The Effect of Stream Interaction Regions on ICME Structures Observed in Longitudinal Conjunction

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Received 2020 November 1; revised 2021 May 21; accepted 2021 May 21; published 2021 July 23

Abstract

We study two interplanetary coronal mass ejections (ICMEs) observed at Mercury and at 1 au by spacecraft in longitudinal conjunction, investigating the question: what causes the drastic alterations observed in some ICMEs during propagation, while other ICMEs remain relatively unchanged? Of the two ICMEs, the first one propagated relatively self-similarly, while the second one underwent significant changes in its properties. We focus on the presence or absence of large-scale corotating structures in the ICME propagation space between Mercury and 1 au, which have been shown to influence the orientation of ICME magnetic structures and the properties of ICME sheaths. We determine the flux rope orientation at the two locations using force-free flux rope fits as well as the classification by Nieves-Chinchilla et al. We also use measurements of plasma properties at 1 au, the size evolution of the sheaths and magnetic ejecta with heliocentric distance, and identification of structures in the propagation space based on in situ data, remote-sensing observations, and simulations of the steady-state solar wind to complement our analysis. Results indicate that the changes observed in one ICME were likely caused by a stream interaction region, while the ICME exhibiting little change did not interact with any transients between Mercury and 1 au. This work provides an example of how interactions with corotating structures in the solar wind can induce fundamental changes in ICMEs. Our findings can help lay the foundation for improved predictions of ICME properties at 1 au.

Unified Astronomy Thesaurus concepts: Solar coronal mass ejections (310); Corotating streams (314); Heliosphere (711)

1. Introduction

Coronal mass ejections (CMEs) are large eruptions of plasma and magnetic field from the Sun (e.g., Webb & Howard 2012), observed to occur at a typical rate of 0.5–5 CMEs per day depending on the phase of the solar cycle (e.g., Lamy et al. 2019). They are observed by coronagraphs (Illing & Hundhausen 1985; Vourlidas et al. 2013) as they propagate away from the Sun into interplanetary space and are eventually probed in situ by spacecraft monitoring the conditions of the interplanetary medium, where they are termed interplanetary CMEs (ICMEs; e.g., Zurbuchen & Richardson 2006; Kilpua et al. 2017). CMEs consist of magnetically dominated (i.e., low-β) plasma that can be often described by a magnetic flux rope morphology, i.e., by a helical magnetic field wrapping around a central axis. At 1 au, ICMEs often present as an interplanetary shock followed by a sheath region of compressed solar wind material, and followed by the magnetic ejecta (ME; e.g., Richardson & Cane 2010; Kilpua et al. 2017; Jian et al. 2018), i.e., the magnetically dominated substructure. MEs are observed passing over Earth at an average rate of one to two per month (Richardson & Cane 2010), where together with their driven shocks and sheaths they are known to be one of the main causes of strong geomagnetic disturbances (e.g., Gosling et al. 1991; Zhang et al. 2007; Lugaz et al. 2016; Kilpua et al. 2017, 2019). In more recent years, studies of ICMEs as key space weather drivers throughout the heliosphere have shed light on their impact on planetary environments at heliocentric distances other than Earth, where the ICME characteristics are intrinsically different than at 1 au (e.g., Burlaga et al. 1982; Liu et al. 2005; Ebert et al. 2009; Winslow et al. 2015; Good & Forsyth 2016; Lee et al. 2017).

ICME properties are known to evolve during propagation in interplanetary space as they expand and interact with the solar wind and other transients therein (e.g., Manchester et al. 2017). The large-scale evolution of ICMEs propagating through interplanetary space is primarily shaped by two effects: the expansion of the ME, which controls its internal density, pressure, magnetic field magnitude, and size (e.g., Démoulin & Dasso 2009); and the interaction with the surrounding solar wind, which controls the ICME kinematic properties and is often described in terms of a drag force (Cargill 2004; Vršnak et al. 2010). As a result, ICME shocks and sheath regions are also the result of the interplay between ICME propagation and expansion (Kilpua et al. 2017). In this respect, ICMEs of differing coronagraph speeds have been observed to have different responses to interaction with the solar wind. It is thought that fast ICMEs go through a period of impulsive acceleration followed by rapid deceleration and finally propagation at a nearly constant speed, while slow ICMEs catch up to the solar wind speed (Liu et al. 2013).

