The Evolution of Interplanetary Coronal Mass Ejections in the Heliosphere

Yutian Chi


1. Institute of Deep Space Sciences, Deep Space Exploration Laboratory, Hefei 230026, China
2. Deep Space Exploration Laboratory/School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China
3. Department of Meteorology, University of Reading, Berkshire, UK
4. Institut fur Geophysik und extraterrestrische Physik, Technische Universitat Braunschweig, Braunschweig, Germany
5. Space Research Institute, Austrian Academy of Sciences, Graz, Austria
6. School of Physics and Astronomy, University of Leicester, Leicester, UK
Coronal Mass Ejections (CMEs/ICMEs) are huge eruptions of plasma, magnetic field, and energy that are expelled from the lower solar corona into interplanetary space.

**Earth:** ICMEs have been recognized as major drivers of severe space weather (e.g. Gosling et al. 1991; Zhang et al. 2007; Shen et al. 2017), which can cause geomagnetic storms and trigger a wide array of undesirable consequences, including anomalies in satellite systems, damage to the ground-based electric power grids, and interference with radio communications and satellite navigation systems (e.g. Cannon et al. 2013).

**Mars or Venus:** ICMEs can also change the plasma environments of Venus and Mars and increased ion escape rates on those planets (Curry et al. 2015; Dimmock et al. 2018; Zhang et al. 2021).
Predict the arrival time and the magnetic field configuration of CMEs is difficult, as they are rotated, deformed, deflected, and disguised during their propagation in the heliosphere by interacting with ICMEs or solar wind.

The deflections of CMEs can be attributed to three primary causes:

- magnetic forces produced by the background corona (e.g., MacQueen et al. 1986; Kilpua et al. 2009; Shen et al. 2011)
- The coronal holes near the CME (e.g., Gopalswamy et al., 2010)
- the background solar wind flow pattern (e.g., Wang et al. 2004; Manchester et al. 2017).
CMEs is not **coherent magnetohydrodynamic structures** after propagate beyond 0.3 AU of the Sun (Owens et al. 2017).

Savani et al. 2010 reported the CME passed through the field of view of the STEREO-B Heliospheric Imagers where the leading edge was observed to **distort into an increasingly concave structure**.

Chi et al., 2021 used the **HUXt model** to simulate the distortion of CME frontal shape and shown that the **latitudinal structure in the ambient solar wind speed** can cause the distortion of CMEs.
Interaction between CMEs

If a slow CME and a fast CME erupt continuously from the adjacent positions, then the fast CME will approach and interact with the slow CME during propagation. The complex structures caused by multiple CME interactions are frequently observed in a variety of forms, including:

- complex ejecta (Burlaga et al. 2002)
- multi-magnetic clouds (multi-MC) (Wang et al. 2003a)
- shock- interplanetary CMEs (S-ICMEs) (Wang et al., 2002, Lugaz et al., 2013, Shen et al 2017)

Wind in-situ observations

Single ICME?

Venus Express in-situ data

Shock-ICME!
➢ **Single in-situ observations can not** reflect the magnetic field evolution and dynamic evolution of the CME

➢ To better understand the structure and evolution of ICMEs, analyzing the ICMEs that are detected by **multiple spacecraft** (Palmerio et al. 2019; Kilpua et al. 2019; Chi et al. 2020, 2021; Weiss et al. 2021; Salman et al. 2020).
China’s first Mars exploration mission-- Tianwen-1 spacecraft

- launched on July 23, 2020
- Since November 16, 2021, the Mars Orbiter Magnetometer (MOMAG) (Liu et al. 2020) on board the Tianwen-1 spacecraft has been continuously measuring the local magnetic field conditions around Mars.
- MOMAG science data from Tianwen-1 (2021-2022) has been released.

