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# On the Relationship Between Coronal Mass Ejections and Magnetic Clouds

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**Abstract.** We compare the substructures of the 1997 February 07 coronal mass ejection (CME) observed near the Sun with a corresponding event in the interplanetary medium to determine the origin of magnetic clouds (MCs). We find that the eruptive prominence core of the CME observed near the Sun may not directly become a magnetic cloud as suggested by some authors and that it might instead become the "pressure pulse" following the magnetic cloud. We substantiate our conclusions using time of arrival, size and composition estimates of the CME-MC substructures obtained from ground based, SOHO and WIND observations.

## Introduction

Coronal mass ejections (CMEs) are associated with nonrecurrent geomagnetic storms and long-lived solar energetic particle events and thus play a vital role in understanding the Sun-Earth connection. After departing from the Sun, the CME travels into the interplanetary (IP) medium and if Earth directed, reaches the Earth in 3–5 days depending on its speed. The magnetic clouds (MCs) in the IP medium are coherent magnetic structures often with a flux rope signature [*Burlaga,* 1991] and are associated with CMEs. However, the exact physical relationship between the CMEs observed near the Sun and the MCs is poorly understood [e.g., *Dryer,* 1996]. With the advent of *Yohkoh*, SOHO and WIND missions, we are now in a better position to bring together what we have learned from the near-Sun and near-Earth regimes. For instance, the SOHO/LASCO coronagraphs can observe CMEs with all their substructures up to an unprecedented heliocentric distance of 0.14 AU and Yohkoh and SOHO/EIT can observe the corona directly above the visible disk.

Close to the Sun, a typical CME consists of the following substructures: (i) a bright frontal structure which could be an expanding coronal arcade or coronal material swept up by the moving structures, (ii) a dark coronal cavity, (iii) an erupting prominence core consisting of cold and partially ionized material, (iv) an arcade formed beneath the erupting prominence [see e.g., *Hanaoka et al,* 1994; *Gopalswamy et al,* 1996], and (v) a shock wave ahead of the CME if the latter travels faster than the local characteristic speeds [*Wagner and MacQueen,* 1983; *Gopalswamy et al,* 1998]. In the IP medium, the CME counterpart consists mainly of an MC and a shock wave ahead of it (if the cloud travels faster than the ambient solar wind). Of the CME substructures observed in the corona, the innermost arcade is a closed structure attached to the Sun and is quasi-stationary (or expands with a speed of about a few $km\ s^{-1}$). If nothing drastic happens to the overall structure of the CME beyond the coronagraph field of view, one expects to observe in the IP medium its substructures in the following sequence: the shock, the frontal structure, the cavity and the prominence core. There is usually no difficulty in identifying the shock with respect to the magnetic cloud, so we do not discuss them further. In this letter, we use CME and MC observations of the 1997 February 07-11 event to argue that the MC could not have originated from the prominence core.

## Observations

Observations of the 1997 February 7-11 event consist of prominence observations from the Nobeyama radioheliograph, CME and prominence observations from the SOHO/EIT and the SOHO/LASCO coronagraphs and solar wind observations from WIND/MFI, SWE and MASS.

**Prominence Observation Close to the Sun:** The 1997 February 07 CME consisted of filament activity along a neutral line over the entire southern hemisphere. The major chunk of filament that became the core of the CME erupted from the southwest quadrant of the Sun (see Fig.1). Associated with the filament eruption was an X-ray arcade formation along the neutral line. The X-ray image was obtained by the *Yohkoh*'s Soft X-ray Telescope (SXT). Note that the X-ray arcade covers almost the entire southern hemisphere and remained so for the rest of the day. The radio observations reveal that filament moved in the westward direction in projection and became a prominence as it arrived at the limb. The prominence moved very slowly and was accelerating. The plane of the sky speed of the prominence was only about 50 $km\ s^{-1}$ near the solar surface. The prominence is actually considerably extended to the south as was seen in a SOHO/EIT 304 Å image [*Plunkett et al, 1997*].

