

# The fraction of interplanetary coronal mass ejections that are magnetic clouds: Evidence for a solar cycle variation

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“Magnetic clouds” (MCs) are a subset of interplanetary coronal mass ejections (ICMEs) characterized by enhanced magnetic fields with an organized rotation in direction, and low plasma  $\beta$ . Though intensely studied, MCs only constitute a fraction of all the ICMEs that are detected in the solar wind. A comprehensive survey of ICMEs in the near-Earth solar wind during the ascending, maximum and early declining phases of solar cycle 23 in 1996 – 2003 shows that the MC fraction varies with the phase of the solar cycle, from  $\sim 100\%$  (though with low statistics) at solar minimum to  $\sim 15\%$  at solar maximum. A similar trend is evident in near-Earth observations during solar cycles 20 – 21, while Helios 1/2 spacecraft observations at 0.3 – 1.0 AU show a weaker trend and larger MC fraction.

## 1. Introduction

Interplanetary coronal mass ejections (ICMEs), the manifestations in the solar wind of coronal mass ejections (CMEs) at the Sun, are characterized by various signatures [e.g., Gosling, 1990; Zurbuchen and Richardson, 2004, and references therein] that include abnormally low plasma proton temperatures, bidirectional suprathermal electron strahls (BDEs) and energetic particle flows, cosmic ray depressions and plasma compositional anomalies. Fast ICMEs also generate shocks in the upstream solar wind. Klein and Burlaga [1982] defined a specific subset of ICMEs with enhanced magnetic field strengths  $> 10$  nT, a smooth rotation of the magnetic field direction through a large angle, durations of  $\sim 1$  day, and low plasma  $\beta$  (the ratio of the plasma/magnetic field pressures). Such “magnetic clouds” (MCs) have been the focus of intense study. They can often be modeled as simple force-free flux ropes [e.g., Lepping et al., 1990] or more complex, non-force-free models [e.g., Osherovich and Burlaga, 1997; Cid et al., 2002]. Similar magnetic configurations may arise naturally during CME eruptions [e.g., Gosling et al., 1995], and helical structures suggestive of flux ropes are occasionally visible in coronagraph images of CMEs [e.g., Chen et al., 1997; Dere et al., 1999]. In addition, magnetic clouds with periods of strong southward magnetic field generate many of the most intense geomagnetic storms [e.g., Cane et al., 2000; Webb et al., 2000; Cane and Richardson, 2003, and references therein]. The large-scale structure of MCs has also been examined using observations

from multiple spacecraft [e.g., Burlaga et al., 1981; Cane et al., 1997; Mulligan et al., 1999a]. Figure 1(a) shows solar wind magnetic field and plasma observations from the Advanced Composition Explorer (ACE) during passage of an MC on April 16 – 17, 1999.

Nonetheless, many ICMEs appear to lack the characteristics of MCs. Figure 1(b) shows an example on March 10 – 12, 1999. The magnetic field is  $< 10$  nT, includes several directional discontinuities and shows no large-scale organization. An intermediate event (October 5 – 7, 2000) is illustrated in Figure 1(c). This includes two periods with indications of organized field rotations, delineated by the vertical dashed lines, though the field intensity is  $< 10$  nT. Otherwise, the ICMEs in Figure 1 share characteristics such as periods of abnormally low proton temperatures relative to the “expected” temperature [e.g., Richardson et al., 1997] indicated by black shading, declining speed profiles consistent with expansion, and upstream shocks (solid vertical lines). Zurbuchen and Richardson [2004] illustrate additional ICME signatures associated with the events in Figure 1.

Various studies have estimated the fraction of ICMEs that are MCs. Gosling [1990] concluded that  $\sim 30\%$  of ICMEs in 1978 – 1982 defined by BDEs were MCs, a widely quoted result. Mulligan et al. [1999b] obtained 38% for ICMEs in mid-1978 – 1979 identified using several signatures but with a more relaxed MC definition, while only 14% of the ICMEs in 1978 – 1982 discussed by Richardson et al. [1997] were MCs reported by other researchers. Cane et al. [1996] found that  $\sim 49\%$  of the ICMEs associated with  $> 3\%$  cosmic ray decreases at Earth in 1964 – 1994 were reported MCs. Bothmer and Schwenn [1996] concluded that  $\sim 41\%$  of ICMEs encountered by the Helios 1 or 2 spacecraft at 0.3 – 1.0 AU in 1979 – 1981 were MCs (increasing to  $\sim 60\%$  for their events that followed strong shocks [Cane et al., 1997]). An MC fraction of  $\sim 60\%$  was estimated by Cane et al. [1997] for ICMEs associated with cosmic ray depressions observed by Helios 1/2 in 1975 – 1979, while Marubashi [2000] has claimed that up to  $\sim 80\%$  of the ICMEs in the near-Earth solar wind during 1978 – 1982 were encounters with magnetic flux ropes. In this paper, we point out that the fraction of MCs appears to depend on the phase of the solar cycle, both in the current and earlier cycles.

