

# Unusual Plasma and Particle Signatures at Mars and STEREO-A Related to CME-CME Interaction

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# Abstract

On 2017 July 25 a multistep Forbush decrease (FD) with a remarkable total amplitude of more than 15% was observed by Mars Science Laboratory/Radiation Assessment Detector at Mars. We find that these particle signatures are related to very pronounced plasma and magnetic field signatures detected in situ by *STEREO-A* on 2017 July 24, with a higher-than-average total magnetic field strength reaching more than 60 nT. In the observed time period *STEREO-A* was at a relatively small longitudinal separation (46°) to Mars, and both were located at the back side of the Sun as viewed from Earth. We analyze a number of multispacecraft and multi-instrument (both in situ and remote-sensing) observations and employ modeling to understand these signatures. We find that the solar sources are two coronal mass ejections (CMEs) that erupted on 2017 July 23 from the same source region on the back side of the Sun as viewed from Earth. Moreover, we find that the two CMEs interact nonuniformly, inhibiting the expansion of one of the CMEs in the *STEREO-A* direction, whereas allowing it to expand more freely in the Mars direction. The interaction of the two CMEs with the ambient solar wind adds up to the complexity of the event, resulting in a long, substructured interplanetary disturbance at Mars, where different substructures correspond to different steps of the FD, adding up to a globally large-amplitude FD.

Key words: solar-terrestrial relations - Sun: coronal mass ejections (CMEs)

# 1. Introduction

Interplanetary counterparts of coronal mass ejections (ICMEs) are the most prominent short-term transient phenomena in the heliosphere that significantly influence the interplanetary space and can have a major impact on Earth and other planets (see an overview by Kilpua et al. 2017, and references therein). The *Heliophysics System Observatory*<sup>9</sup> enables us to observe ICME-related signatures at different heliospheric positions and, combined with remote observations as well as modeling efforts, to better understand the propagation and evolution of ICMEs. Recently, an ICME (i.e., its shock signatures) was tracked and modeled all the way from the Sun to the outer heliosphere (Witasse et al. 2017), using, among other things, Forbush decreases (FDs) as ICME signatures.

FDs are observed as short-term depressions in the galactic cosmic-ray (GCR) flux (Forbush 1937; Hess & Demmelmair 1937), with onset corresponding to the ICME arrival (Cane et al. 1996; Dumbović et al. 2011). The magnitude, shape, duration, and substructuring of the FD depend on the physical properties of the corresponding interplanetary transient (for an overview see, e.g., Cane 2000; Richardson 2004; Belov 2009, and references therein), and more specifically, ICME-related FDs are expected to reflect the evolutionary properties of

ICMEs, such as expansion (Dumbović et al. 2018b). Therefore, they are highly suitable as ICME signatures and are used to indicate ICME arrival when and where other in situ measurements are unavailable (e.g., in the presatellite era or at Mars; see Möstl et al. 2015; Lefèvre et al. 2016; Vennerstrom et al. 2016; Freiherr von Forstner et al. 2018; Winslow et al. 2018). From that perspective, the Radiation Assessment Detector (RAD; Hassler et al. 2012) on board Mars Science Laboratory's (MSL) rover Curiosity (Grotzinger et al. 2012) was shown to be highly suitable for identifying ICMEs' arrival at Mars with detected FDs (Guo et al. 2018b).

While trying to understand the basic physics, often single and simple, textbook-example ICMEs are analyzed, but it is important to note that the frequency of such events can be relatively low. Many in situ detected ICMEs do not show typical magnetic cloud (MC) properties (i.e., magnetic field rotation, low plasma beta, low density and temperature, expanding speed profile; see, e.g., Burlaga et al. 1981; Zurbuchen & Richardson 2006; Kilpua et al. 2017, and references therein), quite likely because of, among other things, coronal mass ejection (CME)–CME interactions. CME–CME interactions are expected to be quite common considering the CME occurrence frequency and their typical propagation time (Lugaz et al. 2017) and can lead to more intense geomagnetic storms (Wang et al. 2003a, 2003b; Farrugia et al. 2006a, 2006b; Xie et al. 2006; Lugaz & Farrugia 2014; Shen et al. 2017), as well

<sup>&</sup>lt;sup>9</sup> https://www.nasa.gov/content/goddard/heliophysics-system-observatory-hso

as larger-amplitude FDs (Papaioannou et al. 2010; Dumbović et al. 2016). Therefore, from the space weather point of view these complex events are especially challenging and interesting to study (see also, e.g., Webb & Nitta 2017). Moreover, understanding the underlying physics in such events offers an opportunity to improve future modeling efforts and predictions of such strong space weather events.

# 2. Data and Method

On 2017 July 25 MSL/RAD observed an FD with one of the biggest relative amplitudes detected by this instrument since its launch (Guo et al. 2018b). The FD not only has an unusually large amplitude but also shows a quite complex time profile, possibly indicating interactions of two or even several interplanetary transients. In order to understand this event and the conditions that lead to these specific signatures, we search for possible solar sources, assuming that (1) a very impulsive CME is most likely involved and (2) CME–CME interaction is very likely.

In a time period 6 days prior to the FD observed at Mars, we search for possible CME candidates. For this we use Solar and Heliospheric Observatory/Large Angle and Spectromeric Coronagraph Experiment (LASCO; Brueckner et al. 1995) coronagraphs C2 and C3, with field of view (FOV) reaching 6 and  $32 R_{\odot}$ , respectively, and STEREO-A(ST-A)/SECCHI (Howard et al. 2008) EUVI/COR1/COR2 image data with FOV reaching 1.7, 2.5, and  $15 R_{\odot}$ , respectively. We find only four CMEs that have a position angle relating to the Mars direction, which was almost in the opposition. The first two CMEs launched on July 20 and the other two launched about 2 days later, around the beginning of July 23, were much stronger and faster. The last of these four CMEs is extremely fast and wide and is very likely interacting with a preceding CME launched shortly before. As the separation angle between ST-A and Mars is not large  $(46^{\circ})$ , we check possible ICME signatures measured at ST-A for more insight on these ICME characteristics. For this we use the PLASTIC (Galvin et al. 2008) and IMPACT (Acuña et al. 2008) in situ plasma and magnetic field instruments. Indeed, we find a very pronounced in situ MC signature on 2017 July 24 with a magnetic field strength reaching more than 60 nT.

The two CMEs that erupted on July 23 are the most likely candidates of the signatures observed in both MSL/RAD and ST-A/PLASTIC+IMPACT, as they best match the timing and direction for causing the observed FD at Mars. Therefore, in the following we focus on these two CMEs, henceforth denoted as CME1 and CME2. The other two CMEs, launched on July 20, are discussed later in the frame of background solar wind effects and are denoted as CMEs 0.1 and 0.2. We hypothesize that the unusual observational signatures are due to the interaction of CMEs 1 and 2. To test this hypothesis, we employ a number of multispacecraft and multi-instrument observations, as well as modeling. We note that the observational methods and models we use to test the hypothesis suffer from a number of uncertainties; therefore, constructing a plausible explanation of this complex event is challenging. Nevertheless, we argue that the combined synergetic view of the results and interpretations obtained from different models and observations indicates the most likely explanation.

# 2.1. CME Observations

A filament/prominence eruption starts around 22:30 UT on 2017 July 22 observed by ST-A/EUVI 304 Å (Figure 1(a)), where one part of the filament continues to move radially outward (Figure 1(b)) and can be observed as CME in COR1 at around 01:05 UT on 2017 July 23 with the same (northward) direction of motion (Figure 1(c)). The source region appears to be Active Region (AR) 12665 at the east limb of ST-A's FOV with approximate Stonyhurst coordinates [0, 155]. The CME (henceforth CME1) is observed in COR2 at 01:55 UT and appears in LASCO/C2 FOV at 01:36 UT.

