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In-situ and remote observations of CMEs

Luciano Rodriguez[1], A. N. Zhukov[1,2], J. Woch[3], N. Krupp[3], R. von Steiger[4], and R. Forsyth[5]

[1]Solar Influences Data analysis Center, Royal Observatory of Belgium, Brussels, Belgium
email: rodriguez@oma.be
[2]Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia
[3]Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany
[4]International Space Science Institute, Bern, Switzerland
[5]The Blackett Laboratory, Imperial College, London, UK

Abstract. We present studies on a series of ICMEs detected by Ulysses and for which the solar sources on the Sun could be identified. EUV and white light data are used in order to correlate characteristics seen during eruption with those measured in-situ. Particularly, an attempt was made to find solar features that show a relationship with the type of ICME seen later (i.e. cloud or non-cloud ICME). For magnetic clouds (MC) the chirality of the magnetic field was then analyzed. Finally, the charge states of oxygen ions contained in ICMEs were used to obtain freezing-in temperatures and then compare these with the presence of flares occurring close (spatially and temporally) to the CME eruption.
We have found no solar feature that could be used to predict the presence of a MC in interplanetary space, they occur with the same frequency for cloud and non-cloud ICMEs. The chirality of the clouds seems to follow only weakly the hemisphere rule. The presence of solar flares do not seem to be correlated with the oxygen freezing-in temperatures seen in-situ.

Keywords. Sun: corona, Sun: abundances, Sun: coronal mass ejections (CMEs), Sun: solar wind, Sun: activity

1. Introduction

Coronal mass ejections (CMEs) are extremely dynamical events in which the plasma, initially contained in closed coronal magnetic field lines, is ejected into interplanetary space. When they are detected in-situ by a spacecraft located in the interplanetary medium, they are termed interplanetary CMEs (ICMEs). If a smooth rotation in the magnetic field is present, together with low variance in the field intensity and low plasma temperatures (Burlaga (1991)), then the ICME is called magnetic cloud (MC). The distinction between cloud or non-cloud ICME can only be made in interplanetary space. Only in-situ data can help discerning between the two types. When the CME is seen remotely, there is no apparent way of forecasting how the interplanetary structure will look like. We have compared the features observed at the Sun before, during and after eruption with the magnetic field structure observed in interplanetary space in order to find possible indications of the internal magnetic field structure of ICMEs.

One characteristic of magnetic clouds, helpful to link them with their solar origin, is chirality (the sign of helicity). It is obtained from an analysis of the rotation of the magnetic field components relative to the cloud's axis, it can be left-handed (negative sign) or right-handed (positive sign). MCs originating in the southern hemisphere should have predominantly a positive chirality, while the opposite should occur for northern hemisphere clouds (Rust (1994), Bothmer and Schwenn (1998)). The chirality of the clouds detected by Ulysses will be analyzed to check the fulfillment of this rule.

Other valuable tool to link solar with interplanetary conditions are the heavy elements in the solar wind, they provide extremely important information about the origin of the solar wind. Since the ionic composition does not change in interplanetary space, it provides a direct measurement of the plasma properties below a few solar radii. Therefore, by means of the freezing-in principle introduced by Hundhausen *et al.* (1968), the electron temperature (or freezing-in temperature) in the low corona can be derived.

Nowadays, it is clear that the periods in which highest freezing-in temperatures are detected correspond almost unambiguously to ICMEs (i.e. Richardson and Cane (2004)). Henke *et al.* (1998), Rodriguez *et al.* (2004) and Rodriguez *et al.* (2005) demonstrated that the ionization level of oxygen is particularly increased if the ICME has a MC structure. Lepri and Zurbuchen (2004) proposed that the elevated iron charge states observed within ICMEs are related to flare heated material from regions magnetically connected to the CME. We will test here this hypothesis using oxygen ions.

2. Data and event selection

The charge state distributions of oxygen were derived from Ulysses SWICS measurements (Gloeckler *et al.* (1992)) and the magnetic field data were obtained from the Ulysses magnetometer (VHM/FGM) (Balogh *et al.* (1992)).

Solar data analysis were carried out using EIT (Delaboudinière *et al.* (1995)) and LASCO (Brueckner *et al.* (1995)) images, both instruments onboard SOHO. Flare information was obtained from the GOES X-Ray Sensor (XRS).

The ICMEs under study were collected from the literature, papers in which ICMEs have been identified in Ulysses data were sought after. Among these events, we selected those for which the author found the corresponding source region at the Sun. In this way, we ended up with the list of ICMEs described in Table 1. This list represents an updated version of the table in Gazis *et al.* (2006).

For all the events, the remote and in-situ data were then carefully analyzed. We have samples occurring on the first two Ulysses' orbits, which encompass the descending phase of solar cycle 22 and the ascending phase of solar cycle 23, respectively. Even though more ICMEs were detected during the second orbit, it was not easy to find unambiguously their solar sources, due to the high rate of CMEs at the Sun. On the other hand, during the fist orbit, the absolute number of ICMEs seen at Ulysses is lower, but the identification of the source regions of these ICMEs on the Sun could be done with greater accuracy due to the smaller amount of CMEs per day. That explains why there are more events selected during the first orbit than during the second.