Through observational and modeling work, studies have shown that during propagation, ICMEs undergo a number of changes, particularly as a consequence of the interaction with high-speed streams (HSSs), stream/corotating interaction regions (SIRs/CIRs), and the heliospheric current/plasma sheet (HCS/HPS) (e.g., Odstrčil & Pizzo 1999b, 1999c; Rodríguez et al. 2016; Winslow et al. 2016; Zhou & Feng 2017; Heinemann et al. 2019; Liu et al. 2019; Odstrčil & Pizzo 1999b, 1999c). Effects include kinks and deformations of the ICME flux rope magnetic structure (Manchester et al. 2004; Savani et al. 2011; Isavnin 2016), large-scale deformations of the ICME front convexity (Odstrčil & Pizzo 1999a; Riley et al. 2004), as well as local magnetic field distortions...
factors, including the limited number of assets available generally constrained by the combination of a number of structure at different heliocentric distances. Such studies are crossings through approximately the same portion of the ICME (The Astrophysical Journal, magnetic terms of missions and instruments continuous observations of the solar wind properties over a reconnection with the surrounding solar wind (e.g., Liu et al. 2014; Lugaz et al. 2017; Shen et al. 2017; Scolini et al. 2020).

The properties of ICME shocks and sheaths also evolve during propagation in interplanetary space (Janvier et al. 2019; Salman et al. 2020; Lugaz et al. 2020a, 2020b). Depending on the driver’s and downstream solar wind’s characteristics, their evolution may result in enhanced magnetic field amplitudes, increased magnetic turbulence, and the formation of planar magnetic structures, all of which are likely to increase the potential space weather impact of such structures with heliocentric distance (Lugaz et al. 2016; Palmerio et al. 2016; Kilpua et al. 2017; Good et al. 2020).

Direct observational studies of the radial evolution of ICMEs are intrinsically linked to our capability to perform high-quality in situ measurements of individual events via multispacecraft crossings through approximately the same portion of the ICME structure at different heliocentric distances. Such studies are generally constrained by the combination of a number of factors, including the limited number of assets available (in terms of missions and instruments); the requirement of continuous observations of the solar wind properties over a time window of hours to days, which are typically difficult to achieve in the case of planetary missions; and the need for appropriate spacecraft trajectories through the ICME structure, necessary to measure some of the ICME properties (e.g., their orientation) with a high degree of confidence. To overcome the scarcity of data, statistical studies have been proven to be extremely powerful in characterizing the overall trends affecting ICME evolution, most importantly in the case of ICMEs observed by multiple spacecraft in longitudinal conjunctions (Good et al. 2019; Salman et al. 2020). However, these kinds of studies only provide an average picture of the actual evolution of individual ICMEs, and—perhaps more importantly in the context of this work—they cannot dive deep into the analysis of individual events to determine the causes behind nonideal evolutionary behavior (recently reported by Lugaz et al. 2020b).

For this reason, studies focusing on individual ICME events observed by multiple spacecraft during periods of longitudinal conjunction are extremely insightful for our understanding of the various phenomena controlling the evolution of ICME magnetic structures. On the one hand, in situ studies by Good et al. (2015, 2018) of two ICMEs observed in perfect conjunction at Mercury and STEREO-B have showcased two events where the evolution of the large-scale flux rope magnetic field within the ICMEs remained essentially self-similar during propagation to 1 au, also in agreement with previous studies of longitudinal conjunction events in the outer heliosphere (e.g., Nakwacki et al. 2011). Similarities in the magnetic flux rope observations at different heliocentric distances had also been previously reported by Möstl et al. (2012) at Venus Express and STEREO-B, despite the ∼18° longitudinal separation between the spacecraft. On the other hand, not all ICMEs are observed to evolve self-similarly in interplanetary space. For example, an event study by Nieves-Chinchilla et al. (2012) using in situ observations from MESSENGER and Wind showed the first direct evidence of a significant reorientation of the ICME flux rope axis during propagation through the inner heliosphere, although there was a ∼20° longitudinal separation between the spacecraft. In Winslow et al. (2016), we also showcased an ICME flux rope observed in near-perfect longitudinal conjunction, which underwent a significant increase in ICME complexity as it propagated from Mercury to 1 au due to interaction/reconnection with the HCS/HPS. More recently, Kennedy et al. (2019) and Ohtani et al. (2019) reached somewhat opposite conclusions regarding the typical evolutionary behavior of ICMEs (i.e., ideal versus nonideal), based on the results of statistical analyses carried out over different sets of ICMEs observed in longitudinal conjunction.

The varied results from previous studies therefore raise the question: what causes some ICME structures, such as the flux rope and sheath, to change drastically during propagation, while in other ICMEs these stay relatively self-similar? More generally, what are the main drivers of increases in ICME complexity during propagation in the heliosphere? These past works and the considerations above highlight the need for more in-depth studies of ICME global changes from the innermost heliosphere to 1 au, in order to determine the causes of drastic alterations in ICME structures during propagation.

In this work, we tackle the questions above by conducting in-depth analyses of two ICME case studies, using in situ measurements at MESSENGER and spacecraft located near 1 au to investigate changes in the global ICME structure that may have occurred during propagation. We also use these observations to identify any intervening ICME, stream interaction region (SIR)/corotating interaction region (CIR), and HCS/HPS that might have affected the propagation of the ICMEs of interest. In addition, to place any observed changes in ICME properties during propagation in context, we simulate the background solar wind using the WSA-ENLIL model available for runs on request at the NASA Community Coordinated Modeling Center3 (CCMC), which enables improved identification of solar wind structures in the propagation space of the ICMEs under study.

