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Elliptical magnetic clouds and geomagnetic storms

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Abstract

Magnetic clouds are simple phenomena which modulate the interplanetary space and they are a subset of Interplanetary Coronal Mass Ejections. Due to the sustained orientation of their magnetic fields south- and northwards, they can influence the Earth's magnetosphere and may give rise to geomagnetic storms. Since such storms are dominant factors of space weather predictions, magnetic clouds are an important factor in this domain. We analyzed six observed magnetic clouds triggered a geomagnetic storm and simulate them in order to identify their characteristics, such as probable shapes, orientation of their axis, duration, etc. geomagnetic storms triggered by these clouds are investigated by their D_{st} indices.

Keywords: Magnetic clouds; Geomagnetic storms; Solar wind; Interplanetary magnetic field

1. Introduction

The theoretical models for the distribution of solar wind and the changes of its temperature and speed were verified by direct measurements by satellites in space. These observations became initially available from satellites VELA and IMP-6 and revealed new attributes and phenomena of solar wind (Geranios, 1980). One of the most important phenomena is the measurement of very low plasma temperatures of the solar wind. Their possible structures have specific characteristics and form plasma clouds that are ejected from the Sun and propagate into the solar wind. Plasma clouds are widely investigated, particularly when they reach the Earth, as the cause of geomagnetic storms. Specific plasma clouds today are called "magnetic clouds". The term magnetic cloud (Burlaga, 1991) is used in order to describe a specific structure of an interplanetary solar ejectum with the following characteristics (at 1 AU):

(a) Stronger magnetic field than in the ambient solar wind.
(b) Large and smooth rotation of the magnetic field with period of 1 day.
(c) Lower temperature than in the ambient solar wind.

These three criteria should be satisfied in order to recognize and characterize a structure as a magnetic cloud. It is remarkable that magnetic clouds are structures embedded into Interplanetary Coronal Mass Ejections (ICMEs) propagating in the interplanetary space. But, only a fraction of ICMEs has signatures of magnetic clouds (e.g., Richardson and Cane, 2005, have found that only about 15% of ICMEs are in this category for Solar Cycle 23).

At near-Earth distance from the Sun (1 AU) the intensity of the magnetic field of a magnetic cloud is larger than surroundings. This results to larger magnetic pressure $B^2/8\pi$. Observations show that also the total pressure $P = B^2/8\pi + nk(T_e + T_p)$ inside magnetic clouds is larger

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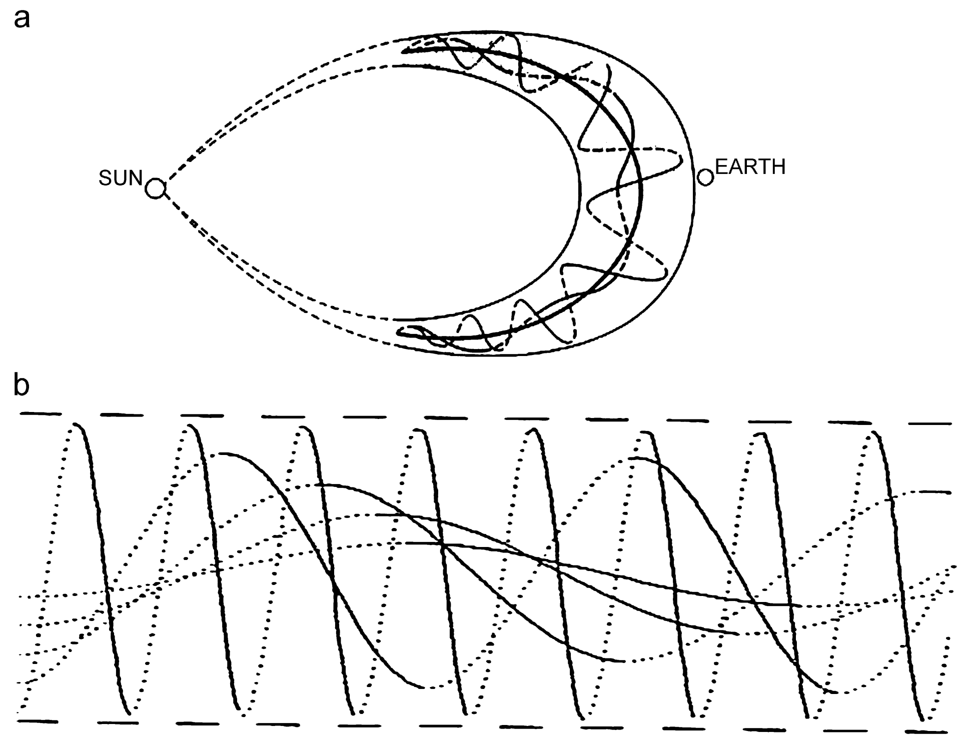

