Magnetic cloud: An important role in space weather research

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Abstract. This issue reviews the research of an important type of interplanetary structure – magnetic cloud (MC) on five aspects including observations, theoretical model, MHD simulation, interaction of shock with MC, and multiple magnetic clouds. During the solar maximum, a majority of non-recurrent geomagnetic storms are related with magnetic clouds. Specially, the recent researches suggest that compressed magnetic clouds are able to cause much large geomagnetic storms probably. Thus, further understanding magnetic clouds is valuable for space weather research and helpful to improve the prediction level of great geomagnetic storms.

1. Introduction

As a type of interplanetary ejecta, magnetic cloud (MC) is very common. According to the statistical study, it is found that nearly half of the ejecta are MCs [Klein and Burlaga, 1982; Gosling et al., 1992; Cane et al., 1997]. Magnetic cloud can be identified by its definite signatures: enhanced magnetic field strength, long and smooth rotation of field vector and low proton temperature [Burlaga et al., 1981]. Due to its relatively regular magnetic field and evident geoeffectiveness [e.g., Burlaga et al., 1987, 2001; Tsurutani et al., 1988, 1992; Wilson, 1990; Farrugia et al., 1997], magnetic cloud has been studied for about two decades.

Magnetic cloud is thought the product of coronal mass ejection (CME) in interplanetary space [Wilson and Hildner, 1984; Gosling et al., 1992; Cane et al., 1997]. CME, one of the most intense solar activities on the Sun, constitutes large-scale ejections of mass and magnetic flux from the lower corona into the interplanetary medium. A typical CME injects roughly 10^{23} Maxwells of magnetic flux and 10^{13} kg of plasma into interplanetary space [Gosling, 1990; Webb et al., 1994]. The characteristics of CME and its geoeffectivensee have been studied by many authors [e.g., Howard et al., 1982, 1985; Hundhausen, 1988, 1993; Gosling, 1990, 1996, 1997; Wolfson and Low, 1992; Low, 1997; St. Cyr et al., 1999, 2000; Webb et al., 2000; Gopalswamy et al., 2000; Wang et al., 2002a] The CME moving in the interplanetary space is named ICME. If the ICME is satisfied with the criteria of magnetic cloud, it is called MC. Near solar activity minimum CMEs occur at a rate of 0.2 events per day, while near solar maximum they occur at a rate of 3.5 events 1/day [Webb and Howard, 1994]. For fast CME, a shock may be formed ahead it. Such event usually creates a notable disturbance of geomagnetic field if the CME is the Earth-directed.

Geomagnetic storm is primarily defined by the enhanced ring current which produces a magnetic field disturbance on the Earth. The primary causes of geomagnetic storms at Earth are strong dawn-to-dusk electric fields associated with the passage of southward directed interplanetary magnetic fields, B_s, past the Earth for sufficiently long duration. The magnetic reconnection between the southward interplanetary magnetic field (IMF) and the Earth's magnetic field provides the opportunity to transfer the solar wind energy to the inner of the Earth's magnetosphere [e.g. Dungey, 1961; Akasofu, 1981; Gonzalez et al., 1989]. As the main mechanism of energy transfer during intense geomagnetic storms, the coupling mode is developed. In all of the "coupling function" [e.g. Perreault and Akasofu, 1978; Murayama, 1986], the plasma speed V and southward components of the IMF are of the most importance. A simple criteria ($B_s \geq 10nT$ and $\Delta T \geq 3hours$) of interplanetary parameters causing intense magnetic storms (Dst $< -100nT$) was obtained by Gonzalez and Tsurutani [1987]. As one of the major sources of strong southward interplanetary magnetic fields, magnetic clouds are well correlated with the non-recurrent geomagnetic storms [Sheeley et al., 1985; Gosling et al., 1991]. Based on the 17 identifications of great geomagnetic storms during 1972 to 1983, Burlaga et al. [1987] concluded that at least 10 (59%) of the events were associated with magnetic clouds. Analyze 10 intense geomagnetic storms (Dst $< -100nT$) near solar maximum (1978-1979), Tsurutani et al. [1988] found that four (or five) of the events were related to the magnetic clouds.

Due to the important position of magnetic cloud in solar-terrestrial events, understanding the magnetic cloud is valuable and helpful for the space weather research, specially for improving the prediction level of the occurrence of intense geomagnetic storms. The purpose of this paper is to review magnetic cloud including the observations, theoretical model, numerical simulation, interaction of shock with MC, multiple magnetic clouds, and so on.

2. Observations

The concept of "magnetic cloud" was proposed by Burlaga et al. [1981]. They used the magnetic field and plasma data from five spacecraft (Voyager 1 and 2, Helios 1 and 2, and IMP 8) to analyze an example of the magnetic cloud in January, 1978. These spacecrafts were all at suitable positions for investigating this event (Figure 1). Voyager 1 and 2 were close to each other at 2 AU; Helios 1 was near the Voyager-Sun line, at 0.9 AU; and Helios 2 and IMP 8 were close to each other near 1 AU. Voyager 1 and 2 were 30°E of the Earth.

The basic characteristics of the magnetic field and flow behind the shock are illustrated by the Voyager 1 magnetic

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field and plasma data shown in Figure 2. The magnetic cloud passed the spacecraft between approximately midday on Jan. 6 and midday on Jan. 8, 1978, as indicated by the vertical dashed lines in Figure 2. Ahead of the magnetic cloud there was a region called 'shock sheath'. In this region, the magnetic field was extremely turbulent and the plasma was unusually hot and dense.

Inside the magnetic cloud, the magnetic field strength is higher than ambient average value. The nearly monotonic variation of the latitude of **B** (δ, in heliographic coordinates) from large southern directions to large northern directions. The proton temperature dropped abruptly by an order of magnitude across the cloud's boundary. **Sudden pattern in the plasma parameters has previously been shown to be characteristics of transient post-shock flows [Hundhausen, 1972; Montgomery et al., 1974; Dryer, 1975; Burlaga and King, 1979; Burlaga et al., 1980].** The solar wind speed was continuously decreasing inside the magnetic cloud. This implies that the magnetic cloud is expanding when moving away from the Sun. The speed of cloud's front is reasonably larger than that of its rear part. Thus, when a spacecraft passes through a magnetic cloud, a continuously decreasing speed curve will be plotted. The expansion of cloud can be presented by comparing the observations from different spacecrafts. The magnetic field strength profiles and the magnetic field latitude angle profiles for Voyager 1 and 2, IMP 8, and Helios 2 are compared in Figure 3. The size of it was a little more than one day at 1 AU, and nearly two days at 2 AU. If assuming that the plasma moved radially away from the Sun at a constant speed between ~ 1 AU and ~ 2 AU, the increased passage time of magnetic cloud reflects its expansion. The further study suggests that the magnetic clouds' diameters are ~ 0.28 AU averagely, lasting for about 25 hours at 1 AU [Lepping et al., 1990], and the expansion speed of magnetic cloud is inferred to be approximately $0.5v_A$ where v_A is the local Alfvèn speed [Klein and Burlaga, 1982].

By using the minimum variance analysis method [Sonnerup and Cahill, 1967], Burlaga et al. [1981] analyzed the magnetic field configurations in magnetic cloud. Figure 4 shows the results obtained from the Voyager 1 and 2 magnetic cloud data. The Z direction is the direction in which the variance of **B** is a minimum, and the X-Y plane is normal to Z. The normal to the plane of maximum variance is specified by its heliographic longitude λ_n and latitude δ_n. **B** rotates relatively smoothly through a large arc in the X-Y plane. The sketch of possible magnetic field configuration in the magnetic cloud is therefore presented in Figure 5.

