Identification of Interplanetary Coronal Mass Ejections (ICMEs) Using Real-Time In Situ Data

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Outline

- CME vs. ICME
- ICME signatures & variability
- Small ICME-like transients
- SIR to distinguish
- Hybrid event
- Other notes
CME

SOHO Large Angle and Spectrometric Coronagraph (LASCO) C3
3.7-32 Rs

Zurbuchen and Richardson (2006)
ICME Example

shock  magnetic obstacle  STA $\log_{10} f$
# ICME Signatures – I

**B: Magnetic field**

<table>
<thead>
<tr>
<th>Signature</th>
<th>Description</th>
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</tr>
</thead>
<tbody>
<tr>
<td>★ B1: B Rotation</td>
<td>$\gg 30^\circ$, smooth</td>
<td>Klein and Burlaga (1982)</td>
</tr>
<tr>
<td>★ B3: B Variance decrease</td>
<td></td>
<td>Pudovkin <em>et al.</em> (1979); Klein and Burlaga (1982)</td>
</tr>
<tr>
<td>★ B4: Discontinuity at ICME boundaries</td>
<td></td>
<td>Janoo <em>et al.</em> (1998)</td>
</tr>
<tr>
<td>★ B5: Field line draping around ICME</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B6: Magnetic clouds</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(B1, B2 and $\beta = \frac{\sum \beta_{\text{rot}}}{B_{\text{rot}}/T_{\text{exp}} < 1}$)  
Klein and Burlaga (1982); Lepping *et al.* (1990)

**P: Plasma dynamics**

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>★ P1: Declining velocity profile/expansion</td>
<td>Monotonic decrease</td>
<td>Klein and Burlaga (1982); Russell and Shinde (2003)</td>
</tr>
<tr>
<td>P2: Extreme density decrease</td>
<td>$\leq 1$ cm$^{-3}$</td>
<td>Richardson <em>et al.</em> (2000a)</td>
</tr>
<tr>
<td>P3: Proton temperature decrease</td>
<td>$T_p &lt; 0.5 T_{\text{exp}}$</td>
<td>Gosling <em>et al.</em> (1973); Richardson and Cane (1995)</td>
</tr>
<tr>
<td>P4: Electron temperature decrease</td>
<td>$T_e &lt; 6 \times 10^4$ K</td>
<td>Montgomery <em>et al.</em> (1974)</td>
</tr>
<tr>
<td>P5: Electron Temp decrease</td>
<td></td>
<td>Sittler and Burlaga (1998); Richardson <em>et al.</em> (1997)</td>
</tr>
<tr>
<td>★ P6: Upstream forward shock/“Bow Wave”</td>
<td>Rankine-Hugoniot relations</td>
<td>Parker (1961)</td>
</tr>
</tbody>
</table>

P7: Pt Enhancement

Jian *et al.* (2006)

Zurbuchen and Richardson (2006)
## ICME Signatures – II

**C**: Plasma composition  
**W**: Plasma waves  
**S**: Suprathermal particles

<table>
<thead>
<tr>
<th>Signature</th>
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</tr>
</thead>
<tbody>
<tr>
<td>C1: Enhanced α/proton ratio</td>
<td>He²⁺/H⁺ &gt; 8%</td>
<td>Hirshberg et al. (1972); Borrini et al. (1982a)</td>
</tr>
<tr>
<td>C2: Elevated oxygen charge states</td>
<td>O⁷⁺/O⁶⁺ &gt; 1</td>
<td>Henke et al. (2001); Zurbuchen et al. (2003)</td>
</tr>
<tr>
<td>C3: Unusually high Fe charge states</td>
<td>(Q)Fe &gt; 12; Q_{Fe}^{15+} &gt; 0.01</td>
<td>Bame et al. (1979); Lepri et al. (2001); Lepri and Zurbuchen (2004)</td>
</tr>
<tr>
<td>C4: Occurrence of He⁺</td>
<td>He⁺/He²⁺ &gt; 0.01</td>
<td>Schwenn et al. (1980); Gosling et al. (1980); Gloeckler et al. (1999)</td>
</tr>
<tr>
<td>C5: Enhancements of Fe/O</td>
<td>\frac{(Fe/O)<em>{ICME}}{(Fe/O)</em>{photosphere}} &gt; 5</td>
<td>Ipavich et al. (1986)</td>
</tr>
<tr>
<td>C6: Unusually high (^{3})He/(^{4})He</td>
<td>\frac{(^{3}\text{He/}^{4}\text{He})<em>{ICME}}{(^{3}\text{He/}^{4}\text{He})</em>{photosphere}} &gt; 2</td>
<td>Ho et al. (2000)</td>
</tr>
<tr>
<td>W1: Ion acoustic waves</td>
<td></td>
<td>Fainberg et al. (1996); Lin et al. (1999)</td>
</tr>
<tr>
<td>S1: Bidirectional strahl electrons</td>
<td></td>
<td>Gosling et al. (1987)</td>
</tr>
<tr>
<td>S2: Bidirectional ~MeV ions</td>
<td>2nd harmonic &gt; 1st harmonic</td>
<td>Palmer et al. (1978); Marsden et al. (1987)</td>
</tr>
<tr>
<td>S3: Cosmic ray depletions</td>
<td>Few % at ~ 1 GeV</td>
<td>Forbush (1937); Cane (2000)</td>
</tr>
<tr>
<td>S4: Bidirectional cosmic rays</td>
<td>2nd harmonic &gt; 1st harmonic</td>
<td>Richardson et al. (2000b)</td>
</tr>
</tbody>
</table>

