Linking CMEs to Associated Solar Phenomena

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Göttingen Magnetischer Verein

• Trinity College Dublin was a site of Göttingen Magnetic Union (1836-1841).

• Magnetic measurements up to every 5 mins.

• Led to magnetic crusades by Edward Sabine and Humphrey Lloyd.

• Sabine (1852): Sunspot cycle identical to geomagnetic cycle.
The Problem: Linking ICMEs to CMEs to Flares to Active Regions
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HELIO Propagation Model

This image shows a screenshot of a software interface for HELIO (Heliophysics Integrated Observatory), which is a tool for modeling the propagation of coronal mass ejections (CMEs) and other solar phenomena. The interface includes options for selecting parameters such as longitude, width, speed, and error in speed, with definitions for each parameter. The software appears to be designed for research and analysis in heliophysics, particularly focusing on CME propagation modeling.

The email address peter.gallagher@tcd.ie is also visible, suggesting a connection to TCD (Trinity College Dublin) and indicating the author or contributor of the document.
HELIO Propagation Model

Perez-Suarez et al. (2012)
Ballistic Propagation Model

<table>
<thead>
<tr>
<th>Input Property</th>
<th>Input Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial time</td>
<td>$\tau_i$</td>
</tr>
<tr>
<td>Initial distance</td>
<td>$R_i$</td>
</tr>
<tr>
<td>Final distance</td>
<td>$R_f$</td>
</tr>
<tr>
<td>Velocity range</td>
<td>$v \pm \Delta v$</td>
</tr>
<tr>
<td>Position angle</td>
<td>PA</td>
</tr>
<tr>
<td>Width</td>
<td>$(PA_N - PA_S) / 2$</td>
</tr>
</tbody>
</table>

- Search time window:
  \[ f \pm f = \frac{R_i}{v \pm} \frac{R_f}{v} \]

- Search PA window:
  \[ PA \pm \Delta PA \]
**HI1 -> COR2**

<table>
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<tbody>
<tr>
<td>Initial time</td>
<td>$\tau_i$</td>
</tr>
<tr>
<td>Initial distance</td>
<td>$12 \text{ } R_S$</td>
</tr>
<tr>
<td>Final distance</td>
<td>$2 \text{ } R_S$</td>
</tr>
<tr>
<td>Velocity range</td>
<td>200-600 km/s</td>
</tr>
<tr>
<td>Position angle</td>
<td>PA$_{fit}$</td>
</tr>
<tr>
<td>Width</td>
<td>$(PA_N - PA_S)/2$</td>
</tr>
</tbody>
</table>

- **Search time window:**

  $$COR_2 \pm COR_2 = HI1 \frac{R_{HI1}}{v_{SW}} \pm \frac{R_{COR2}}{v_{SW}}$$

- **Search PA window:**

  $$PA_{fit} \pm \Delta P$$
Candidate Probability Space

Candidate 1

Candidate 2

Candidate 3
## WP2 Catalogue

**HELIOSPHERIC IMAGER CME CATALOGUE**  
The CME catalogue identified from the STEREO-HI instruments is shown below

This is version: TBD of the catalogue, released yyyy-mm-dd

<table>
<thead>
<tr>
<th>ID</th>
<th>Date [UTC]</th>
<th>SC</th>
<th>PA-N [deg]</th>
<th>PA-S [deg]</th>
<th>Quality</th>
<th>PA fit [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCME_A__20070419_01</td>
<td>2007-04-19 13:30</td>
<td>A</td>
<td>40</td>
<td>140</td>
<td>Good</td>
<td>105</td>
</tr>
<tr>
<td>HCME_A__20070502_01</td>
<td>2007-05-02 00:50</td>
<td>A</td>
<td>65</td>
<td>100</td>
<td>Fair</td>
<td>90</td>
</tr>
<tr>
<td>HCME_A__20070506_01</td>
<td>2007-05-06 06:50</td>
<td>A</td>
<td>85</td>
<td>120</td>
<td>Fair</td>
<td>100</td>
</tr>
<tr>
<td>HCME_A__20070509_01</td>
<td>2007-05-09 13:30</td>
<td>A</td>
<td>50</td>
<td>125</td>
<td>Fair</td>
<td>90</td>
</tr>
<tr>
<td>HCME_A__20070516_01</td>
<td>2007-05-16 01:30</td>
<td>A</td>
<td>30</td>
<td>120</td>
<td>Good</td>
<td>80</td>
</tr>
<tr>
<td>HCME_A__20070518_01</td>
<td>2007-05-18 00:10</td>
<td>A</td>
<td>95</td>
<td>115</td>
<td>Fair</td>
<td>110</td>
</tr>
</tbody>
</table>
# Case Study

## Low Coronal Event Catalogue

Catalogue of events occurring in the low corona which were associated with CMEs detected with the Heliospheric Imagers on board the STEREO spacecraft.

