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

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Abstract
The *Radiation Assessment Detector (RAD)* instrument onboard the *Curiosity* rover has been measuring galactic cosmic rays (GCR) as well as solar energetic particles (SEP) on the surface of Mars for more than 6 years. RAD also detects Forbush decreases (FD) in the GCR dose rate caused by passing interplanetary coronal mass ejections (ICMEs).

This study combines MSL/RAD FD measurements with remote tracking of ICMEs using the STEREO Heliospheric Imager (HI) telescopes. 149 ICMEs propagating towards MSL were observed with HI between 2011 and 2016. We associate 45 of these events with their corresponding FDs at MSL/RAD and investigate both the accuracy of predicted arrival times as well as characteristics of the FDs.

Forbush decreases
- ...are short-term decreases of Galactic Cosmic Radiation (GCR). The decrease usually takes < 1 day, while the recovery period can last ~ 1 week.
- They are caused by turbulent magnetic fields from ICMEs and their shocks shielding away the GCR particles while they pass the measurement location

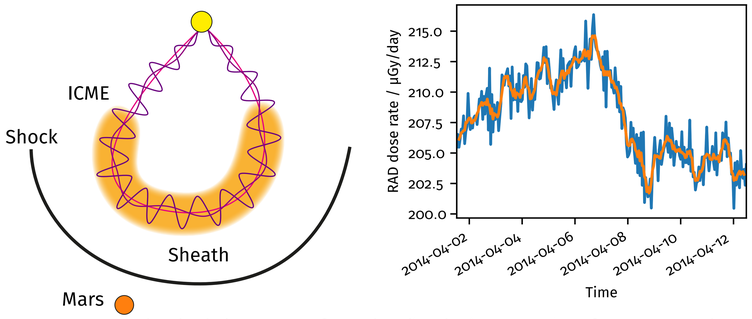
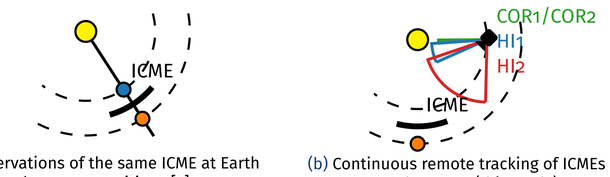


Figure 1: ICMEs and Forbush decreases. Left panel: Heliospheric propagation of an ICME towards Mars (based on [1], Figure 2), Right panel: an example of a Forbush decrease measured at MSL/RAD.

Event selection
- In our previous work [2], we studied 15 ICMEs seen in situ at two locations during oppositions of Earth or STEREO A/B and Mars (Figure 2a)
- The use of remote observations (Figure 2b) increases the sample size, allowing us to study a much larger number of ICMEs propagating towards Mars.



(a) Observations of the same ICME at Earth and Mars close to oppositions [2]

(b) Continuous remote tracking of ICMEs using STEREO-HI telescopes (this study)

Figure 2: Opposition phase constellation and ICME tracking with the STEREO SECCHI instruments

- 149 ICMEs from the HELCATS HIGeoCat catalog between 2011 and 2016 were observed with STEREO-HI and propagate towards MSL's location ±30° (Figure 3).

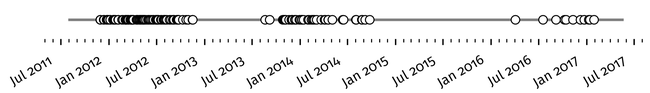


Figure 3: Time distribution of the 149 ICMEs studied in this work. Due to the HI field of view, ICMEs towards Mars cannot be seen when Earth and Mars are on opposite sides of the Sun.

Selection of corresponding FDs
- Based on the Self-similar expansion geometry [3, 4], we extrapolated the ICME trajectories up to MSL to determine the predicted arrival time
- The closest FD to the predicted arrival time (within ±2.5 d) was marked as being related to that ICME, if the correspondence is reasonable with respect to CME-CME interaction and the arrival time at Earth (if applicable)
- ICMEs were sorted into 5 categories, as seen in Figure 4:

