Tracking and validating ICMEs propagating towards Mars
using STEREO Heliospheric Imagers and Forbush decreases at MSL/RAD

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Introduction

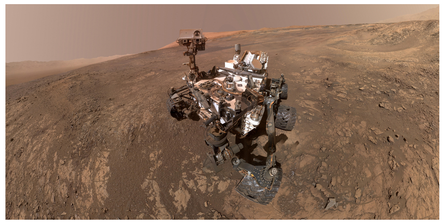
The Heliospheric Imager (HI) instruments on the two STEREO spacecraft were designed to observe interplanetary coronal mass ejections (ICMEs) and predict their arrival at Earth – but they have also observed numerous ICMEs that passed other planets.

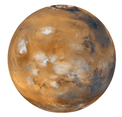
With the *Radiation Assessment Detector* (RAD) instrument on the *Mars Science Laboratory* (MSL) mission's *Curiosity* rover, we can observe Forbush decreases (FDs) related to the passage of ICMEs at Mars. By linking FDs to their corresponding ICMEs observed with STEREO-HI, we can validate the Mars arrival times calculated from HI measurements and derive information about ICME kinematics beyond 1 AU.

Our recent paper [2] focused on ICMEs close to oppositions, where the same event arriving at Mars could previously be seen at Earth or STEREO. By utilizing STEREO-HI observations, we seek to extend our study to a larger number of events.

STEREO Heliospheric Imagers

- HI field of view: from 4° (≙ 15 $R_\odot$) up to almost 90° – limiting factor: CME becomes more faint
- HELCATS HIGeoCat/HIJoinCat databases [1] provide time-elongation profiles for > 1000 ICMEs in total and > 200 matchings between events seen at both STEREOs
- 169 ICMEs in the direction of MSL ±40° during flight to Mars (2011 – 2012) or surface operations (2012 – today)
- Geometric triangulation [4] can be applied to events seen by both STEREOs, for others we use the fixed ϕ model





Mars

MSL/RAD Forbush decreases

- Magnetic structure of interplanetary shock and/or CME deflects galactic cosmic rays (GCR) → Forbush decrease (FD)
- Many FDs have been seen in MSL/RAD dose rate measurements since the rover's landing in August 2012 → RAD serves as a space weather monitor on Mars, similar to Neutron monitors on Earth
- Diurnal variations not related to FDs are compensated for using a notch filter [3]

Example

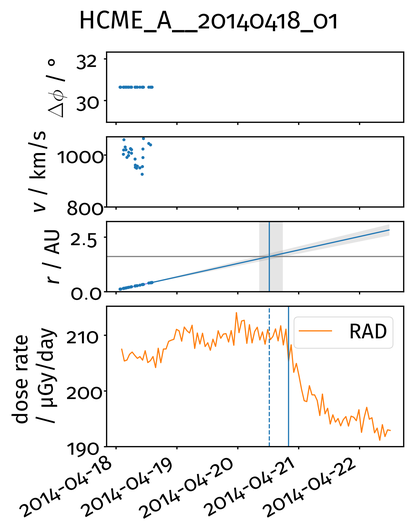


Figure 1: Example of an ICME observation at STEREO-HI combined with MSL/RAD Forbush decrease

- CME launched on 2014-04-17, ~20:40
- ICME was observed only by STEREO A, Fixed-ϕ fitting leads to $\Delta\phi$ = 30.5° away from Mars
- ICME speed derived from time-radius plot: $v \approx 1000\ \mathrm{km\ s^{-1}}$
- Linear extrapolation (v = const. after HI observations end) predicts an estimated arrival at $t_{\mathrm{predicted}} \approx$ 2014-04-20 12:20
- FD at MSL/RAD occurs 7.5 hours later at $t_{\mathrm{FD}} \approx$ 20:00
- ⇒ ICME was decelerated by surrounding solar wind — or the part of the ICME arriving at Mars propagated slower than the ejecta observed in the HI images

Statistical Studies

(preliminary results)

- STEREO-HI data was linked to the corresponding FDs at MSL/RAD for 35 events so far
- ICME arrival time at Mars extrapolated from HI measurements is on average 4 hours before FD onset (Figure 2)

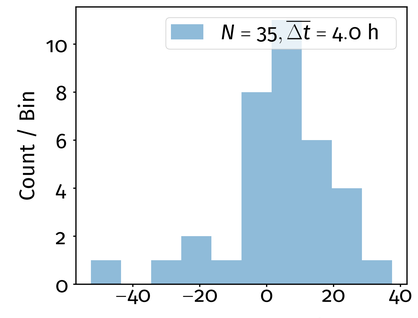


Figure 2: Histogram comparing the Forbush decrease onset times t_{FD} to arrival times $t_{\mathrm{predicted}}$ predicted using STEREO-HI observations

- There can be a delay between the FD onset (≈ shock front arrival) and arrival of the ICME ejecta (which is seen in STEREO-HI). Using Earth-based measurements, we determined this delay to be about 13 h on average
- When accounting for this delay in the above result, Δt increases to ~ 17 h, indicating a tendency of deceleration of ICMEs between 1 AU and Mars in agreement with our previous study [2]

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[3] Jingnan Guo et al. "Measurements of Forbush decreases at Mars: both by MSL on ground and by MAVEN in orbit". In: *Astronomy & Astrophysics* (Dec. 2017).

[4] Ying Liu et al. "Geometric Triangulation of Imaging Observations to Track Coronal Mass Ejections Continuously Out to 1 AU". In: *The Astrophysical Journal Letters* 710.1 (2010).

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