**White Light CME:** The CME associated with this event was observed by the SOHO/LASCO C2 and C3 coronagraphs. Fig. 2 shows the CME at 01:30, 02:30 and 03:30 UT with its familiar three part structure. The frontal structure clearly is an arcade and overlies the X-ray arcade formation shown in Fig.1. The bright blob enclosed by the

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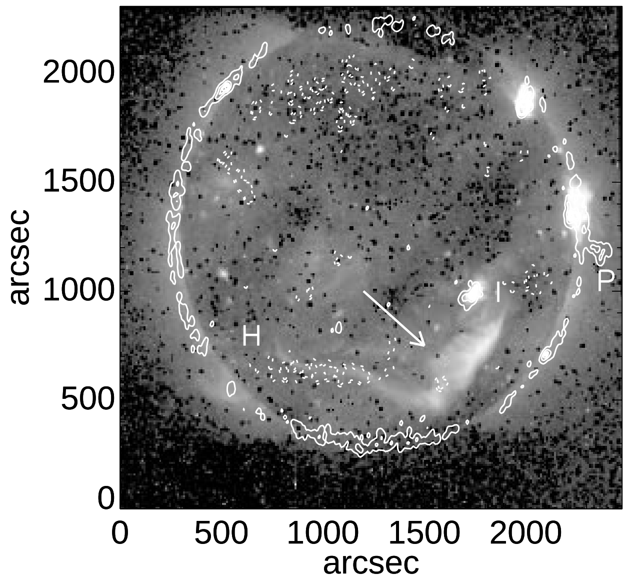


**Figure 1.** Overlay of radio contours (solid for enhancement and broken for depression with respect to the quiet Sun) on *Yohkoh* soft X-ray image showing the arcade formation (pointed at by arrow) in the southwest quadrant at 01:50 UT on 1997 February 07. P is the erupting radio prominence which moved from the location marked I. The horizontal section of the filament channel 'H' showed continuous expansion even after the CME had move far out in the corona.

frontal structure is the prominence core, considerably extended parallel to the limb (pointed by arrow in Fig. 2) under the span of the CME frontal structure. In Figure 3, we have plotted the heights of the frontal structure, the prominence core and the radio prominence close to the solar surface. The heights of the frontal structure and the prominence core fit to parabolic curves (constant acceleration). The acceleration of the frontal structure was ($\sim 17$ $m\ s^{-2}$) and the speed was about 730 $km\ s^{-1}$ at 25 $R_\odot$. At this height, the prominence was moving with a speed of only 390 $km\ s^{-1}$ and the acceleration was four times smaller ($\sim 4\ m\ s^{-2}$). Thus, the prominence lags behind the frontal structure by $\sim$ 5 hr at this height. We shall use these measurements to obtain the arrival time of various structures at the WIND spacecraft.

**Solar wind Observations:** The solar disturbance was observed by the WIND mission's MFI, SWE and MASS experiments. The magnetic field and plasma parameters obtained are shown in Fig. 4: magnetic field (B), polar angle ($\theta$), azimuthal angle ($\phi$), proton density (N), thermal velocity ($V_{THM}$), and solar wind speed (V). The CME associated shock arrived at the WIND spacecraft at 13:00 UT (marked by sharp jump in density N) on February 09 and the MC at about 02:00 UT on February 10. The MC continues until about 19:00 UT. Following the MC, there are three peaks in density (called pressure pulses), the largest one being at 21:00 UT on February 11. The peak density during the third pulse is about 40 $cm^{-3}$. The density is smaller by a factor of 3 compared to a similar pulse at the bottom of the 1997 January 6-11 CME-MC [*Burlaga et al,* 1998]. In the next section, we shall see that this pressure pulse corresponds to the prominence core that lags behind the CME frontal structure.

## Results and Discussion

From the disk observations in radio and X-rays, we infer that the CME originated at $\sim$ W45 so we take the plane of the sky and Earthward components of the velocity to be the same. We also assume that the speed of the CME and the prominence core do not change significantly after they have left the coronagraphic field of view at 30 $R_\odot$. One might expect a change in the height time profile as the CME moves through the interplanetary medium, but we assume that these changes do not affect the average speed of the CME significantly.

**Arrival Times:** With the measured speed of $\sim$ 730 $km\ s^{-1}$ at 25.5 $R_\odot$, the CME frontal structure would arrive at 1 AU after $\sim$ 50 hr. i.e., around 12 UT on February 9. This is about 14 hours before the start time of the MC. The prominence crossed the 25 $R_\odot$ height 5 hours after the frontal structure and this separation would be expected to continue. At 1 AU, the prominence would arrive at 12 UT on February 11. The MC had ended around 18:30 UT on February 10th. The nearest features in time are the pressure pulses and the largest one occurred at $\sim$ 21 UT on February 11. The prominence arrives $\sim$ 9.5 hr before the largest pressure pulse. Thus, based on the CME height–time plot, we see that the prominence at 1 AU arrives about two days after the the CME frontal structure. If we take the onset times of the MC and the pressure pulse to be the arrival times of the frontal structure and the prominence core respectively, then the difference between these two times is about 42 hours. This is very close to the 48 hours obtained from the extrapolated height-time plots of the CME frontal structure and the prominence core. Considering the uncertainties involved and the assumptions made, this represents a significant agreement. The measured and derived time difference between the MC and the pressure pulse is off only by about 12.5%. Thus the 5-hour delay observed towards the edge of the coronagraph field of view has increased to about 2 days when the CME traveled the Sun-Earth distance.

