JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. A1, PAGES 277–285, JANUARY 1, 1998

A magnetic cloud containing prominence material: January 1997

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Abstract. This work discusses the relations among (1) an interplanetary force-free magnetic cloud containing a plug of cold high-density material with unusual composition, (2) a coronal mass ejection (CME), (3) an eruptive prominence, and (4) a model of prominence material supported by a force-free magnetic flux rope in a coronal streamer. The magnetic cloud moved past the Wind spacecraft located in the solar wind upstream of Earth on January 10 and 11, 1997. The magnetic field configuration in the magnetic cloud was approximately a constant-α, force-free flux rope. The $^4He^{++}/H^+$ abundance in the most of the magnetic cloud was similar to that of the streamer belt material, suggesting an association between the magnetic cloud and a helmet streamer. A very cold region of exceptionally high density was detected at the rear of the magnetic cloud. This dense region had an unusual composition, including (1) a relatively high (10%) $^4He^{++}/He^+$ abundance (indicating a source near the photosphere), and (2) $^4He^+$, with an abundance relative to $^4He^{++}$ of $\sim$1%, and the unusual charge states of O^{5+} and Fe^{5+} (indicating a freezing-in temperature of $(1.6-4.0) \times 10^5$ °K, which is unusually low, but consistent with that expected for prominence material). Thus we suggest that the high-density region might be prominence material. The CME was seen in the solar corona on January 6, 1997, by the large angle and spectrometric coronagraph (LASCO) instrument on SOHO shortly after an eruptive prominence. A helmet streamer was observed near the latitude of the eruptive prominence a quarter of a solar rotation before and after the eruptive prominence. These observations are consistent with recent models, including the conceptual model of *Low and Hundhausen* [1995] for a quasi-static helmet streamer containing a force-free flux rope which supports prominence material and the dynamical model of *Wu et al.* [1997] for CMEs produced by the disruption of such a configuration.

1. Introduction

This paper presents an overview of the interplanetary plasma and magnetic field observations related to the magnetic cloud observed at the Wind spacecraft on January 10–11, 1997. The aim of this work is to better understand the relations between a magnetic cloud in the solar wind and the solar observations of a CME and an eruptive prominence, by considering the observations of one event in depth in the context of recent coronal theories and models.

A magnetic cloud is a transient ejection in the solar wind defined by relatively strong magnetic fields, a smooth rotation of the magnetic field direction over $\approx$180°, a low proton β and proton temperature, and a radial extent of $\approx$0.25 AU at 1 AU [*Burlaga et al.*, 1981]. Magnetic clouds are ideal objects for solar-terrestrial studies because of their simplicity and extended intervals of southward and/or northward magnetic fields [*Burlaga et al.*, 1990]. Approximately 1/3 of the interplanetary ejecta are magnetic clouds [*Gosling*, 1990]. There is an extensive literature on the structure and dynamics of interplanetary magnetic clouds (see the reviews by *Burlaga* [1984, 1991, 1995] and *Osherovich and Burlaga* [1997]) and their effects on the Earth's environment [*Farrugia et al.*, 1997]. Magnetic clouds have major effects on the magnetosheath and magnetosphere [*Farrugia and Burlaga*, 1994; *Farrugia et al.*, 1993a, b, c, 1994, 1995a; *Lepping et al.*, 1991, 1997; *Tsurutani et al.*, 1988], the ionosphere [*Freeman et al.*, 1993; *Knipp et al.*, 1993] and the geomagnetic field [e.g., *Wright and McNamara*, 1983; *Burlaga et al.*, 1981; *Burlaga and Behannon*, 1987].

The sources of magnetic clouds have been discussed in many papers. A magnetic cloud observed over the solar limb by Helios was related to a CME observed by the NRL coronagraph on P78-1 [*Burlaga et al.*, 1982]. *Klein and Burlaga* [1982] argued on more general grounds that magnetic clouds are related to CMEs. A correlation between magnetic clouds and CMEs was demonstrated by *Wilson and Hildner* [1984]. *Burlaga et al.* [1981] noted that a magnetic cloud that they discussed was possibly related to a solar flare. An association between magnetic clouds and eruptive prominences was demonstrated by *Wilson and Hildner* [1984, 1986] and *Burlaga and Behannon* [1987]. An association between CMEs and eruptive promi-

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Paper number 97JA02768.
0148-0227/98/97JA-02768$09.00

