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# Bidirectional Proton Flows and Comparison of Freezing-in Temperatures in ICMEs and Magnetic Clouds

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**Abstract.** From all the transient events identified in interplanetary space by in-situ measurements, Magnetic Clouds (MCs) are among the most intriguing ones. They are a special kind of Interplanetary Coronal Mass Ejections (ICMEs), characterized by a well-defined magnetic field configuration. We use a list of 40 MCs detected by Ulysses to study bidirectional flows of protons in the ~0.5 MeV energy range. Solar wind ions are also analysed in order to compare cloud to non-cloud ICMEs.

The enhancement in freezing-in temperatures inside the clouds, obtained with data from the SWICS instrument, provides insights into processes occurring early during the ejection of the material and represents a complementary tool to differentiate cloud from non-cloud ICMEs. At higher energies, directional information for protons obtained with the EPAC instrument allows a comparison with previous results concerning bidirectional suprathermal electrons. The findings are qualitatively comparable. Apparently, the portion of bidirectional flows inside magnetic clouds is neither heavily dependent on distance from the Sun nor on parameters obtained from a flux rope model.

**Keywords.** Sun: corona, Sun: abundances, Sun: coronal mass ejections (CMEs), Sun: solar wind, Sun: particle emission

## 1. Introduction

ICMEs are the interplanetary manifestation of CMEs. As they propagate in the heliosphere, their internal properties and configuration develop to the extent that it is difficult to relate them back to what was seen at a few solar radii from the Sun. An ICME detected at several AUs from the Sun has expanded and distorted, there is no simple picture of what the global topology of these structures might look like (see e.g. Riley & Crooker (2004)). On the other hand, it is only in interplanetary space where an important subset of all the ICMEs can be detected, namely magnetic clouds (MCs). They are defined by the combination of a large-scale smooth field rotation, enhanced magnetic field magnitude, decreased plasma temperature and low plasma-beta (Burlaga (1991)). Furthermore, they represent the interplanetary manifestation of a flux rope expelled from the Sun.

From all the physical parameters which can be measured in-situ by a spacecraft located in interplanetary space, there is one which remains unaltered, not affected by the undergoing development of the solar wind parcel to which it belongs. This parameter is the ionization level of the solar wind ions, which due to the low densities prevailing already at a few solar radii from the Sun, remains unchanged as the solar wind propagates outwards. By measuring charge states of solar wind ions, thermodynamic properties present in the source region of the solar wind, can be analysed at any distance in the heliosphere.

Several previous studies (e.g. Schwenn *et al.* (1980); Galvin (1997); Henke *et al.* (2001); Lepri & Zurbuchen (2001); Rodriguez *et al.* (2004)) have explored the relation between charge states and ICMEs. The general finding is that charge states are increased inside ICMEs, with respect to values observed in quiet solar wind. Henke *et al.* (2001) adduced this increases not to all the ICMEs but mostly to those which show a flux rope structure (magnetic clouds). Rodriguez *et al.* (2004) extended Henke analysis to a set of 40 magnetic clouds detected by Ulysses, finding that the increased charge states are present at all latitudes and phases of the solar cycle. In this work, we will compare two sets of ICMEs, the first one consisting of magnetic clouds and the second one composed only of non-cloud ICMEs. The possible difference between cloud and non cloud ICMEs, regarding their ionization levels, will be studied. In this regard it is important to clarify whether charge states, in addition to the magnetic field structure, provide another in-situ tool to differentiate MCs from non-cloud ICMEs.

Early observations (Morrison (1954); Gold (1959)) prompted the possibility that the footpoints of ICMEs are still connected back to the Sun as they expand and propagate in interplanetary space. More recently an explanation for such connection has been pursued with in-situ data on bidirectional suprathermal electron flows (BDEs, e.g. Crooker *et al.* (1990)), providing that this counterstreaming particles originate in the footpoints of the ICME still anchored back to the Sun. At higher energies, bidirectional fluxes similar to the ones seen for ∼100 eV electrons were first reported by Rao *et al.* (1967) and have been more recently investigated by several authors (e.g. Marsden *et al.* (1987)). The explanation raised for such behavior again suggests the presence of magnetic fields loops connected to the Sun. By using a rich set of events, we are in the position to estimate the degree of bidirectionality (and corresponding connectivity) of MCs in the heliosphere. Similar studies has been carried out for suprathermal electrons, at 1 AU Shodhan *et al.* (2002) found BDE intervals within MCs, covering 0% to 100% of the total duration of the events, with 59% as average value. Less degree of counterstreaming fluxes was detected in solar minimum and the percentage decreases with decreasing cloud size. Similar result (69% average of BDE intervals) was found by Riley *et al.* (2004). We plan to compare here these results with those obtained from near relativistic particles inside MCs.

