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Composition and magnetic structure of interplanetary coronal mass ejections at 1 AU

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Abstract

We study the magnetic structure and charge state ratio of interplanetary coronal mass ejections (ICMEs) observed by ACE and Wind spacecraft. Measurements of abundances and charge state ratio of heavy ions (e.g. O^{7+}/O^{6+}, C^{6+}/C^{5+}, and Mg^{10+}/O^{6+}) in the plasma as well as magnetic field structure are important tracers for physical conditions and processes in the source regions of ICMEs. We used ion composition (from ACE), plasma (from Wind) and magnetic field (from Wind and ACE) data from 1998 to 2002. Using the low proton temperature criterion, a common plasma signature of ICMEs, we identified 154 events which include magnetic clouds, non-cloud ejecta and complex ICMEs. The latter one refers to compound events resulting from the overtaking of successive ICMEs which can include both magnetic clouds and non-cloud ejecta. We find that there is a close relationship between the increase in the charge state ionization factor and the magnetic structure of ICMEs. Events with magnetic cloud topology show higher $Q_{O^{7+}/O^{6+}}$ and $Q_{Mg^{10+}/O^{6+}}$ charge state ratios than those with non-magnetic cloud structure. However, both magnetic cloud and non-cloud events show an increase in these ratios when compared with the ambient solar wind. In contrast, perhaps due to instrumental effects, the charge state ratio $Q_{C^{6+}/C^{5+}}$ for all events does not show a real enhancement when compared with the ambient solar wind. The difference in ionization states between non-cloud ejecta and magnetic clouds is more pronounced in fast solar wind than when events are embedded in slow wind.
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1. Introduction

Interplanetary coronal mass ejections (ICMEs) detected in situ by spacecraft are associated with CMEs from the Sun (Gopalswamy et al., 1998). Several signatures present in ICMEs distinguish them from the normal solar wind: bidirectional suprathermal electrons (Gosling et al., 1987) and energetic ions (Richardson and Reames, 1993), abnormal proton temperature depressions (Gosling et al., 1973; Neugebauer and Alexander, 1991; Richardson and Cane, 1995), helium enhancements (Hirshberg et al., 1972; Borrini et al., 1982), intensified magnetic field (Burlaga et al., 1981; Gosling et al., 1987), smooth magnetic field rotations (Burlaga et al., 1981), and unusual ionization states of heavy ions (Bame et al., 1979; Galvin et al., 1993; von Steiger et al., 1995; Lepri et al., 2001).

Magnetic clouds (MCs) are a subset of ICMEs. They are characterized by: (i) a strong magnetic field magnitude, (ii) a smooth rotation of the magnetic field direction through a large angle, and (iii) low proton

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temperature and low plasma-β (Burlaga et al., 1981). Non-cloud ejecta typically may not have one or more of the MC signatures.

The IP signatures of ICMEs may provide important clues to the physical processes that govern CME initiation in the low corona, and propagation into the heliosphere. Therefore, a study of the processes that produce the variety of observed signatures will result in a better understanding of the structure and composition of ICMEs (see review by Neugebauer and Goldstein, 1997).

Charge state distributions of heavy ions observed in the plasma in the interplanetary medium provide a direct measure of the conditions in the coronal environment where the solar wind and ICMEs originate, and hence may be able to differentiate between solar wind types (i.e., ejecta/CME related, slow and fast wind) (von Steiger et al., 1995). The relative ionization states of ions in the corona depend on the local electron temperature and density, the ion collisional ionization and radiative and dielectronic recombination rates, and ion outflow velocities (Hundhausen et al., 1968). The presence of high ionization states indicates a hot source region. As the solar wind expands, the coronal electron density decreases to the extent that the solar wind ion expansion time scale is short compared to the ionization and recombination time scales. The relative ionization states become constant. Thus, solar wind ions maintain their chemical and charge state identity as they propagate through the heliosphere, providing information of the conditions at the freezing-in altitude. Comparing the freezing-in temperatures from different charge state pairs, we may reconstruct the thermal history of the nascent solar wind and of ICMEs as they flow through the corona and heliosphere.

