Coronal Mass Ejections and Geomagnetic Storms

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From the Sun to the Earth the CMEs may:
- Deflect
- Rotate
- Get deformed

Transfer of energy from ICME to magnetosphere:
- Akasofu (1983) function:
  \[ \varepsilon = 10^7 V B^2 \rho^2 \sin^4 (\theta/2) \text{ (J/s)} \]
- Wang et al. 2014:
  \[ E_{\text{IN}} = 3.78 \times 10^7 n_{\text{SW}}^{0.24} V_{\text{SW}}^{1.47} B_T^{0.86} (\sin^{2.7} (\theta/2) + 0.25) \text{ [J/s]} \]
Filling the gap?
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Unfortunately, the authors do not state the exact type of expansion found but previous studies have found that ICMEs elongate kinematically in angular extent during their outward propagation (e.g. Owens et al., 2006; see review paper by Crooker and Horbury, 2006). Savani et al. (2010) used HI observations and numerical simulations to study an extreme case of interaction between a flux rope and its surrounding solar wind. The flux rope, observed edge-on, started as a quasi-circular structure in COR-2B and changed into a bean-shaped structure following its interaction with the ambient solar wind. No in situ measurements were available for this event; however, it is likely that total pressure was greatly enhanced inside and around this flux rope. The following example presents a direct association between well-defined interaction regions observed in situ and large-scale density structures observed in white light images.

Fig. 5 presents, in the same format as Fig. 4, observations of the outward propagation of density structures associated with a MC detected near Earth on 19–20 November 2007. Like the 2 June event, two density structures can be tracked from the Sun to 1 AU for this event. The passage of the rear density structure is immediately followed by the arrival of high speed streams. Rouillard et al. (2010c) identified the leading density structure as a sheath region and the rear density structure as an interaction region formed by high speed streams compressing the rear of the MC. The trailing density structure is already a large structure (width greater than 5\( \times \) elongation) when it is first evident in the HI-2B difference images suggesting that compression may have already started at a heliocentric radial distance of 0.3–0.5 AU. Comparison of the HI-A and HI-B observations showed that HI-B observed the rear density structure more clearly than HI-A. This was partly associated with the fact that HI-B integrated more sunlight along the plane of CIR-CME interaction (viewing the CIR spiral edge-on) than HI-A which integrated sunlight across this plane (see Section 2.1). The reader is referred to the paper by Sheeley and Rouillard (2010) which discusses this effect in more detail.

The combination of the sheath region, the MC and the interaction region between the MC and the high speed stream forms a continuous region of high total pressure or MIR (Burlaga et al., 1991, 2003). The formation of MIRs is more common near and beyond 5 AU where the entrainment of transients by high speed streams is common (Burlaga et al., 2003). This analysis showed that the onset of MIR formation can occur as close as 0.3 AU from the Sun. Moreover, this analysis exemplifies the inadequacy of the term CME in describing density structures in the HI-2 field of view. Density structures can contain as much if not more plasma that is kinematically and dynamically gathered by the interaction of the flux rope with ambient solar wind than intrinsic plasma released with the 'coronal mass ejection'.
CME propagation

One needs to know:

1) the CME characteristics (area, mass, speed, direction of propagation, magnetic configuration..)

2) the properties of the medium through which CMEs propagate (density, speed, magnetic configuration)

3) the interaction between the CME and the medium (physical processes: deflection, rotation, deformation, reconnection, erosion – see e.g. Wang et al. 2004, Dasso et al. 2006, Lynch et al. 2009, Lugaz et al. 2011, Manchester et al. 2014)
CME propagation

One can use:

• **Observations** – near Sun *(SOHO, STEREO, PROBA2, SDO)*
  – interplanetary space *(STEREO/HI)*
  – in situ *(ACE, WIND, DISCOVR, SOHO, STEREO)*