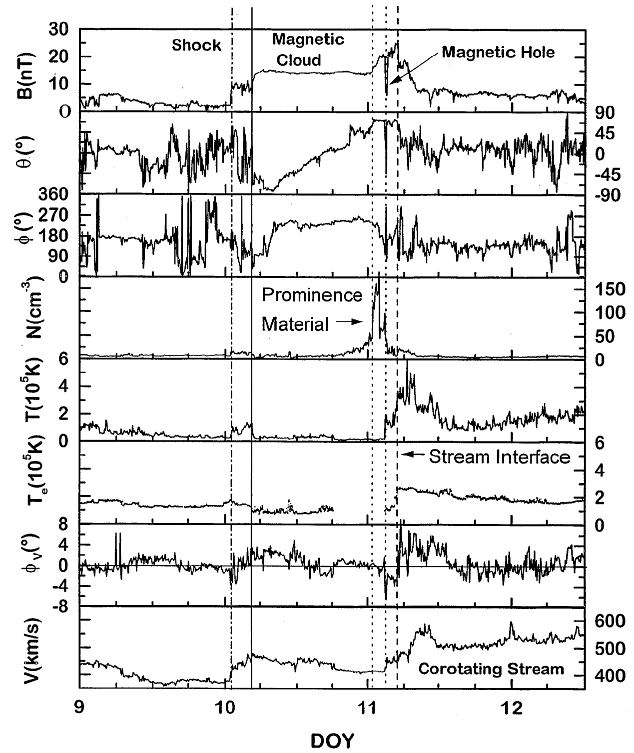

Figure 1. A plot of the magnetic field and solar wind parameters from January 9–12.5, 1997. (top to bottom) the magnetic field strength (B), the elevation (θ) and azimuth (ϕ) of the magnetic field direction in solar ecliptic coordinates, the proton density (N), the moment proton and electron temperatures (T and T_e), the azimuthal flow angle (ϕ_V), and the magnitude of the bulk velocity (V). Vertical lines show the times of a shock, the front boundary of the magnetic cloud, the high-density filament inside the magnetic cloud, a magnetic hole, and the stream interface which marks the arrival of a corotating stream that was overtaking the magnetic cloud. DOY stands for day of year (January 1 is DOY 1).

nences was reported by *Webb* [1988]. *Rust* [1994] showed that the sign of the magnetic helicity in magnetic clouds agrees with the sign inferred from filament observations. Other papers report associations between magnetic clouds and flares and/or eruptive prominences [see *Burlaga*, 1995, p. 93]. A relation between solar flares and filament eruptions flares was demonstrated by *Joselyn and McIntosh* [1981] and *Kahler et al.* [1988]. *Bothmer and Schwenn* [1994] suggested that all magnetic clouds are related to eruptive prominences, and they showed that the directions of magnetic fields in magnetic clouds are related to those in prominences.

This paper aims at relating observations of a CME and an eruptive prominence near the Sun on the one hand, and detailed observations of a magnetic cloud at 1 AU, on the other hand, thus furnishing observational input to coronal theories and models, to which extensive effort is currently devoted.

2. Magnetic Cloud Observed at 1 AU

The Wind spacecraft was located in the solar wind upstream of the Earth during the interval to be discussed, from January 9–12.5, 1997. The basic magnetic field and plasma observations are shown in Figure 1. This paper will focus on the magnetic cloud observed on January 10–11 and a high-density region observed on the sunward side of the magnetic cloud early on January 11. The region into which the magnetic cloud was moving, which passed Wind on January 9, is also important for an understanding of the source and propagation of the magnetic cloud. The magnetic cloud was being overtaken by and interacting with a corotating stream that moved past Wind on January 11 and 12.

The magnetic cloud which passed Wind on January 10–11 is identified in Figure 1 by the relatively high magnetic field strength B, the smooth rotation of the elevation angle θ from south to north and the low proton temperature T. The magnetic cloud was expanding, as indicated by the decreasing speed [*Klein and Burlaga*, 1982; *Farrugia and Burlaga*, 1994]. The electron temperature T_e relative to T, namely, T_e/T, was high, as is generally observed in magnetic clouds [*Burlaga et al.*, 1981; *Osherovich*, 1993a; *Fainberg et al.*, 1996; *Osherovich and Burlaga*, 1997]. The beginning of the cloud on day of year (DOY) 10.20 is marked by (1) an increase in B and the ratio T_e/T and (2) a decrease in T, T_e, and the proton density N. The end of the magnetic cloud is less clearly defined. Possible endpoints are the extraordinary magnetic hole at DOY 11.125 and the stream interface at DOY 11.20. A shock preceded the magnetic cloud at DOY 10.036; the standoff distance was consistent with the shock being driven by the magnetic cloud.

Magnetic clouds were identified as flux tubes with twisted magnetic field lines by *Burlaga et al.* [1981], *Suess* [1988], and *Farrugia et al.* [1997]. *Goldstein* [1983] and *Marubashi* [1986] suggested that magnetic clouds have force-free magnetic field configurations with variable α, described by

$$\mathbf{J} \times \mathbf{B} = 0 \tag{1}$$

or equivalently,

$$\nabla \times \mathbf{B} = \alpha \mathbf{B} \tag{2}$$

where

$$\mathbf{B} \cdot \nabla \alpha = 0 \tag{3}$$

General solutions of these equations are not available. For constant-α (or linear) force-free fields, the problem can be reduced to the Helmholtz equation, for which solutions are known in different systems of coordinates corresponding to different symmetries [*Chandrasekhar and Kendall*, 1957].

Burlaga [1988] showed that the basic types of magnetic field profiles observed in magnetic clouds at 1 AU can be described to zeroth order by the static, constant-α solution of *Lundquist* [1950] in cylindrical coordinates. The simplicity of the constant-α solution allows one to fit it to the observations of the magnetic field components in a magnetic cloud. A least squares fitting algorithm based on this model was developed by *Lepping et al.* [1990], allowing one to estimate several parameters describing a magnetic cloud. Good fits to the data for many magnetic clouds were obtained, confirming that the cylindrical constant-α model can describe the basic magnetic field geometry. Through such a fit, one obtains both the local orientation of a magnetic cloud and the impact parameter for the trajectory of the spacecraft relative to the axis of the magnetic cloud (the closest distance of approach of the spacecraft trajectory to the magnetic cloud's symmetry axis). Given the observed average bulk speed, one can also obtain the radius of the magnetic cloud. This force-free field model describes static magnetic field configurations, decoupled from thermodynamic and dynamic factors. This is a reasonable first approximation in