We have examined all the necessary data and convinced that the CME in question is well isolated. First of all there is no data gap in LASCO observations during the interval of interest (February 02–09). There was only one major CME that erupted above the west limb at 18:18 UT on February 03 with a plane of the sky speed of $\sim$ 500 km s$^{-1}$. Even if we use the projected speed, the CME would arrive at 1

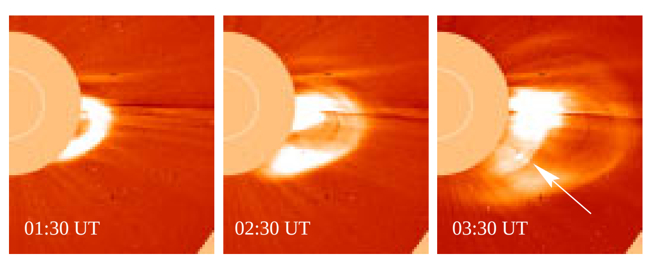


**Figure 2.** SOHO/LASCO C2 images obtained at 01:30, 02:30 and 03:30 UT. Note the arcade structure in the frontal bright feature. The bright blob in the 02:30 image corresponds to the radio prominence seen in Fig. 1 with its southward extension pointed to by an arrow. The white circle represents the optical disk. The occulting disk is at a distance of 2 $R_\odot$ from the Sun center.

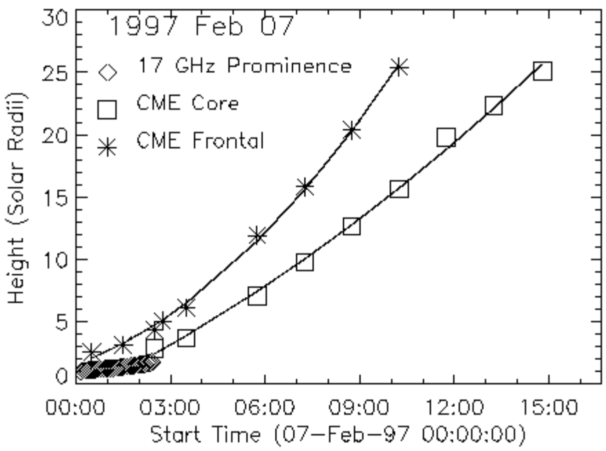


**Figure 3.** Height-time plot of the frontal structure and the prominence as observed by SOHO/LASCO and Nobeyama radioheliograph. The plot symbols correspond to the actual data points. The solid curves are parabolic fits to the LASCO data points.

AU on February 06 and hence cannot be associated with the February 09 MC. The other event of importance was filament disappearance towards the end of February 5 (Solar Geophysical Data, February, 1997) from the same neutral line region of interest. However, there was no CME associated with it in the LASCO and EIT data. There were only some X-ray loop changes associated with the eruption and hence may be a thermic disparition brusque with no eruption.

**Size Comparison:** We estimate the size of the MC and the pressure pulse from their observed duration and the measured speeds of the CME substructures. The MC lasts for about 18 hours and if we use the speed of the frontal structure (730 $km\ s^{-1}$), we find that the MC has a thickness of $\sim$ 0.3 AU. This is close to the typical observed size of magnetic clouds at 1 AU [*Lepping et al*, 1990, *Klein and Burlaga*, 1982]. The pressure pulse has a duration of about 3 hr. Assuming that the speed of the pressure pulse is the same as that of the prominence core, we find the size of the pressure pulse to be .03 AU, an order of magnitude smaller than the MC. In other words, the prominences will result in entities of size much smaller than that of MCs. If we use the average solar wind speed at the time of the MC (480 $km\ s^{-1}$) and the pressure pulse (375 $km\ s^{-1}$), the sizes are still vastly different (.2 AU for the MC versus .027 AU for the pressure pulse).