In order to more reliably derive the direction and geometry of the CME, we use coronagraphic images from different vantage points, ST-A and LASCO, to perform a 3D CME reconstruction using the graduated cylindrical shell model (GCS; Thernisien et al. 2006, 2009; Thernisien 2011). GCS assumes that geometrically a CME can be represented as a hollow croissant with origin in the center of the Sun, i.e., with conical legs, a circular cross section, and a pseudo-circular front. A projection of the croissant (green mesh in Figure 2) at a given time is fitted to coronagraphic images, where two different vantage points are needed to better constrain the fit. We manually fit the GCS model to the CME observations using ST-A/COR2 and LASCO/C3 images from 03:06 and 03:08 UT, respectively (see Figure 2(a)). Assuming the radial propagation direction, we use as a starting position the CME source region, i.e., the AR location. The best fit is derived for a direction slightly different from the AR location (Stonyhurst coordinates [10, 170]), indicating a deflection toward Mars and ST-A. For obtaining a kinematic profile, we assume self-similar expansion, keep all GCS parameters except for height constant, and fit stereoscopic images for several time steps. We note that for later time steps we cannot find a good match anymore for the CME front, as it deforms most probably as a result of a helmet streamer (see Figure 2(b)).

As CME1 exits the ST-A/COR2 FOV around 03:20 UT, an eruption is observed in the same AR 12665 at the east limb in ST-A/EUVI 195 Å, followed by a dimming, an EUV wave, and post-flare loops (Figure 1(d)). A more detailed analysis of the EUVI observations reveals a multistep eruption, where several eruptions are observed very closely in time in the same AR. We first observe erupting loops in EUVI, appearing also in COR1 but as very faint structures and oriented northward (blue arrow in Figures 1(d)-(e)). The second eruption observed in EUVI is associated with a strong EUV wave and is seen as a very prominent structure in COR1 moving more southward (red arrow in Figures 1(d)–(e)). The third eruption is associated with a strong flare, is narrow, and is the most impulsive. In COR1 it is not easily distinguishable from the second eruption; however, it can be seen as a localized emission enhancement, where its outer structure overlaps with the northern loop segment of the previous eruption. For a more detailed analysis of the early multi-eruption signatures we refer the reader to a study by Liu et al. (2019). The single eruptions cannot be individually tracked and appear to move as one entity already in COR1 FOV. In COR2 FOV the structures appear as a single CME. Therefore, in the further analysis we treat this as a multistep eruption resulting in a single CME. The CME (henceforth CME2) is detected by COR2 at 04:54 UT and appears in the LASCO/C2 FOV at 04:45 UT.

We perform a GCS reconstruction of the CME main part in ST-A/COR1 and LASCO/C2 images at 04:45 and 04:48,



**Figure 1.** Low coronal eruption signatures associated with CMEs 1 and 2: (a) prominence eruption associated with CME1 observed by ST-A/EUVI 304 Å; (b) running difference image of ST-A/EUVI 304 Å showing prominence moving radially outward; (c) running difference images of ST-A/EUVI 304 Å and ST-A/COR1 showing CME1; (d) post-flare loops associated with CME2 observed by ST-A/EUVI 195 Å; (e) running difference image of ST-A/EUVI 195 Å with erupting loops associated with CME2; (f) running difference images of ST-A/EUVI 195 Å and ST-A/COR1 showing the "main" part of CME2. Blue arrows in panels (a)–(c) mark the direction of the CME1 eruption. Red and blue arrows in panels (d)–(f) mark the directions of multistep eruptions observed in ST-A/EUVI. (For detailed explanation see main text. Credit: JHelioviewer.)

respectively, where the CME can be reasonably fitted by a croissant model (green mesh in Figure 2(c)). However, in the FOV of COR2 and C3 the simple croissant geometry does not match anymore with the observed CME structure, and a best fit would be obtained for a quasi-spherical geometry (yellow mesh in Figure 2(d)).<sup>10</sup> Even by introducing deflection, rotation, and non-self-similar expansion, it is impossible to obtain a reasonable transition from the croissant fitted in COR1 to the quasi-sphere fitted in COR2. This reflects the interaction of these multiple eruptions very early in their evolution. We therefore abandon the "main" eruption part fitted in COR1/C2, and for obtaining the kinematics of CME2 we track the quasi-spherical bright structure, which we extrapolate backward and forward in time assuming self-similar expansion and radial propagation.

# 2.2. In Situ Observations at STEREO-A

In Figure 3 ST-A/IMPACT and PLASTIC in situ magnetic field and plasma data are shown in the time period 2017 July 24–28. The in situ event shows quite complex signatures, where several different regions can be identified using standard

observational criteria described by, e.g., Zurbuchen & Richardson (2006), Richardson & Cane (2010), Kilpua et al. (2017), and Richardson (2018). The start of the event can be identified on July 24 (DOY 205) around 13:15 UT with a simultaneous jump in magnetic field, temperature, density, and speed followed by the typical sheath characteristics—elevated temperature, density, plasma beta and speed, and fluctuating magnetic field (region 1 in Figure 3). Although the elevated values do not seem prominent compared to the rest of the interval (extreme parameter values in regions 3 and 4), we note that the magnetic field increases from around 3 nT to around 11 nT, a jump comparable to typical events. Therefore, we identify this region as the shock/sheath region.

In region 2 we also observe typical sheath characteristics; however, they are much stronger than in region 1: the magnetic field strength is on average 4–5 times stronger, density is about 6 times higher, temperature is 2–3 times higher, and there is an increase of flow speed throughout the region from about 550 to  $660 \text{ km s}^{-1}$ . This might indicate a second shock/sheath region or a continuation of one common sheath where the plasma and magnetic field are strongly piled up against the strong magnetic field of the magnetic structure in the region that follows (region 3). However, due to the data gap between regions 1 and 2, this cannot be fully resolved.

In region 3 qualitatively typical MC signatures are observed —strong and smoothly rotating magnetic field, low density,

 $<sup>\</sup>frac{10}{10}$  We note that it is unlikely that this bright structure is a shock, as the typical shock signature is a faint front (Vourlidas et al. 2013), which we observe propagating ahead (blue dashed circle in Figure 2(d)).

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**Figure 2.** GCS reconstructions of CMEs 1 and 2 at different times: (a) when the CME1 leading edge can be fitted with a croissant ( $R = 11.6 R_{\odot}$ ); (b) when the leading edge of CME1 cannot be perfectly fitted anymore ( $R = 14.9 R_{\odot}$ ); (c) the "main" part of CME2 fitted with a croissant model (in C2 and COR1,  $R = 4.25 R_{\odot}$ ); (d) a multistep complex CME2 fitted with a quasi-sphere (in C3 and COR2,  $R = 19.2 R_{\odot}$ ). The green mesh outlines the fitted croissant for both CME 1 and 2, the yellow wire outlines a fitted quasi-sphere for CME2, and the blue dashed circle outlines the shock front. Reconstruction parameters for both CMEs are given in Table 2.

temperature, and plasma beta; however, quantitatively this MC is quite unusual. The magnetic field strength is extremely high: at its peak ( $\sim$ 65 nT) it is 6 times higher than MC values typically observed at 1 au (10 nT at Earth; see Richardson & Cane 2010). The MC duration ( $\sim$ 7 hr) is, on the other hand, extremely short, around 4 times shorter than MC durations typically observed at 1 au (around 30 hr; see Richardson & Cane 2010), and finally, the flow speed does not show a typical linearly decreasing (expansion) profile. These are strong indications that the expansion of this CME was inhibited. We perform the Lundquist fitting to the magnetic field data (Leitner et al. 2007) and find a reasonable fit (green curves in

Figure 3(b)) with orientation showing a  $-13^{\circ}$  axis tilt to ecliptic, central magnetic field of 40 nT, and an estimated diameter of 0.12 au, i.e.,  $26 R_{\odot}$ . There is a quite large discrepancy of the fit and data at the beginning of the MC, as the magnetic field shows a quite asymmetric profile, not unusual for the fast CMEs (Masías-Meza et al. 2016), which might be due to a plasma/magnetic field line pileup within the MC near the leading edge.