3. Solar feature vs. ICME type

Table 2 displays the frequency of observation of certain solar features, in correspondence with the in-situ detection of a cloud or a non-cloud ICME later on. SOHO data were carefully analyzed in order to find the occurrence of the following solar features: flares occurring near to the CME (both spatially and temporally); filament eruptions clearly associated with each event; post eruptive arcades; CMEs originating in active regions and the detection of a 3-part structure in coronagraph images.
For the events occurring before the SOHO era (1992-1995), solar information was taken directly from the papers describing the events (see Table 1).

From Table 2, it can be inferred that there is no direct solar observation which can provide clear hints to help predict the magnetic configuration of the corresponding ICME. All solar indicators occur approximately with the same frequency (the difference is always

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Date (yy-mm-dd) Sun	Ulysses	Reference	Date (yy-mm-dd) Sun	Ulysses	Reference
92-02-26	92-03-15	Lemen *et al.* (1996)	96-11-28	96-12-10	Funsten *et al.* (1999)
92-04-17	92-05-09	Lemen *et al.* (1996)	96-12-21	97-01-08	Funsten *et al.* (1999) Watari *et al.* (2002)
92-10-30	92-11-13	Lemen *et al.* (1996)	97-10-23	97-11-13	Lario *et al.* (1998) Watari *et al.* (2002)
92-11-29	92-12-15	Bothmer *et al.* (1996) Weiss *et al.* (1996)	98-02-28	98-03-24	Gopalswamy *et al.* (2001) Skoug *et al.* (2000)
93-05-31	93-06-09	Bothmer *et al.* (1996) Gosling *et al.* (1994a), (1995a) Weiss *et al.* (1996)	98-09-23	98-10-10	Richardson *et al.* (2002)
93-07-09	93-07-20	Gosling *et al.* (1998) Lemen *et al.* (1996)	99-02-16	99-03-03	Lario *et al.* (2001) Leamon *et al.* (2004) Riley *et al.* (2003)
94-02-01	94-02-09	Bothmer *et al.* (1995) Weiss *et al.* (1996), (1996)	01-05-07	01-05-10	Simnett (2003)
94-02-20	94-02-27	Bothmer *et al.* (1995) Gosling *et al.* (1994b), (1995b) Hudson *et al.* (1996) Lemen *et al.* (1996) Weiss *et al.* (1996)	01-10-24	01-10-29	Reisenfeld *et al.* (2003a)
94-04-14	94-04-21	Bothmer *et al.* (1995) Gosling *et al.* (1994b), (1998) Hudson *et al.* (1996) Lemen *et al.* (1996) Weiss *et al.* (1996)	01-11-04	01-11-08	Lario *et al.* (2004) Reisenfeld *et al.* (2003b)
96-10-05	96-10-12	Funsten *et al.* (1999) Watari *et al.* (2002)	01-11-22	01-11-26	Lario *et al.* (2004) Reisenfeld *et al.* (2003a)

Table 1. ICMEs at Ulysses with identified solar sources.

	Flares	Filament eruptions	Arcades	Active regions	3p structure
MC	50	25	50	50	15
Non-cloud	60	40	60	40	20
Difference	10	15	10	10	5

Table 2. Correlation between ICME type and the solar features observed during CME eruption. The numbers represent the percentage of the corresponding ICMEs that were associated with each solar feature. The percentages are taken from 12 MCs and 5 non-cloud ICMEs.

lower than 15%) for cloud as for non-cloud ICMEs. The sample does not include the totality of events listed in Table 1 because some events originated in the back side of the Sun and it was not possible to obtain significant information on them.

4. Magnetic cloud's chirality

In Figure 1, the MCs at Ulysses were ordered according to their chirality, hemisphere of detection and hemisphere of origin. If the classification is done according to the

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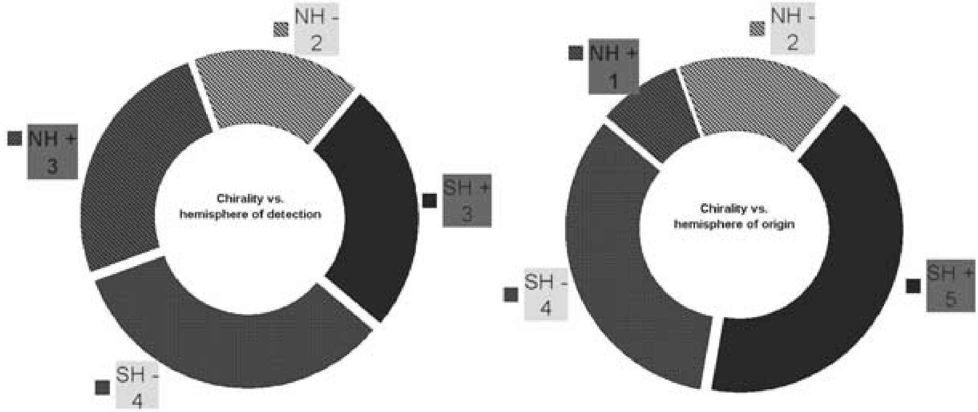