• **Models** – empirical:
  – constant or cessation of acceleration before 1 AU *(Gopalswamy et al. 2000, 2001)*
  – MHD: *ENLIL* *(Odstrcil 2003)*
  – *EUHFORIA* *(Pomoell et al. 2017)*
on the model used, MAS+ENLIL or WSA+ENLIL, we obtain quite different distance ranges at which the CME speed comes adjusted to the ambient solar wind flow. Applying results from MAS+ENLIL for Event 1, the CME would reach the solar wind speed below 30 $R_\odot$, whereas from WSA+ENLIL at $\sim 70 R_\odot$. According to the study of Event 1 by Robbrecht et al. (2009), there are no signatures of magnetic reconnection even during the very early phase of CME evolution close to the Sun. This implies that no driving forces are acting on this particular CME and that it is pulled out by the solar wind from starting from the low corona. This interpretation is supported by observations revealing a continuous increase in CME speed within the COR1+COR2 FoV matching the speed derived in the HI1 distance range. However, the inertia of the CME may cause a delay in the final adjustment. Taking into account the uncertainties in the extracted solar wind speed from WSA+ENLIL and MAS+ENLIL, the CME reaches the same speed as the ambient solar wind flow at a distance range 20–70 $R_\odot$.

From observations within the COR1+COR2 FoV, the CME speed of Event 2 clearly decelerates below 30 $R_\odot$. This can be interpreted as evidence for a strongly acting drag force over that distance range (see also Davis et al. 2010). Results from MAS+ENLIL support this interpretation and the CME speed is most likely adjusted to the background solar wind before entering the HI1 FoV. The increase of the CME speed at a distance of $\sim 150–180 R_\odot$ seems to be related to an increase in the background solar wind speed beyond $\sim 100–140 R_\odot$ revealed from both model runs (MAS+ENLIL and WSA+ENLIL) rather than due to a propelling Lorentz force. This provides further evidence that the CME is well embedded in the ambient solar wind flow during its propagation in IP space.

Event 3 is the first fast CME event of cycle 24 occurring during a period of enhanced solar activity. Therefore, it is more difficult to interpret from the observational as well as from the model side. The CME speed reveals a significant deceleration from $\sim 1100$ km s$^{-1}$ down to $\sim 750$ km s$^{-1}$ within the COR2 FoV and accelerates again up to $\sim 1000$ km s$^{-1}$ at a distance of $\sim 110 R_\odot$. To explain this behavior, we propose a scenario where the CME runs into strong overlying magnetic fields acting as obstacle which drastically slows down the CME already close to the Sun. Taking into account the distribution of the ambient solar wind flow on a qualitative basis, ENLIL shows that the CME crosses an HSS. Most likely, we observe a very weak

Temmer et al. 2011

CME propagation

Solar wind background:
Wang-Sheeley-Arge + ENLIL

Forces acting on CME:
- the propelling Lorentz force -
- the drag force.

Temmer et al. 2011
CME propagation (2008 - 2010)

- CME 3D speeds give slightly better predictions than projected CME speeds.
- The observed CME transit times from the Sun to 1 AU show a particularly good correlation with the upstream solar-wind speed.

Table 2

<table>
<thead>
<tr>
<th></th>
<th>Error [hours]</th>
<th>SDEV [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B: G2001, proj. V</td>
<td>16.31</td>
<td>1.0</td>
</tr>
<tr>
<td>C: G2000, 3D V</td>
<td>15.91</td>
<td>0.2</td>
</tr>
<tr>
<td>D: G2001, 3D V</td>
<td>16.91</td>
<td>1.3</td>
</tr>
<tr>
<td>E: G2000, 3D V</td>
<td>10.97</td>
<td>0.55</td>
</tr>
<tr>
<td>F: G2001, 3D V</td>
<td>15.29</td>
<td>0.99</td>
</tr>
<tr>
<td>G: Upstream SW</td>
<td>10.89</td>
<td>0.7</td>
</tr>
<tr>
<td>H: ICME leading-edge V</td>
<td>9.17</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Kilpua, Mierla et al. 2012

G2000 – Gopalswamy et al. 2000
G2001 – Gopalswamy et al. 2001
CME propagation – deep minimum

- the wide-angle viewpoint from STEREO is crucial to detect solar counterparts for weak ICMEs
- narrow CMEs (angular widths \( \leq 20^\circ \)) can arrive at Earth and an unstructured CME may result in a flux rope-type ICME.
- Ten out of 16 (63\%) of the associated CMEs were stealth CMEs.