*Zurbuchen and Richardson (2006)*
Integrated Space Weather Analysis (iSWA) System

http://iswa.gsfc.nasa.gov/iswa/iSWA.html

- ACE (DSCOVR coming soon) real-time data
  - Solar wind proton density, velocity, and temperature
  - Magnetic field vector
- STEREO beacon data
  - Only STEREO A is available now, about 11-12 days ahead (or 15-16 days behind) of Earth for corotating solar wind
- Add the following parameters to assist identification, assuming $N_\alpha = 0.04N_p$, $T_\alpha = 4T_p$, $N_e = N_p + 2N_\alpha$, $T_e = T_p$

\[
\beta = \frac{\sum_{i=p,\alpha,e}(N_i kT_i)}{\frac{B^2}{2\mu_0}} \quad P_t = \sum_{i=p,\alpha,e} (N_i kT_i) + \frac{B^2}{2\mu_0}
\]

\[
T_{ex} (\times 10^3 K) = \begin{cases} 
(0.031V - 5.1)^2, & \text{if } V < 500 \text{ km/s} \\
0.51V - 142, & \text{if } V \geq 500 \text{ km/s} 
\end{cases} \quad \text{Lopez (1987)}
\]
Variability of ICMEs

**Group 1**
Containing well-defined flux rope (magnetic cloud) with central maximum in $P_t$

**Group 2**
Containing magnetic obstacle with central $P_t$ “plateau”

Jian et al. (2006a)

**Group 3**
Poorly-defined magnetic obstacle with monotonic $P_t$ decrease after the leading shock and/or sheath
Small ICME-Like Transients

1) lasting a few hours  
2) B increase  
3) often seen in the slow wind

Kilpua et al. (2009)
Origin of Small ICME-Like Transients

- **Origin:**
  - Small mass ejecta at the tip of helmet streamers
  - Blobs
  - Glances of large ICMEs too

- Left shows two blobs moving across COR2
- The blob series appear as a series of azimuthal waves in the face-on views

*Sheeley et al. (2009)*
One Large-Scale Solar Wind Structure to Distinguish: Stream Interaction Region (SIR)

~ 80% of SIRs are corotating interaction regions (CIRs)

Gosling (1996)

Jian et al. (2006b), after Pizzo (1978)

Luhmann et al. (2012)
Identification of SIRs

Criteria

1) Increase of $V_p$ (necessary)
2) A pile-up of $P_t$ with gradual decreases at two sides
3) Increase and then decrease of $N_p$
4) Increase of $T_p$
5) Deflection of flow
6) Compression of $B$, usually associated with $B$ shear
7) Change of entropy $\ln(T_{p^{1.5}}/N_p)$

Stream interface (SI)

at the peak of $P_t$, sometime it coincides with the location where $V_p$ and $T_p$ increase and $N_p$ begins to drop after a $N_p$ compression region

Magnetic sector boundary

identified by the long-term changes of the magnetic field polarity

Jian et al. (2006b)
About 30% of SIRs drive shocks, sometimes a pair of forward-reverse shocks
Hybrid Event

One very rare example among hundreds of ICMEs has the interplanetary counterpart of prominence (region c–d)

Unusual composition and charge state in c–d (Burlaga et al., 1998)
Both ICMEs and SIRs can drive shocks. The ICME-driven shocks are generally associated with more significant parameter changes.

Check if the Sun is quiet or active (with eruptions) using the solar observations taken about 2-5 days ago.

Check the solar wind at Earth about 27 days ago at Earth or at STEREO A about 16 days ago (at present). If the latitudes of STEREO A and Earth do not differ much, and if the Sun is relatively quiet, we would expect similar solar wind at Earth.

About 10% of ICMEs and 6% of SIRs are in the hybrid events, where multiple ICMEs interact or ICME and SIR interact. Such events often cause stronger geomagnetic activity.
Backup
ICME Example

shock

magnetic obstacle

STA \ \log_{10} f

Pitch Angle (°)

B (nT)

B_r (B_t B_n)

V (km/s)

N_p (cm^{-3})

T_p (K)

\beta

P_t (pPa)

Q_{Fe}

2013
One Large-Scale Solar Wind Structure to Distinguish: Stream Interaction Region (SIR)

Declining Phase & Solar Minimum
1992-1998

Rising Phase & Solar Maximum
1998-2004

About 80% of SIRs are corotating interaction regions (CIRs)

Jian et al. (2006b), after Pizzo (1978)