Very small-scale flux rope structures were also observed in interplanetary space [Crooker et al., 1996; McComas et al., 1994; Moldwin et al., 1995; McAllister et al., 1998]. Figure 6 shows the solar wind data from 2230 UT on November 3 to 0030 UT on November 4, 1993. The magnetic field components show a clear rotation of the field. The B_z maximum and B_y minimum near the center of the structure indicate a nearly vertical flux rope axis. The low temperature combined with the strong magnetic field are characteristic of magnetic cloud. Is it magnetic cloud? This is still in debate. The much smaller scale suggests a different class of transient.

Except the three characteristics: enhanced magnetic field strength, large and smooth rotation of field vector and low proton temperature, magnetic cloud, as a type of ejecta, also has other signatures. Ejecta have relatively high values of density ratio of H_e^{++}/H^+ (> 0.05) and O^{7+}/O^{6+} (> 1) [Hirshberg et al., 1972; Ogilvie and Hirshberg, 1974; Zwickl et al., 1983; Neugebauer, 1981; Henke et al., 1988; Neugebauer and Goldstein, 1997; Gloeckler et al., 1999; Skoug et al., 1999]. The plasma β (the proton thermal pressure to magnetic pressure) is typically ~ 0.1 [Tsurutani and Gonzalez, 1995; Farrugia et al., 1993a; Burlaga et al., 2001]. By using the OMNI database, Richardson and Cane [1995] concluded that the value of $T_p/T_{exp} < 0.5$ was a reliable ejecta signature. The T_{exp} is the expected temperature corresponding to solar wind speed obtained by an empirical equations [Lopez and Freeman, 1986]. However, these signatures of ejecta are not very definitive. The ejecta with high temperature do exist [Gosling et al., 1987; Gosling, 1990; Richardson et al., 1997]. Moreover, electron temperature and density often appear to be negatively correlated with each other, and $T_e \gg T_p$ in an magnetic cloud (T_e/T_p is approximately 6 to 7 at 1 AU) [Osherovich et al., 1993, 1998; Osherovich and Burlaga, 1997; Gosling 1999]. Thus, Landau damping is not effective in such plasma and these conditions are favorable for ion-acoustic waves, which indeed have been observed in magnetic cloud, as seen in Figure 7 [Stone et al., 1995].

3. Theoretical model

3.1. Configuration of magnetic cloud

Since the concept of 'magnetic cloud' was proposed, some theoretical models have been developed to explain the properties and evolution of magnetic cloud in interplanetary medium. A approximation force-free field model was adopted to describe the magnetic cloud first. Some authors consider magnetic cloud as magnetic flux rope (Left panel in Figure 8), that is, cylindrical configuration with a two component magnetic field, one along the axis of symmetry and another in the azimuthal direction [Goldstein, 1983; Burlaga, 1988; Marubashi, 1986; Richardson et al., 1991; Farrugia et al. 1993b; Osherovich et al., 1993b, 1993c, 1995; Chen and Garren, 1993; Kumar and Rust, 1996; Hidalgo, et al., 2000, 2002]. In this view, the magnetic field of the flux rope still remains connected to the Sun possibly. Locally, however, it is thought that the curvature is negligible, and thus the structure may be approximated there by a straight cylinder. Other authors picture magnetic cloud as consisting of closed magnetic surfaces confined to a volume whose boundary is topologically equivalent to a sphere or an ellipsoid (Right panel in Figure 8) [Ivanov and Harshiladze, 1985; Ivanov et al., 1989; Dryer, 1994; Vandas et al., 1991, 1992, 1993]. This configuration implies that the magnetic field does not attach to the Sun's surface. Other simple configurations such as so called "magnetic tongues" [Gold, 1962] have been sought. However, there is almost no evidence to support this view in aspect of observations.

A force-free field can be obtain by:

$$\mu_0 \mathbf{j} = \nabla \times \mathbf{B} = \alpha \mathbf{B} \quad . \tag{1}$$

With a constant α, we obtain the second-order, linear vector differential equation

$$\nabla^2 \mathbf{B} + \alpha^2 \mathbf{B} = 0 \quad . \tag{2}$$

The general solution of equation (2) is

$$\mathbf{B} = \nabla \times (\mathbf{a}\psi) + \frac{1}{\alpha} \nabla \times \nabla \times (\mathbf{a}\psi) \quad , \tag{3}$$

where **a** is a fixed unit vector and ψ satisfies the Helmholtz equation:

$$\nabla^2\psi + \alpha^2\psi = 0 \quad . \tag{4}$$

In cylindrical coordinates (R, Φ, Z) constant α force-free field is expressed as [Barberio-Corsetti, 1973; Taylor, 1975]

$$\begin{aligned} B_R &= -B_0(\alpha^2 - n^2)^{-1/2}[\alpha J_m'(x) + (mn/x)J_m(x)] \\ &\quad \cdot \sin(m\Phi + nZ) \\ B_\Phi &= -B_0(\alpha^2 - n^2)^{-1/2}[\alpha J_m'(x) + (mn/x)J_m(x)] \\ &\quad \cdot \cos(m\Phi + nZ) \\ B_Z &= B_0 J_m(x)\cos(m\Phi + nZ) \end{aligned} \tag{5}$$

where $x \equiv (\alpha^2 - n^2)^{1/2}R$ and J_m is Bessel function of m order. The lowest mode corresponds to the cylindrically symmetric solution given by Lundquist [1950], namely,

$$\begin{aligned} B_R &= 0 \\ B_\Phi &= HB_0J_1(\alpha R) \\ B_Z &= B_0J_0(\alpha R) \end{aligned} \tag{6}$$

where $H = \pm 1$ indicate the handedness of the magnetic field. Its boundary is reached at the position of the first zero of J_0 (i.e., $R = 2.41/\alpha$). Figure 9 shows the magnetic field lines in a Lundquist flux rope. When a hypothetic spacecraft passes through it, following curves of magnetic fields are depicted (Figure 10). The total field strength has a maximum peak value, and the field direction is rotating within the flux rope. It has the peak value B_0 on the axis and the field at the boundary is $B_0/2$. Lepping et al., [1990] used this model to fit the observations, in which the results were well consistent with the observations. They found that the latitude θ and longitude ϕ of the cloud's axis were $-15^\circ \pm 47^\circ$ and $102^\circ \pm 34^\circ$ respectively. If the variation of magnetic cloud along the time (referenced to the next subsection about evolution of magnetic cloud) was considered, the curve of total magnetic field strength is shown as Figure 11 [Farrugia, 1995; Osherovich and Burlaga, 1997]. The field strength peak approaches to the front of the cloud.

In spherical polar coordinates (r, θ, ϕ), solutions of equation (4) are a linear combination of products of spherical Bessel functions, associated Legendre functions [Chandrasekhar and Kendall, 1957]

$$\begin{aligned} &\sum a_n^m \psi_n^m \\ \psi_n^m &= j_n(\alpha r)P_n^m(\cos\theta)^{\cos m\phi}_{\sin m\phi} \quad , \end{aligned} \tag{7}$$

where a_n^m is constant coefficient, j_n is spherical Bessel function of n order, and P_n^m is Legendre functions of order m and degree n. Corresponding to the lowest order solution, $m = 0$ and $n = 1$, the magnetic field is expressed by

$$\begin{aligned} B_r &= (2B_0/\alpha r)j_1(\alpha r)\cos\theta \\ B_\theta &= -(B_0/\alpha r)[\sin(\alpha r) - j_1(\alpha r)]\sin\theta \\ B_\phi &= \pm B_0 j_1(\alpha r)\sin\theta \quad . \end{aligned} \tag{8}$$

The magnetic field is often called the "classical spheromak" [Rosenbluth and Bussac. 1979]. The field line topology of the classic spheromak is shown in Figure 12. The reference boundary is at $B_r = 0$ coinciding with the first zero of j_1 at $r = 4.49/\alpha$. The shape of total magnetic field magnitude is similar to the cylindrical flux rope. However, at $r = 0$, $B = 2B_0/3$ and at the boundary the field $B = 0.33B_0\sin\theta$. Thus the amplitude of variation of this model field is larger than 2.

