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MULTI-SPACECRAFT OBSERVATIONS OF ICMES PROPAGATING BEYOND EARTH ORBIT
DURING MSL/RAD FLIGHT AND SURFACE PHASES

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Introduction

Forbush decreases (FDs) in the measurements of galactic cosmic rays (GCR) can be caused by the passage of Interplanetary Coronal Mass Ejections (ICMEs) at the observation location. While these effects have been regularly observed at Earth (e.g. using neutron monitors) and other locations close to 1 AU, the Radiation Assessment Detector (RAD) instrument [2] on NASA's Mars Science Laboratory (MSL) mission on the surface of Mars is also continuously measuring GCR particles since its landing in 2012, allowing us to detect the arrival of ICMEs at Mars.

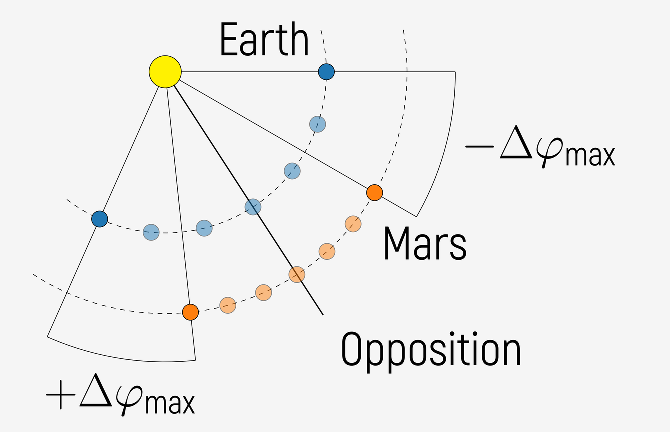

Figure 1: Opposition phases

Near times where Mars and either Earth or the STEREO A or B spacecraft, where FDs can be measured using the HET instrument, are closely aligned on the same side of the Sun (such as in Figure 1), we are likely to **observe the same ICMEs at both locations**. These multi-spacecraft observations of ICMEs during the opposition phases allow us to **determine ICME travel times between Earth orbit and Mars.** The resulting **transit speeds** can also be compared to speed measurements at 1 AU to investigate **deceleration or acceleration**.

Cross-correlation method

We assume that the travel time of the ICMEs between 1 AU and Mars corresponds to the delay time between the onset of Forbush decreases detected at these two locations and that FDs resulting from the same ICME should have similar characteristics at both points. **This delay is obtained by finding the maximum of the cross-correlation function (CCF) of the two datasets** and estimating the error by taking the standard deviation of a Gaussian distribution fitted to the CCF. This method allows to determine the travel time without needing to define exact onset times at both Earth and Mars, which can be difficult when the Forbush decrease is weak and/or rather complex.

Note that we are not comparing the magnitude of the Forbush decreases at 1AU and Mars, which would be an interesting study in the future.

