Using Forbush decreases at Earth and Mars to measure the radial evolution of ICMEs

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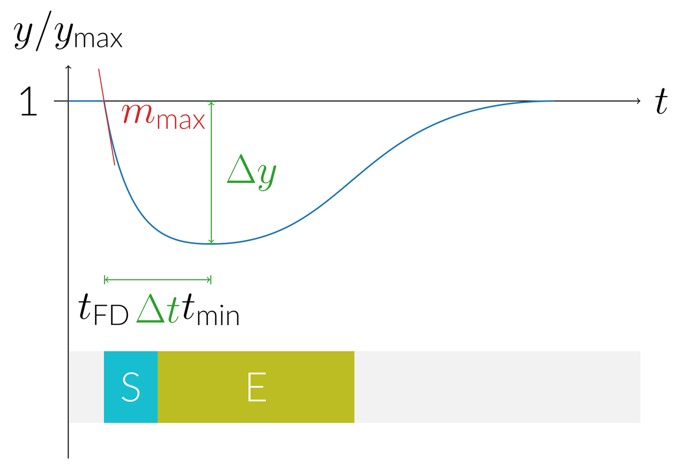
Introduction

Forbush decreases (FDs) are short-term drops in the flux of galactic cosmic rays (GCR) caused by the shielding from magnetic structures in the solar wind. They can be related to **interplanetary coronal mass ejections** (ICMEs) or corotating interaction regions (CIRs). FDs can be observed at Earth, e.g. using neutron monitors, but also at other locations in the solar system, such as on the surface of Mars with the Radiation Assessment Detector (RAD) instrument onboard Mars Science Laboratory (MSL).

FDs are often used as a proxy for detecting the arrival of ICMEs or CIRs, especially when sufficient in situ solar wind measurements are not available. But with sufficient understanding of the FD physics, it is also possible to gain more information about the heliospheric structures than just their arrival times. We demonstrate such an approach, focusing on ICME-related FDs observed at Earth and Mars.

Definitions



y/y_{max}: FD profile ($y(t)$) normalized to the onset value
Δy: Drop ratio of the FD (in %)
Δt: Duration of the FD decrease phase (in h)
m_{max}: Maximum decrease rate during the decrease phase (in % h^{-1})
S, E Sheath and ejecta regions of the ICME (example)

Observations I

Using our catalog of 45 ICME-induced FDs observed at Mars [2], we find a **linear correlation** of Δy and m_{max} (Figure 1). This correlation was already found at Earth [3, 4] and is confirmed by the subset of 14 events also seen on Earth (South Pole neutron monitor). However, the linear regression $\Delta y = A \cdot m_{max} + B$ at Mars has a **steeper slope** A than at Earth by a factor of $E = A_{Mars}/A_{Earth} = 1.9 \pm 0.4$.

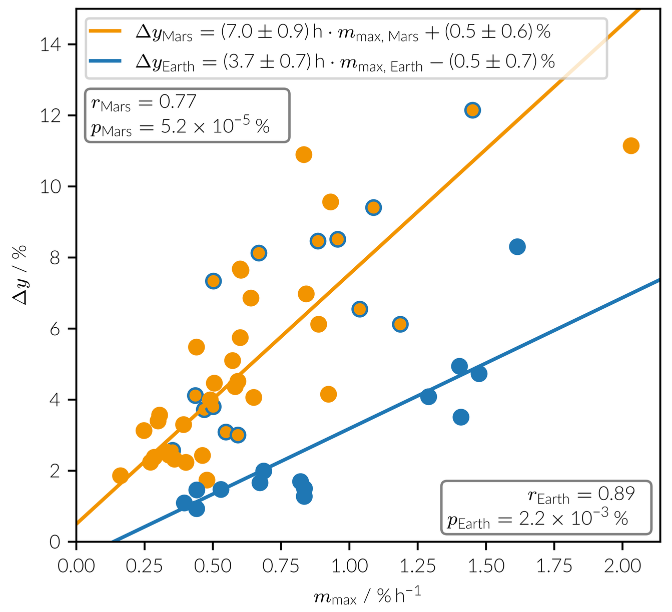


Figure 1. Correlation of Δy and m_{max} at Mars (orange) and Earth (blue). Orange points with blue outline mark the subset of events at Mars also seen at Earth.