Recent studies suggest that ICMEs tend to have charge states indicative of unusually hot electron temperature at their source (von Steiger et al., 1995; Henke et al., 1998; Lepri et al., 2001; Reinard et al., 2001). In this work, we study the abundance of O^{7+}/O^{6+}, C^{6+}/C^{5+}, and Mg^{10+}/O^{6+} ratios inside 154 ICMEs observed by ACE and Wind spacecraft at 1 AU. We compare the composition characteristics of MCs with those of non-cloud ejecta. Our study follows a similar analysis as the one by Henke et al. (1998, 2001). in which they used ICMEs observed by Ulysses at different latitudes and studied O^{7+}/O^{6+}, C^{6+}/C^{5+}, Si^{10+}/Si^{9+}, and Fe^{12+}/Fe^{11+} ratios. In our data set ICMEs are observed at 1 AU on the ecliptic.

2. Observations

In our study, magnetic field data were obtained from the magnetic field experiment on board the ACE spacecraft (ACE/MAG). Plasma parameters are from ACE's solar wind electron, proton, and alpha monitor (SWEPAM) and Wind's three-dimensional plasma analyzer (Wind/3DP) instruments. We have obtained the ion composition data from ACE's solar wind ion composition spectrometer (SWICS) instrument. From lists of ICMEs reported in the literature (Cane and Richardson, 2003), and those available on line (http://lepmfi.gsfc.nasa.gov), we selected a set of 154 ICMEs between February 1998 and November 2002, which were classified as magnetic cloud (28 events) and non-cloud ejecta (117 events). The events classified as magnetic clouds satisfy the three criteria given on the MC definition given in the introduction after Burlaga et al. (1981). The non-cloud ejecta satisfy the low proton temperature criterion given by Richardson and Cane (1995). Those cases in which succesive ICMEs are present, with an interval between them of less than 6 h, are considered as complex ejecta (9 events). These events may include both magnetic clouds and non-cloud ejecta. To be sure that all magnetic clouds in our data set fulfill the main characteristics pointed out in the magnetic cloud definition (Burlaga et al., 1981), with a smooth magnetic field rotation on a plane, we performed a minimum variance analysis (Sonnerup and Cahill, 1967).

Fig. 1 illustrates an ejecta and a MC with their corresponding magnetic field hodograms. Fig. 1(a) shows the plasma and magnetic field parameters of the ejecta observed during days 24–26 of year 2000. The ejecta interval, according to the low proton temperature criterion (Richardson and Cane, 1995), is marked with vertical solid lines. The total magnetic field strength is not significantly enhanced with respect to the ambient magnetic field. The second panel shows that no smooth magnetic field rotation was present in the elevation angle θ. Thus, this ejecta does not fulfill the characteristics of a MC. The alpha to proton ratio is not significatively increased and the plasma-β has some spikes. The magnetic field hodogram for this ejecta is shown in Fig. 1(b). The variation of the magnetic field in the direction of minimum variance (min var) is not much smaller than the direction of maximum variance (max var). Moreover, the error criteria of the minimum variance method (Lepping and Behannon, 1980) ($\lambda_2/\lambda_3 \geqslant 2$; λ_2 and λ_3 correspond to the eigenvalues of the directions of intermediate and minimum variance) was not satisfied ($\lambda_2/\lambda_3 \sim 1.6$), which means that the magnetic field rotation is not confined to a plane.

Fig. 1(c) shows the plasma and magnetic field parameters of the MC observed during days 225–226 of year 2000. The MC interval, defined by the magnetic field and proton temperature depression signatures, is marked with vertical solid lines. The total magnetic field strength is enhanced relative to the background. The elevation angle θ changes sign as it rotates smoothly from south to north. Other panels show an enhanced alpha to proton ratio ($\geqslant 0.08$) as well as a decrease in the plasma-β. The decrease of the bulk speed is indicative of a