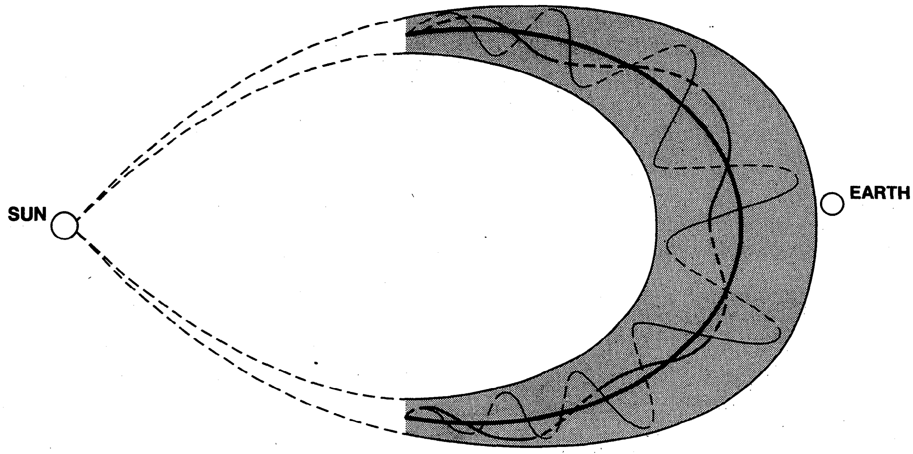

Figure 2. A sketch of the geometry of a magnetic cloud and the field lines in the magnetic clouds, which are helices viewed here in projection. The figure, drawn by A. Burlaga, is reproduced from *Burlaga et al.* [1990].

view of the low proton beta typical of these configurations and which, in this case, was less than 0.1.

More accurate models must consider that magnetic clouds expand as they move away from the sun and might interact with other flows [*Burlaga et al.*, 1981; *Behannon and Burlaga*, 1982, 1991; *Klein and Burlaga*, 1982]. Models of expanding magnetic clouds are reviewed by *Burlaga* [1995] and *Osherovich and Burlaga* [1997]. In particular, we note the recent work of *Farrugia et al.* [1992, 1993c, 1995b], *Osherovich et al.* [1993b, 1995], *Vandas et al.* [1995], and *Vandas and Fisher* [1996]. Magnetic clouds can interact with other flows [*Burlaga et al.*, 1987; *Burlaga*, 1995]. In fact, the magnetic cloud that is the subject of this paper was being overtaken by a corotating stream. The theory of such interactions remains to be developed.

The global topology of a magnetic cloud on a scale of 1 AU is illustrated in Figure 2 from *Burlaga et al.* [1990], based on an analysis of multispacecraft data. The topology is that of a large flux rope with both ends connected to the Sun. The magnetic field lines are helices whose pitch angle increases with increasing distance from the axis of the magnetic cloud. Of course, this simple configuration is idealized, but it has proven to be very useful. In general, the shape of the flux rope can be distorted in myriad ways by the rotation of the Sun and by interactions with the solar wind [*Crooker et al.*, 1990; *Crooker and Intriligator*, 1996], but we shall not examine such distortions for the event under consideration.

Fitting the Lundquist solution to the observations of the January 10–11, 1997, magnetic cloud using the method of *Lepping et al.* [1990] gives the results in Figure 3. The fit is made to the magnetic field hour-average data in the interval beginning at January 10, hour 5.0 and ending on January 11, hour 2.0 (see Figure 1). The front boundary is well defined. There is uncertainty in the time of passage of the rear boundary, as discussed above; we choose this time as that of the magnetic hole, where the elevation angle of the magnetic field is a maximum. The results of the fit are not sensitive to the position of the rear boundary within the limits of uncertainty of the boundary position. The top three panels of Figure 3 show that the fit (solid curves) describes the observations (dots) of the three components of the magnetic field rather well. The reduced chi-squared to the fit, $\chi^2/(3N - n)$, where $N = 22$ is the number of points and $n = 5$ is the number of parameters in the fit, is only 0.013. Two other parameters which are chosen to fit the observations are the sense or rotation of the magnetic field (±1) and a scaling parameter to adjust the field strength B.

The variation of the magnetic field strength is not modeled accurately, in part because (1) a static model does not take into account the evolution of the field strength in time, (2) the interaction with a corotating stream at the rear has compli-

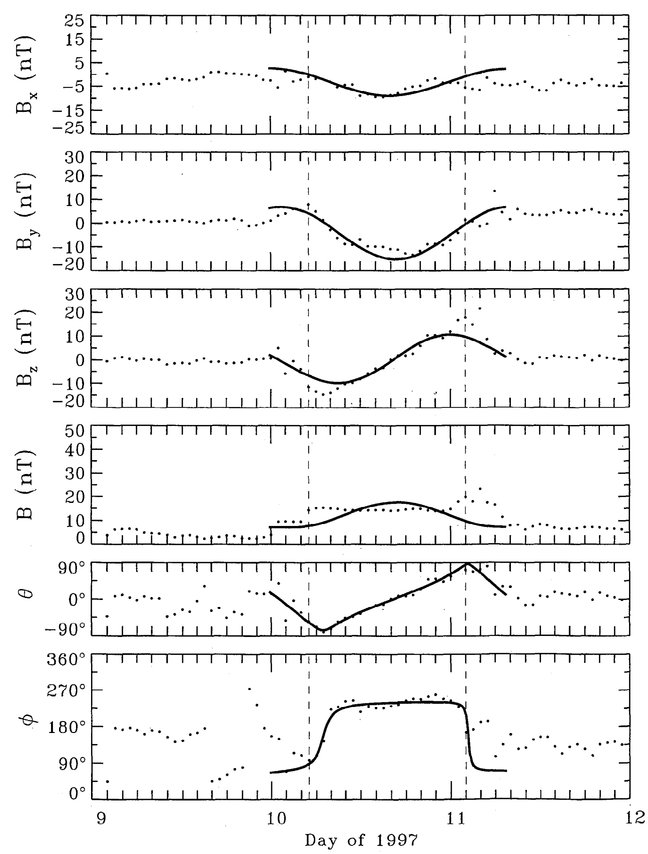

Figure 3. The dots show the magnetic field observations: the X, Y, and Z components (GSE coordinates) are in the top three panels, and the magnetic field strength and direction are shown in the bottom three panels. The curve is a fit of the data between the vertical lines to the Lundquist solution for a constant-alpha, force-free, static, cylindrical magnetic cloud.