For magnetic cloud with closed magnetic surface, spheromak is a special type. The shape of cloud may be ellipsoidal: oblate and prolate. To describe oblate cloud, we introduce the coordinates system with coordinates η, ξ, φ

$$\begin{aligned} x &= c_2(\eta^2 + 1)^{1/2}(1 - \xi^2)^{1/2}\cos\varphi \\ y &= c_2(\eta^2 + 1)^{1/2}(1 - \xi^2)^{1/2}\sin\varphi \\ z &= c_2\eta\xi \quad , \end{aligned} \tag{9}$$

where $c_2 = (a^2 - c^2)^{1/2}$ and $\eta \in [0, \infty)$, $\xi \in [-1, 1]$, $\varphi \in [0, 2\pi)$. Here, $\eta = c/c_2$ determines the surface of the reference ellipsoid with semiaxes a, a, c. The detail of the magnetic field solution can be found in the paper by Ivanov and Harshiladze [1985]. The topology of magnetic field lines in an oblate cloud is shown in Figure 13. Magnetic field lines are not confined inside the reference ellipsoid. Some magnetic field lines are limited to only one hemisphere (as seen in Figure 13 in the top hemisphere).

For prolate cloud, the following similar coordinates system is introduced

$$\begin{aligned} x &= c_2(\eta^2 - 1)^{1/2}(1 - \xi^2)^{1/2}\cos\varphi \\ y &= c_2(\eta^2 - 1)^{1/2}(1 - \xi^2)^{1/2}\sin\varphi \\ z &= c_2\eta\xi \quad , \end{aligned} \tag{10}$$

where $c_2 = (c^2 - a^2)^{1/2}$ and $\eta \in [1, \infty)$, $\xi \in [-1, 1]$, $\varphi \in [0, 2\pi)$. Here, $\eta = c/c_2$ determines the surface of the reference ellipsoid. Figure 14 shows the topology of magnetic field. **It is similar to the oblate cloud.**

An interesting feature of oblate or prolate cloud is a double-peak structure of magnetic field magnitude [Vandas et al., 1993]. However, the double-peak structure is not always observed, and it is related to the observing path of hypothetic spacecraft (Figure 15). The double-peak structure is not consistent with the observations usually.

There are also other models of magnetic cloud, such as toroidal loop model [Chen, 1989; Chen and Garren, 1993], non-force-free model [Hidalgo et al., 2000, 2002], and so on. In these models, all of the primary features of magnetic cloud can be described clearly.

3.2. Evolution of magnetic cloud

By using cylindrically symmetrical force-free flux rope model, Kumar and Rust [1996] studied the evolution of magnetic cloud. They assumed the plasma has high electrical conductivity which means the magnetic flux along the axis of a cloud remains constant over time. From equation (6), the total axial flux is

$$\Psi_Z = B_0R_0^2k_1 = const \quad , \tag{11}$$

where R_0 is the radius of flux rope, and

$$k_1 = \frac{2\pi}{x_0^2}\int_0^{x_0} xJ_0(x)dx \tag{12}$$

is a dimensionless constant and x_0 is the first zero of J_0. The total magnetic helicity in MHD is conserved [Elsasser, 1956; Ruzmaikin and Akhmetiev, 1994; Berger and Field, 1984; Jensen and Chu, 1984], so the following equation is obtained

$$H_m = B_0^2 R_0^3 l k_2 = const \quad , \tag{13}$$

where l is the length of flux rope, and

$$k_2 = \frac{2\pi}{x_0^3}\int_0^{x_0} x[J_1^2(x) + J_0^2(x)]dx \tag{14}$$

is also a dimensionless constant. The total magnetic energy is given as

$$E_m = B_0^2 R_0^2 l k_3 \quad , \tag{15}$$

Thus, the scaling laws can be written

$$\begin{aligned} R_0 &\propto l \\ B_0 &\propto R_0^{-2} \\ E_m &\propto R_0^{-1} \\ V &\propto R_0^3 \\ n &\propto R_0^{-3} \quad , \end{aligned} \tag{16}$$

where V is the total volume and n is the number density of flux rope. When magnetic cloud moves outward from the corona, its magnetic energy is decreasing, then some energy is converted into other forms. It is the explanation of high electron temperature in magnetic cloud. If the center of the cloud moves at a constant speed v_c, then the cloud expansion speed v_{exp} is given as

$$v_{exp} = \frac{dR_0}{dt} = \frac{R_0}{d}v_c \quad , \tag{17}$$

where $d = l/\pi$ is the distance from the Sun (Figure 16). Assuming that during the cloud's passage across a spacecraft, its speed v_c and therefore v_{exp} do not vary, the slope of velocity profile is given as

$$slope = \frac{(v_c + v_{exp}) - (v_c - v_{exp})}{\Delta t} = \frac{2v_{exp}}{\Delta t} \approx \frac{v_c^2}{d} \quad , \tag{18}$$

where Δt is the time interval of passage. By compared with observations of 24 clouds, Kumar and Rust [1996] found that

$$\frac{v_c^2}{d} = 1.04 \times measured\ slope \quad , \tag{19}$$

which shows excellent agreement between theory and observations.

Nonlinear evolution of magnetic flux rope were studied by some authors [Osherovich et al., 1993b, 1993c, 1995]. A self-similar solution is obtained in this evolution. By define

$$\eta \equiv R/y(t) \quad , \tag{20}$$

where $y(t)$ is defined to be the "evolution function", the evolving magnetic field of Lundquist solution can be expressed in the following form

$$\mathbf{B}(\eta, t) = B_1(\eta)y^{-1}\mathbf{e_\Phi} + B_0(\eta)y^{-2}\mathbf{e_Z} \quad , \tag{21}$$

where $B_0(\eta)$ and $B_1(\eta)$ is the Lundquist field, namely,

$$\begin{aligned} B_0(\eta) &= B_0 J_0(\alpha\eta) \\ B_1(\eta) &= \pm B_0 J_1(\alpha\eta) \quad . \end{aligned} \tag{22}$$

By imposed a relation between the amplitude of the field, $B_0(\eta)$ and $B_1(\eta)$ as follows:

$$\chi B_0(\eta)\frac{d}{d\eta}B_0(\eta) = -\frac{B_1(\eta)}{\eta}\frac{d}{d\eta}\eta B_1(\eta) \quad , \tag{23}$$

where χ is a constant, assumed positive, the complete set of MHD equations is reduced to a second order nonlinear differential equation for the evolution function [Osherovich et al., 1993c]

$$\frac{d^2y}{dt^2} = Sy^{-3} - Qy^{-1} + Ky^{-2\gamma+1} - \nu\frac{dy}{dt} \quad , \tag{24}$$

where S, Q, K, ν and the polytropic index γ are constants. For $K = \nu = 0$ there is no expansion; the magnetic flux rope oscillates around the force-free state (in which the gradient of $B^2/2\nu_0$ is exactly balanced by the pinch force). Expansion may occur only when the gas pressure in included, and only when $\gamma < 1$ [Osherovich et al., 1993c, 1995; Osherovich and Burlaga, 1997]. The asymptotic solution of equation (24) for $t \to \infty$ is

$$y = \frac{2\gamma K}{\nu}t^{1/2\gamma} \quad . \tag{25}$$

From this solution, assuming an unvarying average bulk speed v_c of the center of the magnetic cloud. Osherovich, et al., [1993c] found that the following relationships

$$\begin{aligned} B_{max} &\propto d^{-1/\gamma} \\ T &\propto n^{\gamma-1} \quad , \end{aligned} \tag{26}$$

where d is the distance from the Sun, T is the temperature, and n is number density. The asymptotic expansion speed is given as

$$v_{exp} = \frac{R}{2\gamma t} = \frac{R}{2\gamma d}v_c \quad , \tag{27}$$

When $\gamma = 0.5$, the expansion speed of magnetic cloud, which coincides with that of free expansion, and the relationship between the B_{max} and d are the same as those derived from force-free flux rope model by Kumar and Rust [1996]. By fit the observations of magnetic clouds, Osherovich et al. [1993a] found $\gamma_e \approx 0.48 \pm 0.2$ and $\gamma_p \approx 1.2 \pm 0.1$. In magnetic cloud, the electron pressure is dominating.