Observations II

A similar trend is also visible in the larger catalog from Papaioannou et al. [5]. In this case, we applied a filter to only look at FDs associated with ICMEs (middle panel of Figure 2) as well as a threshold condition

$$\Delta y \geq f \cdot \mathrm{median}(\Delta y) \quad (1)$$

to exclude FDs with low amplitude where the uncertainty of the Δy and m_{max} parameters can be large.

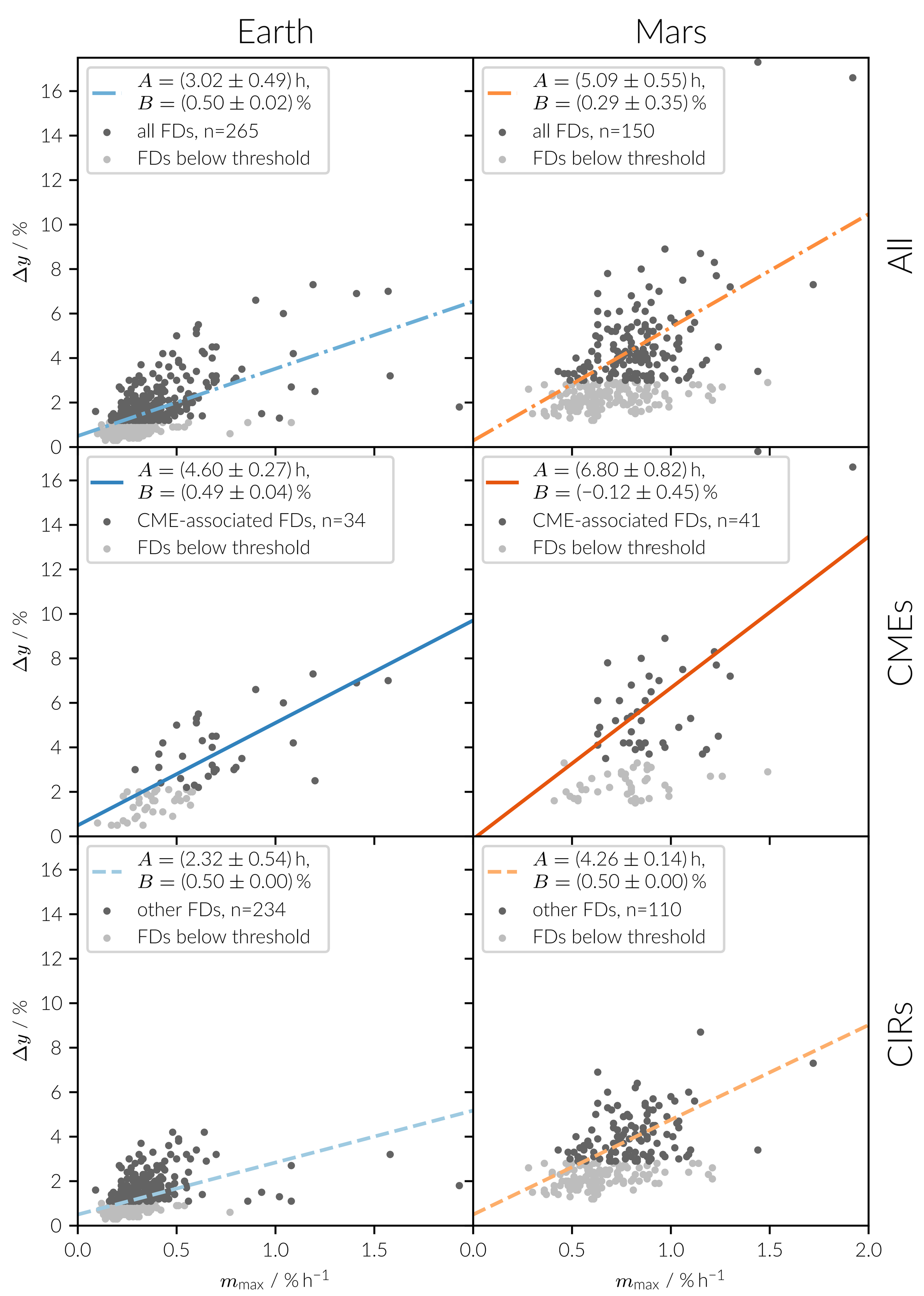


Figure 2. Same correlation plot for Earth and Mars based on a larger catalog from [5]. Events are plotted all together (top row) and separately for ICME-induced Forbush decreases and others (mainly CIRs). The threshold condition from Equation 1 is applied with $f = 1.0$.

The uncertainties of the fit parameters were calculated using a bootstrap method. An investigation of the dependence of A on the threshold parameter f shows that A_{Earth} and A_{Mars} become significantly different above $f \gtrsim 0.8$ (not shown here, see paper for details). At $f = 1.0$ (shown in Figure 2), the ratio E is 1.5 ± 0.2.

Interpretation

Two possible reasons:

- **Lower GCR energy** observed at Mars than at Earth
  Mars (MSL/RAD dose rate): mainly 1 GeV to 3 GeV protons
  Earth (global survey method): 10 GV rigidity ≙ 9.1 GeV protons
  ⇒ *Only affects the FD magnitude, not duration.*
- ICME evolution between Earth and Mars, **e.g. expansion**
  ⇒ *Affects both FD magnitude and duration.*

Modeling of m_{max} vs. Δy relation

Figure 3 shows an idealized schematic illustration of FDs at Earth and Mars, taking into account both effects mentioned above. It can be seen that only the **expansion of the ICME structure results in a steeper slope** A of the m_{max} vs. Δy relation at Mars, while a change in GCR energy does not significantly affect the slope.