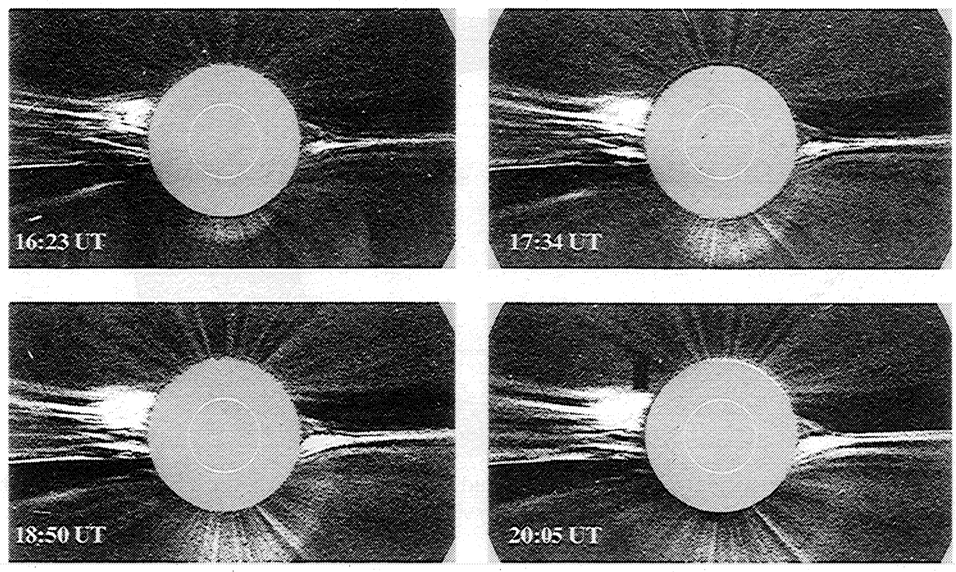

Figure 4. Observations of a halo CME by the LASCO coronagraph on SOHO.

cated this evolution by compressing the magnetic field at the rear, and (3) there was a strong interaction of the magnetic cloud with the ambient flow ahead, which gave rise to a forward shock. The flat magnetic field strength profile might also indicate that the magnetic cloud does not have and exactly constant-α force-free configuration and that the magnetic cloud is relatively old [*Farrugia et al.*, 1992, 1993c; *Osherovich et al.*, 1993b; *Osherovich and Burlaga*, 1997], consistent with its relatively low speed $\langle V \rangle$ = 440 km/s. Our primary concern is in determining the basic parameters of the magnetic cloud, which can be obtained from the fit in Figure 3.

The bottom two panels of Figure 3 show that despite the unusual magnetic field strength profile, the constant-α, force-free model provides an excellent fit to the variation of the direction of the magnetic field, indicating that the "force-free flux-rope" geometry was preserved during the interaction. The local segment of the magnetic cloud that moved past Wind (Figure 2) had approximately the form of a cylinder. The local axis of the cylinder is the line of symmetry of the cylinder, and it coincides with a magnetic field line indicated by the heavy curve shown in Figure 2. The local orientation of the axis of the magnetic cloud is estimated to be in the direction $\theta = 3°$, $\varphi = 250°$ in solar ecliptic coordinates, i.e., nearly parallel to the ecliptic and 70° from the radial direction, which is rather typical [*Lepping et al.*, 1990]. The magnetic cloud was right-handed, consistent with its association with an eruptive prominence in the southern hemisphere [*Rust*, 1994; *Kumar and Rust*, 1996; *Low*, 1996; *Bothmer and Schwenn*, 1994]. Taking the end of the magnetic cloud 1 hour later (hour 3) gives $\theta = 8°$, $\varphi = 254°$, and taking the end four hours later (hour 6, an extreme value in view of the changes in the magnetic field direction) gives $\theta = 15°$, $\varphi = 261°$. Thus the uncertainty in these parameters is small ($\sigma_\theta \approx 5°$, $\sigma_\phi \approx 5°$). The axis of the magnetic cloud passed close to the Wind spacecraft, y_0/R_0 being 0.143, where y_0 is the closest approach distance to the axis of the magnetic cloud and R_0 is its minor radius. This result is consistent with the observation of an extended interval of negative B_z followed by a similar interval of positive B_z. The diameter of the magnetic cloud was 0.20 AU, which is typical for magnetic clouds at 1 AU.

The closest approach distance of the Wind spacecraft to the magnetic cloud was y_0 = 0.015 AU, above the axis of the magnetic cloud, at hour 16.8 on January 10. The Wind spacecraft was 4.1° (0.072 AU) below the solar equatorial plane at the time. Thus the axis of the magnetic cloud at Wind was 0.087 AU below the solar equatorial plane. Since the diameter of the magnetic cloud was 0.20 AU, 94% of the magnetic cloud was below the solar equatorial plane at closest approach to Wind. The magnetic cloud was moving toward the south at ≈15 km/s and radially outward at ≈450 km/s.