This paper is structured as follows. In Section 2, we provide an overview of the methods used to investigate in situ plasma and magnetic field observations of ICMEs and their driven sheaths at different spacecraft and heliocentric distances. In Section 3, we present one case study ICME observed in almost perfect longitudinal conjunction at MESSENGER and ACE, and which exhibited little change in the magnetic and plasma properties during its propagation from Mercury’s to Earth’s orbit. On the other hand, in Section 4, we present a second case study ICME that, although having been observed by MESSENGER and STEREO-B at a longitudinal separation of ∼30°, exhibited significant changes in its internal and sheath properties between Mercury and 1 au that cannot be attributed to the longitudinal separation alone. We further compare the two cases and investigate the possible causes of the alterations observed in the second event. Finally, in Section 5, we discuss the main findings and present our conclusions.

3 https://ccmc.gsfc.nasa.gov
2. Methods: Flux Rope Orientation and Plasma Parameters

To investigate the ICME properties at 1 au, we use in situ magnetic field and plasma data from the magnetometer (MAG; Smith et al. 1998) and the Solar Wind Electron, Proton and Alpha Monitor (McComas et al. 1998) on board the Advanced Composition Explorer (ACE) mission (Stone et al. 1998), orbiting the Sun–Earth Lagrange 1 (L1) point; and in situ magnetic field and plasma data from the magnetometer (MAG; Acuña et al. 2008), the In situ Measurements of Particles And CME Transients (Luhmann et al. 2008), and the Plasma And Suprathermal Ion Composition (Galvin et al. 2008) on board the Solar TERrestrial RElations Observatory—Behind (STEREO-B) (Kaiser et al. 2008) spacecraft. At Mercury, we make use of in situ data provided by the magnetometer (MAG; Anderson et al. 2007) on board the MERCURY Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER; Solomon et al. 2007) mission. Remote-sensing CME observations from Earth’s viewpoint are provided by the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) on board the Solar and Heliospheric Observatory (SOHO; Domingo et al. 1995) satellite, while observations from additional vantage points are provided by the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al. 2008) instrument on board STEREO-B and STEREO—Ahead (STEREO-A).

With regard to MESSENGER data, we note that MESSENGER provided magnetic field data; however, it did not provide reliable plasma measurements in the solar wind. The spacecraft was in orbit around Mercury during the two ICME events highlighted in this paper. We thus used the methods described in Winslow et al. (2013) to identify the crossings of Mercury’s bow shock and magnetopause (and therefore the magnetosphere) and remove them from the data analyzed and presented here. Both case studies presented below, but especially the first one, have numerous bow shock crossings throughout the ICME passage as a result of the motion of the bow shock relative to the spacecraft. These cause MESSENGER to remain in the planetary magnetosheath for extended periods where the interplanetary magnetic field (IMF) is modified by Mercury’s bow shock. This further complicates studying the ICME characteristics because during some periods there is little pristine IMF data available. For these two case studies, we started by identifying every instance of bow shock crossing during the ICME passage and adding in all possible times when the spacecraft was outside of the magnetosheath. To further increase the usable MESSENGER ICME data, we followed the method of Lugaz et al. (2020a) to extrapolate the IMF measurements by dividing the measured magnetic field inside the magnetosheath by the jump experienced through the bow shock for the magnitude and each individual component. We refer the reader to Lugaz et al. (2020a) for further details, and we note that this procedure allowed us to recover valuable additional hours of magnetic field data during both ICME passages described below.

At MESSENGER, due to the lack of direct solar wind observations (Andrews et al. 2007) we also developed a method to estimate the solar wind dynamic pressure using magnetic field measurements (see Winslow et al. 2017 for details). Using the modified Newtonian approximation during magnetospheric transits of Mercury by MESSENGER (described in detail in Section 2.2 and Equation (4) of Winslow et al. 2017), we determined a proxy for the solar wind ram pressure from the magnetopause magnetic field strength. This method has been tested in both Winslow et al. (2020) and Lugaz et al. (2020a) and has been found to yield results that compare favorably with measured dynamic pressure values at 1 au scaled back to Mercury’s heliocentric distance.