In region 4 we observe a typical stream interface signature a drop of density followed by an increase in temperature and speed, a fluctuating and elevated magnetic field, and a small spike in the plasma beta, a common feature of stream



**Figure 3.** In situ measurements at ST-A and Mars. Left: ST-A/PLASTIC+IMPACT measurements for July 24–28 (DOY 205–209), with panels from top to bottom showing magnetic field strength, *B*, three magnetic field components,  $B_x$ ,  $B_y$ , and  $B_z$ , plasma density, *N*, plasma temperature, *T*, and plasma beta and speed, *v*. Differently colored shading outlines different regions (1–5; for explanation see main text). Small panels embedded in the top three larger panels show a zoomed-in region 5 (DOY 206–210). The green curves in the top two panels mark the Lundquist fit (hourly values,  $\chi^2$ -test *p*-value is 0.011). Right: MAVEN and MSL/RAD measurements for July 24–August 7 (DOY 205–219), with panels from top to bottom showing magnetic field strength, *B*, three magnetic field components,  $B_x$ ,  $B_y$ , and  $B_z$ , plasma density, *N*, temperature, *T*, plasma beta and speed, *v*, and GCR count proxy by MSL/RAD. Differently colored shading outlines different regions (1–6; for explanation see main text). The red curve in the bottom panel marks the ForbMod fit (FD model; for explanation see Section 3.3).

interaction regions (SIRs). This is, however, not followed by the typical high-speed stream (HSS) signatures in region 5, where high flow speed is accompanied by a relatively low temperature, plasma beta, and density. The speed that peaks on the front with about  $800 \text{ km s}^{-1}$  shows a highly expanding profile, with speed at the trailing edge reaching 400 km s<sup>-1</sup>, and the duration of the region is about 50 hr, which is quite long compared to the typical ICME duration at 1 au (around 30 hr; see Richardson & Cane 2010). The magnetic field is relatively smooth but weak and shows no obvious rotation, although there are indications of substructuring. These might be indications of a highly expanded CME, a specific trajectory of the spacecraft through the leg of the CME (see, e.g., Möstl et al. 2010), or a complex ejecta/compound stream (see, e.g., Burlaga et al. 2003; Lugaz et al. 2017).

## 2.3. In Situ Observations at Mars

In Figure 3 MAVEN (Mars Atmosphere and Volatile EvolutioN; Jakosky et al. 2015) in situ magnetic field and plasma data, as well as MSL/RAD relative count rates, are shown in the time period 2017 24 July–7 August. To avoid

contamination from measurements taken inside the bow shock, we use an algorithm described by Halekas et al. (2017). Similar to STEREO-A, the in situ event at Mars shows quite complex signatures, where several different regions can be identified. We note that the identification here is not as straightforward as with ST-A, due to uneven coverage of the solar wind. We interpolate the measurements to guide the eye; however, we note that one has to be careful not to misinterpret the interpolation for measurements. Nevertheless, using MAVEN in combination with MSL/RAD data, which provides additional information on the associated FDs, we are able to identify different substructures. For that purpose we use sol-filtered MSL/RAD data in which the daily pressure-induced oscillations have been removed (for details on the method see Guo et al. 2018b). As a proxy of the CR count we use relative values of the dose rate normalized to the beginning of the observed period.

Region 1 is characterized by what appears to be typical stream interface properties with a corresponding decrease in GCRs of about 4% as detected by MSL/RAD, which starts on July 25 around 00:00 UT. Unfortunately, MAVEN was not measuring the solar wind plasma and magnetic field throughout region 2; however, we do discern this as a separate region for

two reasons. First, the plasma speed and the  $B_y$  component show distinctively different properties at the start and end of this gap. Second, MSL/RAD data show an increase of 5% at the start of this region, followed by a rapid decrease of 5% (measured from the onset point, not the peak point), which are typical shock/sheath-related FD properties (e.g., Cane 2000). Therefore, we suggest that this is most likely a shock/sheath region, where the speed increase throughout the region indicates that the shock is still driven.

Region 3 is characterized by a relatively low plasma beta and what appears to be a decreasing speed profile indicating expansion of the magnetic structure. The magnetic field also seems to be somewhat elevated; however, due to the data gap in the first half-period, it is not possible to make a reliable estimation about the strength or rotation of the magnetic field. MSL/RAD, on the other hand, shows the start of another, less rapid decrease at the beginning of this region, which might indicate the beginning of the ejecta-related FD. However, the depression does not return to the onset value but is "interrupted" by another decrease at the start of region 4. In region 4 we again identify what appears to be stream interface signatures; however, the reliability is questionable owing to the MAVEN data gap, and moreover MSL/RAD data show a double-decrease structure, which indicates that this region might not be a simple stream interface region.

Region 5 is again characterized by an expanding speed profile; the plasma beta is not low at the very start of the region but drops later. In the second part, where the MAVEN data are more consistent, the magnetic field components show a relatively smooth profile, although the magnetic field strength is not really elevated. These are characteristics similar to CME2 identified in ST-A. Finally, in region 6 we observe elevated temperature and speed, which are the typical HSS signatures.

We note that the whole period encompassing in situ regions 1–6 corresponds to a single, long-duration multistep FD, where different regions (i.e., substructures) correspond to different steps of the FD. The unusually large FD amplitude might therefore be related to the complexity of the event, where different steps add up into a single global FD, as suggested by some previous studies (e.g., Papaioannou et al. 2010; Dumbović et al. 2016).

# 3. Results

# 3.1. Preconditioning of the Heliospheric Background

In order to analyze and understand the propagation and interaction of CMEs 1 and 2, it is imperative to analyze and understand the heliospheric background. For that purpose we check the remote ST-A observations prior to CME 1 and 2 eruptions to identify any relevant coronal holes (CHs) and/or CMEs that might act to precondition the interplanetary space. As can be seen in Figure 1(d), there is a CH passing the central meridian as seen from ST-A on the day of the eruptions (CH1; see Figure 4(a)). Visually, the CH area crossing the central meridian slice does not appear very large, and thus we do not expect the corresponding HSS to be very fast (Nolte et al. 1976; Vršnak et al. 2007; Tokumaru et al. 2017; Hofmeister et al. 2018). Therefore, it might be likely that the two CMEs "catch up" with the SIR corresponding to CH1, which might influence their propagation. We observe another possibly relevant CH that is at the time of the eruption behind the eastern limb as viewed from ST-A (CH2; see Figure 4(b)). CH2

is "trailing" the eruption site; however, due to its proximity to the AR, it might interact with the eruptions through interchange reconnection (e.g., Crooker et al. 2002). In Figure 4 CH1 and CH2 are shown at the time crossing the central meridian as observed from ST-A, where their corresponding area is extracted using a thresholding technique based on the study by Heinemann et al. (2018a, 2018b). The CH area values are presented in Table 1 for both CHs. CH2 consists of the top and bottom part; therefore, we present three area calculations: for the top part only, for the bottom part only, and for both (full). In addition, based on the calculated area, we calculate the peak speed of the associated solar wind using the CH area-SW speed relations given by Nolte et al. (1976) and Tokumaru et al. (2017), as well as the latitude-dependent CH area—SW speed relation by Hofmeister et al. (2018). These are also presented in Table 1. It can be seen that the HSS originating from CH1 is most probably slower than CMEs 1 and 2; hence, a kinematical interaction between them is likely. It can also be seen that CH2 is expected to yield a faster stream than CH1; therefore, although the angular separation between the two is roughly 90°, if undisturbed we would expect the time difference between two corresponding SIRs to be <7 days.

In Section 2 we noted that, in addition to CMEs 1 and 2, we observed two more CMEs that have a position angle relating to the Mars direction. These two CMEs (marked as CME0.1 and CME0.2) erupted from the same AR on 2017 July 20 and might therefore be important for preconditioning of the interplanetary space (Temmer & Nitta et al. 2015; Temmer et al. 2017), especially in the direction of Mars. In Figure 5 we present the GCS reconstruction of these two CMEs. CME0.1 starts with loop motions observed at the east limb in the ST-A EUVI 195 Å, followed by the CME observed in COR1 at 13:25 UT. The CME appears in the ST-A/COR2 and LASCO/C2 FOV at 14:35 and 15:48 UT, respectively, and appears to be moving linearly with a speed of about  $300 \text{ km s}^{-1}$ . It is a very faint CME and is not observed in LASCO/C3. The first signatures of CME0.2 are very similar, with similar loop motions close to the same AR as CME0.1, followed by a CME detection by COR1 at 17:50. The CME appears in the ST-A/ COR2 at 19:10 UT, in LASCO/C2 at 18:24 UT, and in LASCO/C3 at 19:30 UT. CME0.2 decelerates in LASCO/C3 and has a highly distorted "wavy" leading edge, reaching a speed of around  $600 \text{ km s}^{-1}$  at approximately  $20 R_{\odot}$ . The interaction of the two CMEs is very likely, but their main propagation direction is oriented more toward STEREO-B. Therefore, we conclude that the interplanetary space will not be affected by the two CMEs in the ST-A direction, but there might be some preconditioning in the Mars direction.