3. Relation Between the Magnetic Cloud and Solar Events

The magnetic cloud was associated with a halo CME observed by the large angle and spectrometric coronagraph (LASCO) experiment on SOHO. The first observation of the CME was at 1730 UT on January 6, 1997, and clear evidence of a halo CME was obtained at 1623–2005 UT on January 6 (Figure 4). The CME formed a partial arc in the southern hemisphere, consistent with a source in that hemisphere. It is estimated that the CME was launched sometime between 0900 and 1400 UT, on January 6. The event was actually reported while it was in progress, by D. Michels at an ISTP meeting. On the basis of an estimated speed of 450 km/s and assuming that the CME was headed toward the Earth rather than away from it, he predicted that the effects of the CME would be seen at Earth on January 10.

While it thus seems reasonable that the CME was related to the magnetic cloud observed by Wind, there is no evidence that the high-density material that constitutes the visible CME is the same as the material in the magnetic cloud. In fact, the bright CME observed by the coronagraph on January 6, 1997, is not understood. It could in large part represent the compressed postshock material and/or the compressed material produced adjacent to an expanding ejection, rather than exclusively the ejection itself [*Gibson and Low*, 1997; *Wu et al.*, 1997]. In general, CMEs observed over the limb have a three-part structure: a bright exterior shell, a dark cavity, and a bright

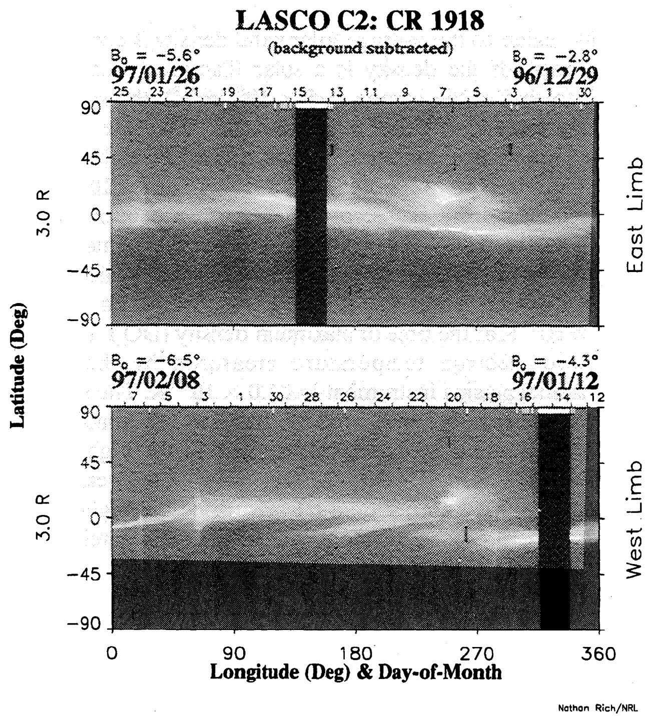

Figure 5. Maps of coronal brightness as a function of solar latitude and Carrington longitude made by LASCO C2 observations over the (top) east limb and (bottom) west limb near the times of the halo CME observed on January 6, 1997.

core [*Illing and Hundhausen*, 1985, 1986; *Hundhausen*, 1988, 1997].

The magnetic cloud and CME were related to an eruptive prominence. These associations can be made unambiguously, because the sun was relatively quiet. On the basis of Hα images from Sac Peak, SOON, and Pic du Midi, S. Keil reported that a filament on the disc disappeared between January 5 and 6. Preliminary results reported by the SHINE group headed by D. Webb (http://umbra.nascom.nasa.gov/SHINE_report.html) indicate the following: (1) The disappearing filament was related to a prominence that erupted at S24 ± 3°, W01 ± 1° between 1301 and 1453 UT on January 6 (Ramey Air Force Base site report). (2) N. Gopalswamy reported a "radio filament" consistent with the location of the Hα filament between 0643 and 2345 UT on January 6. (3) N. Gopalswamy and H. Hudson reported that Yohkoh SXT images showed a faint loop system, which disappeared between 0830 and 1511 UT.

On the basis of the neutral line computed by the Wilcox Solar Observatory group (http://quake.stanford.edu/~wso/wso.html), the eruptive prominence was near the base of the heliospheric current sheet (HCS), which was probably beneath a helmet streamer. Maps of coronal brightness as a function of solar latitude and Carrington solar rotation, based on measurements made the LASCO C2 instrument, are shown in Figure 5. The top panel, based on measurements made over the East limb, shows CR 1918 (December 29, 1996 to January 26, 1997); the lower panel, based on measurements made over the West limb, shows the interval from January 12, to February 8, 1997. The dark vertical bands represent data gaps. Despite the eruption of CMEs during these times, there is a relatively stable bright band close to the equator that marks the location of the streamer belt. The top panel indicates that on January 1, approximately a quarter of a solar rotation before the eruptive prominence and CME at central meridian on January 6, there was a dense closed field region (a helmet streamer) over the east limb at ≈S 15°. The lower panel in Figure 5 indicates a similar structure over the west limb at ≈S 15° approximately a quarter of a solar rotation after the eruptive prominence. These observations suggest that the CME and the magnetic cloud originated either within or near to a helmet streamer associated with the streamer belt.

