Multispacecraft Observations of interacting CME flux ropes

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Motivation  Interactions between successive coronal mass ejections (CMEs) in interplanetary space can greatly modify their properties and evolution → significant modifications to their space weather response. The nature of interactions and the outcome varies considerably depending on the relative speed and launch direction of CMEs involved, as well as the magnetic configuration of their flux ropes. One of the challenges in studying interactions is the lack of observations in heliosphere at different radial distances as well as lack of realistic information of intrinsic CME parameters to coronal and heliospheric models.

Results shown  We present here results of the analysis of three CMEs that erupted from the Sun between June 12-14, 2012. They were observed by almost radially aligned Venus Express and near-Earth spacecraft (Wind used). Observations showed at Earth a weak edge encountered CME ejecta and one coherent flux rope CME with high peak magnetic field (~40 nT). Measurements at Venus however revealed that the big flux rope at Earth was composed of two separated CMEs. Observational analysis is complemented by modelling using EUHFORIA (Pomoell & Poedts, 2019) and heliospheric imaging from STEREO.

Spacecraft Locations

Venus Express and Wind separated by $5.4^\circ$ in longitude and in $0.2^\circ$ latitude
Solar wind observations

Near-Earth solar wind (L1, Wind)

0.72 AU (Venus Express)

S: shock
E: ejecta
FR: flux rope

seems one coherent structure
clearly two separate CMEs
Solar observations


• Geometric and kinematic CME parameters determined using Gradual Cylindrical Shell (GCS) fitting

• CME magnetic parameters (helicity and axial field direction) were determined using the observational scheme described in Palmerio et al. 2017; 2018 for CME2 and CME3. They had NES – type magnetic flux rope (i.e. field rotating from North to South, being East at the axis). CME1 was too complex to perform the analysis, it originated from two sympathetic eruptions that merged very early on to produce complex ejecta.

• EUHFORIA was run for all three CMEs with the cone model using parameters from GCS.

<table>
<thead>
<tr>
<th>CME</th>
<th>Time at 0.1 AU [UT]</th>
<th>Θ [°]</th>
<th>Φ [°]</th>
<th>ω/2 [°]</th>
<th>V [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CME1</td>
<td>6/13 00:35</td>
<td>0.0</td>
<td>-5.0</td>
<td>27.5</td>
<td>521.8</td>
</tr>
<tr>
<td>CME2</td>
<td>6/13 19:54</td>
<td>-35.0</td>
<td>-10.0</td>
<td>38.6</td>
<td>657.0</td>
</tr>
<tr>
<td>CME3</td>
<td>6/14 17:18</td>
<td>-28.0</td>
<td>-5.0</td>
<td>57.0</td>
<td>966.3</td>
</tr>
</tbody>
</table>

Θ: latitude
Φ: longitude
ω/2: half angle
EUHOFRIA run results

- **CME1** arrives first both to Venus and Earth. It makes only a glancing encounter and is much weaker than two other CMEs.

- **CME2** and **CME3** were still separate at the orbit of Venus, but catch and merge while reaching the Earth → consistent with double shock feature at Earth.

- Arrival times match well with in-situ observations as well as STEREO Heliospheric Imager movie.

See Supplementary Kilpua et al., 2019 for the full EUHFORIA and for the HI movie: https://www.frontiersin.org/articles/10.3389/fspas.2019.00050/full#supplementary-material
Venus vs. Earth comparison

- Mapping technique (Good et al., Sol. Phys., 2018) between Venus (pale-coloured curves) and Earth (darker-coloured curves) show close match for magnetic field components of the flux ropes related to CME2 and CME3 (FR2 and FR3) between two locations.
Interpretation

• **CME1** was related to merging of two sympathetic eruption forming a complex and weak ejecta in interplanetary space

• **CME2** reached **CME3** about at the orbit of Venus with two separate flux ropes and well separated shocks visible. Flux rope related to **CME3** was observed as compressed in the Venusian magnetosheath.

• **CME3** propagated in the wake of **CME2**, experiencing thus very little drag, maintain thus its high speed and strong magnetic field.

• Significant interaction occurred between Venus and Earth (in about 0.3 AU distance): **CME3** and **CME2** interacted and shock of **CME3** propagated through **CME2**. (consistent with simulation studies showing merging of CME shocks, e.g., Odstrcil et al., 2003; Lugaz et al., 2013). Flux ropes were of similar polarity (NES) → **CME3** mainly compressed **CME2** with little merging (e.g., Schmidt&Cargill, 2004) → one seemingly coherent structure at Earth.
Discussion

• CME-CME interactions can drastically affect CME properties and evolution

• Drastic interactions can occur over relatively small radial distances (here \( \sim 0.3 \) AU)

• Spacecraft observations of radially (almost) aligned spacecraft with varying heliospheric distances are crucial for studying interactions and making correct interpretation of data

• This study highlights the importance of heliospheric simulations (such as EUHFORIA, ENLIL, SUSANOO-CME) with realistic CME input parameters and heliospheric imaging to get the global understanding of the situation

• Future joint observations by L1 spacecraft, STEREO-A, BepiColombo, Solar Orbiter and Parker Solar Probe provide interesting possibilities for radial and longitudinal multi-spacecraft studies of interacting CMEs (Bepi XXX)