# 3.2. CME Propagation

In Figure 6(a) a 2D representation of CME 1 and 2 widths and directions in the HEEQ<sup>11</sup> system is shown, as obtained from the GCS reconstruction. It can be seen that if we assume that the direction and the geometry do not change, CME1 is not expected to hit ST-A. Furthermore, CME1 in situ signatures at ST-A indicate lack of expansion, whereas at Mars there are expansion signatures, indicating that CME2 is "pushing" CME1 much stronger in the ST-A direction than in the Mars direction, i.e., that the CME2 apex is directed closer to ST-A than Mars. As will be shown in the next section, the

<sup>&</sup>lt;sup>11</sup> Heliocentric Earth Equatorial.





Figure 4. (a) CH1 and (b) CH2 in EUVI/ST-A 195 Å crossing the central meridian as observed from ST-A July 23 and 29, respectively. The red contours outline the CHs, and the yellow cross marks the center of mass of the CH. The arrow points to AR 12665, which is the source region of CMEs 1 and 2.

propagation/evolution modeling of the CMEs gives reasonable results supporting that CMEs 1 and 2 are deflected toward ST-A by 15° and 20°, respectively. We might consider CH2 (see Figure 4(a)) as a potential deflection source, as it lies just east of the AR and deflection by  $15^{\circ}-20^{\circ}$  would not be an unusual value given its proximity to the CME source regions (see, e.g., Gopalswamy et al. 2009). However, the deflection by CHs usually occurs at lower heights, within a couple solar radii, where we would expect to observe it already in coronagraphs (e.g., Kay et al. 2013), and therefore the deflection of CMEs 1 and 2 at heights  $>15 R_{\odot}$  due to CH2 is not likely. Another possible explanation is the deflection in the interplanetary space due to CME-CME interaction (Gopalswamy et al. 2001). CME1 might also be deflected owing to interaction with CME2 similarly, as it would be expected that slow CMEs are deflected toward the west when moving in a fast solar wind (Wang et al. 2004, 2014); however, even considering that the momentum of CME1 is not negligible compared to CME2, this cannot easily explain the deflection of CME2. Finally, one should not forget the limitations of the observational methods, where a  $10^{\circ}$  error in the CME direction is not unusual (Mierla et al. 2010). We also note that CME2 is a complex CME, which also might influence the determination of the direction. Based on these considerations, as well as modeling attempts/efforts, for the purpose of analysis of CME propagation, evolution, and their interaction, we can assume that the directions of CMEs 1 and 2 in the HEEQ system are changed with respect to the ones obtained by the GCS reconstruction (see Table 2 and Figure 6(c)).

Figure 6(b) shows the CME 1 and 2 early kinematics, as obtained by the GCS reconstruction. The measured kinematic curves of CME 1 and 2 apexes are given in a distance–time plot, where an error of 5% was assumed. It can be seen that measured 3D kinematics is in both cases represented well by motion with constant speeds of 950 and 2700 km s<sup>-1</sup>, respectively. To estimate the CME speed at the inner boundary

for the propagation models used in Sections 3.2.1 and 3.2.2 (20 and  $21.5 R_{\odot}$ , respectively) we extrapolate GCS-obtained kinematics assuming constant speed.

The angular extent of CMEs 1 and 2 in the equatorial plane was estimated as  $\omega_{\text{max}} - (\omega_{\text{max}} - \omega_{\text{min}}) \times |\text{tilt}|/90$ , where  $\omega_{\rm max}$  and  $\omega_{\rm min}$  are face-on and edge-on widths according to Thernisien (2011) and the tilt is the angle of the croissant axis with respect to the equatorial plane. This method was used previously to estimate the CME half-width with the assumed cone geometry by Dumbović et al. (2018b) and Guo et al. (2018a) and takes into account CME tilt, but not the latitude. Therefore, to cross-check the validity of this method, we in addition estimate the CME opening angle using the ecliptic cut of the GCS reconstructions,<sup>12</sup> obtaining a similar result (within  $\pm 5^{\circ}$ ). For the purpose of simulating an elliptical cross section of the cone, which is needed for numerical simulations shown in Section 3.2.2, the method is adapted to calculate the major and minor axis obtaining  $r_{\min} = 23^{\circ}$  and  $r_{\max} = 38^{\circ}$  for CME1 and  $r_{\min} = 22^{\circ}$  and  $r_{\max} = 40^{\circ}$  for CME2. All initial CME parameters used as an input for propagation models, as well as GCS reconstruction parameters, are given in Table 2. We note that GCS reconstruction was performed separately for COR1 and COR2, but for the purpose of heliospheric propagation COR2 reconstruction was used (see Section 2.1 for details). CMEs 0.1 and 0.2 are included in Table 2, as their input was used for simulations in Section 3.2.2.

#### 3.2.1. Drag-based Model (DBM)

We model the kinematics of CMEs 1 and 2 separately for the ST-A and Mars directions using the DBM (Vršnak et al. 2013) adapted for the cone geometry (Žic et al. 2015). The initial CME parameters are based on the GCS reconstruction (see Table 2), whereas the parameters used to describe the effect of

 $<sup>\</sup>frac{12}{12}$  This method takes into account both the latitude and the tilt, but the estimation is performed by the observer and is therefore somewhat subjective.

 Table 1

 CH Area Values and Peak Speed of the Associated Solar Wind Calculated Using the CH Area—SW Speed Relation from Different Studies

	CH1	CH2 (Top)	CH2 (Bottom)	CH2 (Full)
$A (10^{10} \text{km}^2)$	$4.8\pm0.3$	$1.28\pm0.05$	$5.3\pm0.4$	$6.5\pm0.5$
$v \text{ (km s}^{-1}\text{)} \text{ (Hofmeister et al. 2018)}$	$552 \pm 4$	$505 \pm 1$	$588 \pm 9$	$630\pm10$
$v (\text{km s}^{-1})$ (Tokumaru et al. 2017)	$476^{+5}_{-3}$	$462 \pm 3$	$477^{+7}_{-3}$	$483^{+7}_{-3}$
$v  (\text{km s}^{-1})$ (Nolte et al. 1976)	$790^{+60}_{-10}$	$525^{+15}_{-7}$	$810^{+80}_{-20}$	$910^{+90}_{-20}$

the ambient solar wind are taken to be different in the two directions. In the ST-A direction we assume that there is no influence on the CME kinematics by the previous two CMEs (CME0.1 and 0.2) and therefore assume the "standard" drag for CME1 ( $\gamma = 0.2 \times 10^{-7} \text{ km}^{-1}$ ; see Vršnak et al. 2013, 2014). For CME2 we estimate a reduced drag ( $\gamma = 0.1 \times 10^{-7} \text{ km}^{-1}$ ) caused by preconditioning of the IP space due to CME1. We use a "standard" solar wind speed for both CMEs in the ST-A direction (400 km s<sup>-1</sup>; see Vršnak et al. 2014; Dumbović et al. 2018a). The solar wind speed observed in situ before the arrival of the CMEs at ST-A is somewhat higher  $(500 \text{ km s}^{-1})$ ; however, we note that the ambient solar wind speed used by DBM corresponds to the solar wind the CME moves through, and therefore it does not necessarily correspond to the in situ speed measured before the ICME. On the other hand, the observed solar wind speed after the CME passage, which might be a better proxy for the ambient solar wind speed, is  $\sim 400 \, \mathrm{km \, s^{-1}}$ 

In the Mars direction we assume that the drag parameter for CME1 is lower than the "standard" value of  $\gamma = 0.2 \times$  $10^{-7}$  km<sup>-1</sup>, due to preconditioning by previous CMEs (CMEs 0.1 and 0.2) that "cleared the path," similar to Rollett et al. (2014). Based on the in situ observations by MAVEN and MSL/RAD, but also based on the GCS-related estimates of directions and angular extent of CMEs 0.1 and 0.2, we do not expect their interaction with CMEs 1 and 2 in the Mars direction. However, we find it likely that their propagation partly influences the ambient solar wind through which CMEs 1 and 2 propagate on their way to Mars. Therefore, we estimate a somewhat lowered drag for CME1 ( $\gamma = 0.15 \times 10^{-7} \text{ km}^{-1}$ ) and reduced drag for CME2 ( $\gamma = 0.1 \times 10^{-7} \text{ km}^{-1}$ , as assumed for the ST-A direction). In the Mars direction we initially use the same solar wind speed as in the ST-A direction; however, we note that much better results are obtained with an estimated speed of  $500 \text{ km s}^{-1}$ . We note that solar wind speed observed in situ before the arrival of the CMEs at Mars is somewhat lower  $(350 \text{ km s}^{-1})$ ; on the other hand, the observed solar wind speed after the CME passage is  $\sim 600 \text{ km s}^{-1}$ .