## 2. Observations

When assessing the fraction of ICMEs that are MCs, a comprehensive list of ICMEs is required to provide a reliable normalization for the number of MCs. The present study uses first a list of near-Earth ICMEs we have compiled for the years 1996 – 2002, encompassing the rising and maximum phases of solar cycle 23 [Cane and Richardson, 2003]. This list is based on in-situ observations (principally of solar wind plasma and magnetic field) and aims to provide a comprehensive survey of ICMEs in the near-Earth solar wind. We have updated the list to include events in 2003 and have made a few minor corrections to the original list. Note that a subsequent study [Richardson and Cane, 2004] indicates that solar wind compositional anomalies that are

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characteristic of ICMEs show an excellent association with the ICMEs identified by *Cane and Richardson* [2003].

Figure 2(a) shows the monthly sunspot number during 1996 – 2003 (from the Royal Observatory of Belgium). The yearly number of ICMEs during this period is indicated in Figure 2(b). Reflecting the increase in the CME rate at the Sun observed by LASCO [*St. Cyr et al.*, 2000], the ICME rate increases by around an order of magnitude, from 4/year in 1996, to  $\sim 50$ /year around solar maximum (the lower rate in 1999 was previously noted by *Cane et al.* [2000]). To identify those ICMEs that are MCs, we have referred to the list of MCs made available by the WIND MFI team ([http://lepmfi.gsfc.nasa.gov/mfi/mag\\_cloud.pub1.html](http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud.pub1.html)). From examination of the magnetic field and plasma data, we generally corroborate these identifications, though with occasional exceptions. Figure 2(b) indicates the number/year of our ICMEs that are MCs, while Figure 2(c) shows the ratio of MCs to all ICMEs. This ratio clearly varies with the solar cycle, from 100% in 1996 (with low statistics), declining to  $\sim 15\%$  around solar maximum. There is evidence of a recovery in 2002 as the ICME rate declines, but this does not appear to have continued into 2003. The “error bars” in Figure 2(c) (and Figures 3 and 4 below) simply indicate how the MC fraction would change if the number of ICMEs or MCs were to be changed by one event.

We next examine whether ICMEs during previous solar cycles show a similar variation in the MC fraction. Filled circles in Figure 3 show the MC fraction as a function of time relative to solar minimum for events during 1964 – 1994 in the cosmic ray study of *Cane et al.* [1996] where an ICME was present (“Class 1/3” events). Only events with adequate magnetic field coverage are included. Though again there are few ICMEs near solar minimum (years from minimum with  $\leq 2$  events are not shown in the figure), there is evidence of a decline in the MC fraction from  $\sim 40\%$  during 1 – 3 years following minimum to  $\sim 25\%$  during 3 – 7 years from minimum (i.e., around solar maximum). Also shown in Figure 3 by open circles is the MC fraction for ICMEs (with magnetic field data) we have identified in the OMNI solar wind data for 1972 – 1982, encompassing the decline of solar cycle 20 to the decline of cycle 21 (this is the most extended period of nearly complete 1 AU solar wind observations prior to the current cycle). Again there is a decrease in the MC fraction as solar activity levels increase, followed by a recovery as the cycle declines. The low MC fraction 1 – 2 years before sunspot minimum may be associated with a temporary increase in solar activity during 1974.

We have also estimated the MC fraction for  $\sim 150$  probable ICMEs observed at 0.3 – 1.0 AU by the Helios 1 or 2 spacecraft in 1975 – 1981 or 1976 – 1980, respectively. These ICMEs are identified predominantly from plasma and magnetic field signatures, cosmic ray modulations (observed by the University of Kiel experiments, e.g. *Cane et al.* [1997]), and associations with interplanetary shocks. The Helios MC fraction (Figure 4, filled circles) again tends to decline with time from solar minimum, though this variation is much weaker than in the near-Earth observations. Note also that overall, the MC fraction is higher than that inferred from near-Earth studies, as suggested by the results of *Cane et al.* [1997] and *Bothmer and Schwenn* [1996]. This result is not understood. We have considered the possibility that the MC fraction may be higher closer to the Sun. For example, Figure 4 also shows the MC fraction in the distance range 0.3 – 0.8 AU – the Helios spacecraft spent approximately equal periods inside and outside of 0.8 AU. These results, and other divisions of the observations by radial distance, provide little evidence of a higher MC fraction closer to the Sun.

### 3. Summary and Discussion

Observations near the Earth during cycle 23 and cycles 20 – 21 indicate a decrease in the fraction of ICMEs that are magnetic clouds as solar activity levels increase, from  $\sim 70\%$  around solar minimum to  $\sim 20\%$  around solar maximum. This trend is also present, though much weaker, in observations from Helios 1 and 2 made at 0.3 – 1.0 AU from the Sun, which also suggest higher MC fractions  $\sim 60\%$ .