Download the Data from the Planet Exploration Program Scientific Data Release System
http://202.106.152.98:8081/marsdata/

Contact mail: Ytchi@mail.ustc.edu.cn
Ymwang@ustc.edu.cn
• The magnetic field detected by Tianwen-1 is comparable to Maven in the solar wind.
• Tianwen-1 spacecraft is a good complement to MAVEN to monitor the interplanetary magnetic field and to record the passage of huge solar transient structures like ICMEs and SIRs.
**ICME criteria**

- higher magnetic-field strength compared to its surroundings;
- reasonably monotonic, smooth rotating magnetic field direction;
- abnormally lower proton temperature;
- decreasing plasma velocity;
- lower plasma beta (\(\beta\))

[Shen+2017, Chi+2016]

<table>
<thead>
<tr>
<th>No.</th>
<th>Shock Time</th>
<th>Begin Time of the Ejecta (UT)</th>
<th>End Time of the Ejecta (UT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2021-12-10T00:00</td>
<td>2021-12-11T14:10</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2021-12-29T00:00</td>
<td>2021-12-30T20:00</td>
<td></td>
</tr>
</tbody>
</table>

[Chi+2023, ApJS]
An excellent opportunity to study the dynamic evolution, expansion, and interaction of the ICMEs with the background solar wind by Tianwen-1, MAVEN, and BepiColombo spacecraft.
Using GCS model to obtain the parameters of the CME

HUXt model to predict the arrival time of the CME at BepiColombo and Mars

<table>
<thead>
<tr>
<th>CME Initial Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (UT)</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>2022-12-22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Predicted Arrival</th>
<th>Actual Arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (UT)</td>
<td>Time (UT)</td>
</tr>
<tr>
<td>2021-12-24</td>
<td>2021-12-24</td>
</tr>
<tr>
<td>21:17(+7/-6)</td>
<td>18:52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Predicted Arrival</th>
<th>Actual Arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (UT)</td>
<td>Time (UT)</td>
</tr>
<tr>
<td>2021-12-28</td>
<td>2021-12-29</td>
</tr>
<tr>
<td>23:28(+10/-14)</td>
<td>00:00</td>
</tr>
</tbody>
</table>

[Chi+2023]
FAST CME 2021/12/04 FAST CME EVENT

GCS MODEL

HUXt MODEL

CME Initial Parameters

<table>
<thead>
<tr>
<th>Time</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Half angle</th>
<th>Height</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021-12-04 17:39</td>
<td>149(±5)</td>
<td>-11(±5)</td>
<td>43.6(±10)</td>
<td>17.55(±2)</td>
<td>761.2(±50)</td>
</tr>
</tbody>
</table>

Predicted Arrival | Actual Arrival
Time (UT) | Time (UT)
2021-12-06 | 2021-12-06
18:25(+3.5/-3) | 15:07

Predicted Arrival | Actual Arrival
Time (UT) | Time (UT)
2021-12-10 | 2021-12-08
07:50(+7/-5.5) | 19:20

[Chi+2023]
The fast CME undergoes clear deflection (~ 40°) and rotation (~ 16.5°) during its propagation.

Mostl + 2017

Chi et al 2024 in prepare
The propagation longitude of the CME event changes about 16° at BepiColombo, and changes about 31° at Mars.
The relationship of the axial field strength and the distance is \( B_0 \sim r^{-1.78} \).

The axial magnetic flux of the flux rope \( F_z \) and the total magnetic helicity of the flux rope \( H_m \) are nearly invariant.

The number of turns (twist) at 1.5 AU \( \tau \) increased about 17%.

Chi et al 2024 in prepare
✓ The version MOMAG scientific data has been released to the public from 2021 November 15 to 2022 November 4.

✓ This is the first time that BepiColombo is used as an upstream solar wind monitor ahead of Mars and that Tianwen-1 is used to investigate the magnetic field characteristics of ICMEs.

✓ The fast CME event show clearly rotation, deflection, and distortion by ambient solar wind structure.

✓ The axial magnetic field strength ($B_0$) derived from the force-free flux rope model decreases with heliocentric distance as $r^{-1.78}$, showing a self-similar manner in expansion.

✓ The axial magnetic flux and helicity of the magnetic cloud decreased approximately 13% and twist increased 17% from BepiColombo spacecraft to Mars, which implies that the CME event was eroded by the ambient solar wind.

Email: ytchi@mail.ustc.edu.cn
Thanks For Your Attention!