However, the γ obtained by the above method is not the traditional polytropic index. It is only a consequence of different expansion histories of the different plasma parcels, that can not mirror the coupled evolution of density and temperature experienced by any one plasma parcel as it expands outward through the heliosphere, within an MC by single-point measurements [Gosling 1999]. The numerical simulation suggests that a flux rope also can expand when the polytropic index $\gamma = 5/3$ [Vandas et al., 1996b, 2000].

For Spheromak model, Low [1982] found a self-similar solution for a $\gamma = 4/3$ polytrope. The field can be expressed as

$$\begin{aligned} B_r &= \tfrac{2B_0}{\alpha\xi F^2(t)} j_1(\alpha\xi)\cos\theta \\ B_\theta &= -\tfrac{B_0 \sin\theta}{\alpha\xi F^2(t)}[\sin(\alpha\xi) - j_1(\alpha\xi)] \\ B_\phi &= \tfrac{B_0}{F^2(t)} j_1(\alpha\xi)\sin\theta \quad , \end{aligned} \tag{28}$$

where $\xi \equiv r/F(t)$, and $F(t)$ is the evolution function. The asymptotic speed of radial expansion is given as

$$v_{exp} = \frac{r}{3t} \quad . \tag{29}$$

It is 1/3 of the speed of flux rope.

The comparison between the observations and models suggests that the magnetic cloud apparently prefers being flux rope to being spheromak. However, whether these fields remain connected to the Sun or not is currently being debated.

4. Numerical simulation

Following the proposition of model, MHD simulation of magnetic cloud was carried out. Vandas et al. [1995, 1996a, 1996b] study the magnetic cloud propagation in 2.5 dimensions by assuming the cloud is cylindrical force-free flux rope at the initiation. In their simulation, the field is spiral in ecliptic plane and unipolar in meridional plane, and the region is from 18 R_s to 2 AU approximately. Results show that the propagation of these clouds practically does not depend on the inclination of their axes to the ecliptic plane and they maintain their magnetic structure basically. The expanding speed of magnetic cloud is faster near the Sun and faster in the azimuthal direction (Figure 17). The clouds are deflected from straight radial propagation to the side where the inner and outer magnetic fields have the opposite sense (Figure 18). By choosing different initial conditions, Vandas et al. [1996b] found that clouds with a higher momentum (higher initial velocity or density) or a lower resistance (lower background magnetic field) arrive earlier at 1 AU (as seen in the last two panels of Fig. 17).

Spheromak cloud is also studied by simulation [Detman et al., 1991; Vandas et al., 1997a, 1997b, 1998]. It is found that the spheromak's polar axis tends to take a radial direction [Vandas et al., 1998]. If spacecraft pass through the center of spheromak (toroid's hole), it would register a large magnetic field increase without a temperature drop and rotation of the magnetic field vector. Compared the simulation results between cylindrical cloud and spherical cloud [Vandas et al., 1997a], it is found that the deceleration and transit time to 1 AU of them is comparable, and the bow shock ahead of spheromak is about 2 times closer than for cylindrical cloud. Usually, it is difficult to distinguish spheromak from flux rope if there is only a spacecraft and it does not pass through the center of spheromak.

However, in these simulations, the authors did not consider the effect of the heliospheric current sheet. The background magnetic field is too simple to accord with the fact. The further work should be performed under the more real simulative environment.

5. Interaction of shock with MC

When the speed of ejecta is faster than local fast magnetosonic wave speed, a shock may be produced ahead the ejecta. Tsurutani et al. [1992] ever studied the five great geomagnetic storms (Dst $\leq -200nT$) occurred between 1971 to 1986. They found that 3 of 5 events were caused by field draping [Gosling and McComas, 1987] and shock compression of preexist southward interplanetary magnetic field, and the other two were resulted from MCs. Thus, it is suggested that percursor southward fields ahead of the high speed streams allow the shock compression mechanism to be particularly geoeffective.

The likelihood of the existence of shock within magnetic cloud was discussed in previous work [Tsurutani and Gonzalez, 1997; Gonzalez et al., 1999]. Generally, the presence of shock may not be possible within MC because of the large Alfvèn/magnetosonic speed in the low β cloud. However, if the overtaking ejecta moves fast enough, a shock can still be produced ahead the ejecta and exist within magnetic cloud.

Figure 19 shows the such event in which a fast forward shock was advancing into a preceding magnetic cloud and produced a great geomangetic storm (Dst $= -277nT$) on November 6, 2001 [Wang et al., 2002b]. In this event, the magnetic field strength jumped from $20nT$ to $60nT$ approximately at the shock arrival. The preexisting southward component of magnetic field in cloud was compressed largely. The plasma parameters was not available because the detector does not work probably under the impact of the much strong shock. By the identification of its solar source and the comparison between the observations from WIND and ACE spacecrafts, the speed of the driver gas of the shock was estimated above $900km/s$, much larger than the threshold $610km/s$. Thus the shock can be formed within the cloud.

Other similar events of shock overtaking preceding magnetic cloud have ever been mentioned, for example the April 5, 1979 event [Burlaga et al. 1987] and the October 19, 1995 event [Lepping et al. 1997]. In those two events, the fields behind the shock were compressed from $20nT$ to $40nT$ approximately. Although intense geomagnetic storms occurred in these events, they were both caused by the southward fields within the MC but not the fields in compressed regions after shocks, since the overtaken preexisting magnetic fields at the tail of the preceding MC were northward. Wang et al. [2002b] suggested that the geoeffectiveness of such events was correlative to the direction of preexisting magnetic fields, the intension of overtaking shock, and the deepness of the shock penetrating the preceding MC. Due to the absence of multispacecrafts observations, the detail of the evolution of shock advancing into magnetic cloud is not very clear.

By using the numerical simulation method, Vandas et al. [1997c] studied the interaction of shock with magnetic cloud. They concluded that the faster shock should slowing down and transfer a part of its energy to the cloud when it penetrated through a cloud. The MC should be compressed in the radial direction and become very oblate (Figure 20) without changes of fundamental characteristics.

6. Complex structure: Multiple magnetic clouds

In several instances more than one interplanetary structure can be associated with the origin of intense storms. Such complex structures have started to receive more attention in the literature [Burlaga et al., 1987; Behannon et al., 1991; Lepping et al., 1997; Cane and Richardson, 1997; Crooker et al., 1998; Knipp et al., 1998; Burlaga et al., 2001, 2002;]. Generally, complex structure may involve fast shock, magnetic cloud, another high speed stream, corotating stream, and so on.