To investigate changes in the global magnetic field structure of ICMEs as detected in situ at various heliocentric distances, we employ two different methods: (1) a constant-α force-free field fitting (Burlaga 1988; Lepping et al. 1990) and (2) the classification method proposed by Nieves-Chinchilla et al. (2019), which allows the classification of ICME flux rope structures based on the extent and number of observed magnetic field rotations through the analysis of magnetic hodograms. This method avoids the introduction of further assumptions on the 3D magnetic configuration as required by more advanced fitting techniques, and it hence appears particularly suitable to investigate and compare the ICME magnetic complexity measured at various heliocentric distances and spacecraft. To investigate and reconstruct the global structures of the ICME magnetic field and determine their changes during propagation, we apply the two aforementioned techniques to magnetic field data at both Mercury and at 1 au from single spacecraft crossings through the MEs. The comparison of the reconstructed global properties obtained at the two heliocentric distances then allows us to determine if substantial changes in the flux rope have occurred during propagation. We note that because of the lack of direct plasma density measurements at Mercury, some more sophisticated flux rope reconstruction techniques, such as the Grad-Shafranov method (Hau & Sonnerup 1999) or the elliptical cross-section technique (Hidalgo et al. 2002), which require information on the plasma velocity and thermal pressure, are essentially impossible to apply.

To characterize the solar wind conditions along and around the propagation path of the ICMEs under study, we use heliospheric simulations obtained from the WSA-ENLIL model and available on the NASA CCMC website. ENLIL (Odstrcil 2003) is a time-dependent three-dimensional (3D) magnetohydrodynamic model of the inner heliosphere designed to model the ambient solar wind as well as CMEs propagating through it. In this work, we use results obtained with ENLIL version 2.8f in combination with the Wang–Sheeley–Arge (WSA) semiempirical coronal model (Arge & Pizzo 2000; Arge et al. 2004). In this work, we performed simulations using a heliospheric computational domain spanning between 0.1 au and Mars, orbit in the radial direction, and covering ±60° in latitude and ±180° in longitude in Heliocentric Earth EQuatorial (HEEQ). In the simulations, a medium resolution, with 512 grid cells in the radial direction, 60 grid cells in the latitudinal direction, and 180 grid cells in the longitudinal direction, was used. As input for the WSA coronal model, we used daily-updated synoptic magnetograms generated by the National Solar Observatory/Global Oscillation Network Group. The CMEs were modeled using the cone model and initialized with parameters taken from the Space Weather Database Of Notifications, Knowledge, Information (DONKI4) catalog. In addition to performing new simulations of the solar wind and CME conditions, we also considered pre-existing simulations of the steady-state ambient solar wind alone, in

4 https://kauai.ccmc.gsfc.nasa.gov/DONKI/search/
order to better contextualize the environment through which the CMEs propagated.

In what follows, we describe in detail two CMEs and their propagation between Mercury and 1 au, with one event affected, and the other not affected, by corotating structures in the propagation space.

3. CME with No Corotating Structures in the Propagation Space

The first case study considered is a CME launched from the Sun on 2013 July 9 (first observed in LASCO C2 at 15:12 UT) that impacted both Mercury and Earth, which were in radial alignment at this time (within 3° of longitudinal separation). This event had been previously studied by Möstl et al. (2018) to test a new space weather modeling tool and by Lugaz et al. (2020a) to investigate its evolution and sheath region. Given the detailed analysis of this CME/ICME documented in both Möstl et al. (2018) and Lugaz et al. (2020a), here we only provide a summary of the remote-sensing and in situ observations in the corona and heliosphere and instead focus on the investigation of in situ properties that were not addressed in those papers. We refer the reader to the aforementioned papers for more detailed information on the remote observations and kinematics of this CME.

At the Sun, this CME was associated with an obvious filament eruption, occurring around 14 UT at θ ∼ 15°, φ ∼ −5° in Stonyhurst coordinates on the solar disk. Prior to the eruption, the filament exhibited a clear inverse-S topology (see Figure 2 in Möstl et al. 2018), indicative of magnetic fields characterized by a left-handed (negative) chirality (e.g., Green et al. 2007, 2018). Additionally, measurements of the photospheric magnetic field suggest the axial field of the magnetic flux rope formed in the source region was inclined by roughly 45° with respect to the solar equator (as marked by the orientation of the magnetic polarity inversion line; e.g., Titov & Démoulin 1999). The magnetic polarity signs at two sides of the polarity inversion line further suggest the axial field was pointing toward the southwest direction (as shown in Figure 2 in Möstl et al. 2018). The resulting magnetic flux rope is therefore expected to be a mid-inclination configuration between NWS and WSE types (following the classifications by Bothmer & Schwenn 1998 and Mulligan et al. 1998; as indicated in Figure 2 in Möstl et al. 2018).