4. Corotating Stream Behind the Magnetic Cloud

A fraction (≈1/3) of the magnetic clouds observed at 1 AU is followed by corotating streams [*Klein and Burlaga*, 1982]. A corotating stream followed the magnetic cloud on January 11 and 12. This is evident in Figure 1, where one sees the high speed, the relatively high proton temperature and a relatively low proton density. The stream interface probably occurred at DOY 11.20, indicated by the last dashed vertical line in Figure 1. The identification of the stream interface is based on the abrupt increase in bulk speed, the change in azimuthal flow direction ϕ_V from east to west, and the increase in the proton and electron temperatures. One expects a decrease in density, but that is not observed, possibly because of the complex interaction between the corotating stream and the magnetic cloud. A peak in the total pressure occurred at the interface, which is a general feature of a stream interface [*Burlaga*, 1974]. The corotating stream was associated with an equatorial coronal hole observed at Kitt Peak at 10°W on January 8 at 2043 UT (ftp://pandora.tuc.noao.edu/kptv/daily/lowres/97.01/).

5. He^{++} in the Magnetic Cloud

Observations of $^4He^{++}$ from January 10–11 made by the SWE plasma analyzer on Wind [*Ogilvie et al.*, 1995] are shown in Figure 6. The proton flow speed is plotted in the top panel, for reference, showing the locations of the magnetic cloud and related features. The dotted-dashed vertical line shows the shock (S) ahead of the magnetic cloud, the solid vertical line shows the front boundary of the magnetic cloud, and the dashed line shows the stream interface. The relative helium abundance, N($^4He^{++}$)/N(H^+) in percent, is plotted in the second panel from the top of Figure 6. In the corotating stream, the $^4He^{++}$ abundance is ~3.5%, close to the typical value of 4% in the solar wind (see, e.g., the review of *Neugebauer et al.* [1981]). Inside most of the magnetic cloud, however, the $^4He^{++}$ abundance is very low, ≈1.5%. Low $^4He^{++}$ abundances are observed near the heliospheric current sheet [*Borrini et al.*, 1981; *Ogilvie et al.*, 1992] and are presumed to be related to an extension of the streamer belt observed in the corona. Thus we have the important result that the low $^4He^{++}$ abundance in the magnetic cloud is consistent with an association between the magnetic cloud and a helmet streamer.

The most probable thermal speed of the $^4He^{++}$, assuming an isotropic Maxwellian velocity distribution, is $V_{THe++} = (\sqrt{2kT_{He}/m_{He}})$, where T_{He} is the temperature of He and m_{He} is its mass, and is plotted in the third panel of Figure 6 in units of km/s. The thermal speed is high in the corotating stream and low in the magnetic cloud, just as it is for protons. The thermal speed for $^4He^{++}$ is particularly low at the rear of the magnetic cloud, corresponding to a temperature of T_{He++} ≈4000 °K. The ratio of the thermal speed for $^4He^{++}$ to that for H^+ is 1

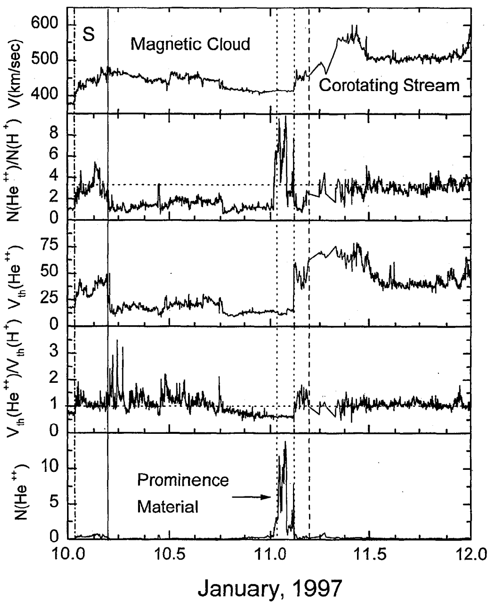

Figure 6. Observations of $^4He^{++}$ by Wind. (top) Proton speed for reference. The next panel shows the abundance of $^4He^{++}$ relative to the solar wind proton density in percent. Below that is the thermal speed of $^4He^{++}$ ($\sqrt{2kT_{He++}/m_{He++}}$) in km/s followed by a panel with the thermal speed of $^4He^{++}$ relative to the thermal speed of the protons, in percent. (bottom) Density of $^4He^{++}$, where the prominence material stands out by virtue of its very high density.

in the corotating stream, as one generally observes in the solar wind. The same ratio is somewhat greater than 1 in much of the magnetic cloud, but is significantly less than 1 in the rear of the magnetic cloud, owing to the low $^4He^{++}$ temperature there. Thus the $^4He^{++}$ near the rear of the magnetic cloud is unusually cold, both in absolute terms and relative to the protons.

6. Prominence Material in the Magnetic Cloud?

The most significant feature of the January 10/11, 1997 magnetic cloud is the region of very high density at the rear of the magnetic cloud, whose boundaries are denoted by the vertical dotted lines in Figure 1. The proton density rises to 185 particles/cm^3, which is 31 times the average solar wind density of 6 particles/cm^3. The $^4He^{++}$ density is also high in the filament (Figure 6, bottom panel) reaching $\approx$18 particles/cm^3. The region of highest densities is relatively small, passing the spacecraft between DOY $\approx$11.0348 to 11.1314, corresponding to a radial extent of only $\approx$0.02 AU. The proton density actually begins to increase gradually inside the magnetic cloud at approximately hour 18 on January 10, coincident with a decrease in the temperature of the protons and electrons (Figure 1) and that of the $^4He^{++}$ (Figure 6).