One of the interesting complex structure is formed due to the overtaking successive magnetic clouds, which was supposed by Gonzalez et al. [1999], as shown in Fig. 21. Bothmer and Schwenn [1995] studied the storm during July 3-6, 1974, which was produced by a series of fast CMEs. However it is difficult to identify the driver gas or magnetic cloud signatures by using the available data for this event. Recently, Wang et al. [2002c] approved the existence of such complex interplanetary structure, so called "Multiple

Magnetic Cloud" (Multi-MCs). Figure 22 shows the configuration of magnetic field within the simplest Multi-MCs by using cylindrical force-free flux rope model. The characteristics of magnetic fields are different if the sub-clouds' field vectors do not rotate along the same direction.

By studied the three definite examples of Multi-MCs [Wang et al., 2002d], the characteristics of Multi-MCs are concluded (as seen in Figure 23): (1) Multi-MCs contains and only contains several magnetic clouds and interacting regions between them. (2) Each sub-cloud in Multi-MCs is primarily satisfied with the criteria of isolated magnetic cloud except that the proton temperature is sometimes not low as that in typical magnetic cloud due to the compression between the sub-clouds. (3) The speed of solar wind at the rear of the former cloud does not decline continuously, but increases again because of the overtaking of the latter cloud. (4) Within interacting region, the magnetic field becomes less regular and its strength drops to minimum. (5) β value increases to a high level in the interacting region between sub-clouds. The passive time of Multi-MCs are approximately one day, consistent with that of the typical magnetic cloud. The results imply the very large compression of the sub-clouds. The Multi-MCs on March 31, 2001 caused the largest geomagnetic storm (Dst $= -358nT$) during 2000-2001 (Fig. 23) due to the strong compressed magnetic field within Multi-MCs. In this event, the second sub-cloud not only prolonged the great geomagnetic storm but also produced another peak of Dst ($-285nT$) at 2200 UT [Wang et al. 2002e]. Other similar events associated with double or triple-step storms have been analyzed previously [Tsurutani and Gonzalez, 1997; Kamide et al., 1998].

It is still difficult to conclude quantitatively the effect of Multi-MCs on the Earth's magnetosphere. But Multi-MCs' ability in producing great geomagnetic storm is obvious. Because only several Multi-MCs were studied, many more details can not be described. The conditions of Multi-MCs producing geomagnetic storm and the fact of Multi-MCs' evolution are still unrevealed. Recently, Gopalswamy et al. [2001, 2002] reported the interaction of coronal mass ejections. The latter CME overtook the former and merged into it finally. However, in Multi-MCs, the sub-clouds are not merged into each other obviously. What are the conditions of successive CMEs to form Multi-MCs in interplanetary medium?

7. Discussion and current outstanding problems

We review the study progress about magnetic cloud. By the analysis of a quantity of observations from spacecrafts, we know the structure within magnetic cloud primarily, and the development of theoretical models and numerical simulations of magnetic cloud let us understand the magnetic cloud further. However, due to the absence of multi-points observations, the integral picture of magnetic cloud, the evolution of it and the interaction between magnetic cloud and other interplanetary structures are not very clear yet. Some questions has been listed above. There are still many other outstanding problems need to be study.

Magnetic clouds is originated from CMEs, but not every CME may become MC in interplanetary space. Sometimes the magnetic fields taken by CMEs are disordered [Burlaga, 2002]. Such CME can not form MC, and has non-geoeffectiveness. Then, which are the conditions of CMEs to form MCs? How do they develop initially?

A classical CME has three-part structure [Hundhausen, 1988]: bright outer loop, dark cavity and embedded bright core (filament material). As the products of CME in interplanetary space, how does the magnetic cloud correspond to the CME? Tsurutani and Gonzalez [1995] speculated that the magnetic cloud most probably corresponds to the central, dark region of the CME. This is because magnetic clouds are characteristics by low ion temperatures [Farrugia et al., 1997]. The region just upstream of a magnetic cloud contains higher density and temperature plasma [Gosling et al., 1987; Galvin et al., 1987; Tsurutani et al., 1988, 1994], so it is speculated that this plasma is the remnant of the bright loops of a CME. Recently, Burlaga et al. [1998] found a very cold region at the rear of a magnetic cloud, which is the filament material possibly. These speculations are all need more positive observations.

Although the evolution of magnetic cloud has been studied by using MHD simulation, the fact of the evolution of magnetic cloud and the interaction of magnetic cloud with ambient solar wind is still perplexed. Whether the magnetic cloud's fields remain connected to the Sun or not is currently being debated. If there are footpoints of magnetic cloud on the Sun's surface, does the magnetic cloud exchange material with the Sun?

The interaction of shock with magnetic cloud can accelerate the speed of MC and make it more oblate. The compressed southward magnetic field component enlarges the cloud's geoeffectiveness. However, when does the geoeffectiveness reach the maximum while shock compressing preceding MC and which factors is it related with?

The study concerning Multi-MCs is just beginning. The geoeffectiveness of Multi-MCs is obvious, but it is not sure that every Multi-MCs is able to create intense geomagnetic storm. As mentioned in last part of section 6, it is not known how the Multi-MCs formes. Meanwhile, there are also other meaningful questions: What is the view of Multi-MCs' evolution in interplanetary space? Do these sub-clouds within Multi-MCs merged into one other finally? How do these sub-clouds interact each other within it?

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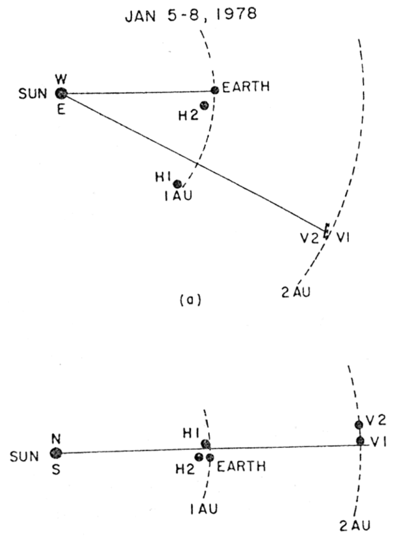
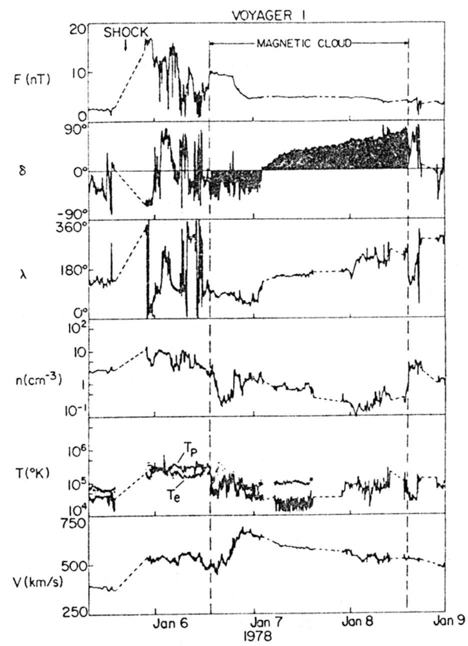


Figure 1. (Burlaga et al. [1981])



