A ULYSSES ICME EVENT
AND ITS TRACK BACK TO THE SUN

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Abstract. The interplanetary coronal mass ejection (ICME) event registered by Ulysses on 10 June 2001 is analyzed by using data from VHM, SWOOPS, and SWICS instruments on board of the spacecraft. We focus on the ICME characteristics as identification conditions of the event, by applying plasma and composition signatures, as well as the classical criteria known in the literature for the ICMEs. We tracked this event back to the Sun considering a linear model, and found, as source, explosive events occurred near the active regions NOAA 09475 and 09486.

Key words: Sun – CME – ICME.

1. THE ICME CHARACTERISTICS

In this paper we analyze the interplanetary coronal mass ejection (ICME) event registered by Ulysses on 10 June 2001. We have used data from VHM, SWICS and SWOOPS instruments on board of Ulysses spacecraft. The studied ICME duration is 38.4 hours, starting on DOY (day of the year) 161.2 and ending on DOY 162.8.

Usually, the interplanetary mass ejections are analyzed by means of:
– classical identification conditions (high abundance of alpha particles, abnormally low proton temperature than expected $T_p/T_{exp} < 0.67$ (Neugebauer et al. 2003), decreasing velocity, low plasma $\beta$, increased magnetic field strength);
– plasma dynamics signatures (proton temperature depressed than expected, electron/proton temperatures ratio threshold $T_e/T_p > 2$);
– plasma composition signatures (enhanced alpha/proton ratio above 0.06–0.08, high Fe charge state, elevated oxygen charge state ratio, anomalies of heavy ion species abundance, low ions temperatures and speeds).

The magnetic field and plasma parameters registered by Ulysses spacecraft for an interval of 5 days, starting with DOY 160, are displayed in Fig. 1. Top panel plots the
magnetic field intensity (solid line), and proton density (dashed line) vs. time. Middle panel plots the alpha/proton abundance ratio times 10 (dots), the $T_p/T_{\text{exp}}$ ratio (dashed line), and the proton plasma beta (solid line) vs. time. The time is expressed in DOY. Vertical dashed lines mark the borders of the studied event, horizontal solid line represents the threshold 0.1 for plasma beta, and horizontal dashed line represents the 0.67 line threshold. Bottom panel displays the solar wind speed along the same time interval.

Fig. 1 – Magnetic field and plasma parameters indicating the presence of the ICME.
Within an ICME, both proton and electron temperatures tend to be lower as compared to the temperature of the surrounding solar wind. According to Richardson et al. (1997), the condition $T_e/T_p > 2$ represents a marker of ICMEs. In Fig. 2, the comparison between the proton temperature (dots) and electron temperature (solid line) provides information about the ICME presence. The criterion $T_e/T_p > 2$ is fulfilled for the analyzed event, as one can observe on the figure.

Additional to the most used compositional signature of alpha/proton abundance ratio, obtained from SWOOPS data, is important to analyze the abundance anomalies of heavy ion species and also their charge state from SWICS data. The optimum threshold value for the average Fe charge state is considered to be $Q_{Fe} = 11$. The overtaking of this threshold represents a strong indicator for the presence of ICMEs.

Fig. 3 (top panel) presents the distributions of Fe average charge-state (steps) and Fe/O abundance (bars). We observe high values of $Q_{Fe}$ reaching 13–14, and also a high Fe/O abundance during the entire event. The same Fig. 3 (bottom panel) plots the charge-state ratios of C(6+)/C(5+) (solid lines) and O(7+)/O(6+) (steps), the latter one exceeding the threshold 0.8.

Fig. 4 displays the temperatures of He++, C(6+), and O(6+): the condition of low ion temperatures are satisfied for the analyzed ICME event.

The magnetic field components of the interplanetary space, as registered by Ulysses, are plotted in Fig. 5. We can see the magnetic cloud lasting between DOY 161.4 to almost DOY 163. This means that 11 June 2001 was a full day of the event registered by Ulysses. Also considering the fulfilled conditions of strong magnetic field magnitude, low proton temperature, low plasma beta, and enhanced alpha-to-proton ratio (see Fig. 1, too), we can conclude that this event has the characteristics of a magnetic cloud.
Fig. 3 – The distributions of $Q_{Fe}$, and Fe/O abundance (top panel); C(6+)/C(5+) charge-state ratio, and O(7+)/O(6+) charge-state ratio (bottom panel).

Fig. 4 – Different elements exhibit low temperatures during the ICME event.
2. TRACKING BACK FROM ULYSSES TO THE SUN

In this section we discuss about the track back of the 10–11 June 2001 event from the ICME registered by Ulysses spacecraft to the Sun. This is a difficult task and could not be performed for every event. The ICME reached Ulysses with almost 400 km/s during 10 June 2001.