We model CMEs 1 and 2 separately and obtain their DBM kinematical curves for the ST-A and Mars directions. For each direction we estimate the interaction point for the two CMEs based on the condition that the two kinematical curves cross each other. We note that physically this is highly idealized because we implicitly assume that the CME is fully represented with an infinitesimally thin leading edge. Nevertheless, the procedure provides a quick and simple estimate of the interaction point, whereas any idealizations can be regarded as introducing an uncertainty in the timing. A similar procedure was used by Guo et al. (2018a), where the interaction point was derived based on the kinematical curves for the apexes of the corresponding CMEs assuming that all CME leading edge segments interact at the same time. Here the angular separation

of the CME apexes is too large, and thus we allow that the interaction of different segments can occur at different times. We find that the interaction occurs almost immediately after the CME 2 launch by DBM, at 18.2 and  $26 R_{\odot}$  in the ST-A and Mars directions, respectively.

We assume that the momentum is conserved during the interaction and that after the interaction the two CMEs continue to propagate as a merged entity, similar to Temmer et al. (2012) and Guo et al. (2018a). The direction of the merged entity is presumably defined by the direction of the faster CME (which "drives" the whole entity), whereas the width is determined by the angular extent of the wider CME. The mass of the merged entity is given as the sum of masses of the two CMEs, where we assume that both CMEs have comparable masses. We note that this is a somewhat arbitrary mass estimation because we do not actually measure the CME mass. On the other hand, we note that both CMEs are quite bright and interact very close to the Sun; therefore, mass measurements might very likely have large uncertainties, and moreover we are only interested in the mass ratio. With these assumptions, DBM can be recalculated for the merged entity, where the initial speed is given by the momentum conservation and the new drag parameter is recalculated as  $\gamma_{1+2} = \gamma_1 M_1 \sin^2 \omega_{1+2} / [(M_1 + M_2) \sin^2 \omega_1],$ where  $M_1$  and  $M_2$  are masses of CME 1 and 2,  $\omega_1$  and  $\omega_{1+2}$  are half-widths of CME 1 and merged entity, and  $\gamma_1$  is the drag parameter of CME 1 (calculation based on Equation (2) in Vršnak et al. 2013). Note that the recalculated drag parameter is different in the ST-A and Mars directions, as is the solar wind speed. The kinematic curves for the interacting CMEs are plotted in Figure 6(d). The estimated arrival time at ST-A is July 24 at 20:30 UT with an arrival speed of  $690 \,\mathrm{km \, s^{-1}}$ , whereas the measured arrival time is July 24 23:00 UT with an arrival speed of  $660 \text{ km s}^{-1}$ . The estimated arrival time at Mars is July 26 at 04:00 UT with an arrival speed of 680 km s<sup>-1</sup> whereas the measured arrival time is July 26 02:00 UT with an arrival speed of  $700 \text{ km s}^{-1}$ .

In addition, we perform an ensemble run of the drag-based model (DBEM; Dumbović et al. 2018a), where the ensemble input is produced manually based on the standard DBM input as obtained from GCS reconstruction using the method described by Dumbović et al. (2018a). DBEM is not suitable to take into account CME-CME interaction; therefore, we regard only the merged entity as derived by DBM. We produce 48 CME ensemble members separately for the ST-A and Mars directions for the merged entity based on the input used in DBM assuming error ranges of 1 hr for the start time,  $200\,km\,s^{-1}$  for the initial speed, and  $10^\circ$  for longitude and width, whereas we use 15 synthetic values for solar wind speed and drag parameter assuming error ranges of  $0.05 \times 10^{-7}$  km<sup>-1</sup> and  $50 \,\mathrm{km \, s^{-1}}$ , respectively. In the ST-A direction DBEM predicts a 100% arrival probability with likeliest arrival time (median) at July 24 21:30 UT and a spread of  $\pm 4.5$  hr, whereas

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Figure 5. GCS reconstruction of two CMEs that erupted on 2017 July 20 and precondition the interplanetary space: (a) a narrow, faint, and slow CME0.1 directed between Mars and *STEREO-B*; (b) a wider, brighter, and faster CME0.2 directed toward *STEREO-B*. Parameters of the two CMEs are given in Table 2.

the likeliest arrival speed is  $690 \text{ km s}^{-1}$  with a spread of  $-80 \text{ km s}^{-1}/+110 \text{ km s}^{-1}$ . In the Mars direction DBEM also predicts 100% arrival probability with likeliest arrival time (median) at July 26 06:00 UT and a spread of -7.5 hr/+7 hr, whereas the likeliest arrival speed is  $670 \text{ km s}^{-1}$  with a spread of  $-60 \text{ km s}^{-1}/+80 \text{ km s}^{-1}$ . In both cases the observed arrival times and speeds are within the predicted spread. Given the usual forecast errors for CME propagation (e.g., Dumbović et al. 2018a; Riley et al. 2018; Wold et al. 2018, and references therein), this is a reasonable agreement with the observations. Therefore, based on the DBM/DBEM results, we conclude that it is highly likely that both CMEs interact close to the Sun, they arrive "together" at ST-A and Mars, and the ambient solar wind through which CMEs propagate is different in the ST-A and Mars directions. There are indications that two previous CMEs precondition the IP space in the Mars direction, lowering the drag, and, moreover, that in the Mars direction CMEs propagate through higher-speed solar wind than in the ST-A direction.

#### 3.2.2. WSA-ENLIL+Cone Simulation

We perform a WSA-ENLIL+Cone heliospheric simulation (Odstrcil 2003; Odstrcil et al. 2004, 2005), which is available through the Runs-on-Request system of the Community Coordinated Modeling Center (CCMC<sup>13</sup>). The runs consider not only the merging CMEs 1 and 2 but also the preconditioning CMEs 0.1 and 0.2 and are based on the initial parameters given in Table 2. They are based on National Solar Observatory /GONG magnetogram synoptic maps with a boundary condition type of time-independent single daily update. We note that there is an existing run published by Luhmann et al. (2018); however, since the focus of their study are SEPs, they do not consider CMEs 0.1 and 0.2. The input is based on GCS, similar to that for DBM, adapted for ENLIL (cone elliptical

cross section). The simulation is available at https://ccmc.gsfc. nasa.gov/database\_SH/Manuela\_Temmer\_112618\_SH\_1.php and selected timeframes are represented in Figure 7.