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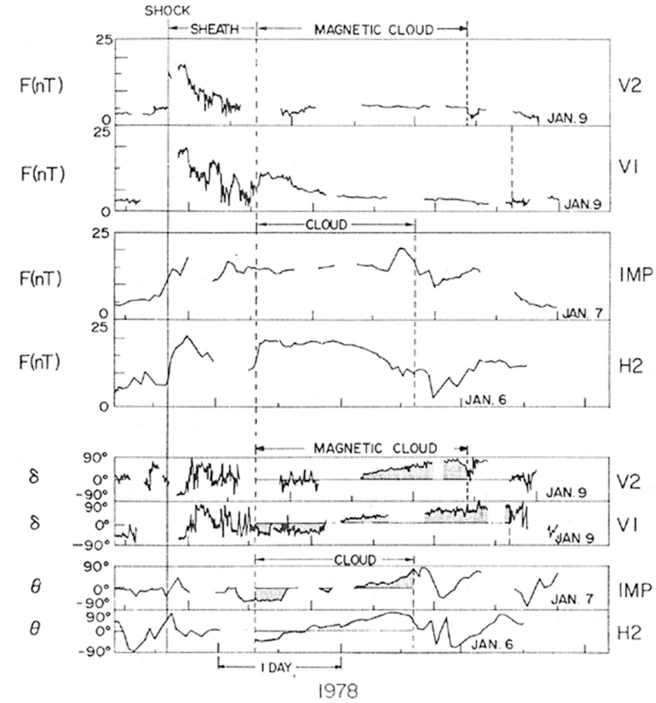

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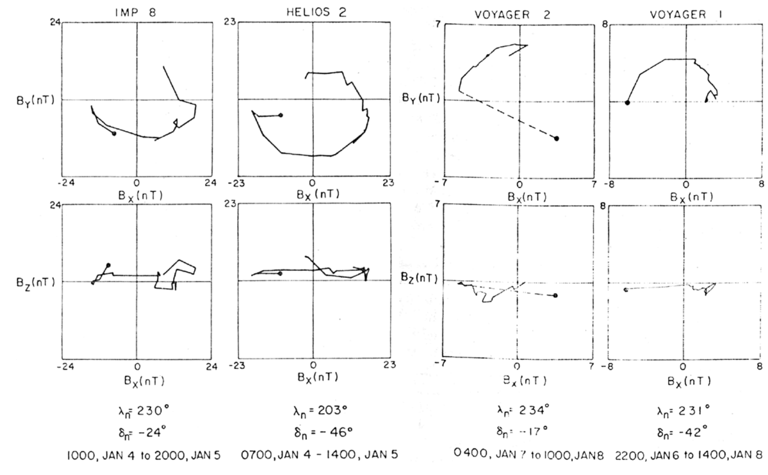

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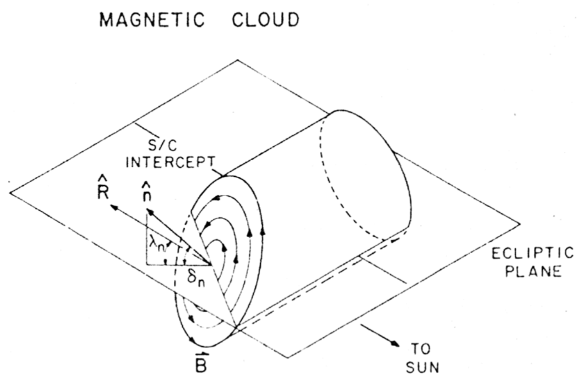

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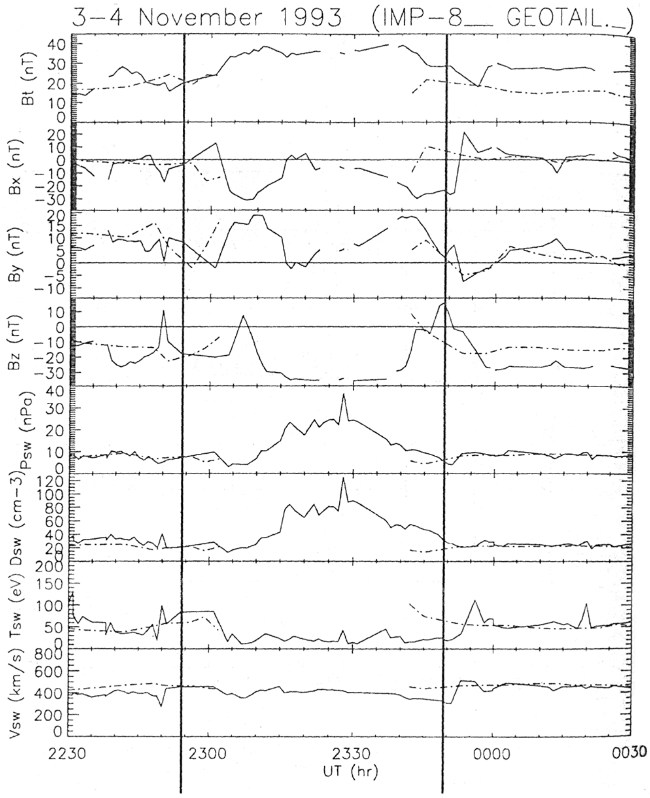


Figure 6. (McAllister et al. [1998])

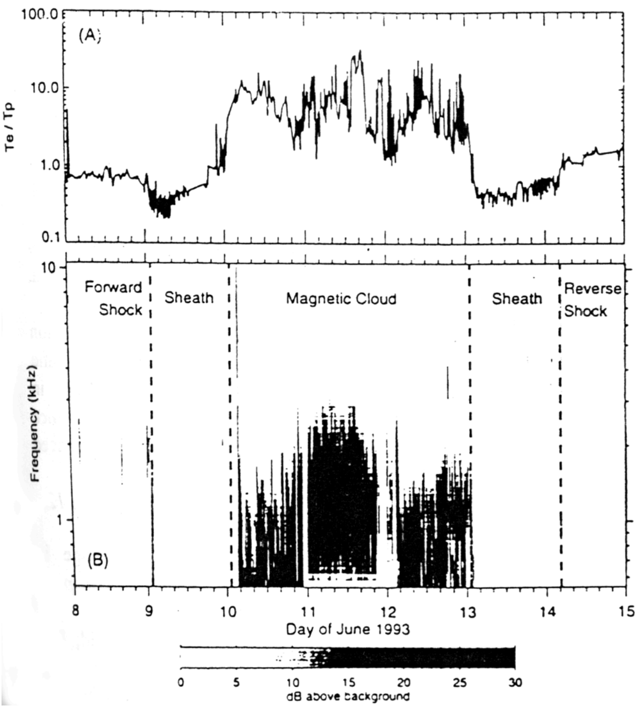


Figure 7. (Stone et al. [1995] ???)

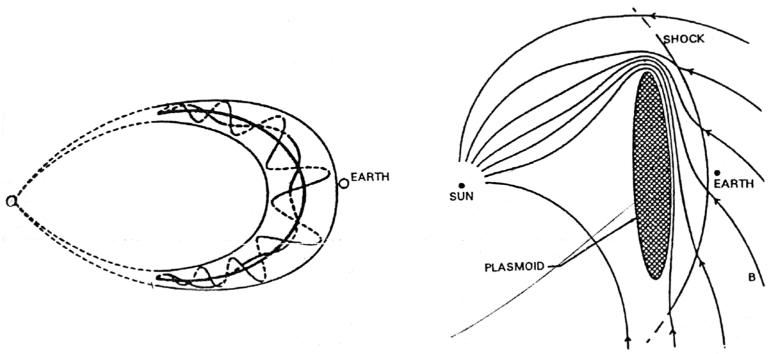


Figure 8. (Burlaga et al., [1990] (left) and Gosling [1990] (right))