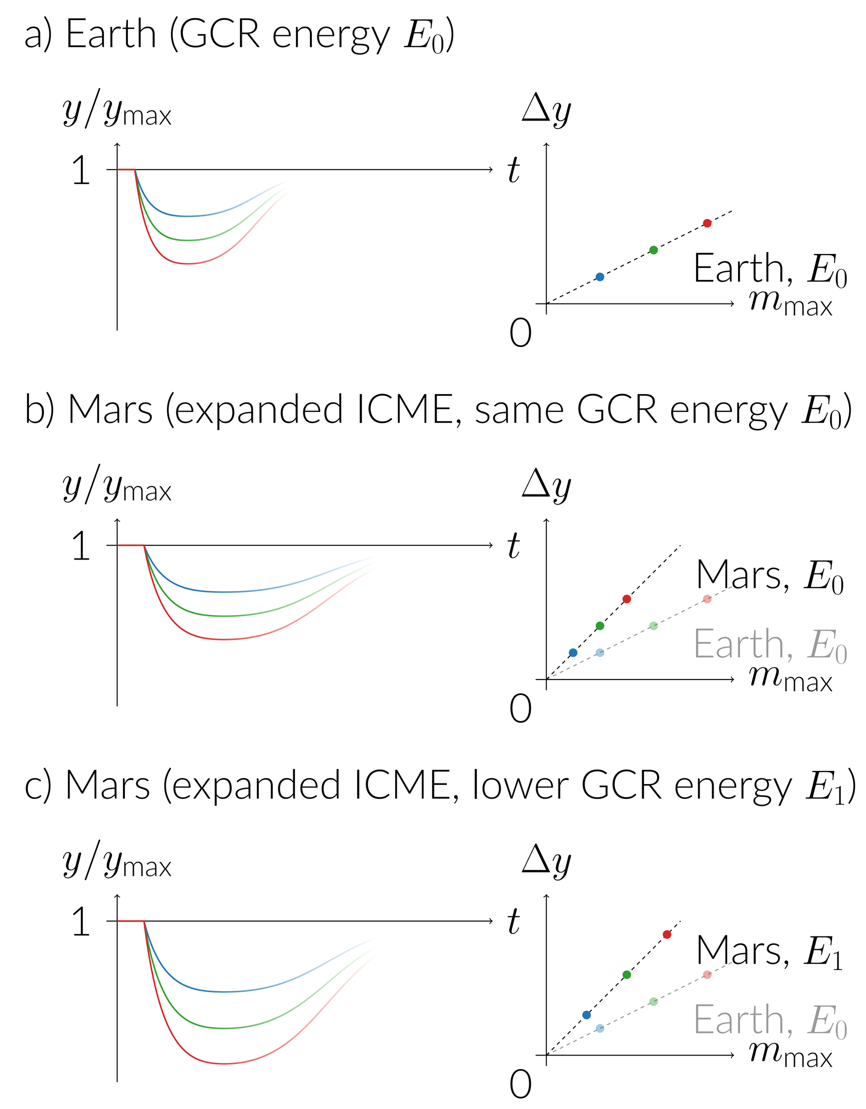


Figure 3. Cartoon illustration of the Δy vs m_{max} correlation for Earth and Mars.

We have performed analytical modeling calculations using the propagating diffusive barrier model (PDB) [6] for the sheath and ForbMod [7] for a flux rope ejecta, confirming that **A is proportional to the duration of the ICME passage and does not depend on the GCR energy** for both the sheath and ejecta regions of the ICME. As m_{max} most often occurs in the sheath, we suspect that our results are **mostly affected by the sheath region**. This was also validated by applying another threshold condition to the catalog to only include FDs where m_{max} occurs close to the onset time, resulting in similar values of $E = 1.5 \pm 0.4$. Thus, E should correspond to the **sheath broadening factor** between Earth and Mars.

Calculation of sheath broadening

As a comparison to the ratio obtained from FD measurements, we estimate the expected increase in sheath width S between 1 au and 1.5 au. In this region, it is probably dominated by two processes:

- Pileup of ambient solar wind in front of the shock:

$$\Delta S_{pileup} \propto (v_{shock} - v_{sw})\Delta t$$

- Expansion/contraction due to sheath velocity profile:

$$\Delta S_{exp} = (v_{sheath,front} - v_{sheath,rear})\Delta t$$

Other effects are considered to be insignificant beyond 1 au for a first-order approximation. Based on these equations and typical values obtained from statistical studies [8], we estimate the broadening factor $E = S_{Mars}/S_{Earth}$ to be between 1.2 and 1.8, comparable to the ratios of our linear regression slopes in the FD analysis.