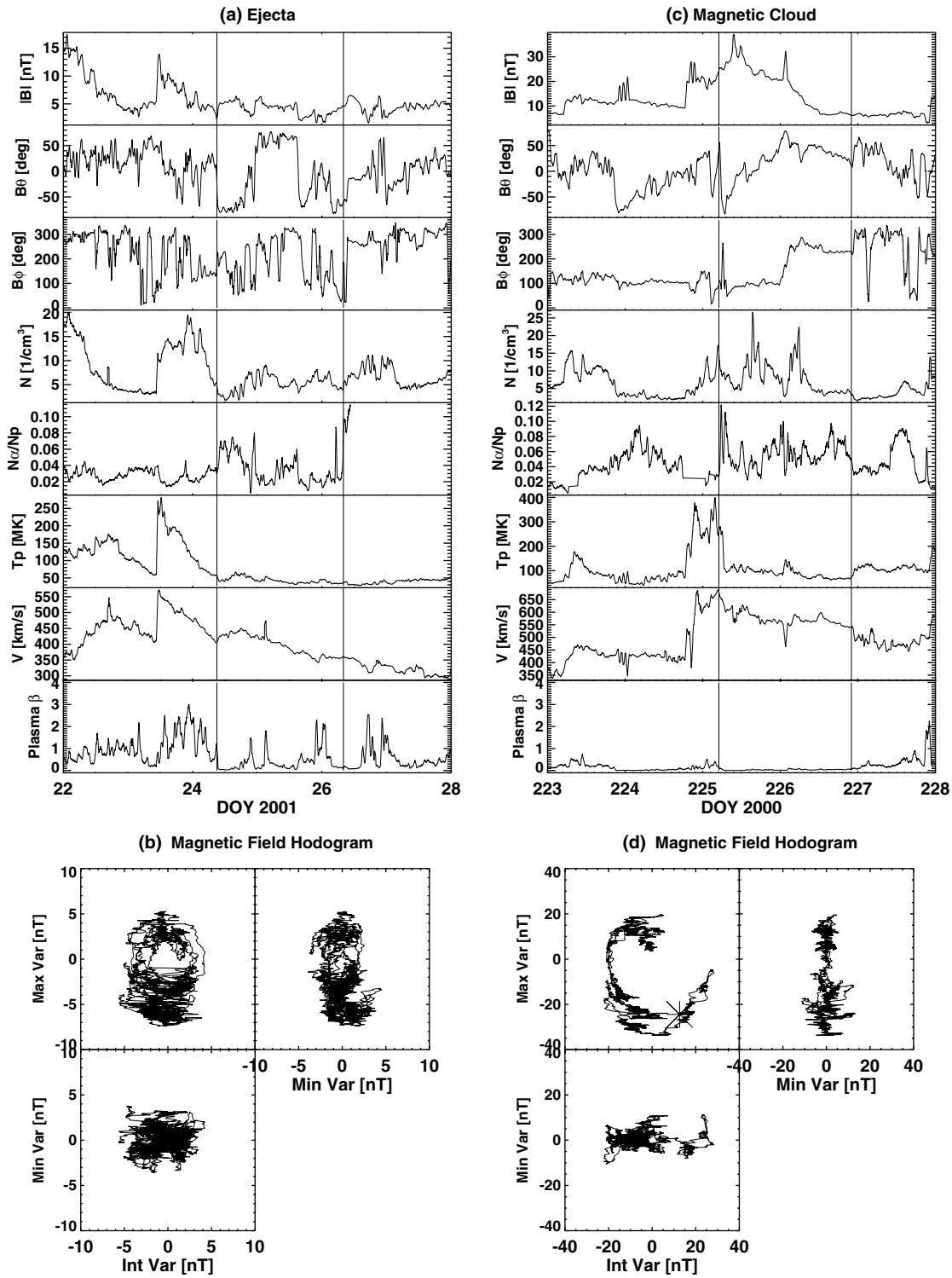

Fig. 1. Magnetic field and plasma parameters for two ICMEs observed by ACE and WIND. Magnetic field hodograms are shown in figures (b) and (d).

possible expansion of the MC. The magnetic field hodogram (Fig. 1(d)) shows that the variation of the magnetic field in the direction of minimum variance is much smaller than in the direction of maximum variance. The magnetic field has a smooth rotation over an angle of $\sim 136°$ in the plane perpendicular to the direction of minimum variance. The error criteria is satisfied ($\lambda_2/\lambda_3 \sim 10.44$).