Several factors could contribute to the solar cycle variation in the MC fraction. One possibility is that MCs near the Sun evolve into more complicated structures by interactions with other ICMEs en route to 1 AU [e.g., *Burlaga et al.*, 2002]. (Thus, the ICME in Figure 1(c) may include two components with different senses of field rotation.) Such interactions are more likely at high activity levels, consistent with the decrease in the MC fraction around solar maximum. However, to reduce the MC fraction from say 70% to  $\sim 20\%$  as a result of single ICME – ICME interactions would require  $\sim 80\%$  of ICMEs to make an interaction. This high prevalence of interactions seems unlikely given typical separations of  $\sim 1$  week between ICMEs passing the Earth at solar maximum (cf. Figure 2) which is considerably longer than typical ICME transit times to 1 AU. Furthermore, the absence of a clear decrease in the Helios MC fraction with heliocentric distance suggests that if such interactions do influence the MC fraction, they must predominantly occur inside the orbital range of Helios (i.e.,  $< 0.3$  AU from the Sun). The increasing spread in the latitudes of the central axes of CMEs as activity levels increase [*Hundhausen*, 1993; *St. Cyr et al.*, 2000] may also increase the probability that an MC will only make a glancing encounter with the Earth or low-latitude spacecraft. In such cases, clear MC signatures may not be observed, reducing the apparent MC fraction as activity increases.

Our favored cause of the solar cycle variation is an increase in the typical magnetic complexity of CMEs as they are formed at the Sun during the solar cycle. Simple flux-rope like configurations may be predominant at lower activity levels, when ICMEs principally originate from the streamer belt. As activity increases, CMEs originate more frequently from active regions, which have more complicated magnetic structures. Reconnection of multiple loop systems, and the complex overlying coronal field, may result in CMEs and subsequently ICMEs with complicated magnetic field structures. Supporting this view, none of the 40 energetic shocks associated with interplanetary type II radio emission in cycle 21 identified by *Cane* [1985] were followed by magnetic clouds [*Richardson and Cane*, 1993]. On the other hand we recognize that some notable ICMEs from active region sources, such as that associated with the “Bastille Day”, 2000 event, are MCs. Thus, the suggestion that ICMEs from the streamer belt tend to have MC configurations, while those from active regions do not, is certainly not clear cut.

A solar cycle variation in the MC fraction may have important implications for space weather forecasting. For example, the probability of a given ICME propagating towards the Earth producing a geomagnetic storm may be higher at solar minimum since there is a greater likelihood of it having a magnetic cloud-like magnetic field which in turn may have a prolonged, strong southward component (cf., *Cane and Richardson*, [2003], Figure 6). Evidence of such an effect is found by *Zhao and Webb* [2003]. They note that the solar minimum period in 1996 – 1997 discussed by *Webb et al.* [2000], in which six apparently Earthward-directed CMEs were all followed by shocks, MCs and moderate geomagnetic storms, is exceptional, and that relatively fewer

geomagnetic storms followed similar CMEs closer to solar maximum. They attribute this to the increased inclination of the streamer belt at solar maximum which increases the inclination of the axis of MCs ejected from the streamer belt, reducing their geoeffectiveness.

In addition to the solar cycle dependence suggested by the present study, variations in the MC fraction reported in individual studies may be attributable to differences in the set of ICMes used to normalize the number of MCs and the criteria used to compile the MC list (which may or may not exclude MCs with significant data gaps, or relax the *Klein and Burlaga* [1982] criteria). Furthermore, around half of the ICMes observed at 1 AU show evidence of a field rotation that might be a relic of a cloud-like structure [*Cane and Richardson*, 2003], even though the fraction of "classic" MCs is much smaller. On the other hand, there are complicated events, such as that in Figure 1(b), which seem difficult to interpret as either a conglomeration of simple MC-like structures or a glancing encounter with a region of organized magnetic field. A final complication is that multi-spacecraft observations suggest that MCs can be substructures of ICMes [*Cane et al.*, 1997], so that the same ICME may be identified as an MC at one location but not at another.

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**Figure 1.** ACE solar wind magnetic field and plasma parameters during ICMes with (a) a clear MC signature, (b) a weak, fluctuating magnetic field with no obvious organization, and (c) a weak field with two intervals of organized rotations in direction. All follow a shock (solid vertical line) and are associated with regions of depressed proton temperatures (black shading).

**Figure 2.** (a) Monthly sunspot number for 1996 - 2003; (b) Total number of ICMes/year, updated from *Richardson and Cane* [2003] and the number of these events that are magnetic clouds; (c) Percentage of ICMes that are magnetic clouds.

**Figure 3.** Variation in the MC fraction vs. years from sunspot minimum for *Cane et al.* [1996] class 1 or 3 events (•) and ICMes in 1972 - 1982 (cycles 20 - 21; ○).

**Figure 4.** Variation in the MC fraction for Helios 1/2 ICMes vs. time from sunspot minimum for heliocentric distances 0.3 - 1.0 AU and 0.3 - 0.8 AU.