**Composition of the Pressure Pulse:** We present another piece of evidence supporting the identification of the pressure pulse with the prominence core. On February 11, 1997 from 1815-2200 UT a cold ($V_{th}$ < 20 $km\ s^{-1}$) and dense (proton density N $\sim$ 40 $cm^{-3}$) solar wind was observed on the WIND spacecraft. During this time period, WIND/MASS observed Fe charge state ranging from five to eleven. The presence of the low Fe5+, Fe6+ in relatively high abundance ratio indicates that this plasma had originated from a relatively cold region in the corona, viz. the prominence. There were two other weaker pulses prior to the largest one and they are consistent with other prominence fragments ejected from under the same CME envelope (see Fig. 2).

**What, then, is the Magnetic Cloud?** If the prominence does not become the MC, the coronal cavity or the frontal structure or a combination of the two must become the magnetic cloud. In the past, there were attempts to identify the magnetic cloud with the eruptive prominence [*Bothmer and Schwenn* 1994; *Rust* 1994], the cavity [*Chen,* 1996] and the frontal structure [*Gosling,* 1990]. In the model of *Chen* [1996], the flux rope is already formed near the Sun prior to eruption and simply moves to the IP medium. Based on the flux rope patterns derived from MC and prominence observations and from the similarity of the MC and prominence expansions, *Bothmer and Schwenn* [1994] concluded that MCs originate from the eruptive prominences. It must be pointed out that the expansion curves from *Mouschovias and Poland* [1978] and *MacQueen and Cole* [1985] quoted by Bothmer and Schwenn [1994] are not for prominences but for the bright frontal structure in CMEs. As we showed in

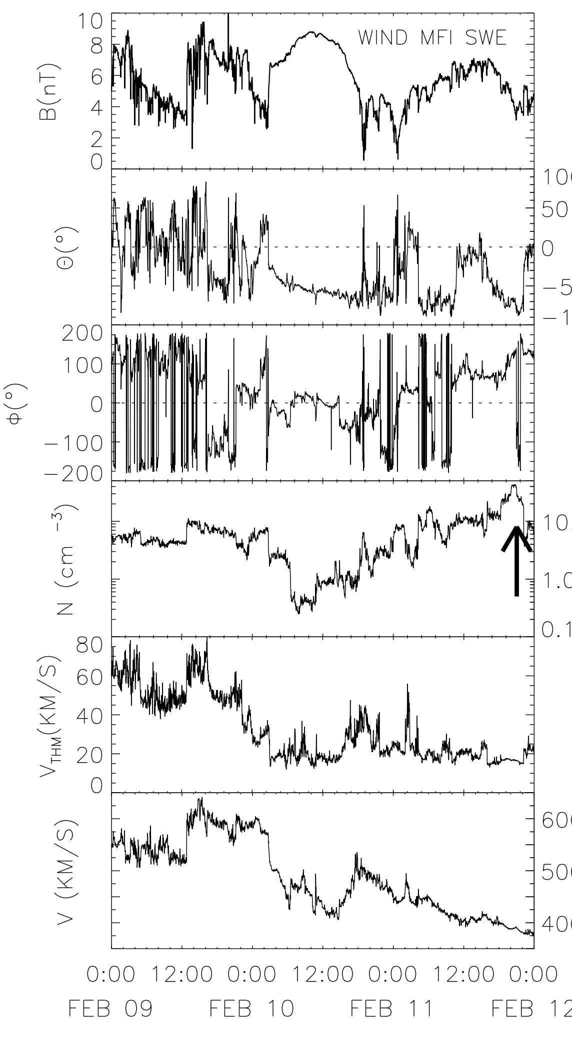


**Figure 4.** WIND/MFI, SWE summary plot showing the magnetic field (B), the polar angle ($\theta$), the azimuthal angle ($\phi$), the proton density (N), the thermal velocity ($V_{thm}$) and the solar wind velocity (V). The largest pressure pulse is indicated by an arrow mark.

this paper, it is difficult to form the MC out of the prominence owing to its smaller speed and size. In *Gosling's* [1990] model, the flux rope is formed out of the frontal arcade overlying the prominence due to reconnection. An implication of this model is that the MC will contain the prominence material if the reconnection occurs below the prominence. Reconnection above the prominence would be consistent with the present observations.

## Conclusions

We have presented observations and arguments against the suggestion that magnetic clouds are formed out of eruptive prominences associated with CMEs. We have attempted to identify various substructures of a CME near the Sun with those of the interplanetary counterpart. We have also shown that the prominence becomes the pressure pulse observed in the solar wind following the magnetic cloud based on the time of arrival, composition and size of the pressure pulse. The magnetic cloud itself must originate from the structures overlying the prominence. This structure could be a combination of the coronal cavity and the bright frontal structure.

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