The simulation reveals that CMEs 0.1 and 0.2 already merge close to the Sun and practically move as one entity, which is a bit slower in the Mars direction compared to STEREO-B and does not arrive at STEREO-A. CMEs 1 and 2 also merge quite close to the Sun and "pick up" CMEs 0.1 and 0.2 in the Mars direction. However, it can be seen that the fastest part of the merged CME1 + 2 entity is directed toward STEREO-A and not Mars, probably due to the longitudinal direction of the much faster CME 2 (150°). The predicted arrival time of the disturbance at ST-A is July 24 around 12:00 UT, which fits very well with observation (July 24 around 13:00 UT; see region 1 in Figure 3, left panel). The predicted arrival time of the disturbance at Mars is July 26 around 15:00 UT, which is almost 1 day later than the observed shock arrival (July 25 around 17:00 UT; see region 2 in Figure 3, right panel). In addition, we perform an ENLIL ensemble run (Mays et al. 2015), where the ensemble input is produced manually based on the standard ENLIL input as obtained from GCS reconstruction using the method described by Dumbović et al. (2018a). The input is slightly different from that for DBEM, because for DBEM we produced a unique ensemble based on the merged entity parameters, whereas for ENLIL we produced an ensemble input (24 ensemble members) for each of the four CMEs separately. The full input and the results of the run are available at https://iswa.gsfc.nasa.gov/ENSEMBLE/ 2017-07-20 ncmes4 sims23 HILOX069/. In the ST-A direction the simulation predicts a 100% arrival probability with a median input arrival time at July 24 10:30 UT, an average arrival at July 24 11:20 UT, and a spread of -6 hr/+18.5 hr. In the Mars direction the simulation predicts only 61% arrival probability with a median input arrival time at July 26 06:00 UT, an average arrival at July 26 02:00 UT, and a spread of -14 hr/+6.5 hr, i.e., the observed arrival time is within the

<sup>&</sup>lt;sup>13</sup> https://ccmc.gsfc.nasa.gov/requests/requests.php



Figure 6. CME directions and kinematics obtained by GCS reconstruction and drag-based model (DBM): (a) 2D representation of CME 1 and 2 half-widths and directions in the HEEQ system as obtained from GCS reconstruction (the red and blue arrows mark the IP direction of CMEs 1 and 2, respectively, whereas differently colored arcs provide the angular extent of a corresponding CME); (b) GCS-reconstructed kinematics of the CME1 and CME2 apexes; (c) 2D representation of CMEs 0.1, 0.2, 1, and 2 half-widths and directions in the HEEQ system as used in modeling (the red, blue, magenta, and green arrows mark the IP direction of CMEs 1, 2, 0.1, and 0.2, respectively, whereas differently colored arcs provide the angular extent of a corresponding CME); (d) DBM-obtained kinematics of the interacting CMEs (the merged CME1+2 structure) in the ST-A and Mars directions.

predicted spread. We note that the low hit probability is most likely related to the underestimated longitudinal spread. It is important to highlight that we used CME (magnetic structure) input for the simulations, whereas ENLIL simulates the evolution/propagation of the density disturbance and is therefore more suitable for simulation of the shock. The shock can have a larger spatial extent than the magnetic structure of CME 2, be driven closer to the Mars direction, and not be significantly influenced by July 20 CMEs. However, in our study we are more interested in the qualitative description of the CME 1 and 2 interaction than accurate CME 2 shock propagation; therefore, we do not attempt to obtain a better arrival time match by introducing the shock-related input.

For a better qualitative analysis of the events observed at ST-A and Mars, we use the ENLIL multiple block runs. The multiple block runs allow us to see how the simulation results change by consecutively adding CMEs in the simulation. The first run describes the ambient medium, without any CMEs; the second run includes the first CME of July 20 (marked as CME0.1); the third run includes both the first (CME0.1) and the second CME of July 20 (marked CME0.2); the fourth run includes both CMEs of July 20 and CME1; and finally, the last run includes all four CMEs. The performed multiple block runs are available as separate synthetic in situ profiles at different targets in the output files of the simulation. In Figures 8 and 9 ENLIL multiple block-run results are shown for heliospheric positions corresponding to ST-A and Mars, respectively. From top left to bottom right different panels show runs starting from no CMEs to inclusion of all four CMEs (as described above), where the last panel shows in situ measurements on the same timescale.

Two sector boundaries are observed in the multiple blockrun plots in Figure 8. The first one corresponds to the SIR originating from the CH observed to pass the central meridian (as seen from Earth) around July 5 and very likely corresponds to CH1 analyzed in Section 3.1. The second one corresponds to the SIR originating from the CH eastward of the AR from which CMEs 1 and 2 originate, which is observed to pass the central meridian (as seen from Earth) around July 13 and very likely corresponds to the CH2 analyzed in Section 3.1. It can be seen that inclusion of two CMEs that preceded CMEs 1 and 2 does not impact the in situ observations at ST-A. Furthermore,

 Table 2

 CME Parameters Obtained from GCS Reconstruction (a) and Used for Heliospheric Propagation (b)

				1 10 0	
	CME1	CME2 (COR1)	CME2 (COR2)	CME0.1	CME0.2
(a) GCS Reconstruction	Parameters				
Longitude (deg)	170	185	190	150	117
Latitude (deg)	10	-7	-17	-5	-6
Tilt (deg)	-5	15	0	-25	-37
Aspect ratio	0.35	0.5	0.9	0.27	0.35
Half angle (deg)	25	60	10	20	30
(b) Initial Parameters for	r Heliospheric Propagation				
Longitude (deg)	-175		-150	150	117
Latitude (deg)	10		-10	-5	-6
Half angle (deg)	44		74		
r <sub>min</sub> (deg)	23		22	20	23
$r_{\rm max}$ (deg)	38		40	32	38
Start date and time	2017 Jul 23 05:20		2017 Jul 23 06:00	2017 Jul 21 01:00	2017 Jul 21 02:30
Speed (km s <sup>-1</sup> )	950		2700	300	600

it can be seen that in a full suite run (CME0.1+CME0.2 +CME1+CME2) there is a qualitative agreement with the observed in situ double-CME signatures. Moreover, the simulation indicates that SIR1 is "squeezed" in the sheath region of CMEs 1 and 2. Although this cannot be confirmed by in situ measurements owing to the data gap, we note that we do not find SIR1 signatures in front of CMEs 1 and 2. We also note that the complete lack of an expanding profile of CME1 also indicates that there might be a structure in front of it, inhibiting its expansion, with SIR1 being the only candidate to explain this. Therefore, we argue that it is indeed possible that the SIR1 is "squeezed" in the sheath region of CMEs 1 and 2, as the simulation indicates. The timing of the second sector boundary roughly corresponds to the observed SIR signatures between DOY 211 and 212, likely originating from CH2.

In Figure 9 again two sector boundaries can be observed in the ENLIL multiple block runs, corresponding to the same CH as the ones observed in Figure 8. However, it can be seen that in the Mars direction the first SIR reaches Mars before it interacts with CMEs 1 and 2 and roughly corresponds with the timing of the SIR signatures observed in region 1 in Figure 3. On the other hand, according to the simulation SIR2 is strongly affected by CMEs. It can be seen that inclusion of CME0.1 and CME0.2 impacts in situ observations at Mars, but their signatures are entirely lost in a full suite run. This indicates that CME0.1 and CME0.2 affect the ambient solar wind, but we would not expect to see their significant impact at Mars. Furthermore, in a full suite run we observe SIR2 being "squeezed" between CMEs 1 and 2, which seems to be in contradiction with the fact that CH2 is trailing the AR and that the two CMEs merge already in the corona. While this might be an artifact related to the fact that ENLIL runs do not involve magnetic structures (CMEs are introduced as pressure pulses), it is important to note that the SIR signatures are indeed observed in the MAVEN data between the two CMEs, with the timing roughly corresponding to SIR2 from simulations. A possible explanation is that an interchange reconnection occurs between the open field lines of CH2 and the leg of CME1 (similar to that described by Crooker et al. 2002). This might result in open field lines of both CME1 and the nearby CH2 (see the northern part of CH2 in Figure 4(b)) being caught between CMEs 1 and 2, producing SIR-like signatures between the two CMEs. This would lead to SIR-like signatures observed at

Mars, but also at ST-A, where we do indeed find SIR signatures. However, the latter is not expected from the ENLIL simulation.

We want to emphasize that the quantitative correspondence between synthetic in situ measurements of the ENLIL multiple block runs and real in situ measurements by MAVEN and ST-A is quite poor (e.g., magnetic field at ST-A is 4 times weaker in the simulation). On the other hand, we find that the multiple block runs in synergy with the in situ measurements are very insightful in understanding the "chronological" order of substructures observed in situ.