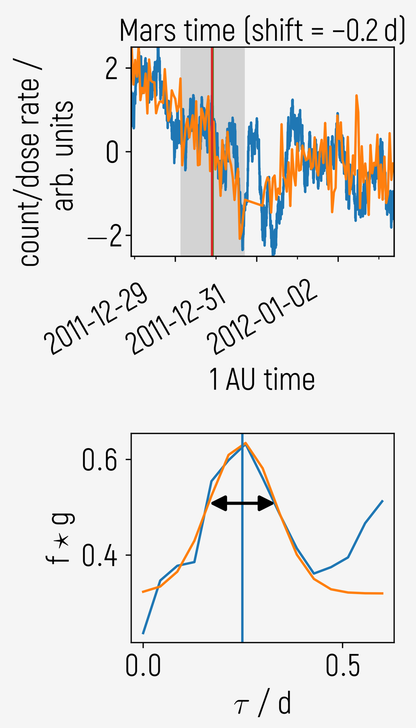

Figure 2: Cross-correlation method

Analysis of MSL surface phase events

Our first paper [1] contains a statistical study of ICMEs close to the oppositions of Mars with STEREO B in 2012, STEREO A in 2013, Earth in 2014 and 2016, using $\Delta\varphi_{max} = 30°$ as the maximum separation between the observation locations. The Richardson & Cane and Jian ICME lists [6, 3] contain 43 events in these periods, but we only kept the 15 events in the study where the onset time from the list corresponded to a clear FD at 1AU and where a convincing correspondence to a FD at Mars found using the cross-correlation analysis – this was not the case e.g. when multiple ICMEs were launched from the Sun in quick succession and merged on their way, or a coinciding solar energetic particle (SEP) event obstructed the FD at STEREO HET.

Results

For each ICME, the measured maximum speed v_{max} at 1 AU, which is considered to be the ICME propagation speed $v_{1\,AU}$, was compared to the mean speed $\bar{v}$ between 1 AU and Mars calculated using the derived travel time and the known radial distance. On average, we obtain a value of $\langle \bar{v}/v_{1\,AU} \rangle = 0.86 \pm 0.06$, indicating that **the average ICME in our sample decelerates slightly** during its propagation not only from the Sun up to 1 AU, but also beyond between 1 AU and Mars.

The **amount of deceleration tends to correlate with the ICME speed relative to the ambient solar wind** measured at 1 AU before the arrival time ($\overline{v_{sw}} - v_{1\,AU}$, Figure 3). However, this correlation is affected by a significant amount of variation, which can be due to interaction with other structures (such as co-rotating interaction regions) or an influence of the ICME shape, as demonstrated in Figure 5.

The average acceleration a between 1 AU and Mars can also be calculated using the measured travel time and $v_{1\,AU}$, and there is also a trend to the acceleration between 1 AU and Mars being related to the one between the Sun and 1 AU, as seen in Figure 4. However, due to error propagation, the a values have larger uncertainties.

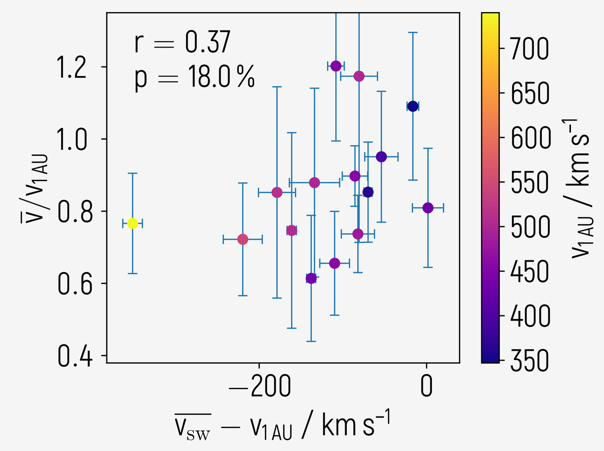

Figure 3: Correlation of ICME deceleration with $v_{1\,AU}$ relative to the ambient solar wind speed