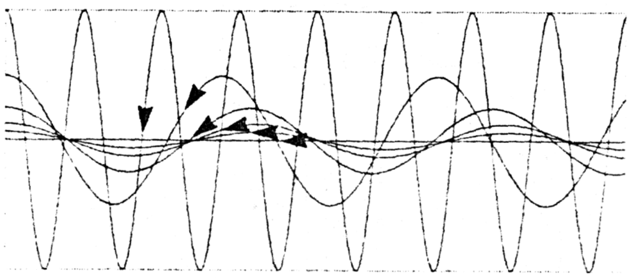
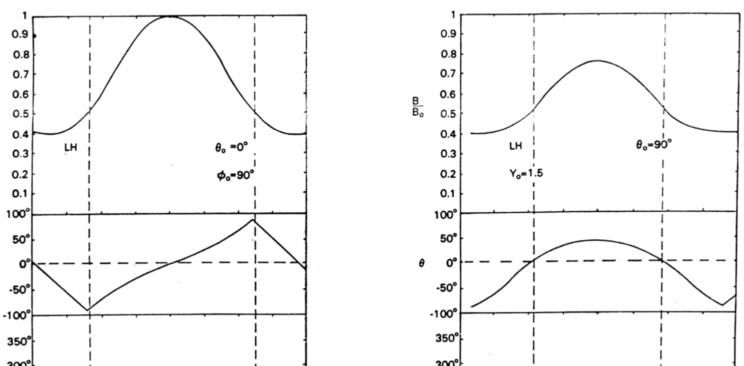


Figure 9. (Farrugia et al. [1995])



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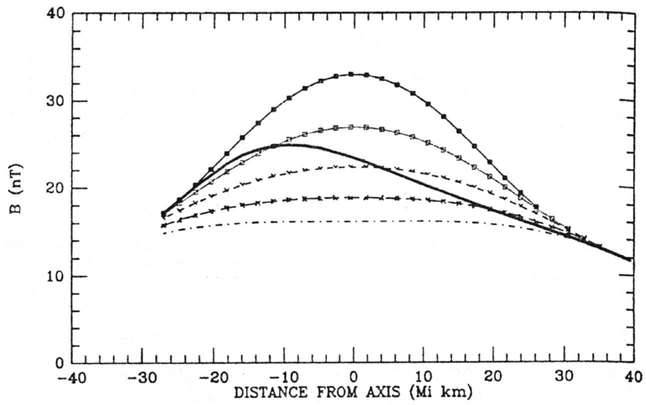
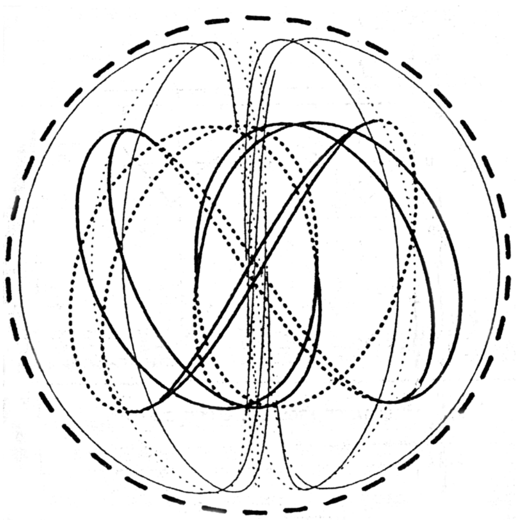


Figure 11. (Farrugia et al. [1995])



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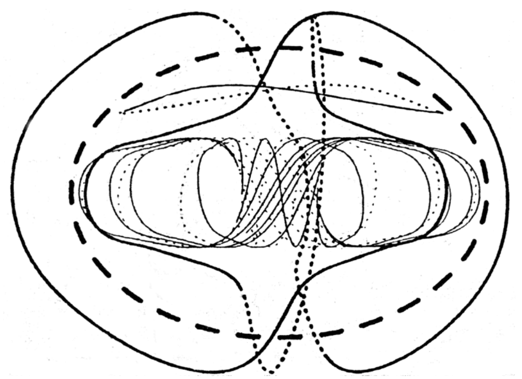

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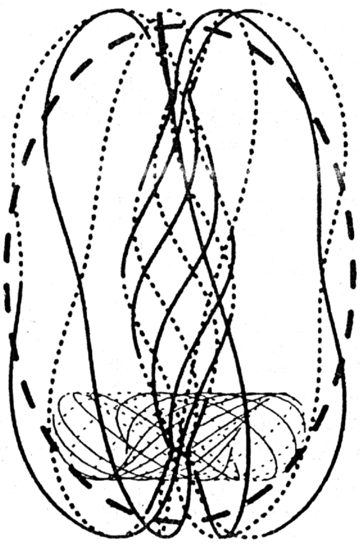
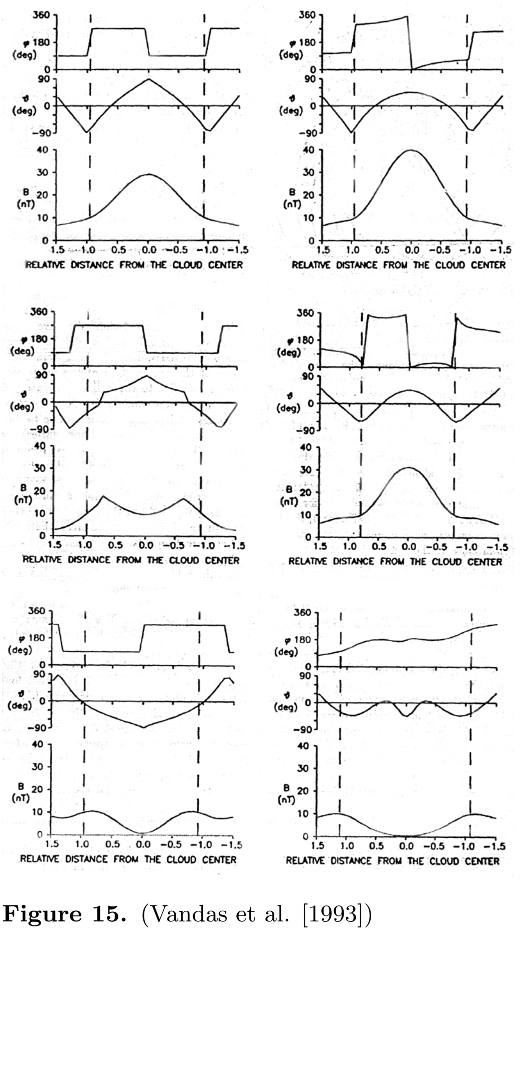


Figure 14. (Vandas et al. [1993])



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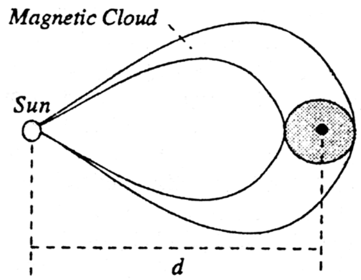
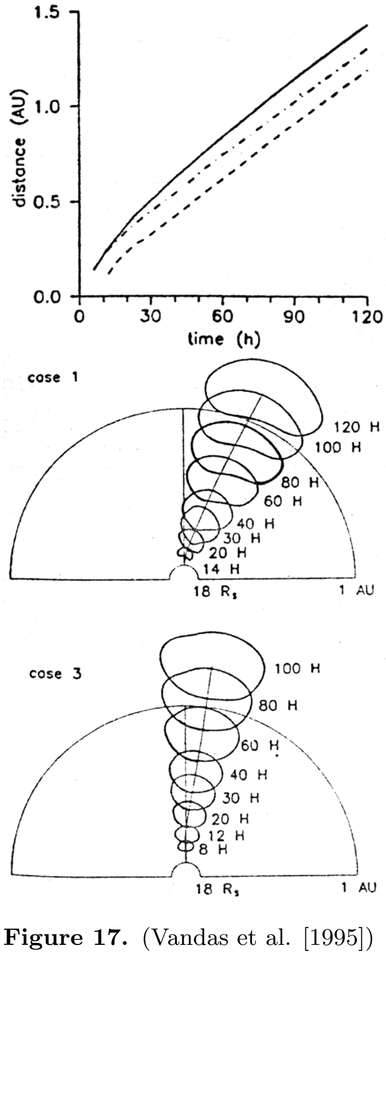