We suggest that the high-density region at the rear of the magnetic cloud might be prominence material. Recall that the magnetic cloud was associated with an eruptive prominence. A solar prominence is a thin sheet of dense, cold material with an abundance characteristic of the photosphere [*Priest*, 1989; *Tandberg-Hanssen*, 1974, 1995], so our hypothesis would imply similar characteristics of the high-density region at the rear of the magnetic cloud. The region is indeed extraordinarily dense, as discussed above. The ratio 31 of the density in the high-density region to the average solar wind density is comparable to the ratio of the density in a solar filament ($\sim$1.5 $\times$ 10^{10} cm^{-3}) to that of the corona ($\sim$5 $\times$ 10^8 cm^{-3}); the solar densities are from *Zirin* [1988, p. 279 and 218]. The $^4He^{++}$ abundance in the high-density region is unusually high (second panel from the top in Figure 6); its density reaches 10 percent of the density of protons, consistent with the photospheric abundance of $^4He^{++}$. The temperatures of the primary components of the filament are exceptionally low. The proton temperature measured by the SWE instrument on Wind is $<1.1 \times 10^4$ °K at the time of maximum density (DOY 11.0825). The core electron temperature measured by the three-dimensional plasma instrument is $<1.0 \times 10^4$ °K. The moment electron temperature measured by the Goddard Space Flight Center instrument is too low to measure in the high density region, but it is $<8 \times 10^4$ °K. The $^4He^{++}$ temperature is $<1.1 \times 10^4$ °K. Another unusual feature of the high-density region is the presence of $^4He^+$, with an abundance relative to $^4He^{++}$ of $\sim$1%, and unusual charge states of O^{5+} and Fe^{5+}, observed with the solar wind ion composition (SWICS) and high mass resolution spectrometer (MASS) instruments on Wind. This implies a freezing-in temperature of (1.6–4.0) $\times$ 10^5 °K, which is unusually low, but again consistent with that expected for prominence material. Although the geometry of the high-density material in the magnetic cloud is not known, it is notable that the ratio ($\sim$0.1) of the radial extent of the high density material to that of the magnetic cloud is comparable to the ratio of the filament height ($\sim$0.05 solar radii) to the coronal helmet height ($\sim$0.5 solar radii). Altogether then, the observations of the material in the thin high-density region at the rear of the magnetic cloud are consistent with the hypothesis that it is prominence material.

The $^4He^+$ has been observed in the solar wind on only a few occasions. The first definitive evidence of $^4He^+$ was reported by *Schwenn et al.* [1980], where it was found in only 1 among 105 transient events in the Helios data. *Gosling et al.* [1980] quickly confirmed the existence of $^4He^+$ in the solar wind in a postshock flow observed by IMP 7 and IMP 8. *Zwickl et al.* [1982] found only three identifiable events of $^4He^+$ in eight years of data at 1 AU. They suggested a possible association of the $^4He^+$ with disappearing filaments and magnetic clouds, but they did not present explicit support for this suggestion.

7. Discussion

The interplanetary observations made by Wind from January 9–12, 1997 are related to the static coronal model of *Low* [1994] and *Low and Hundhausen* [1995] (see also *Demoulin and Forbes* [1992]), which is related to the three-part structure of CMEs described. This model and its broader significance are reviewed by Low [1996]. In the model, illustrated in Figure 7 from *Low and Hundhausen* [1995], the high-density, cold prominence material is supported by a locally cylindrical, force-free flux rope extending out of the plane of Figure 7, and imbedded in the closed field region of a helmet streamer. The relations between the Wind observations and the static model of Low and Hundhausen are as follows. The material ahead of the magnetic cloud corresponds to the streamer belt material, with its relatively high density, low speed, and its relatively weak, irregular magnetic field. The magnetic cloud corresponds to the force-free flux rope in the helmet streamer. The thin, high-density, very cold region containing $^4He^+$, O^{5+},

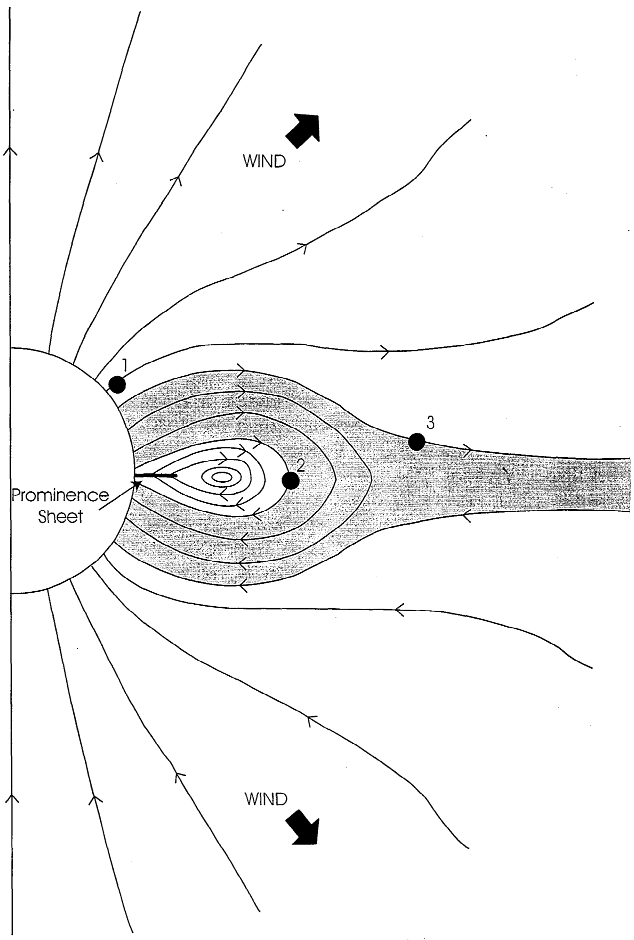

Figure 7. Static model of *Low and Hundhausen* [1995] showing a three-part coronal structure: a helmet streamer (shaded) containing a vertical force-free flux rope (white region below "2") holding up a prominence sheet. A process that causes the flux rope to rise gives the structure observed in the solar wind: material in the heliospheric plasma sheet corresponding to the helmet streamer; a magnetic cloud corresponding to the flux rope, with a low helium abundance indicating an origin in the streamer; and high density, cold material with unusual composition corresponding to the prominence material. (After a figure provided by B. C. Low.)

