First multi-spacecraft observations of ICMEs propagating from Earth (orbit) to Mars

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Introduction

The interplanetary propagation of Coronal Mass Ejections (CMEs) is a phenomenon currently studied by numerous researchers. With the Curiosity rover of NASA's *Mars Science Laboratory* (MSL) mission, whose *Radiation Assessment Detector* (RAD) instrument [2] is continuously measuring GCR particles on the surface of Mars (at approximately 1.5 AU) since its landing in 2012, another device capable of capturing Forbush decreases is available.

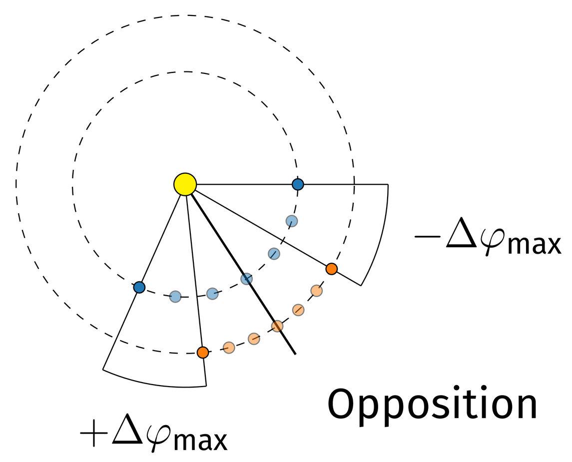

Figure 1: Opposition phases

Close to times where Mars and either Earth or the STEREO A or B spacecraft form a straight line with the Sun (such as in Figure 1), we can observe the same ICMEs at both locations using *in situ* data (RAD at Mars, Neutron monitors at Earth, HET at STEREO).

These multi-spacecraft observations of ICMEs during the opposition phases allow us to determine their travel times between Earth orbit and Mars. The resulting speeds can be compared to speed measurements at 1 AU to investigate deceleration or acceleration.

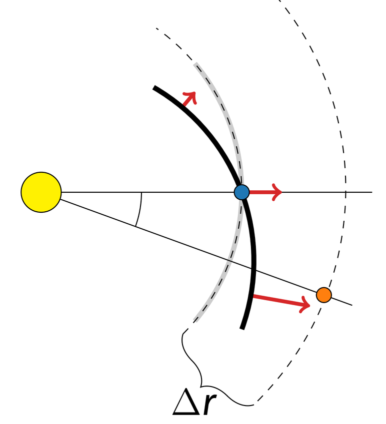

Figure 2: Influence of the ICME shape on the derived travel times

When the two observers are not perfectly aligned, the shape of the ICME will influence the derived travel times, as shown in Figure 2. This will result in an additional spread in the calculated speeds. Keeping the longitudinal separation $\Delta\varphi_{max}$ low (we currently use 30°) minimizes this influence.

Method

To determine the travel time of ICMEs between 1 AU and Mars, we use a method based on the cross-correlation function $(f \star g)(\tau)$ between the measurements of Forbush decreases at Earth or STEREO (f) and Mars (g) using a ± 1 sol (solar day on Mars) window around the ICME onset time at Earth.

The value of the time lag τ where $(f \star g)$ assumes a maximum is considered to be the ICME's travel time T between 1 AU and Mars. We fit the peak with a Gaussian distribution to estimate the error of T.

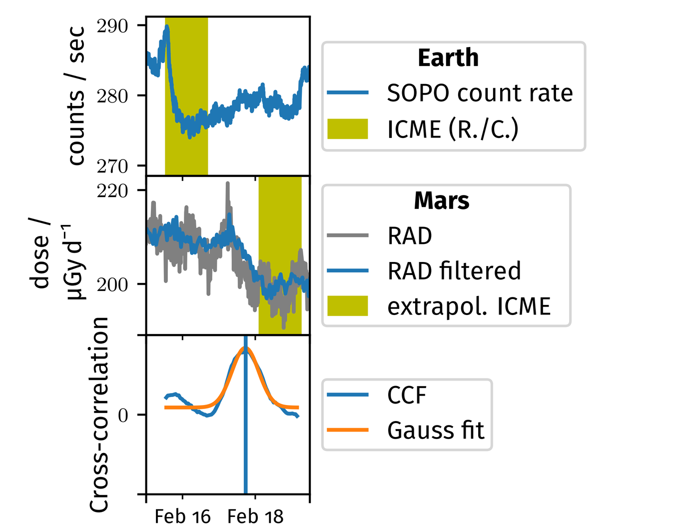

Figure 3: Example of an application of the cross-correlation method. Disturbance and ICME end times are marked in yellow as derived by Richardson and Cane [3] *(R./C.)* and extrapolated to Mars assuming a constant speed.

Results

We applied the method to 18 ICMEs observed at Earth or the STEREO spacecraft and Mars close to their oppositions between 2012 and 2016. Some difficult cases where ICMEs interact with each other and/or with CIRs were not included as they can cause problems with the cross-correlation method. The travel time could be calculated with an estimated standard deviation of between 0.2 and 0.5 d for most events.