Figure 2: STEREO/COR2-B (left), STEREO/COR2-A (right) and LASCO-C3 (middle) coronagraph base-difference images on 27 October 2009 at 23:24 UT. The CME is seen only in STEREO-A and STEREO-B. Lower panels display the same images as the top panels, but the contours show the fit of the CME with the flux rope model (see Section 2).

As indicated in Table 4, the CME described above starts very slowly; its first appearance in COR1-A is reported at 15:30 UT and in COR1-B at 10:30 UT. An EUV dimming associated with a small eruption occurred in Active Region (AR) 11029 located at N27W37 (Earth view) on 27 October around 8 UT. No other CME-related EUV signatures were detected. However, the dimming occurred relatively far from the CME apex as estimated by the FM analysis and triangulation (the difference in longitude was about 30\(^\circ\)). For wide CMEs, relatively large differences in the source and CME apex longitudes may occur (e.g. Lara, 2008; Nieves-Chinchilla et al., 2013) since EUV activity can be related to only one of the CME legs. Considering the narrow width of the 27 October CME (note that it is categorized as a narrow CME and not as a normal CME) and the reconstruction results, we do not consider it likely that the dimming was associated with the CME described above.

3.2. Example 2: 30 January – 4 February 2009

Figure 3 shows OMNI measurements during the ICME in early February 2009. The ICME drove a weak shock detected on 2 February at 20:16 UT. At the shock, the solar wind speed increased from about 300 to 350 km s\(^{-1}\). The ICME started on 4 February at 1 UT and extended until 4 February at 18 UT. The ICME leading edge speed was 368 km s\(^{-1}\) and its duration was 17 hours. The maximum magnetic field magnitude during the ICME was 11.3 nT. The magnetic field had relatively large variations, and because of the relatively high density, the plasma \( \beta \) is only slightly lower than unity. However, the rotation of the magnetic field is clear, which suggests a flux rope structure. The \( P_t \) profiles show a rapid increase at the shock and then a plateau, suggesting that this flux rope was encountered at the intermediate distance from the center. Using the ICME leading edge speed, we estimate that the CME erupted on 30 January 7 UT. There were three CME candidates within the three-day time...
Geomagnetic storms

- Major storms are produced by CMEs (Gopalswamy et al. 2007, Zhang et al. 2007)

- Geomagnetic storms are highly correlated with $B_z$, $V\cdot B_z$, CMEs speeds as well as with the ram pressure (Gonzalez et al. 1994, Srivastava and Venkatakrishnan, 2004, Gopalswamy et al. 2008, Echer et al. 2013).

- The major storms and superstorms meet the GT criteria (Echer et al. 2005, Gonzalez and Tsurutani 1987).

(GT criteria: a necessary IP condition for an intense geomagnetic storm to occur is the presence of an intense m.f. ($B_s > 10$ nT) for long durations ($t > 3$ h) of time.)
Geomagnetic storms

- Period 1: 1995-1999
- Period 2: 2006-2012

- the weak southward IMF and the lack of strong ICMEs led to weak Dst activity in Period 2.

- Low solar wind densities may have further weakened the ring current response and the solar wind–magnetosphere coupling efficiency.