The CME was later observed in the corona by the LASCO C2 and C3 instruments (starting at 15:12 UT and 16:30 UT, respectively) on board SOHO, as well as by the COR2 instruments on board STEREO-A and STEREO-B (first observations at 15:24 UT and 15:36 UT, respectively). Previous studies by Hess & Zhang (2017) and Möstl et al. (2018) using the Graduated Cylindrical Shell model (GCS; Thermisien et al. 2006, 2009) estimate a CME deprojected speed in the corona around 550–600 km s⁻¹, with the main direction of propagation toward θ ∼ −1°, φ ∼ 1° in HEEQ coordinates, i.e., close to the Sun–Mercury–Earth line. An overview of the white-light CME observations in the corona, including a visualization of the CME 3D reconstruction based on the GCS model, can be found in Figure 3 in Möstl et al. (2018). By comparing the source region location with the CME direction of propagation in the corona, Möstl et al. (2018) concluded that a deflection of about 20° away from the initial direction took place during the early CME evolution. Coronal and heliospheric observations in the days before and after the CME eruption also show little front-sided solar activity, indicating this event likely propagated without interacting with any other CMEs from the Sun to Earth.

ICME signatures were later detected at MESSENGER (Figure 1) and ACE (Figure 2) about two and three days after the eruption, respectively. At the time of the ICME impact, the MESSENGER spacecraft was orbiting Mercury, which was located at HEEQ coordinates (r, θ, φ) = (0.45 au, −2°, 3°), while ACE was orbiting L1 at HEEQ coordinates (r, θ, φ) = (1.02 au, 4°, 0°). The ICME shock arrived at MESSENGER on July 11 (day of year 192) at 01:05 UT, while the ME started on July 11 at 04:10 UT and ended at 23:14 UT on the same day. These boundary choices lead to a sheath length of ∼3.1 hr and an ME length of ∼21.3 hr, corresponding to a sheath-to-ME duration ratio equal to 0.16. The ICME shock arrived at ACE on July 12 at 16:28 UT, while the ME arrived on July 13 at 05:10 UT and ended at 23:18 UT on July 14. At 1 au, the ICME was therefore observed to have a sheath length of ∼12.7 hr and an ME length of ∼42.1 hr, corresponding to a sheath-to-ME duration ratio equal to 0.3. At both spacecraft, the sheath-to-ME duration ratio is lower than typical values reported by Janvier et al. (2019), and an investigation of the sheath and ME individual duration reveals this is due to the fact that the slightly longer-than-typical sheath was followed by a very extended ejecta compared to typical observations at both heliocentric distances (Lugaz et al. 2020a).

We note that at MESSENGER we have chosen 04:10 UT as the start time of the ME in order to be consistent with the flux rope start time, i.e., when smooth rotations of the magnetic field components start in Figure 1. This choice is also consistent with empirical arguments on the expansion/accumulation of material into the sheath during propagation based on typical observations of the sheath increase factor between Mercury and 1 au (Janvier et al. 2019). In fact, with these choices of boundaries, the sheath and ME increase by factors of 4.1 and 2, respectively, between Mercury and 1 au. For comparison, typical factors of increase in the sheath and ME size of 5 and 2.7, respectively, have been reported by Janvier et al. (2019) based on observations of statistical sets of ICMEs at Mercury’s (∼0.4 au) and Earth’s (1 au) orbits.

For this ICME event, we showed in Lugaz et al. (2020a) that the estimates of the solar wind dynamic pressure at MESSENGER using the methodology described in Section 2 are well matched by the values obtained from the scaling of 1 au $P_{dyn}$ data using a 1/r² dependence. In situ observations therefore suggest a fairly typical decay of the shear dynamic pressure between Mercury and 1 au. The suprathermal electron pitch angle distribution data at ACE completes the picture of the ICME at 1 au, showing clear bidirectional electrons throughout the large majority of the ME period. Counterstreaming electrons inside ICMEs are interpreted as signatures of the passage of a magnetic structure still connected at both ends to the Sun (e.g., Zurbuchen & Richardson 2006; Kilpua et al. 2017), thus these measurements at ACE imply that the ICME did not go through significant reconnection during its propagation to 1 au.

We previously showed in Lugaz et al. (2020a) that the magnetic field measurements at Mercury matched those at 1 au remarkably well after scaling the field to account for CME expansion during propagation. However, in that work, the ME orientation and complexity were not analyzed in detail. Using the two different magnetic field characterization and modeling...
methods described in Section 2, we also confirm below that the global magnetic field structure did not change significantly between Mercury and 1 au. In particular, following the classification of Nieves-Chinchilla et al. (2019), we find that the ME is compatible with an NWS left-handed flux rope with orientation \( \phi \sim 90^\circ \) and \( \theta \sim 0^\circ \) (in radial-tangential-normal, hereafter RTN, coordinates) at both spacecraft, in agreement with the photospheric magnetic field measurements and EUV observations of the source region discussed above. From the magnetic hodograms shown in Figure 3, we find that the ME looks like an \( F^+ \) flux rope at both spacecraft, i.e., with no change in classification between the two locations.