Conclusion

We have estimated the factor E by which the size of an ICME sheath region increases between Earth and Mars based on analysis of only Forbush decrease measurements. This was made possible by the choice of two characteristic FD parameters which are linearly correlated, and the analytical modeling of the dependence of this relation on the properties of the ICME. Based on different data sets, we could calculate three results for E, which are in good agreement with each other (Table 1). Theoretical estimations of this factor also give similar results.

E value	Description
1.9 ± 0.4	FDs in Freiherr von Forstner et al. [2] catalog
1.5 ± 0.2	FDs in Papaioannou et al. [5] catalog, threshold $f = 1$
1.5 ± 0.4	FDs in Papaioannou et al. [5] catalog, threshold $g = 0.3$
1.2 to 1.8	Theoretical estimation of broadening factor

Table 1. Results for the sheath broadening factor E estimated in different parts of this study.

Our results for E extend on previous direct measurements of the sheath evolution closer to the Sun, such as by Janvier et al. [9]. They showed that the speed at which the broadening occurs decreases further away from the Sun, and our results between Earth and Mars agree with this trend.

References

Main citation: [1] Freiherr von Forstner et al. "Comparing the Properties of ICME-Induced Forbush Decreases at Earth and Mars". In: *JGR Space Phys.* 125.3 (2020), e2019JA027662, https://doi.org/10.1029/2019JA027662 — **Open Access**

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