behave as expected: they analyzed velocity vectors in Cartesian GSE (geocentric solar ecliptic) coordinates and found a clear expansion signature only in the x component. The first comparison of velocity vectors between a model and observations has been done by Vandas et al. (2005). They concluded that velocity components exhibited regular patterns but fits with a model were not satisfactory. It was due to the fact that they used GSE velocity components for comparison (and, e.g. a large observed V_Z component (along the cloud axis) would largely changed all three GSE components, while in the model this component is not specified and assumed to be zero). Here we use cylindrical components (in the cloud's system), namely the radial velocity. According to Eq. (4), the radial velocity is proportional to the distance from the axis (r): it is large at the spacecraft entry and exit, and minimum reaches at the closest approach to the axis. Therefore the radial velocity has a "U" shape inside a cloud (shape like the character U).

3 Data analysis

We have analyzed magnetic cloud observations from the magnetic cloud list given in Table 1 of Lepping et al. (2006). The table lists 82 magnetic clouds for the period 1995–2003 and we selected 21 clouds with a clear signature of expansion (i.e. a regular larger decrease of the velocity magnitude within the cloud). Hourly averages of solar wind data from OMNIWeb (http://omniweb.gsfc.nasa.gov) were used for our study. The selected cases were fitted by the above described model. Fitting procedure used a comparison of magnetic field components and velocity magnitude profiles between observations and the model. In all selected cases we found "U" shape of the radial velocity.

In some cases the agreement between model and "observed" radial velocity was quite remarkable. One such an

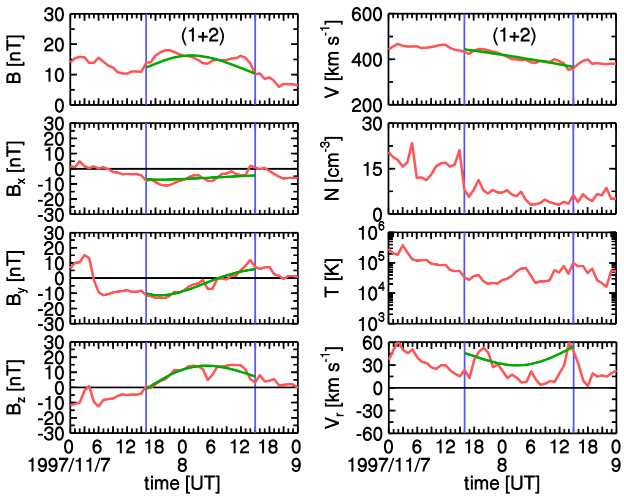

Fig. 3. The same observations as in Fig. 2, but modeled as one event (1+2).

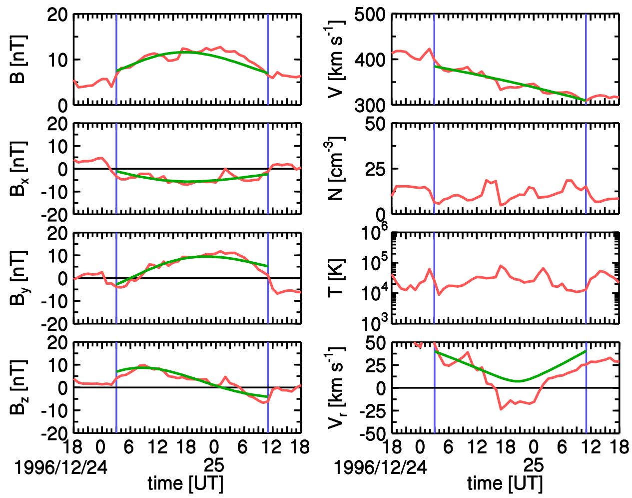

Fig. 4. Magnetic cloud of 24 December 1996. The layout of the figure is similar to Fig. 1.

example is shown in Fig. 1. Observations of the magnetic cloud of 5 March 1998 are plotted (in red) together with model values (in green). Note a clear smooth decrease of the velocity magnitude and the "U" shape of the radial velocity, features pointing to expansion, as it has been described above. Figure demonstrates a good match of the magnetic field components, as well as the magnetic field and velocity magnitudes, and a fairly good match of the radial velocity. The fit yielded the inclination $\theta_c = 21°$ of the cloud axis to the ecliptic plane, its azimuthal angle (in GSE) was $\phi_c = 125°$, the cloud radius was $r_0 = 0.15$ AU (i.e. at the entry), the closest approach was $0.11\,r_0$, and the field had left handed chirality.