The force-free field fits at both spacecraft (Figure 4) also yield a negative helicity flux rope at both spacecraft, with \( \theta \sim -6^\circ \), \( \phi \sim 90^\circ \), and \( B_0 \sim 46 \) nT at MESSENGER, and \( \theta \sim -22^\circ \), \( \phi \sim 104^\circ \), and \( B_0 \sim 14 \) nT at ACE. Here, \( \theta \) is the angle between the flux rope axis and the ecliptic plane, \( \phi \) is the angle from the antisunward direction counterclockwise to the projection of the axis direction onto the ecliptic plane, and \( B_0 \) is the field strength along the flux rope axis. The impact parameter was small at both spacecraft (0.04 at MESSENGER and 0.05 at ACE), where the impact parameter is defined as the distance of closest approach of the spacecraft to the flux rope axis normalized by the radius of the flux rope, indicating that both spacecraft likely crossed the ICME near the flux rope axis. It is also worth mentioning that the fits had low \( \chi^2 \) values of 0.04 at both spacecraft, indicating good-quality fits. To get an estimate of how close to the center/flanks the spacecraft crossed through the ICME structure, we compute the location angle \( \lambda \) as defined by Janvier et al. (2013), based on the results of force-free fittings at MESSENGER and ACE. This yields \( |\lambda| \sim 0^\circ \) at MESSENGER and \( |\lambda| \sim 13^\circ \) at ACE, both indicating spacecraft crossings close to the ICME center.

The surprisingly little change in the magnetic field components of this ME from Mercury to Earth prompted us to further investigate the conditions that allowed for this to happen. We therefore performed a simulation of the inner heliosphere as described in Section 2 (https://ccmc.gsfc.nasa.gov/database_SH/Camilla_Scolini_010421_SH_1.php), using the WSA-ENLIL model available at the NASA CCMC to provide context for the background solar wind and global CME propagation. In the simulation, we initialized the CME using the cone model and parameters from the DONKI catalog. Figure 5 shows the modeled solar wind conditions in the ecliptic plane during the ICME propagation from Mercury to Earth.

As discussed above, in situ observations indicate that the ICME hit Mercury early on July 11 and arrived at ACE in the second half of the day on July 12. Furthermore, WSA-ENLIL simulations indicate that the HCS arrived at Mercury around the same time as the ICME did (left panel in Figure 5). Therefore, any interaction between the ICME and the HCS occurred at or before the orbit of Mercury. As the ICME traveled from Mercury to ACE faster than the HCS (as visible from the rightmost panel in Figure 5, which depicts the interplanetary space conditions around the time the ICME arrived at ACE), there was likely no structure (e.g., SIRs/CIRs,

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Figure 1. Magnetic field data for the 2013 July 9 CME event, measured in situ at MESSENGER on 2013 July 11. The data are in RTN coordinates with \( B_R \) in red, \( B_T \) in green, and \( B_N \) in blue. The magnetic field magnitude \( B \) and its negative \(-B\) are in black. The same color coding for the magnetic field data is used in the following figures as well. The ICME shock arrived at Mercury while MESSENGER was still inside the magnetosphere; therefore, we only show data starting at 1:30 UT (i.e., 25 minutes past the shock arrival) after MESSENGER had exited the magnetosphere, and the data interval shown goes until the end of the ICME on July 11 at 23:14 UT (after which MESSENGER re-entered the magnetosphere). The vertical magenta line denotes the start time of the ME. The data gaps correspond to MESSENGER’s passage through Mercury’s magnetosphere.
HCS) in the propagation space of the ICME as it traveled from Mercury to ACE. Magnetic field data supports this at both MESSENGER and ACE: at MESSENGER, $B_R$ changed sign (from positive to negative) on July 11, just as the ICME arrived, while the HCS arrived at ACE after the ICME had gone by, likely on or after July 17. We note that the CME arrival time at MESSENGER in the WSA-ENLIL simulation is very consistent with in situ observations at MESSENGER (less than 1 hr difference), while the arrival time at ACE is modeled to occur about 7 hr earlier than observed (which is still within the typical uncertainties associated with CME arrival time predictions in such models; Riley et al. 2018). For this reason, the time steps chosen in Figure 5 are not exactly matching the observed arrival times of the ICME at MESSENGER (Figure 1) and ACE (Figure 2).

4. CME with Corotating Structures in the Propagation Space

The second CME study was launched from the Sun on 2013 December 26 at 03:24 UT, and it was later observed in situ in conjunction between MESSENGER and STEREO-B, even though there was a fairly large longitudinal separation (of 32°) between the two spacecraft at that time. At the time of the ICME impact, the MESSENGER spacecraft was orbiting Mercury at HEEQ coordinates ($r, \theta, \phi$) = (0.46 au, $-3^\circ$, $177^\circ$), while STEREO-B was at HEEQ coordinates ($r, \theta, \phi$) = (1.09 au, $5^\circ$, $-151^\circ$). Salman et al. (2020) list this CME as a conjunction event, and predictions of the arrival of the event at various locations based on WSA-ENLIL simulations of the CME listed on the DONKI catalog also indicate the ICME hit both Mercury and STEREO-B as the result of its very large half-angular width ($\sim$90° based on the WSA-ENLIL model input available on DONKI). This result is confirmed in the WSA-ENLIL simulation of the CME event performed in this work, as later discussed in Section 4.3 and shown in Figure 11.