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<tr>
<th>&lt;1&gt; No.</th>
<th>&lt;2&gt; Spacecraft (Stereo A/B)</th>
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<th>&lt;4&gt; HI PA North (degrees)</th>
<th>&lt;5&gt; HI PA South (degrees)</th>
<th>&lt;6&gt; COR2 Date and Time search window (UT)</th>
<th>&lt;7&gt; COR2 Candidates Date and Time (UT)</th>
<th>&lt;8&gt; Flare Estimated Date and Time (UT)</th>
<th>&lt;9&gt; GOES Class</th>
<th>&lt;10&gt; NOAA Region (Location)</th>
<th>&lt;11&gt; Hale Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>A</td>
<td>29-Jul-2007 07:30</td>
<td>240</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[Image of HELCATS logo with astronomical background]
Case Study

- ***** HI2 Parameters *****
  - HI2 Start Time: 29-Jul-2007 07:30:00.000

- ***** COR2 Search Parameters *****
  - COR2 End Time: 29-Jul-2007 05:05:12.500
  - Window (hours): 10.457176
  - COR2 PA-N: 240.000
  - COR2 PA-S: 300.000

- ***** Flare Search Parameters *****
  - Flare End Time: 28-Jul-2007 18:01:34.793
  - Window (mins): 36.197919
## Case Study

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Case Study

Search Times: 28-Jul-2007 18:37
29-Jul-2007 05:05

Search PAs: 240-300

CME Candidate: 29-Jul-2007 01:37 | PA 275° | Width 96° | 625 km/s
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Case Study

GOES X-ray Flux (5 minute data)

GOES X-rays:

17:25 – 18:01

Active Regions

Updated 2007 Jul 29 23:41:04 UTC
NOAA/SEC Boulder
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Position Angle Variation with Distance

STEREO-A: 12/11/08 12:40:00 AM
CME Deflection

Byrne et al. (2010)
Byrne et al. (2010)
Improved Inverse Tracking

- Use variable velocity profile

\[ t_f = t_i + \int_{R_i}^{R_f} \frac{1}{v(R)} dR \]

- Drag-based propagation model to obtain \( v(R) \)

- SOTERIA Drag-Based Model
  
  [http://oh.geof.unizg.hr/DBM/dbm.php](http://oh.geof.unizg.hr/DBM/dbm.php)

- E.g Vršnak et al. (2010)
Modelling of CME Motion

• Simple model for CME propagation in heliosphere

\[
\frac{dv}{dt} = \frac{1}{2} v^2 AC_D
\]

• Numerical integration gives \( v(r) \).

• Vršnak et al. (2002), Reiner et al. (2003), Tappin (2006).
Slow CME

(a)

(b)

(c)

Start Time (08-Oct-07 12:00:00)
Fast CME

(a) Height (R$_{\odot}$)

(b) Velocity (km s$^{-1}$)

(c) Acceleration (m s$^{-2}$)

Start Time (25-Mar-08 18:00:00)

Maloney & Gallagher (2010)
Coronal Mass Ejections

Coronal Waves

Radio Bursts

How are these related?
How are shocks formed?
CME and Shock-Front Positions

obstacle (CME)

shock

\[ \text{R}_S, \text{R}_O, \text{D}_O, \text{D}_S \]
CME-Driven Shock Properties

Shock standoff distance ($\Delta$) varies linearly with height.

Linear extrapolation gives $\Delta \sim 40 \, R_{\text{sun}}$ at Earth.

Can give improved estimate of shock arrival time at Earth.
CME and EUV Wave
Birr, STEREO and Nancay Radio Spectra

Carley et al. (2013)
Radio Spectra & Images and EUV Wave
How do we find shock heights?

Plasma frequency:

\[ f_{p}[Hz] = 9000 \sqrt{n_e[cm^{-3}]} \]

Example model:

\[ n_e(h) = n_0 e^{h/H} \]
Type II Height Problem

Given frequency gives single density but *model dependent* heights!

\[ f_p [Hz] \quad 9000 \sqrt{n_e [cm^{-3}]} \]

=> Given frequency gives single density but *model dependent* heights!
Shock Height Problem

1.4 $R_s$ => Shock

2.1 $R_s$ => No shock

500 km/s CME
Solution: Data-constrained Alfvén Maps

\[ v_{Alfven}(x, y) = \frac{B(x, y)}{\sqrt{m_p n_e(x, y)}} \]

- Potential magnetic field model (PFSS)
- Electron density maps (SDO/AIA and SOHO/LASCO)
Densities in low corona (<1.3 $R_S$)

Aschwanden et al. (2011)
Densities in high corona (>2.5 $R_S$)

$\text{Brightness} \mu = n_e(r)G(s)ds$

SOHO/LASCO Intensity $\rightarrow$ Electron Density
Electron Density Map

Electron density (cm\(^{-3}\))

LASCO

SDO
Two-component Density Model

• Spherically symmetric corona in hydrostatic equilibrium:

\[
n_{ss}(r) = n_{ss}(r = 1 \ R_\odot) \exp \left[-\frac{\mu m_p G M_\odot}{k T R_\odot} \left(\frac{r_0}{r} - 1\right)\right]
\]

• At \( r < r_0 \), reduces to plane parallel solution

\[
n_{pp}(r) = n_{pp}(r = 1 \ R_\odot) \exp \left[-\frac{r}{H}\right]
\]

• Combine spherically symmetric and plane parallel

\[
n(r) = n_{pp}(r) + n_{ss}(r)
\]

Zucca et al. (2014)
Electron Density Map

Electron density (cm$^{-3}$)

LASCO
MODEL
SDO
Electron Density Map

Electron density (cm$^{-3}$)
Magnetic Field Extrapolations

Magnetic field (Gauss)

2 $R_{\text{Sun}}$
Alfvén Speed Map

Alfvén speed (km/s)

Zucca et al. (2014)
Conclusions

• Linking heliospheric to coronagraph features
  – Ballistic model works well

• Linking coronagraph to low corona and surface
  – Challenging - deflection important
  – Activity in EUV images key

• Linking CMEs to IP and coronal Type II bursts
  – Difficult without radio images
  – Density and Alfven maps key
Solar Wind Velocity Distribution

Velocity Search Range

De Toma (2009)
CME Velocity Distribution

Velocity Search Range

Robbrecht et al. (2009)