## 2. Data

Charge state distributions of oxygen were derived from SWICS (Gloeckler *et al.* (1992)) measurements. From charge state ratios (3-hour resolution data, described in von Steiger *et al.* (2002)) the freezing-in temperatures of oxygen (Hundhausen *et al.* (1968)) was calculated assuming the equilibrium ionization rates of Arnaud & Rothenflug (1985).

Directional information of protons (0.63-0.77 MeV) was obtained with the EPAC instrument (Keppler *et al.* (1992)). The Energetic PArticles Composition instrument EPAC was designed to provide information on the flux, anisotropy and chemical composition of energetic particles in interplanetary space. It comprises four telescopes, each of them with a geometric factor of about 0.08 $cm^2sr$ and a field-of-view with a full angle of 35°. The telescopes are inclined at angles of 22.5°, 67.5°, 112.5° and 157.5°, with respect to the spacecraft spin axis (which points towards Earth). For protons, each of the four telescopes is divided in 8 sectors, providing 32 possible directions to detect incoming particles. Telescopes, sectors and the spacecraft spin, allows EPAC to sample 80% of the sphere.

The mentioned data is used in this work to analyze a list of 40 magnetic clouds detected throughout the Ulysses mission and described in Rodriguez *et al.* (2004). The non-cloud ICMEs were obtained by selecting the events present in the Ulysses ICME list, (maintained by the SWOOPS team and available at http://swoops.lanl.gov/cme_list.html) which were not defined as MCs in the first list.

## 3. Bidirectional protons

We have analyzed protons in the energy range 0.63 - 0.77 MeV. The information from the 32 available different incoming directions (8 sectors and 4 telescopes) have been extended using a spherical expansion method described in Fränz & Krupp (1993). With this method we obtain the harmonic coefficients up to second order which allow us to characterize the particles' directional anisotropies.

More specifically and due to the points discussed in the Introduction, we are interested in bidirectional field aligned flows. Therefore we deal mainly with the second order harmonic coefficient $A_{20}$. Positive values of it represent field aligned bidirectional particle fluxes with stronger bidirectionality as $A_{20}$ increases. For values lower than zero, the particles gyrate around the magnetic field, with a pitch angle close to 90°. In this work we use the dimensionless value of $A_{20}$, obtained after dividing it by $A_0$, which is the zero order coefficient, representing the isotropic portion of the distribution. The use of this coefficient is an important aid which complements and helps to quantify the eye inspection of pitch angle plots. Figure 1 shows a colored pitch angle representation, along with the $A_{20}$ coefficient for one event. This MC (delimited by the vertical solid lines in Figure 1) occurred in 2001, when Ulysses was located at 25° south of the ecliptic during its second fast latitude scan. During cloud passage, the pitch angle plot (top panel) shows a clear bidirectionality along the field, with high fluxes at 0° and 180° and minima close to 90°. $A_{20}$ encompasses this description by increasing above 1, during the whole duration of the event. The bidirectional flows extent further into the trailing part of the cloud as more closed field lines seem to trail the MC. It is not the case for the frontal part in which the bidirectional flows appear suddenly and near to the commencement of the flux rope structure. This particular MC will be further analysed in a future work.

Two values of $A_{20}$ were obtained analyzing 1-hour averages of EPAC data for each event. The first value represents the average over the positive $A_{20}$ counts (bidirectional field aligned population); the second one was taken from the negative $A_{20}$ values (indication for a population with $\sim$90° pitch angle gyrating around the magnetic field). In Table 1, a brief summary of the results obtained is given. The energetic protons are predominantly bidirectional (in 88% of the cases) in comparison with few cases in which they were found with pitch angles close to 90° (12%). Considering their duration, relative to that of the MC, we find that (in average) positive values of $A_{20}$ are present during 60% of the duration of the MC and negative ones during 44% (both percentages were calculated using the respective subsets to which they belong, i.e. $A_{20}>0$ or $A_{20}<0$, as 100%). Low positive values of $A_{20}$ do not indicate a clear bidirectionality, as can be seen directly by eye inspection of the pitch angle plots. In order to assure bidirectionality, we have set a threshold for $A_{20}$ at 0.5. In this way, we can estimate that clear bidirectionality is present in 33% of the studied cases with duration averaging 52% of the total duration of the event.