4.1. Differences in In Situ Data at the Two Spacecraft

From the catalog of Salman et al. (2020), the ICME shock arrived at MESSENGER on December 27 at 04:14 UT, while the ME arrived at 05:36 UT and ended at 15:28 UT on the same day. This implies a sheath length of $\sim$1.25 hr and ME length of $\sim$10 hr at MESSENGER, corresponding to a sheath-to-ME duration ratio equal to 0.13. Figure 6 shows the magnetic field magnitude and components in RTN coordinates at MESSENGER, with the magnetospheric pass of Mercury removed from the observations. The magnetic field data at Mercury show a fairly simple ICME, with the ME dominated by the $B_T$ magnetic field component and a clear rotation visible in the $B_N$ component.

At STEREO-B, Salman et al. (2020) list the ICME shock arrival on December 28 at 17:06 UT, the ejecta arrival on December 29 at 04:12 UT, and the ejecta end on December 30 at 14:00 UT. Figure 7 shows the magnetic field magnitude and components (also in RTN coordinates), the solar wind density,
temperature, speed, plasma $\beta$, dynamic pressure, and the suprathermal electron pitch angle distribution at STEREO-B. From a quick glance at these data, it is clear that the ICME observed at STEREO-B is more complex than what had been observed at MESSENGER.

First, the beginning and end boundaries of the ME are not as simple to identify at STEREO-B as they are at MESSENGER. Because we want to explore the changes in the ME during propagation in detail, it is important first to properly identify the boundaries of the ME. Due to the long duration of the ICME and the number of rotations in the magnetic field, we considered the possibility that there could be two ME at STEREO-B: one ME between December 28 22:40 UT and December 29 08:35 UT (marked by the dashed and solid vertical lines on Figure 7), while another one between December 29 08:35 UT and December 30 07:33 UT (marked by the two solid vertical lines in Figure 7). However, we can rule out this possibility based on the fact that the first “ME” does not exhibit typical ME signatures. In this region, there are (1) high variability in the $B_N$ component and no smooth rotation in any of the field components; (2) high solar wind density and temperature; (3) plasma $\beta \sim 1$; and (4) highly variable suprathermal electron pitch angle distribution, with a clear lack of bidirectional electrons. Furthermore, and perhaps more importantly, as described in more detail below, there is no other ICME in the propagation space that this ICME is likely to have interacted with and that could have led to the observation of a double ME at STEREO-B but not at MESSENGER.

Based on these considerations, we chose the ME start time to be December 29 08:35 UT, which coincides with the start of the smooth rotation in the magnetic field, drops in solar wind density, temperature, and plasma $\beta$, as well as less variable suprathermal electron pitch angle distribution. We chose December 30 07:33 UT as the end of the ME in order to be able to conduct flux rope fitting; however, we note that the ICME likely continued on until December 30 14:00 UT as indicated by the increased magnetic field in this region. This $\sim 7$ hr long “back” region of the ICME could have formed through reconnection with the IMF as suggested by Dasso et al. (2007). These boundary choices then lead to a sheath length of $\sim 15.5$ hr and an ME length of $\sim 23$ hr, which correspond to a sheath-to-ME duration ratio equal to 0.67. By considering the sheath-to-ME duration ratios at the two spacecraft, we note that contrary to the first ICME case study considered in Section 3, in this case a significantly larger ratio is observed at 1 au (0.67) compared to Mercury (0.13). This indicates a much more extended sheath relative to the ejecta duration at 1 au than was observed at Mercury. Furthermore, based on the boundary choices at the two spacecraft, we recover an ME increase factor equal to 2.3, i.e., very similar to the typical ME increase factor of 2.6 observed between these two heliocentric distances (Janvier et al. 2019). On the other hand, the increase in the

![Figure 3. Magnetic hodograms of the 2013 July 9 CME event at MESSENGER and ACE, in RTN coordinates. The red dots mark the initial values of the magnetic field components.](image)
sheath duration is significantly larger, around 12.4, compared to a typical increase factor of only 5. Similar evidence of an over-increase of the sheath duration compared to typical can be recovered based on the relations proposed by Salman et al. (2020), who reported a typical sheath duration increase with heliocentric distance as $\Delta t_{sh} = 15.28 - 3.67 \cdot r$ (in hr). Using this relation to estimate the expected sheath duration at MESSENGER and STEREO-B distances, one would have expected an increase of a factor 3.9 between the two spacecraft, which is significantly lower than the observed one (12.4).