3. Charge state ratios

To describe the variation of charge state of ICMEs with respect to the ambient solar wind, a ratio Q of the charge state ratio inside the ICME and in the ICME's adjacent solar wind is defined for O^{7+}/O^{6+}, C^{6+}/C^{5+} (Henke et al., 2001) and for Mg^{10+}/O^{6+}

$$Q_{x(i+1)i} = \frac{\left(X^{(i+1)+}/X^{i+}\right)_{\mathrm{ICME}}}{\left(X^{(i+1)+}/X^{i+}\right)_{\mathrm{SW}}}, \quad (1)$$

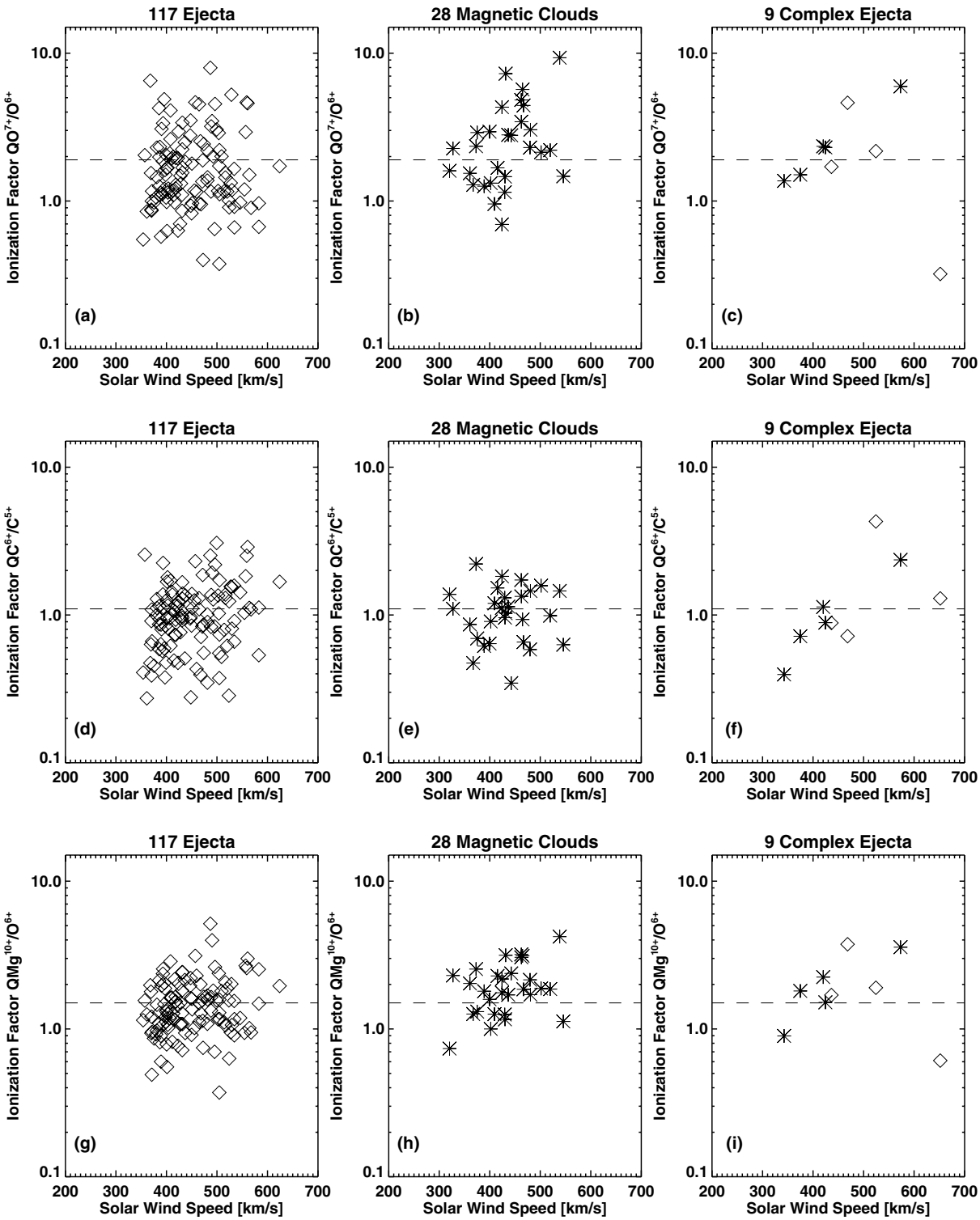

Fig. 2. Ionization factors ($Q_{O^{7+}/O^{6+}}$, $Q_{C^{6+}/C^{5+}}$, and $Q_{Mg^{10+}/O^{6+}}$) versus ambient solar wind speed of non-cloud ejecta, MC and complex ICMEs. The dashed line in each plot indicates the limit obtained to differentiate between increased and not increased ratios.