These results are qualitatively in agreement with those from Shodhan *et al.* (2002) and Riley *et al.* (2004). By inspection of the pitch angle plots it has been inferred,

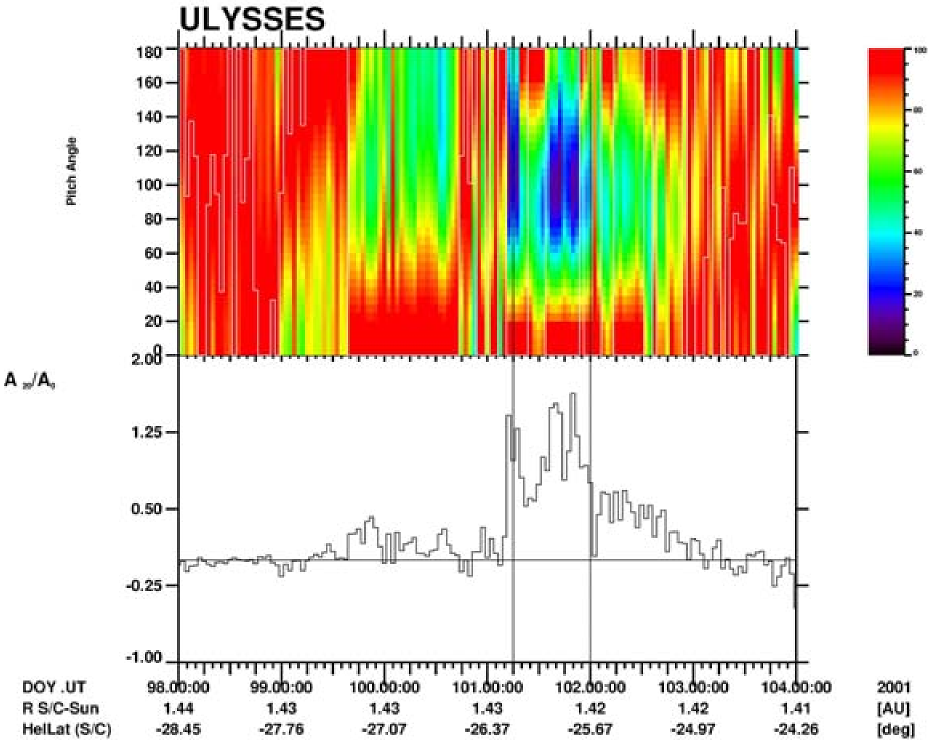

**Figure 1.** Pitch angle and $A_{20}$ harmonic coefficient for the MC detected by Ulysses in April 2001. The solid vertical lines demark the MC interval as identified by Rodriguez *et al.* (2004)

| | $A_{20}>0$ | $A_{20}<0$ | $A_{20}>0.5$ |
|---|---|---|---|
| % of cases | 88 | 12 | 33 |
| % duration | 60 | 44 | 52 |
| Avg. value | 0.47 | -0.2 | 1.09 |

**Table 1.** Summary of the behavior of the $A_{20}$ coefficient inside magnetic clouds.

nevertheless, that the bidirectional characteristics of the more energetic particles studied here show a higher degree of patchiness than its low energy counterparts. This has not been quantified here, since no difference was made on whether the values of $A_{20}$ were contiguous or randomly spread over the event.

Based on calculations on reconnection rates, Riley *et al.* (2004) estimated a decrease of connectivity as the ICMEs propagates outwards of ~2%/AU. A similar trend was found here using $A_{20}>0$, Figure 2. Somewhat steeper (5%/AU), the slope of the linear fit should be only carefully taken into consideration, due to the high level of scatter present in the data.

In a further approach to try to correlate these periods in which bidirectional fluxes are detected and may, therefore, represent a possible connection of the field lines back to the Sun, we have used an elliptical flux rope model described in Hidalgo *et al.* (2002). By its application to the events under study one obtains parameters such as the orientation of the flux rope axis, current densities and geometric variables describing the expected shape of the clouds. After a thoughtful comparison we can conclude that there is no