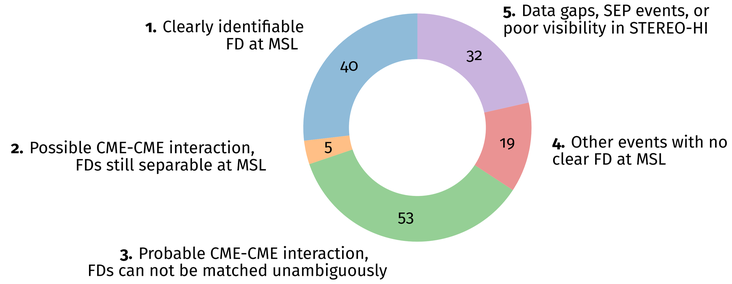


Figure 4: Separation of the 149 ICMEs into 5 categories, depending on their properties and visibility of FDs

⇒ **39 ± 6 % chance** that an ICME seen in STEREO-HI and predicted to arrive at MSL shows a clear FD at RAD (categories 1 and 2, excluding category 5 — consistent with results from Möstl et al. [5]). This increases to **68 ± 14 %** if interaction events are excluded.

Accuracy of predicted arrival times
submitted to *Space Weather*
- in Figure 5, we compared the **accuracy of the arrival times predicted from HI data** for the 45 events in the first 2 categories using three models: Fixed Phi [6], Harmonic Mean [7], and Self-similar expansion.

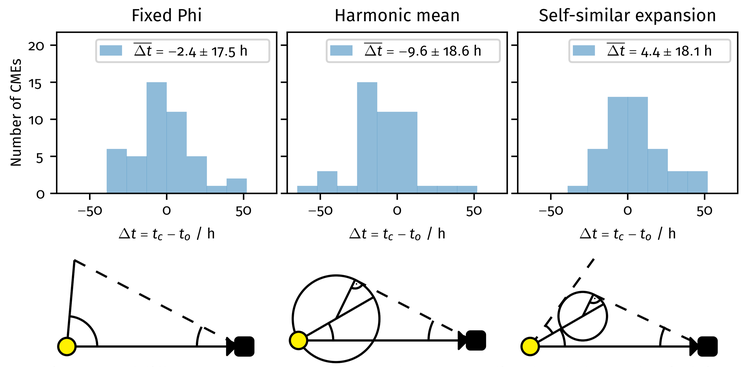


Figure 5: Histogram of differences $\Delta t = t_{\text{calculated}} - t_{\text{observed}}$ between predicted and observed arrival times for the Fixed-phi, Harmonic mean and Self-similar expansion geometries (as displayed in the cartoons below). The legend shows the mean values and standard deviations.

- Concerning the standard deviation of results, **all three methods perform similarly well**, only the systematic offset changes slightly.
- Standard deviations are also similar to predictions at locations closer to the Sun [5] as well as other approaches, such as WSA-ENLIL+Cone simulations or drag-based models
- The accuracy might improve in the future with more sophisticated geometric models applied to observations from both STEREO spacecraft

Forbush decrease properties
preliminary results
- The FD magnitude Δy (drop ratio) and the maximum hourly decrease m_{max} are also correlated, as seen previously at Earth [8, 9].
- The **linear regression slope is significantly steeper** (−7.5 ± 0.9 h instead of −2.9 to −4.3 h) at MSL than previously found at Earth, as seen in Figure 6

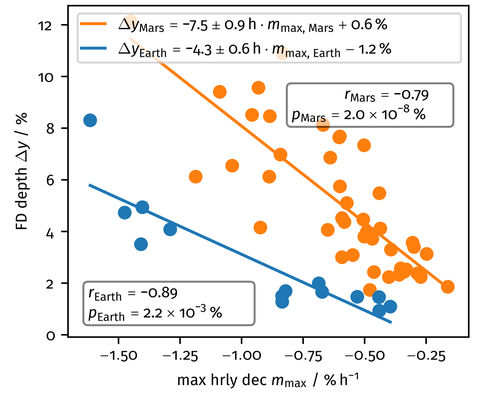


Figure 6: Correlation between the FD maximum slope m_{max} and FD magnitude Δy, for 45 FDs at Mars (orange) and for the subset of 14 events also seen at Earth's South Pole neutron monitor (blue).

- Possible reasons for this are the FD's dependence on the observed energy range of primary GCR particles as well as the ICME expansion. We are working on investigating this further.
- Papaioannou et al. [10] found no difference between slopes at Earth and Mars, but they probably also included decreases caused by CIRs
- Additional correlation was found between the ICME speed v (from HI data) and the FD average slope $\overline{m} = \frac{\Delta y}{\Delta t}$, with $r = -0.61$.

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