Figure 1. Helicity sign (chirality) of magnetic clouds, ordered by the hemisphere in which Ulysses was when they were detected (left) and by the solar hemisphere from which they were ejected (right). The letters represent the hemisphere, the sign corresponds to the helicity sign and the number shows the amount of MCs with that helicity sign and for that hemisphere.

hemisphere in which they were detected by Ulysses (left panel of Figure 1) then the hemisphere rule (see Introduction) is not fulfilled, a better agreement (even though weak) is reached when the information used corresponds to the actual solar hemisphere from which the clouds originated (right panel of Figure 1).

5. Freezing-in temperatures vs. flare occurrence

The freezing-in temperature (Hundhausen *et al.* (1968)) is a proxy for the electron temperature in the low corona, it is derived from charge states of solar wind ions. One possibility for the high freezing-in temperatures present in many ICMEs is related to the influence of flare heated material during the eruption. Lepri and Zurbuchen (2004) proposed this hypothesis to explain the elevated iron charge states observed in connection to ICMEs. We have carried out a similar study with the charge states of oxygen, converted into freezing-in temperatures. Figure 2 shows the averaged temperatures inside ICMEs, with a distinction made between those ICMEs for which we observed a related flare occurring in close spatial and temporal association to the eruption and those ICMEs which did not show a clear association with a flare. From the figure, it can be inferred that there exist no obvious correlation between oxygen freezing-in temperatures and flare occurrence.

The main difference between this work and that of Lepri and Zurbuchen (2004) is that higher temperatures are required to obtain the iron charge states observed by those authors (more than 5 MK), while the temperatures for oxygen are lower, around 2 MK.

6. Summary and conclusions

After compiling a list of ICMEs with identified solar sources, we have analyzed some characteristics of these events in order to find correlations between the solar and the interplanetary observations.

The event selection turned out to be easier during periods of low solar activity, due to the low rate of CMEs, which increased the accuracy of the identification.

The conclusion of a straight forward comparison between solar features and magnetic structure of the corresponding ICME (cloud or non-cloud), is that there is apparently no

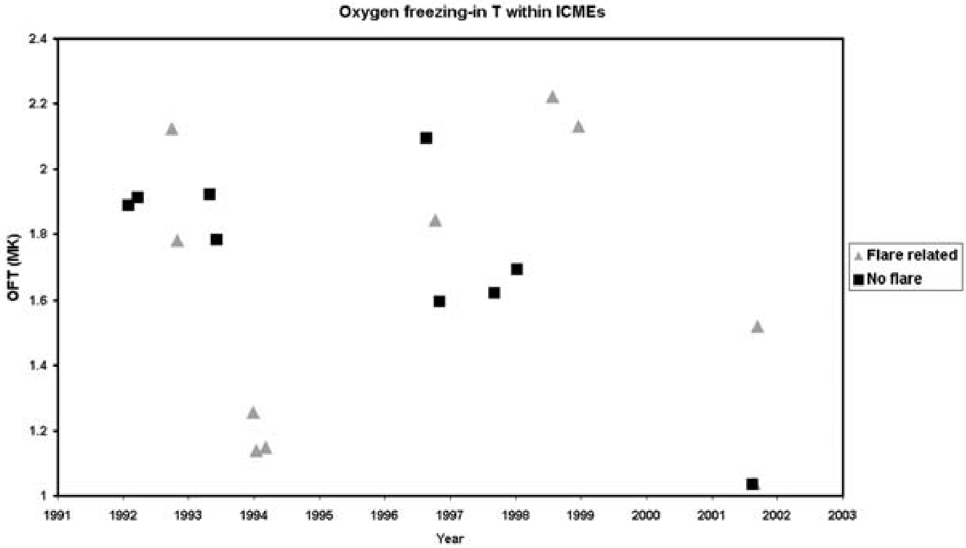

Figure 2. Freezing in temperature inside ICMEs, obtained from oxygen ions. The triangles represent the temperature inside ICMEs for which a related flare could be found during eruption, the rectangular ones are those for which no flaring activity was detected in correspondence with the CME.

solar indicator, among the most commonly used CME signatures, that could help predict the in-situ magnetic field configuration of the ejecta.

The chirality of this set of MCs follows weakly the hemisphere rule, and it should be stressed that the hemisphere in which the ICMEs are detected by Ulysses is not necessarily the same solar hemisphere from which they were ejected.

A correlation between flare occurrence and high oxygen freezing-in temperatures was not found for the events analyzed here. The required temperature to ionize iron ions is higher than 5 MK, justifying the presence of flares, whereas for oxygen temperatures around 2 MK would suffice. Therefore, it is logical to conclude that oxygen ions do not need strong flaring activity to reach high ionization states.

Acknowledgements

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