- No difference in solar wind speed between the 2 periods

Kilpua et al. 2014
Energy transfer - Coupling functions

CMEs in SC23, Dst < -150 nT

Oprea, Mierla et al. 2013

\[ r(Bz, Dst)_{-2} = 0.76 \]
\[ r(Bs \cdot V, Dst)_{-2} = -0.74 \]
\[ r(V, Dst)_{-3} = -0.29 \]
\[ r(\rho, Dst)_{-1} = -0.13 \]
Energy transfer - Coupling functions

Geomagnetic storm on April 11, 2001

Figure 2: Temporal profiles of ε and EIN during April 11 – 13, 2001 (black lines results using high resolution data; red lines results using low resolution data). For comparison, PC, Ey and Ds profiles taken from OMNI data. Date format in this figure is day (hour:min.).

Even though the high resolution data (when available) show higher variability during the main phase of the geomagnetic storm, it is clear that the energy is transferred not only during this phase, but much longer (almost 24 hours of continuous energy input, energy that has values about four to six times the non-storm ones). During the main phase of the storm we observe the highest values of the energy injected per second (in the ε and EIN evolution). The epsilon parameter has another peak comparable as magnitude with the one during the main phase, that coincides with the last minimum Bz value from the high resolution data (00:00 on April 12, 2001 – one hour after the end of the storm's main phase). As general profiles ε and EIN are similar, but differ in magnitude. The difference in magnitude comes from the different evaluation method of the scaling factor. This is in accordance with remarks made by authors such as Palmroth et al. (2003) or Koskinen and Tanskanen (2002) that the scaling factor should include plasma sheet heating and the energy carried by the plasmospheres in the magnetotail.

On the third row of Figure 2 we plotted the PC index (Troshichev and Andrezen, 1985) as a reliable proxy for characterising the solar wind energy that entered the magnetosphere (Troshichev et al., 2011). PC also shows energy being transferred for about the same period as ε and EIN. Troshichev et al. (2011) suggested PC = 2 mV/m as a threshold for the solar wind energy input. As clearly seen in Figure 2 (third row) this limit is valid from April 11, 2001, 13:00 UT until April 12, 2001, 18:00 UT. This interval is consistent with the interval of excess energy deposition as calculated by the two formulas used in this study.

In the fourth row of Figure 2 we plotted the interplanetary Ey calculated by OMNI as Ey = -Vx·Bz. The Ey's significant variations limit to the main phase duration of the storm. Gosling et al. (1990) as well as Khotyaintsev et al. (2004) found proof of reconnections happening during strong (negative) By. For the analysed storm, By has a second minimum, the lowest minimum during the entire storm, just after the moment the minimum Dst value is reached (Figure 1, second row). This could explain the second major peak in ε and EIN that is visible in Figure 2.

Therefore, using the “classical” consideration that the energy is input into the magnetosphere during the main phase of the storm (Akasofu, 1981), which in our case lasts for seven hours (the interval marked by dash-dotted vertical lines in Figures 1 and 2), we obtained the total input energy during this time:

\[ W(\epsilon) = 1.35 \times 10^{17} \text{[J]} \]
\[ W(E_{IN}) = 1.33 \times 10^{18} \text{[J]} \]

\( W(E_{IN}) \) is one order of magnitude larger than \( W(\epsilon) \). This is a larger discrepancy as compared to the results obtained by Wang et al. (2014) – where the difference was by a factor of 2 only.

Integrating over the entire period in which both ε and EIN show a significant increase as compared to a background level – in this case from April 11 at 13:00 UT to April 12, 2001, 18:00 UT.
Summary

Still needed:

To understand the CME propagation into IP space:

- To improve the background solar wind
- To understand the interaction between the CMEs and SW
- To improve the forecast of the CME arrival at the spacecraft and the forecast of Bz

To understand the coupling between ICME and magnetosphere
CME propagation:

Geomagnetic storms:
- extreme geomagnetic storms: Cid+ 2014, 2015, etc.
- SC23 storms: Andriyas+ 2017, Hema+ 2017, etc.
- prediction: Kataoka+ 2016, Kubicka+ 2016, etc.