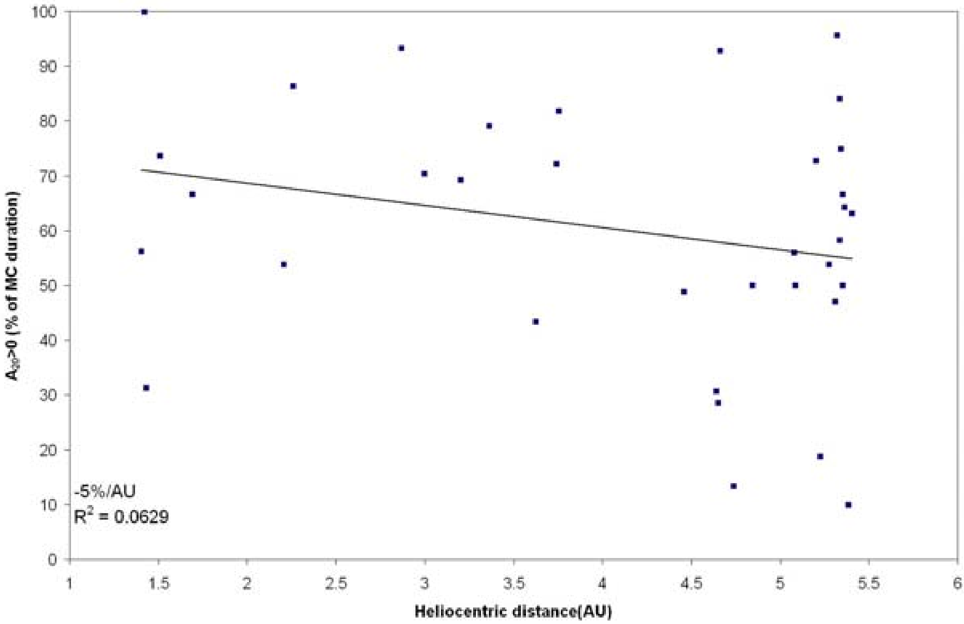

**Figure 2.** Development of the $A_{20}$ coefficient with respect to distance from the Sun. A negative trend is seen, though the highly scattered points preclude further conclusions to be drawn.

striking dependence between the different parameters obtained from the model and the $A_{20}$ coefficient. The degree of connectivity of the clouds seems to be independent of the local geometric characteristics as inferred from the model.

## 4. Freezing-in temperatures

Early observations of ions in the solar wind other than protons and alpha particles, such as singly ionized helium or several charge states of oxygen (e.g. Bame *et al.* (1968); Hundhausen (1968)), opened an active field in the investigation of coronal characteristics by means of in-situ interplanetary data. As the solar wind expands outward, the coronal electron density decreases to the extent that the time scale of coronal expansion is short compared to the ionization and recombination timescale. At this height in the corona (a few solar radii), the relative ionization states become constant, they 'freeze-in', reflecting the conditions at this altitude. At any further distance in space, the measurement of the charge states can be used to infer the electron temperature at the freezing-in altitude, providing thus a link between interplanetary and coronal conditions. Although this might be a simplified approximation, it constitutes a valid tool to derive coronal properties in interplanetary space. Charge states represent in this way an imprint of the solar wind source, in contrast to other plasma parameters such as density, velocity and temperature, which vary significantly between the corona and interplanetary space.

For the reasons exposed in the previous paragraph, charge state distributions of heavy ions in the solar wind are a good indicator of the solar wind type (e.g. von Steiger *et al.* (2000)), providing a robust tool for differentiating fast wind (from coronal holes), slow wind (associated with streamers) and transient-related solar wind. It is the latter the one that concern us here, as was stated in the Introduction to this paper, there have been

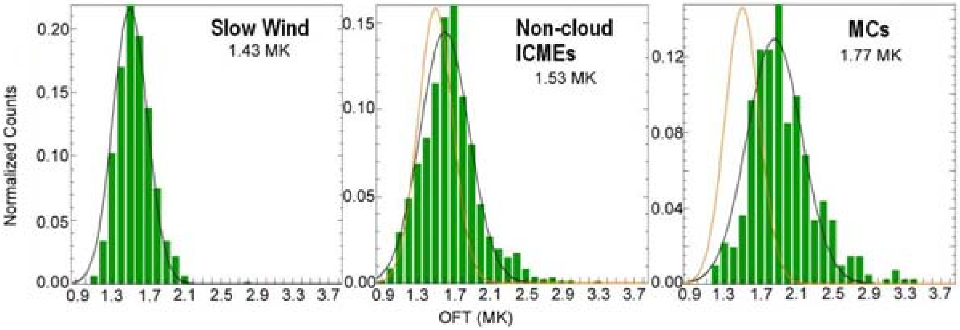

**Figure 3.** Oxygen freezing-in temperature distributions for slow wind, non-cloud ICMEs and MCs. Solid lines represent a Gaussian fit to the data. The slow wind Gaussian is shown for comparison in the ICME and MC distribution.

ongoing discussions in the past on whether all ICMEs or only those defined as magnetic clouds show increases in freezing-in temperature (or charge states).