Figure 16. (Kumar and Rust [1996])



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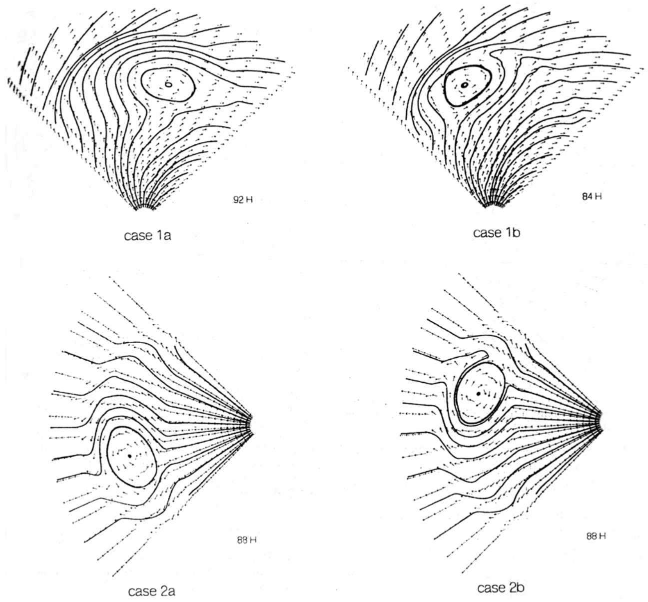


Figure 18. (Vandas et al. [1996a])

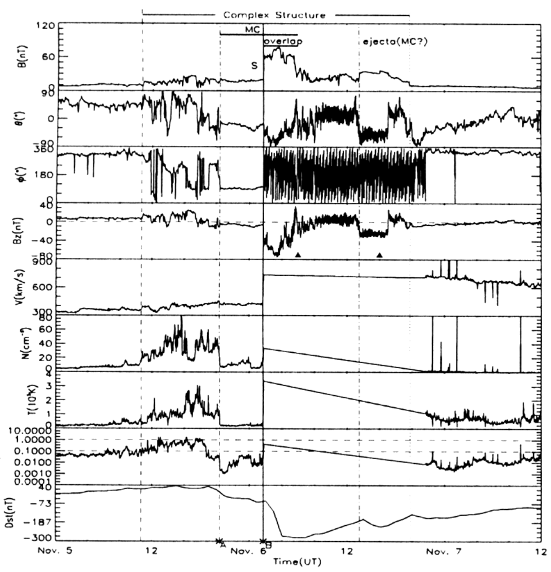


Figure 19. (Wang et al.[2002b])

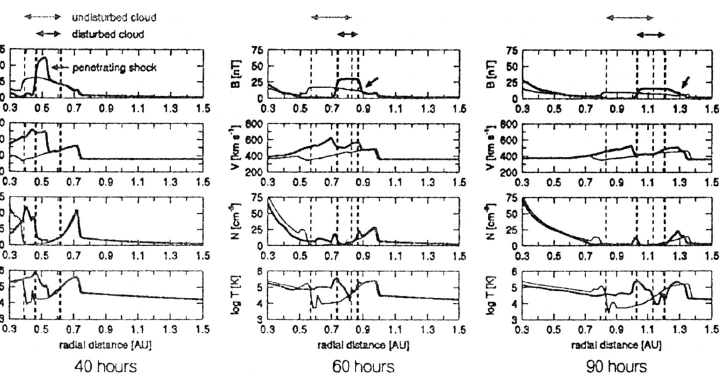


Figure 20. (Vandas et al. [1997c])

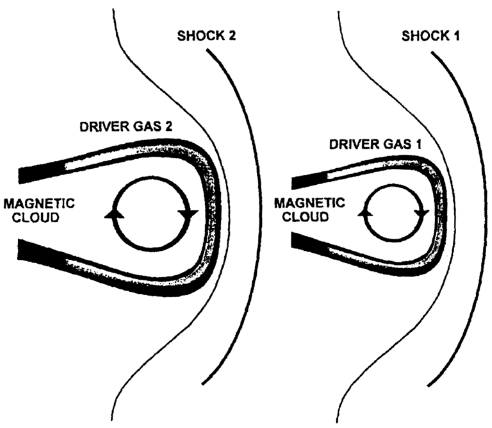
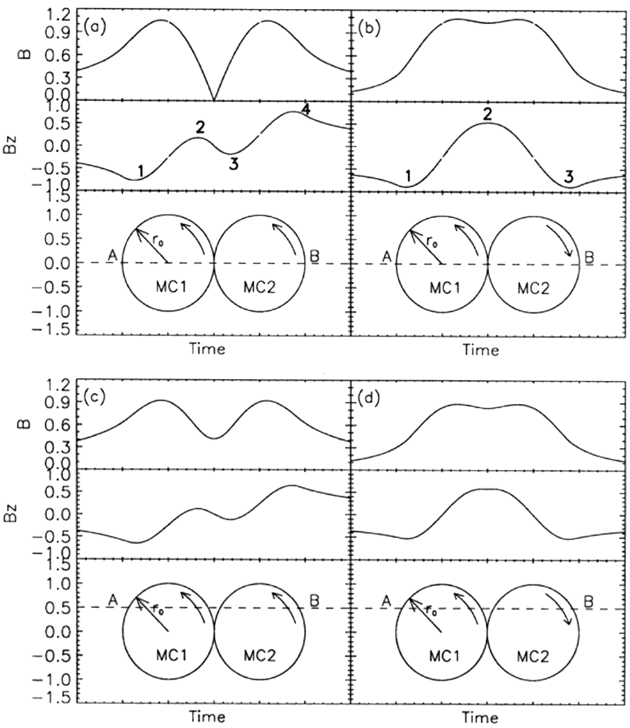


Figure 21. (Gonzalez et al. [1999])



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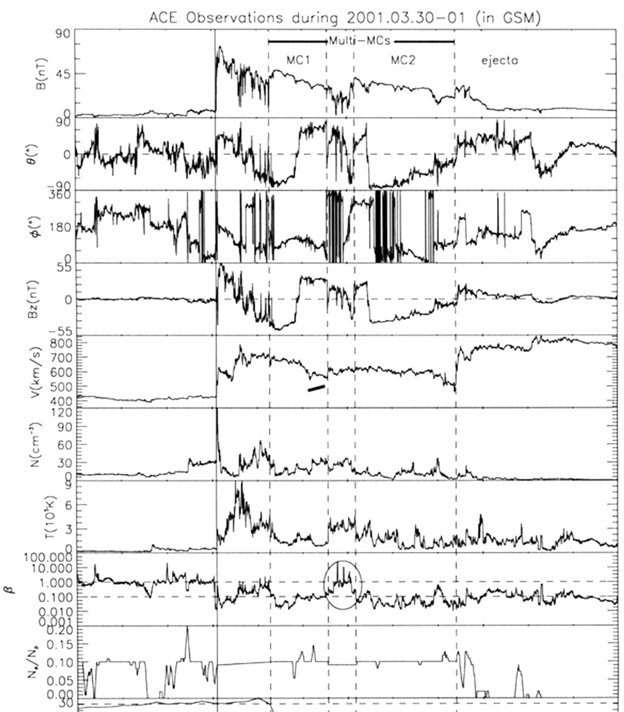

Figure 23. (Wang et al. [2002e])