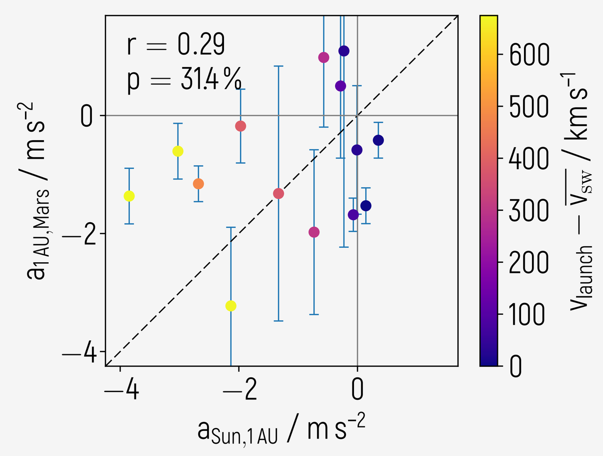

Figure 4: Accelerations between the Sun and 1 AU and between 1 AU and Mars

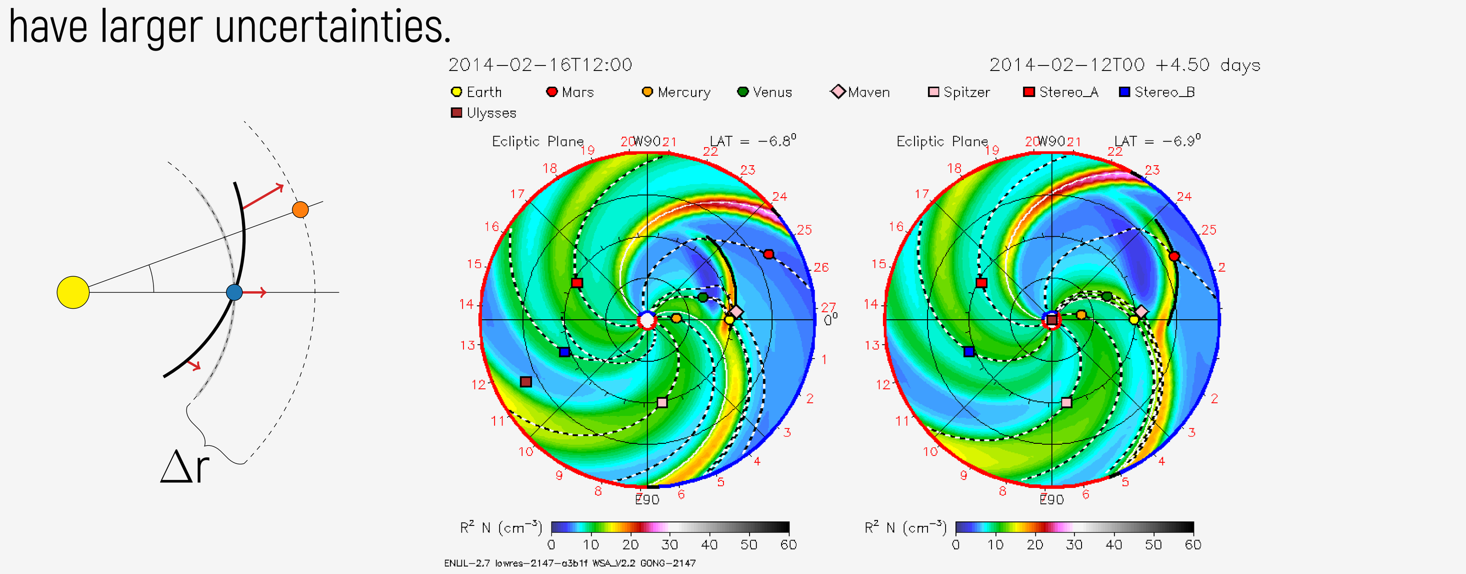

Figure 5: Shape of the 2014-02-15 ICME causing a shorter travel time measurement (cartoon and simulation)

Comparison to models

A comparison of our measured propagation times with WSA-ENLIL+Cone [4] and DBM [7] simulations was carried out as well. **Unlike ENLIL, DBM allowed us to use the observations at 1 AU as the input and simulate only the propagation from 1 AU to Mars, which led to a better agreement with the measurements** (Figure 6). This highlights the importance of space weather modeling taking into account not only information about the launch of CMEs at the Sun, but also the in situ measurements further away, e.g. at 1 AU, to improve forecasts for locations further out in the heliosphere.