We remember that Ulysses spacecraft flew on 10 June 2001 at 1.35 AU; this position allowed it to receive the mass ejected from the Sun at a polar angle above 290 degrees. Fig. 6 (top panel) plots the spacecraft position during this event; the small square marks the spacecraft position.
We have used a linear approach to compute the occurrence day of the ICME event started on DOY 161.2 back to the Sun. Fig. 6 (bottom panel) plots a diagram with days of the year of events registered by Ulysses on vertical axis, while on the horizontal axis there are the days of the year of events should appear on the Sun. The dashed line (tu) represents the DOY 161.2 of beginning of the ICME detected in the spacecraft data; the dotted curve represents Ulysses events registered at moments doy\(_i\), expressed in day of the year and fraction of the day. This one is plotted versus ts\(_i\) (\(=\) doy\(_i\)\(-\)dt\(_i\)), in which dt\(_i\) is the time interval necessary to an event to cross the interplanetary space from the Sun to the spacecraft with the velocity registered at Ulysses. The intersection of both graphs should give the CME occurrence day that we read on the horizontal axis. We got DOY 155 as the day when the event started from the Sun, i.e., on 4 June 2001 a coronal mass ejection occurred in the solar atmosphere.

3. THE SOLAR SOURCE

The CDAW CMEs catalogue indicates several candidates as being possible CME counterparts of the ICME registered by Ulysses on DOY 161.2. All these events were registered by LASCO/C2 coronagraph on board of SOHO spacecraft, and had the right direction (namely, a polar angle of almost 290 degrees). Their characteristics are summarized in Table 1. In this table we have also computed the travel of the CME to Ulysses spacecraft, using the same linear model, but the value of the velocity registered by SOHO spacecraft.
The first CME we analyze occurred on 4 June 2001, at 0:54 UT and gives an arrival time to Ulysses on DOY 160.35. The second CME occurred on 4 June 2001, at 16:30 UT and gives an arrival time to Ulysses on DOY 160.73. The third event was registered at 0:30 UT, on 5 June 2001, and gives an arrival to Ulysses on DOY 161.88.

All these events raised in the active region NOAA 09486. The ICME reached Ulysses with a speed of about 400 km/s. The most appropriate event that accomplishes the time and velocity conditions seems to be the last one from Table 1. But, if we look better to the ICME characteristics, and especially to $B_z$ interplanetary magnetic field component deduced from Ulysses registrations, we conclude that all the CMEs arrived successively to Ulysses.

Fig. 7 displays this last CME event as it was registered by C2/LASCO. Perusing the EIT (195 Å) images, we observe the occurrence of the flare as a solar source of the CME. In Fig. 8 there is a negative EIT image of this solar source, where the arrow points the flare place.

![Fig. 7 – CME’s image registered by LASCO/C2 coronagraph from SOHO. The arrow points the CME movement direction.](image-url)
Fig. 8 – The flare that was the CME solar source indicated by the arrow. The image is a negative of a 195 Å EIT/SOHO coronal registration.

The Hα image (Fig. 9) registered by BBSO indicates a complex active region. Two neighboring active regions, NOAA 09475 and 09486, make the magnetic topology into the zone of the CME solar source more intricate. These regions had produced several CME previously.

Fig. 9 – Hα image of the solar source.
4. CORONAL MAGNETIC FIELD EXTRAPOLATION
IN THE SOLAR SOURCE ZONE

In order to understand the phenomenon, we investigated the circumstances of the CME onset looking in the 3D coronal extrapolated magnetic field lines. Using MDI photospheric magnetograms and a force-free field model, we extrapolated the coronal magnetic field lines in 3D setting up of ten dipoles to be detected in the flare zone.

Fig. 10 – Coronal magnetic field lines extrapolated from MDI/SOHO magnetograms.
We have considered the MDI magnetograms registered on 4 and 5 June 2001, before the CME onset. The results are displayed in Fig. 10. One can see the magnetic field lines opening at the flare and CME onset and during the event. The CME was registered on 5 June 2001, 0:30 UT, by the LASCO/C2 coronagraph on board of SOHO satellite. Fig. 10 indicates that the magnetic field lines opened starting with 23:08 UT, on 4 June 2001, and a maximum of field opening appeared at about 23:30 UT. At 0:35 UT, on 5 June 2001, we see a new configuration of the field lines. Fig. 10 displays all the dynamics of the magnetic field lines during the CME event, and how they reconnected after.

After analyzing these 3D plots, we could conclude that the event started before midnight UT, on 4 June 2001, as could be seen on EIT observations, too.

5. CONCLUSIONS

The event registered by Ulysses spacecraft between 10 and 11 June 2001 presents all ICME characteristics, as well as a magnetic cloud with significant rotation of the magnetic field.

The track back to the Sun indicates, as solar source, three events occurred on 4 and 5 June 2001, in NOAA 09475 and 09486 active regions zone. The follow up of these events registered by SOHO to Ulysses spacecrafts indicated us that all three CMEs produced successive ICMEs but the last one was more important.

The last event causing a CME was a small flare as solar source of the CME event we have tracked back. Extrapolation of the coronal magnetic field lines in a 3D topology, where the field lines open during the explosive events, reveals that the CME onset was on 4 June 2001, after 23:00 UT, but before that midnight.

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