# 3.3. CME Evolutionary Properties

In order to analyze how CME1 evolves, i.e., how the size and the magnetic field change with heliospheric distance, we compare the initial FR properties (obtained from GCS) with in situ measured properties at ST-A and Mars. For that purpose, we estimate the initial radius of the flux rope based on the last time step of the performed GCS reconstruction, which is taken as the initial time of the FR evolution. The radius of the FR obtained from the GCS reconstruction is different across the FR -it is largest at the apex and smallest at the flanks. Based on the direction of CME1 and the relative positions of the spacecraft, as the starting radius in the Mars direction we take the apex radius and in the ST-A direction we take the flank radius, and we assume a 5% error (see Table 3). Based on the start time and the observed in situ arrival time, we calculate the transit time to ST-A and Mars and assume  $\pm 1h$  error. The final radius of the FR at ST-A was obtained based on the FR orientation and impact parameter obtained from the Lundquist fitting (Lundquist 1951; Leitner et al. 2007), according to the method described by Vršnak et al. (2019). At Mars we estimate the radius assuming that the spacecraft passes the FR vertically with respect to the FR axis using the expanding profile of plasma flow speed. The error of the radius is determined via error propagation assuming SW speed and FR duration errors of 5%. The central axial field strength at ST-A is obtained from the Lundquist fitting, whereas at Mars we estimate it based on in situ measurements assuming that it corresponds to the maximum measured value (note that there is a data gap at the start of the ICME; therefore, the maximum is around ICME center). In both cases we assume an error of 1 nT, which is around 15% for Mars, but we note that, due to the MAVEN



Figure 7. Selected time frames of the ENLIL simulation: (a) quiet time and (b) propagation phase, where the first propagating disturbance represents the merged CME0.1 and 0.2 entity (CME0.1+0.2) and the second represents the merged CME 1 and 2 entity (CME1+2). SIR1 and SIR2 are approximately highlighted at the density change by a magenta dashed line. SIR2 is disconnected before and after the CMEs in panel (b).

data gap at the front of the CME, it is reasonable to assume larger error. Using these in situ values, we calculate the axial magnetic flux of the flux rope using Equation (52) from DeVore (2000) derived for Lundquist solution FR,  $\Phi_{FIN} =$  $1.4B_{c,FIN}a_{FIN}^2$ , where  $B_c$  is the central axial field strength. The obtained flux values at Mars and ST-A are different (see Table 3), indicating different evolution in two different directions of propagation. Note that the result shown in Table 3 is closely related to the assumption of the Lundquist solution, whereas considering different sets of assumptions might yield that the factor of 2 difference in the flux is not significant.

Assuming that the FR radius *a* is expanding self-similarly following a power law,  $a = a_0 (R/R_0)^{n_a}$  (see, e.g., Démoulin et al. 2008; Gulisano et al. 2012; Vršnak et al. 2019), the power-law index  $n_a$  can be derived using the initial and final distance/FR radius. We note that  $n_a = 1$  indicates an isotropic self-similar expansion, whereas  $n_a < 1$  and  $n_a > 1$  could indicate a weaker or stronger expansion, respectively, as the observational studies roughly constrain  $n_a$  to  $0.45 < n_a < 1.14$ (e.g., Bothmer & Schwenn 1998; Leitner et al. 2007; Gulisano et al. 2012; Vršnak et al. 2019). Using the values presented in Table 3, we calculate the power-law index  $n_a$  in the ST-A and Mars directions separately, allowing that the FR expands differently in two different directions. The errors are calculated by estimating the upper and lower power-law curves based on the error bars of the data points (for a more detailed description see Vršnak et al. 2019). We observe that  $n_a$  is much smaller in

the ST-A direction than the Mars direction, indicating that radial expansion is much weaker in the ST-A direction, in agreement with in situ observation.

Self-similar expansion of the FR is also related to the drop in the magnetic field, which can also be described via power law,  $B = B_0 (R/R_0)^{-n_B}$  (see, e.g., Démoulin et al. 2008; Gulisano et al. 2012; Vršnak et al. 2019). We note that  $n_B = 2$  indicates an isotropic self-similar expansion, but observations constrain it to  $0.84 < n_B < 2.19$  (e.g., Gulisano et al. 2012; Vršnak et al. 2019, and references therein). Deriving the power-law index  $n_{R}$ is not trivial because we do not know the initial central magnetic field strength. For that purpose, we use the ForbMod model (Dumbović et al. 2018b), which describes the interaction of GCRs and a flux rope during its propagation and evolution in the heliosphere. The model assumes that the FR is initially empty of GCRs, expands self-similarly, and fills up slowly with GCRs that diffuse into it. As a result, after a certain time the FR will be partly filled with particles, and consequently GCR observation will show a drop during the FR passage, i.e., an FD. The FD amplitude at a specific heliospheric distance therefore depends on the expansion rate of the FR and the diffusion rate (i.e., diffusion coefficient) and is given by an analytical expression (for a detailed description of the model see Dumbović et al. 2018b). Using the measured FD amplitude and with several simple assumptions, we can use the model to estimate the initial central magnetic field strength. First, we assume that the observed FD amplitude can be associated with particles of a relatively narrow specific energy range, i.e., that



**Figure 8.** ENLIL multiple block-run results for ST-A for quiet-time ambient (without any CMEs; top left panels); inclusion of CME0.1 (top middle panels); inclusion of CMEs 0.1 and 0.2 (top right panels); inclusion of CMEs 0.1, 0.2, and 1 (bottom left panels); a full suite run with CMEs 0.1, 0.2, 1, and 2 (bottom middle panels); and in situ measurements by ST-A/PLASTIC (bottom right panels). The panels in each block correspond to (top to bottom) (1) total magnetic field strength, (2) magnetic field strength of three components of the magnetic field, (3) plasma density and temperature, and (4) plasma velocity and beta parameter. The magnetic field components of the ENLIL runs correspond to the RTN coordinates of the HEEQ system, whereas for the ST-A they correspond to RTN coordinates with radial component defined by the Sun–spacecraft line. (DOY = day of year 2017.)

MSL/RAD is mostly sensitive to particles of certain energy. We note that this a somewhat arbitrary assumption because MSL/RAD measurements have contributions from different particles, i.e., radiation sources, including both primary and secondary GCRs, electrons, etc. Nevertheless, MSL/RAD measurements were found to be a very useful proxy for GCRs, especially regarding FD measurements (Guo et al. 2018b). The Martian atmosphere shields away lower-energy GCRs (<150 MeV, i.e., 0.55 GV) and modifies incoming GCR spectra so that higher-energy particles are less modulated (Guo et al. 2018b). On the other hand, the interplanetary GCR spectrum drops very fast with rigidities above 1 GV; thus, it is reasonable to assume that MSL/RAD is mostly sensitive to particles around a certain energy. We use a particle transport model, the Atmospheric Radiation Interaction Simulator (AtRIS; Banjac et al. 2019), which was validated for MSL/ RAD by Guo et al. (2019), and estimate that MSL/RAD is mostly sensitive to particles of rigidity  $\sim 2.5$  GV. Second, we assume that the expression for the diffusion coefficient is governed by the power-law behavior owing to its relation to the magnetic field (i.e.,  $D \sim 1/B$ ) and that it is scaled to the radial perpendicular diffusion coefficient at Earth as given in Potgieter (2013). With these assumptions, and fitting the model to observations (see Figure 3, right panel), it is possible to estimate  $n_B$  in the Mars direction (see Equation (1) in Rodari et al. 2019)

and therefore make an order-of-magnitude estimation of the initial FR central magnetic field strength and flux.

We find that the magnetic field inside the FR drops faster in the Mars direction than in the ST-A direction, which is in agreement with in situ observations, where the magnetic field at ST-A is unusually strong compared to MAVEN. Namely, if we calculate the power-law index of the magnetic field drop,  $B = B_0 (R/R_0)^{-n_B}$ , using  $B_0$ ,  $R_0$  and B, R for ST-A and Mars, respectively,  $n_B = 3.3$  is obtained, which is much higher than observationally constrained values, indicating that the magnetic field drop rate is in fact different in the ST-A and Mars directions, as obtained from the *ForbMod* calculation.