Next two examples are specific cases and deserve more discussion. Fig. 2 shows solar wind observations with two magnetic clouds, labeled (1) and (2), as have been identified by Lepping et al. (2006). The result of our fit of the first cloud was not successful, as far as the V_r component is concerned: the "U" shape is modeled but not observed. The velocity slope smoothly covers whole interval (1+2), as well as magnetic field components behave rather smoothly. Therefore we extended our analysis to the whole interval (1+2) under an assumption that it is one event (cloud). The results of a fit is shown in Fig. 3 and it is quite satisfactory. Magnetic components and velocity are well fitted, the radial velocity exhibits the "U" shape (but not well described by the model profile). Our analysis suggests that one cloud was observed. According to our fit, its parameters were: inclination $\theta_c = 66°$, azimuthal angle $\phi_c = 316°$, radius $r_0 = 0.13$ AU, the closest approach $0.59\,r_0$, and right handed chirality.

According to Eq. (4), the radial velocity should be positive. But in 4 cases we obtained negative values of "observed" radial velocity, even though the "U" shape was observed. One such an example is shown in Fig. 4. The fit yielded the following parameters: inclination $\theta_c = 17°$, azimuthal angle $\phi_c = 110°$, radius $r_0 = 0.14$ AU, the closest approach $0.16\,r_0$, and right handed chirality.

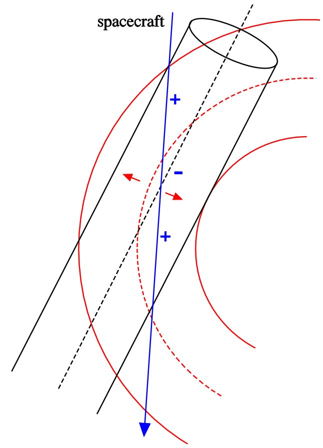

Fig. 5. Sketch: magnetic cloud as a curved flux rope (red) is approximated by a straight cylindrical flux rope (black).

The radial velocity (red) has minimum in negative values. One must be aware of the fact that the "observed" radial velocity (red) is model dependent. Therefore we write "observed" in quotas (it is subject to transformations from observed GSE components). One can suppose that a change in the flux rope axis orientation could fix the problem and get the radial velocity into positive values. But it is not the case. The magnetic field components are well fitted and even a small change in the axis orientation yields quite worse field fit but not substantially improves the behavior of the V_r component. Negative radial velocity means velocity towards the axis. We can suggest a possible explanation of this situation. Magnetic clouds as flux ropes are not straight, but loop-like, they are curved. But we fit them by a straight cylinder, see Fig. 5. Here the magnetic cloud is shown as a part of a torus and a spacecraft traverses the flux rope axis twice. The magnetic cloud expands from its axis, the dashed red curve in Fig. 5. But the model assumes a different axis, the dashed black line. When a spacecraft is close to the entry point, plasma flow is from both axes and V_r is positive (labeled + in Fig. 5). But when it crosses the magnetic cloud axis (red dashed curve) but not the model axis (black dashed line), the plasma flow is away from the cloud's axis but towards the model axis, so "observed" V_r is negative in the model frame (labeled − in Fig. 5). After crossing of the model axis, V_r again becomes positive. This is a preliminary analysis and these peculiar cases needs to be analyzed in more detail. Namely, within the frame of an expanding toroidal configurations for magnetic clouds, in a similar way to Marubashi and Lepping (2007). If the described scenario is correct, than negative radial velocities would be manifestations of flux rope curvatures.

4 Conclusions

We have analyzed 21 clouds with well expressed expansion and compared magnetic field components, velocity magnitude profile and behavior of the V_r component between observations and the model of an expanding cylindrical flux rope. The model described behavior of compared quantities satisfactorily. In 4 cases V_r profiles reached negative values, but the "U" shape (profile resembling the character U) was also observed as in other events. These cases may be a manifestation of curved magnetic cloud axes. Analysis of velocity components put models under a more strict test and yields more confidence into models and derived magnetic cloud parameters.

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