where $(X^{(i+1)+}/X^{i+})_{\mathrm{ICME}}$ and $(X^{(i+1)+}/X^{i+})_{\mathrm{SW}}$ are the charge state average values inside the ICME and in the adjacent solar wind, respectively. Using the data set corresponding to the non-cloud events, we obtained a mean ICME ionization factor ($\overline{Q}$) for each charge state ratio

$$\overline{Q}_{\mathrm{O}^{7+}/\mathrm{O}^{6+}} = 1.9, \quad \overline{Q}_{\mathrm{C}^{6+}/\mathrm{C}^{5+}} = 1.1, \quad \overline{Q}_{\mathrm{Mg}^{10+}/\mathrm{O}^{6+}} = 1.5.$$

Fig. 2 shows the different ionization factors for magnetic clouds, non-clouds and complex ejecta versus the ambient solar wind speed in the intervals before and after the ICME. This speed was evaluated in the intervals before and after the ICME, having the same length as the ICME event itself. The dashed line in each plot corresponds to the mean value obtained from the ionization factor of the ICMEs without magnetic cloud structure given above. This limit gives us a way to distinguish between ICMEs with significantly increased ionization factor and those without it. Complex ejecta are separated in events which consisted of at least one MC (asterisks), and those without an MC (diamonds).

Figs. 2(a)–(c) show $Q_{\mathrm{O}^{7+}/\mathrm{O}^{6+}}$ for non-cloud ejecta, MC and complex ICMEs, respectively. The classification limit is at $\overline{Q}_{\mathrm{O}^{7+}/\mathrm{O}^{6+}} = 1.9$. Our results show that 35% of the non-cloud ejecta, 61% of the MCs, and 56% of the complex ICMEs present ionization factors above the classification limit. Although some events in magnetic cloud and complex ICMEs lie below the classification limit, it is important to point out that their ionization factor values are higher compared with those for non-cloud ejecta. Table 1 summarizes these results. From Eq. 1, we can see that when $Q = 1$, the charge state ratio inside the ICME is equal to the nominal ionization state of the solar wind in which the ejecta is embedded (i.e., $Q_n = 1$). We find that for the ionization factor $Q_{\mathrm{O}^{7+}/\mathrm{O}^{6+}}$, 76% of non-cloud ejecta, 93% of the magnetic cloud, and 89% of complex ICMEs have an average ionization factor greater than this nominal value for the ambient solar wind. This indicates that the sources of the three ICME types are connected mostly with regions that are hotter than the regions where the ambient solar wind originates. In the case of complex ejecta, the number of events is small and our results must be interpreted with care as there are not enough statistics.

Table 1
Ionization factors $Q_{\mathrm{O}^{7+}/\mathrm{O}^{6+}}$, $Q_{\mathrm{C}^{6+}/\mathrm{C}^{5+}}$ and $Q_{\mathrm{Mg}^{10+}/\mathrm{O}^{6+}}$ for non-cloud, MC and complex ICMEs

Ionization factor	Non-cloud ejecta	Magnetic cloud	Complex
$Q_{\mathrm{O}^{7+}/\mathrm{O}^{6+}} > 1.9$	35%	61%	56%
$Q_{\mathrm{O}^{7+}/\mathrm{O}^{6+}} > Q_n$	76%	93%	89%
$\langle Q\rangle_{\mathrm{O}^{7+}/\mathrm{O}^{6+}}$	1.9	2.8	2.5
$Q_{\mathrm{C}^{6+}/\mathrm{C}^{5+}} > 1.1$	41%	50%	44%
$Q_{\mathrm{C}^{6+}/\mathrm{C}^{5+}} > Q_n$	49%	54%	44%
$\langle Q\rangle_{\mathrm{C}^{6+}/\mathrm{C}^{5+}}$	1.1	1.1	1.4
$Q_{\mathrm{Mg}^{10+}/\mathrm{O}^{6+}} > 1.5$	44%	71%	78%
$Q_{\mathrm{Mg}^{10+}/\mathrm{O}^{6+}} > Q_n$	78%	80%	78%
$\langle Q\rangle_{\mathrm{Mg}^{10+}/\mathrm{O}^{6+}}$	1.5	2.0	2.0

Q_n represents the nominal ionization state of the solar wind in which the ejecta is embedded.