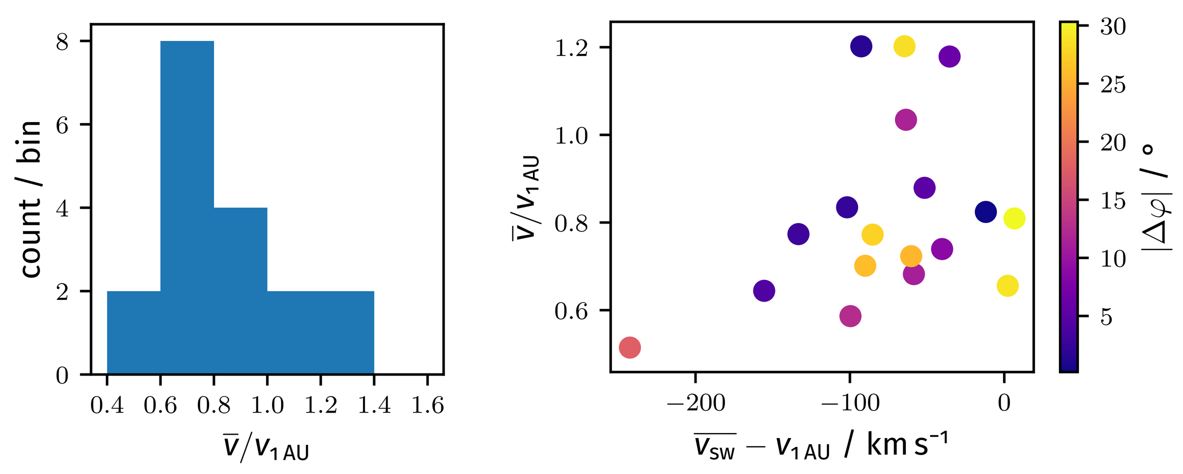

Figure 4: Histogram of ICME speed changes between 1 AU and Mars and comparison to the ambient solar wind speed. v_{sw} is the 7-day mean value of the solar wind speed measured at the ACE spacecraft, $\bar{v}$ is the mean speed of the ICME between Earth and Mars (calculated from the cross-correlation result) and $v_{1\,AU}$ is the maximum solar wind speed measured at 1 AU during the passing of the ICME, which is assumed to be the ICME speed at 1 AU. The colors in the right plot also show the longitudinal separation of Earth (or STEREO) and Mars.

We found that on average, ICMEs decelerate during their propagation between 1 AU and 1.5 AU ($\bar{v}/v_{1\,AU} = 0.82 \pm 0.05$) and ICMEs that are fast compared to the ambient solar wind decelerate the most, as seen in Figure 4. However, these findings need to be put on firmer ground by adding more ICMEs to the study in the future, which will enhance the meaningfulness of statistical studies.

Detailed results will soon be published [1].

Comparison to models: WSA-ENLIL with Cone model

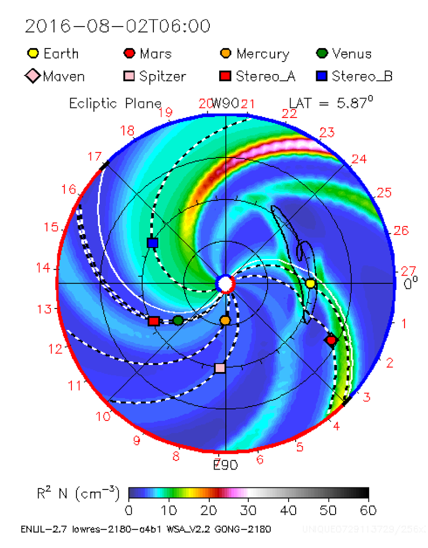

Figure 5: The 2016-08-02 event in the ENLIL simulation.

We compared the travel times between 1 AU and Mars with results from WSA-ENLIL+Cone simulations. The same cross-correlation method was used to derive travel times using magnetic field data obtained from the ENLIL simulation. On average, ENLIL predicts a faster propagation from 1 AU to Mars, but the accuracy of the ENLIL results also seems to vary depending on the ICME speed.

For example, the 2015-12-25 event at STEREO B agrees well with travel times of (1.11 ± 0.26) d (correlation) and (1.20 ± 0.21) d (ENLIL). On the contrary, for the 2016-08-02 event at Earth, the travel time predicted by ENLIL is approximately one day shorter than the result of the correlation method. This might have been caused by the collision of the CME with a CIR, whose influence could have been underestimated by ENLIL.

Comparison to models: Drag-Based Model

A more simple model for the propagation of ICMEs is the Drag-Based Model (DBM) [4]. The advantage of the DBM over ENLIL is that it can be run very quickly as it is not based on numerical MHD simulations - the drag equations can be solved analytically.

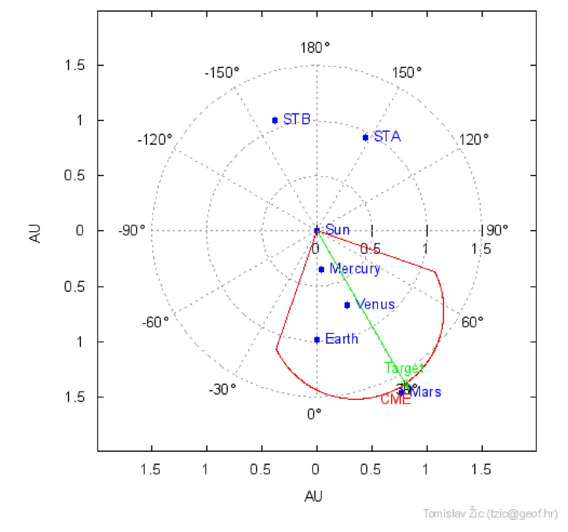

Figure 6: DBM simulation result for the 2014-02-15 ICME.

We ran a DBM simulation for one of the ICMEs (the one arriving at Earth on 2014-02-15) as a comparison to the results from both the *in situ* measurements and the ENLIL simulation, using default values for the drag parameter Γ and the solar wind speed w. The predicted travel time of 1.8 d is a little shorter than the (2.01 ± 0.25) d predicted by ENLIL, but still agrees with the measured $T_{correl} = (2.14 \pm 0.37)$ d.

References

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Title photo: NASA/JPL-Caltech/Malin Space Science Systems

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