Fe^{5+}, and a high abundance of $^4He^{++}$ on the sunward side of the magnetic cloud corresponds to the prominence material.

Chen [1989, 1990, 1996], *Chen and Garren* [1994], and *Cargill et al.* [1995, 1996] have shown that a current driven flux rope near the Sun can expand out to 1 AU and move at speeds corresponding to those of magnetic clouds if sufficient current flows through the tube. The basic cause of the acceleration in their model is the Lorentz force [*Chen*, 1989]. The initial configuration for this model is a flux rope in a uniform solar wind. It does not account for the association of "streamer-belt" material ahead of the January, 1997 magnetic cloud, the low $^4He^{++}$ abundance in the cloud, and the prominence material at the end of the magnetic cloud.

A more realistic initial configuration for the January 10–11 magnetic cloud is that of *Low and Hundhausen* [1995] in which one has a force-free flux rope threading through an arcade of closed field lines under a helmet streamer. Thus, one basic problem to solve is the acceleration and motion of an accelerating flux rope (possibly containing high-density prominence material at the rear) which is within a helmet streamer. If the flux rope is in the helmet streamer and if one increases the azimuthal current in the flux rope by means of an ad hoc current, then the flux rope expands and moves radially away from the sun into the closed field region of the helmet streamer [*Wu et al.*, 1997; *Wu and Guo*, 1977]. The Lorentz force and buoyancy drive the flux rope. The motion of the flux rope disrupts the streamer and causes the mass in the helmet dome to form the bright loop usually observed in loop-like CMEs. Expansion of the flux rope produces a relatively large density enhancement at the flanks. Together, these effects of motion of the flux rope should produce a halo like that observed by LASCO in the January 1997 event, but the details have not yet been modeled. A shock observed ahead of the magnetic cloud is formed near the sun by the motion of the flux rope. The model does not extend to 1 AU, and it does not include the prominence material that is in the static model of Low and that was observed by Wind in January 10–11, 1997. A self-similar solution for the expansion of a magnetic cloud with the initial configuration of *Low and Hundhausen* [1995] was presented by *Gibson and Low* [1997]. This remarkable solution describes the essential feature of a CME, but its relation to interplanetary observations remains to be determined.

All of the models described above are single fluid, polytropic, MHD models with and polytropic exponent greater than 1. In magnetic clouds at 1 AU (including the January 10–11, 1997, magnetic cloud) the electron temperature T_e greatly exceeds the proton temperature T [*Burlaga et al.*, 1981; *Osherovich et al.*, 1993a; *Farrugia and Burlaga*, 1994; *Fainberg et al.*, 1996]. In the solar wind upstream of the magnetic cloud, $T_e \sim T$; and in the sheath between the magnetic cloud and the solar wind, $T_e \ll T$. The analytic model of *Osherovich et al.* [1993a, b, c, 1995], *Farrugia et al.* [1993a, b], *Osherovich and Burlaga* [1997] shows that a magnetic cloud will expand out to $\approx$10 AU in the manner observed if $T_e \gg T$ and if the polytropic index γ is less than unity. Thus it is necessary to consider two-fluid models for the propagation of magnetic clouds. The analytic models do not include the interaction of a magnetic cloud with a helmet streamer and the solar wind.

A value of $\gamma < 1$ is consistent with the anticorrelation between T_e and the density which is observed in magnetic clouds at a large range of distances from the sun and over a large range of latitudes. This anticorrelation is basic characteristic of magnetic clouds and must be explained by any model that aims to describe magnetic clouds. For the January 10–11, 1997 magnetic cloud the anticorrelation is observed in the front half of the magnetic cloud, not in the prominence material. Although $\gamma < 1$ is not possible for a single fluid gas, such a γ is possible for the moment temperature in a collisionless plasma where the electron distribution function includes both a thermal core and a hot halo whose density relative to that of the core depends on the solar wind density. The moment temperature is the relevant temperature for MHD processes involving pressure, which includes contributions from both the core and the halo. This is a subject that requires further study.

We conclude that current models and theories of magnetic clouds appear to account for some of the basic features of the January 10–11, 1997, magnetic cloud. We are beginning to obtain closure between the theories/models of interplanetary clouds and the theories/models of helmet streamers, prominences and CMEs. The principal problem is to construct a comprehensive model/theory which includes (1) the mechanism for accelerating the magnetic cloud; (2) the evolution of magnetic cloud/helmet streamer configuration to 1 AU; (3) the inclusion of dense prominence material at the end of the magnetic cloud, allowing for drainage of some of this material back to the Sun; and (4) the inclusion of both electrons (with a two-component distribution function) and protons.

Acknowledgments. C. F. acknowledges support by NASA grant NAG5-2834. We thank D. Webb for providing information about the solar configuration, and Jean-Claude Viol for a discussion of filaments. Simon Plunkett prepared Figure 4 and Nathan Rich prepared Figure 5. We acknowledge stimulating conversations with J. Chen, A. Hundhausen, and B. C. Low concerning the origin and acceleration of magnetic clouds.

The Editor thanks J. Feynman and D. M. Rust for their assistance in evaluating this paper.

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(Received August 6, 1997; revised September 19, 1997; accepted September 24, 1997.)