Figs. 2(d)–(f) show the $Q_{\mathrm{C}^{6+}/\mathrm{C}^{5+}}$ ionization factor versus ambient solar wind speed for the three ICME groups. In this case, there is not a clear (see Table 1) difference in the ionization factor between non-cloud, MC, and complex ICMEs. When comparing with the nominal value of the ambient solar wind, we find that 49% of non-cloud ejecta, 54% of MC, and 44% of complex ICMEs have an ionization factor greater than 1. It is necessary to point out the fact that the ACE/SWICS data analysis for the $\mathrm{C}^{6+}/\mathrm{C}^{5+}$ ratio is not sufficiently elaborated (see paper by Richardson and Cane, 2004, and references therein), and this can influence our results, which must be taken with care.

Figs. 2(g)–(i) show (see Table 1) that most of MC and complex ICMEs have an ionization factor $Q_{\mathrm{Mg}^{10+}/\mathrm{O}^{6+}}$ greater than the defined limit of 1.5. In contrast, this is not the case for non-cloud ejecta, for which 56% have a decrease in their ionization factors. Comparison with the nominal ambient solar wind value shows that 78% of ejecta, 80% of magnetic cloud, and 78% of complex ICMEs have $Q_{\mathrm{Mg}^{10+}/\mathrm{O}^{6+}} > 1$.

We also studied the helium abundance (He^{4+}/proton > 0.08) inside ICMEs and found that while the majority (82%) of MCs have helium enhancements, only 39% of non-cloud events had this signature.

4. Summary and conclusions

We find that there is a close relationship between the increase in the charge state ionization factor and the magnetic structure of ICMEs. Events with magnetic cloud topology show an increase in their $Q_{\mathrm{O}^{7+}/\mathrm{O}^{6+}}$ and $Q_{\mathrm{Mg}^{10+}/\mathrm{O}^{6+}}$ charge state ratio with respect to the ambient solar wind, whereas non-cloud ICMEs do not show a similar increase. We find that for $Q_{\mathrm{C}^{6+}/\mathrm{C}^{5+}}$ there is no clear difference between values inside magnetic clouds and non-cloud ICMEs. Complex ejecta be similar to the MC events. This suggests that charge state abundances of heavy ions inside complex ejecta are increased by the presence of an MC in the event. Charge state abundances in complex ejecta should be further investigated. Our study also shows that all the three types of ICMEs have large ionization states when compared to the ambient solar wind (nominal values), suggesting that they come from regions hotter than the source regions of the slow solar wind.

Our results show that in the slow solar wind, the difference in ionization states between non-cloud ejecta and magnetic clouds is not as marked as when the events are embedded in fast solar wind. In our data set most of the ICMEs are embedded in slow solar wind

($V < 650$ km/s). This is in contrast to the data set of Henke et al. (2001), where many ICMEs observed by Ulysses were embedded in faster solar wind. They found a stronger difference between the charge states of magnetic clouds and non-cloud ejecta when the events were embedded in fast solar wind. For ICMEs embedded in slow solar wind, they found that 38% of magnetic clouds and 21% of non-cloud ejecta had an increase in their $Q_{O^{7+}/O^{6+}}$ charge state ratio, whereas for those ICMEs embedded in fast solar wind, 70% of magnetic clouds and 17% of non-cloud ejecta had an increase in this charge state ratio.

Although, we still do not know what determines the formation of a magnetic cloud, i.e., why sometimes a magnetic cloud forms and others no, our results suggest that magnetic cloud material tends to originate from hotter regions than the material injected in non-cloud ICMEs. Our results support the idea that unusual ionization states, above nominal solar wind values, are indicative of ICME material. It is important to mention that the compositional signatures are highly time-dependent, i.e., not constant inside ICMEs, indicating very variable conditions at source region, or possibly that plasma from hotter and cooler regions made its way into the ejecta structure. To explain the presence of high ionization states inside ICMEs, Lepri and Zurbuchen (2004) have proposed a scenario in which high Fe charge states are the result of magnetic connectivity to flaring regions. Reinard et al. (2003) found a casual relationship between CMEs with large flares and ICMEs with enhanced oxygen charge state ratios. Further studies are required to see if observations of coronal events and flares support these ideas.

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