Based on the self-similar expansion expressions and considering a Lundquist-type solution with a circular cross section, it can be seen that the axial magnetic flux rope can also be expressed by a power law as  $\Phi = \Phi_0 (R/R_0)^{-x}$ , where  $x = n_B - 2n_a$  denotes an expansion type (for x = 0 the flux is conserved, for x < 0 increased, for x > 0 decreased; see Dumbović et al. 2018b). Based on these considerations, we find that in both the ST-A and Mars directions x > 0, indicating that the axial flux of the FR is effectively reduced, possibly through erosion due to interaction. Assuming that the initial flux is the same in both directions, our results suggest that the axial flux might be reduced more efficiently in the ST-A direction than in



**Figure 9.** ENLIL multiple block-run results for Mars for quiet-time ambient (without any CMEs; top left panels); inclusion of CME0.1 (top middle panels); inclusion of CMEs 0.1 and 0.2 (top right panels); inclusion of CMEs 0.1, 0.2, and 1 (bottom left panels); a full suite run with CMEs 0.1, 0.2, 1, and 2 (bottom middle panels); and in situ measurements by MAVEN (bottom right panels). The panels in each block correspond to (top to bottom) (1) total magnetic field strength, (2) magnetic field strength of three components of the magnetic field, (3) plasma density and temperature, and (4) plasma velocity and beta parameter. The magnetic field components of the ENLIL runs correspond to the RTN coordinates of the HEEQ system, whereas for MAVEN they correspond to RTN coordinates of the MSO system, with the radial component defined by the Sun–Mars line. (DOY = day of year 2017.)

the Mars direction (Table 3); however, we note that the uncertainties are too large to make a more reliable conclusion.

## 4. Discussion and Conclusion

We study the solar and interplanetary sources of one of the biggest FDs observed by MSL/RAD on Mars on 2017 July 25. The analysis of in situ observations at ST-A and Mars presented in Sections 2.2 and 2.3 indicates that regions 3/ yellow and 5/red in Figure 3 correspond to two ICMEs, most likely CME1 and CME2. At both ST-A and Mars shock/sheath signatures are observed; however, in the ST-A direction there is a data gap in the shock/sheath region that hampers a reliable and unique interpretation of the in situ signatures within this region. At both ST-A and Mars an interaction region is observed between the two CMEs (region 4/orange in Figure 3); however, the interaction region is much longer/ broader at Mars compared to ST-A. Finally, at Mars an HSS signature is observed at the back of the second ICME (region 6/green in Figure 3), whereas such a region is not observed in ST-A. Combining the DBM results with the in situ signatures described in Sections 2.2 and 2.3, there are strong indications that regions 3/yellow and 5/red in Figure 3 correspond to CME1 and CME2 at ST-A and Mars, respectively. In addition, we do not observe in situ signatures of CMEs 0.1 or 0.2 at ST-A or Mars. Finally, we note that region 6 in Figure 3 (with

HSSs) supports the DBM result of CMEs propagating through higher-speed solar wind in the Mars direction.

The ENLIL simulations are in agreement with the DBM results and in situ interpretations of CMEs 1 and 2 corresponding to regions 3 and 5 at ST-A and Mars, respectively. Moreover, the simulations indicate that SIR1 is "squeezed" in front of CME1 in the ST-A direction, which might be in agreement with a very intense second part of the shock/sheath (region 2/blue) observed in Figure 3. However, due to the data gap in the in situ measurements, this cannot be confirmed. On the other hand, in the Mars direction SIR1 arrives shortly before CME1, corresponding to the stream interface signatures and a first decrease in RAD data observed in region 1/green in Figure 3.

The most likely source of SIR1 is a CH passing the central meridian of ST-A at the day of eruption (CH1; see Figure 4(a)). The simulation is also in agreement with the expansion profiles observed in situ at ST-A and Mars. In the ST-A direction CME1 is, according to the simulation, constrained between CME2 and SIR1 and thus should not expand notably, as is indeed observed. In the Mars direction, on the other hand, both the simulations and in situ measurements indicate that SIR1 is not "pushed" by CME1. Therefore, we might expect CME1 to expand more freely in the Mars direction, in agreement with the expanding profile observed in the in situ measurements. The analysis of the CME evolutionary properties further supports

 Table 3

 Flux Rope Initial (GCS), In Situ, and Evolutionary Characteristics

	ST-A	Mars
Start time	2017 Jul 23	2017 Jul 23 03:54 UT
	03:54 UT	
Start height, $R_0$	$15 R_{\odot}$	$15 R_{\odot}$
GCS radius, $a_0$	$(2.8\pm0.1)R_\odot$	$(3.9\pm0.2)R_\odot$
Final distance, $R(t)$	$208 R_{\odot}$	$352 R_{\odot}$
Transit time	$(43 \pm 1) hr$	$(70 \pm 1) hr$
In situ radius, $a_{\rm FIN}$	$(13 \pm 2) R_{\odot}$	$(48 \pm 5) R_{\odot}$
In situ central magnetic field strength, $B_{c,FIN}$	$(40 \pm 1) \text{ nT}$	$(7 \pm 1) \text{ nT}$
In situ magnetic flux, $\Phi_{\text{FIN}}$	$(5\pm1)\cdot10^{20}\ Mx$	$(1.1 \pm 0.3) \cdot 10^{21} \text{ Mx}$
Power-law radius expansion index, $n_a$	$0.58\substack{+0.07\\-0.08}$	$0.80\pm0.05$
FD magnitude		$(2.8 \pm 0.2)\%$
Power-law magnetic field expansion index, $n_B$	~1.8	~2.1
Expansion type, $x = n_B - 2n_a$	x > 0	x > 0
Initial central magnetic field strength, $B_0$	$\sim 0.05 G$	$\sim 0.05 G$
Initial axial flux, $\Phi_0$	${\sim}5\cdot10^{21}~Mx$	${\sim}5\cdot10^{21}~Mx$

Note.  $B_0$  and  $\Phi_0$  were modeled based on cosmic-ray data and are assumed to be the same for both directions (for a detailed explanation on the calculation see main text).

the interpretation that the expansion of CME1 is hindered in the ST-A direction, whereas it expands more freely in the Mars direction.

The most likely source of SIR2 is a horseshoe-shaped CH lying just next to the AR where CMEs 1 and 2 originate (CH2; see Figure 4(b)). The simulation shows how CMEs 1 and 2 "disconnect" SIR2 (see Figure 7), which partly becomes trapped between CMEs 1 and 2, whereas the HSS continues to stream out from CH2, propagating behind the two interacting CMEs in the ST-A direction. These simulation results are probably related to the fact that the simulations do not involve magnetic structures; on the other hand, they do agree with the in situ measurements showing SIR signatures between two CMEs at both ST-A and Mars. These specific CME-SIR-CME signatures could be related to the interchange reconnection (e.g., Crooker et al. 2002) of the CME1 leg with a nearby CH2, where the open field lines get "squeezed" between CMEs 1 and 2, whereas the majority of the HSS originating from CH2 propagates/corotates behind the CME2, lagging significantly behind CMEs in the ST-A direction, but not in the Mars direction.

Finally, we might consider the possible consequences such an extreme space weather event might have had if it had been Earth-oriented. In Figure 3 a very strong south-oriented  $B_z$  can be seen at ST-A, which could have produced a serious geomagnetic storm at Earth. Liu et al. (2019) calculated that it would cause a severe geomagnetic storm with a disturbance storm time index Dst < -300nT. We note that Liu et al. (2019) offered an alternative interpretation of the solar sources of the IP signatures observed by ST-A and Mars. They, however, also stress the complexity of the event, as well as preconditioning.

To summarize, based on the presented analysis, which combines multi-instrument and multispacecraft measurements,

as well as different modeling approaches, we find that peculiar in situ signatures at ST-A and Mars can be explained by CME-CME and CME-SIR interactions. In the ST-A direction the interaction inhibited the expansion of the first CME, thus resulting in MC signatures with an extremely high magnetic field strength and of extremely short duration. On the other hand, in the Mars direction CME-CME interaction accompanied by interaction with the ambient interplanetary plasma resulted in a complex, long-duration IP disturbance with many substructures, each of which added to the multistep FD, thus producing one of the biggest FDs ever detected on Mars. We underline that there is a highly speculative aspect of the proposed scenario, as it is based on the methods and models suffering from significant uncertainties. Hence, other scenarios explaining this complex event might also be considered. However, we note that despite the uncertainties, different methods and models used in this study overlap in the proposed scenario, making it the most plausible explanation of the complex events.

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