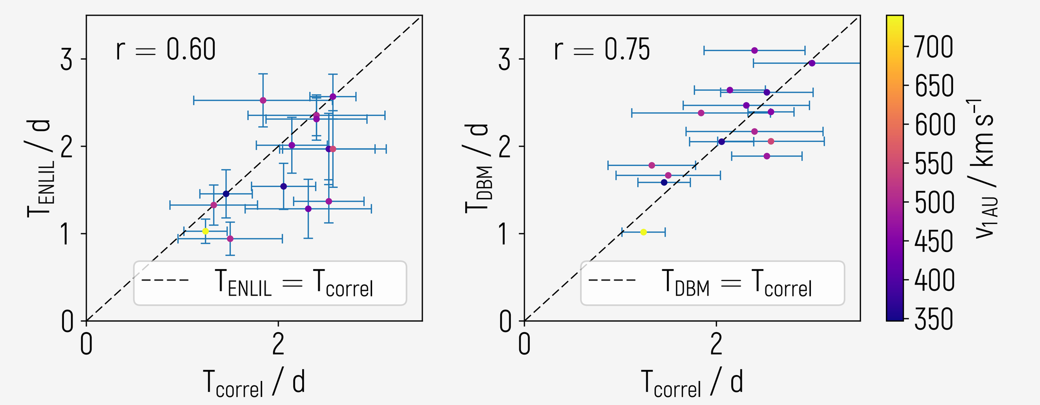

Figure 6: Comparison between measurements, WSA-ENLIL+Cone and DBM models.

Analysis of events during MSL's flight to Mars

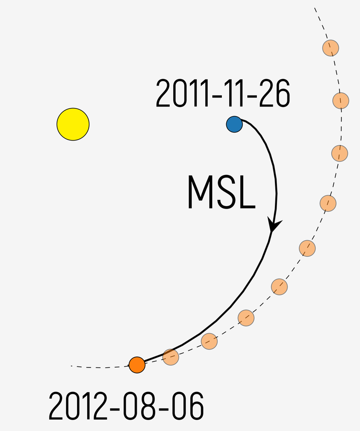

Figure 7: MSL's trajectory from Earth to Mars (as seen from a reference frame co-rotating with Earth)

As the RAD instrument was also turned on from December 2011 to July 2012, i.e. for the most part of **MSL's flight to Mars** [5], this phase is also a good opportunity to study multiple ICMEs that hit both Earth and MSL. During the flight phase, where MSL/RAD was not surrounded by the Martian atmosphere, it was however more sensitive to solar energetic particle (SEP) events, which cause strong enhancements in the dose rate measurements that can sometimes obstruct a FD.

The Richardson and Cane ICME catalog [6] contains 19 ICMEs detected near Earth during the MSL flight phase. After excluding events where the FD was not detected at RAD due to SEP events, data gaps or the ICME missing Mars completely (the latter especially towards the end of the flight phase), and situations where multiple CMEs launched in quick succession merged between Earth and MSL, we have 5 events that can be reliably studied using our cross-correlation method.

Flight phase results

Unfortunately, the number of ICMEs in our flight phase sample is too low to allow for meaningful spatially-resolved statistical studies with these events, such as drawing conclusions about a change in acceleration or a change of the FD shape with increasing radial distance. However, **the events studied in the flight phase can be used to extend our previous list** of events seen on the surface of Mars [1] and compared with them. For example, Figure 8 shows a histogram of the calculated average acceleration a between 1 AU and MSL locations for all 20 ICMEs, indicating that the flight phase events **seem to follow a similar trend** as the previously studied events observed on the surface of Mars.

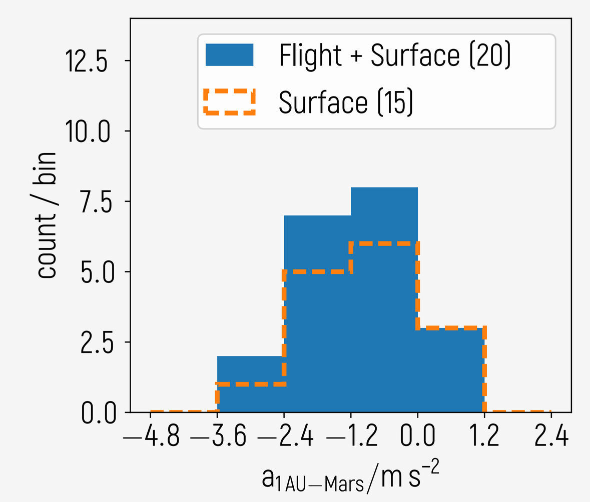

Figure 8: Histogram of the acceleration of events in our flight and surface phase samples

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Acknowledgements

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