Figure 3 shows a comparison of oxygen freezing-in temperatures distribution for slow wind and ICMEs with and without MC structure. The magnetic clouds are the 40 events listed in Rodriguez *et al.* (2004). Non-cloud ICMEs were obtained from the Ulysses ICME list, maintained by the SWOOPS instrument team, this list does not differentiate between cloud and non-cloud ICMEs, which were obtained simply by using those events not present in the MC list. The solar wind samples were selected from several periods in different years of the Ulysses mission, with special care taken in order to include only periods in which no transient events were present. A Gaussian curve was fitted to the three distributions and the values of the oxygen freezing-in temperature (OFT) shown in the plot are those obtained as the center of the Gaussian. Between slow wind and MCs there is a difference of 0.34 MK, whereas for the case slow wind-non-cloud ICMEs this difference reduces to 0.1 MK.

The difference with respect to the slow wind is three times higher in flux rope type ICMEs with respect to those without magnetic cloud signatures. We believe that this statistic comparison clarifies that the enhancement in freezing-in temperatures is clear for MCs, though also increased for non-cloud ICMEs to a much lesser extent.

## 5. Summary and conclusions

We have pursued a two-fold analysis using a set of magnetic clouds and non-cloud ICMEs relating them with energetic particles and solar wind ions.

In the first part of this work we believe to have shown that the behavior of the energetic protons of ~0.5 MeV is qualitatively similar to that of the suprathermal electrons, as measured by other authors, regarding their bidirectionality. Nevertheless the energetic particles seem to be less bidirectional if one poses stricter conditions to the classifications process (i.e. $A_{20}>0.5$), we believe that this threshold describes the bidirectional flows much clearer than simply using positive values of $A_{20}$. The harmonic expansion of data with sufficient directional information provides the possibility to use anisotropy coefficients to complement the analysis of pitch angle plots. There is only a weak correlation between percentage of bidirectional periods inside magnetic clouds with respect to distance from the Sun. The trend is negative as expected, but the high scatter in the data prevents us to make further conclusions. As a result of comparing the $A_{20}$ coefficient with parameters obtained from a flux rope model we conclude that there is no apparent correlation between them.

The second part of the present paper consisted in a comparison of oxygen freezing-in temperatures between magnetic clouds and ICMEs without a cloud structure. It was established that the increases in oxygen freezing in temperature, and therefore charge states, are more than three times higher for magnetic clouds than for non-clouds ICMEs, compared to quiet solar wind values. The oxygen freezing in temperature (OFT) can be used as a further magnetic cloud identifier, complementing in this way the signatures used at present. It is clear that there is a very important relation between charge states and magnetic configuration. For example, the ∼0.3 MK difference in OFT between fast and slow wind originates from the open vs. closed (respectively) magnetic field configuration present at the source region of the solar wind. Therefore, using the same way of thinking to associate the different magnetic field topology of a MC and a non-cloud ICME similar conclusions can be drawn. It is the characteristic magnetic field configuration of a MC, most probably present at the height where the ions freeze-in, what creates a difference in temperatures that can be detected later in interplanetary space. In turn, this would mean that the magnetic field configuration in cloud and non-cloud ICMEs is present since their birth and early development, and would then not be consequence of interplanetary effects (deformation, expansion, etc).

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## Discussion

Tylka: Do you see these magnetic clouds at all latitudes? Does the correlation between SEP composition inside and outside the MC depend on latitude?

Rodriguez: We see MCs at all latitudes. Nevertheless most of them are found below 40°. Apparently latitude is not a determinant factor for energetic particles' composition inside MCs. The important factor seems to be the presence and characteristics of shocks. This needs nevertheless, further study.

Gopalswamy: Have you looked at the difference composition signatures of filament and active region related ICMEs? One expects temperature difference in these two source regions.

Rodriguez: It is very difficult to unambiguously find the source region of ICMEs observed by Ulysses. This is due to the orbit of Ulysses, which introduces big error margins in the back mapping procedure. Also many CMEs have originated behind the solar limb. Nevertheless this is an interesting point and we will analyze the events which source region can be identified.