Fig. 1. (a) Magnetic cloud as a magnetic loop which can be attached to the Sun (Lepping et al., 1990, Fig. 7). Reproduced by permission of American Geophysical Union. (b) Magnetic field lines for different distances from the axis for a cylindrical magnetic cloud (Vandas et al., 1991, Fig. 1). Full lines are above the plane of the sheet and dotted lines below. Dashed line is the cloud's boundary.

than in the surrounding solar wind. Thus, the magnetic cloud will expand while it is moving far from the Sun. Namely, the expansion of the magnetic cloud is related with the characteristics of the surrounding solar wind. Thus, while the magnetic cloud is expanding, its density continuously decreases, the dynamic pressure of the cloud ($P_{\mathrm{dyn}} = \rho V^2$) and its speed decrease while the cloud travels away from the Sun. Finally, for the study of magnetic clouds, the ratio of thermal pressure to the magnetic pressure, $nk(T_e + T_p)/(B^2/8\pi)$ is also to be considered. It is obvious, that this ratio takes very small values inside magnetic clouds since from definition the intensity of magnetic field is high while the temperature is low with respect to the corresponding values in the solar wind. The number density of particles is considered to remain constant due to the conservation mass inside the cloud. For this reason many times the small values of the ratio are used as characteristics of magnetic clouds.

A lot of magnetic clouds have been detected and studied up to today (e.g., Lepping et al., 1990, 2006; Marubashi, 1997; Bothmer and Schwenn, 1998; Bothmer, 2003; Huttunen et al., 2005), although the structure and geometry of the magnetic field lines inside the cloud sometimes are hard to be determined. The topology of the magnetic field inside the magnetic cloud is still under study. As a basic structure for the cloud it is proposed cylindrical topology (Burlaga, 1991), according to which the magnetic cloud is presented as a large loop (flux-rope, Fig. 1a), which can be locally described as a cylinder. The magnetic field lines may be attached to the Sun surface and have thermal connection with the solar corona.

According to this model the magnetic field lines are wrapped around the axis of the magnetic clouds, helically. In its simplest case, it is assumed that the flux-rope cross-section is circular and the field is force-free with constant α (Lepping et al., 1990). Assuming axial symmetry, the magnetic field depends only on the radial distance from the cloud axis (Fig. 1b) and it is described by the Lundquist solution in cylindrical coordinates:

$$B_r = 0$$
$$B_\phi = B_0 J_1(\alpha, r)$$
$$B_z = B_0 J_0(\alpha, r),$$

where B_0 is the magnetic field at the axis and J_0 and J_1 are Bessel functions.

MHD numerical simulations (Vandas et al., 1995, 2002) show that initially-cylindrical flux ropes are deformed during their propagation in the solar wind and become oblate. Therefore, a more complex model assumes that the cross-section is elliptical (Vandas et al., 2006) (Fig. 2). The solution of force-free field with constant α involves Mathieu functions and depends on three parameters, B_0, α and oblateness.

The models may include cloud's expansion via time dependent parameters B_0 and α (Vandas et al., 2006), which depend on a single parameter t_0. The t_0 is determined from the slope (decrease) of the velocity magnitude profile