In order to estimate the expected sheath and ME growth from expansion only, we fit the typical sheath and ME duration provided by Janvier et al. (2019) at selected heliocentric distances in the inner heliosphere with a power-law function. We recover exponents equal to 1.77 and 1.08, respectively, which we take as indicators of the typical sheath and ME growth rates between Mercury and 1 au. By extrapolating the structures’ size from MESSENGER to STEREO-B assuming the typical growth rates above, we estimate the following duration at 1 au: $\Delta t_{sh} = 1.25 \cdot (1.09/0.46)^{1.77}$ hr $\sim 5.8$ hr for the sheath, and $\Delta t_{ME} = 10 \cdot (1.09/0.46)^{1.08}$ hr $\sim 25.4$ hr for the ME. For comparison, the 23 hr long ME observed at STEREO-B well matched the expected size estimated from a typical increase rate. On the other hand, the observed sheath duration is a factor of 2.7 larger than predicted using empirical relations, which again highlights the anomalous growth of this structure during propagation between Mercury and 1 au.

We can also compare the dynamic pressure observed at STEREO-B to that at MESSENGER. As described in Section 2, we estimate the dynamic pressure ($P_{dy}$) from the outbound portion of MESSENGER’s magnetospheric pass around Mercury, which occurred during the middle of the ME of this ICME event. This yields $P_{dy} \sim 5.5$ nPa, which is close to the average value of 7 nPa at Mercury’s heliocentric distances (Winslow et al. 2013). Although this is a single point estimate, which does not allow us to put bounds on the maximum dynamic pressure that could have been observed by MESSENGER during this time, we note that Mercury’s magnetosphere was not highly disturbed by this ICME event.

This is another indication that the dynamic pressure was likely not unusually high during this time, as events with very high $P_{dy}$ are known to cause extreme changes in Mercury’s magnetosphere (e.g., magnetopause compressed to the surface, very large cusps, etc.; e.g., Winslow et al. 2020). At STEREO-B, the maximum observed $P_{dy}$ is 11.3 nPa, and the average value in the ICME is 2.4 nPa. Scaling this to Mercury’s location with a $1/r^2$ scaling yields a maximum $P_{dy} \sim 63$ nPa and an average value of 13 nPa, much higher than the value estimated at MESSENGER. Thus, the fact that the observations indicate a fairly average dynamic pressure event at MESSENGER while at STEREO-B we observe a high dynamic pressure event provides further evidence that the ICME has sustained significant changes in propagation between MESSENGER and STEREO-B. Furthermore, to explain such a high dynamic pressure observed at STEREO-B compared to what was estimated at MESSENGER, we expect the ICME to have interacted with a dense structure, such as an SIR/CIR in the intervening interplanetary space (further justification in support of this hypothesis is given in Section 4.3 below).

Using the classification of Nieves-Chinchilla et al. (2019) and the hodograms in Figure 8, we find an $F^-$ flux rope type at MESSENGER and an $Fr$ flux rope type at STEREO-B. Looking at the $B_N$ and $B_T$ components only in Figure 8 (right-hand top and bottom panels), they imply an NES-type flux rope at both spacecraft, with the lack of a full 180° rotation at MESSENGER possibly due to the spacecraft crossing far from the flux rope axis. However, it is clear from the left and center panels of Figure 8 that there is a significant $B_R$ component of opposite sign at the two spacecraft, which complicates the classification. This could be due to one spacecraft crossing far above and the other spacecraft crossing far below the flux rope axis, but we also note that in situ flux rope observations that have a significant $B_R$ component can also be due to a flux rope with a substantial tilt in longitude ($\phi$ direction). However, because the initial direction of the CME in latitude was $\theta \sim 15°$ (see next section for details), in this case it is likely that the flux rope axis passed south of both MESSENGER and STEREO-B (based on the spacecraft’s latitude at this time), and

![Figure 4. Linear constant-$\alpha$ force-free flux rope fits to RTN magnetic field data for the 2013 July 9 CME event at MESSENGER (left column) and ACE (right column).](image-url)
thus that both spacecraft crossed the ICME above the flux rope axis, which should have yielded positive $B_R$ components at both spacecraft. Based on the fact that opposite sign $B_R$ components are observed at MESSENGER and STEREO-B, we infer that the most likely reason for the significant $B_R$ differences at the two spacecraft is due to the flux ropes having undergone a substantial rotation in the $\phi$ direction with respect to the $\phi = 90^\circ$ line, as further discussed below and in Section 4.2.

The force-free field fits (Figure 9) yield a positive helicity flux rope at MESSENGER, with $\theta \sim -4^\circ$, $\phi \sim 327^\circ$ and $B_0 \sim 64$ nT, and a positive helicity flux rope at STEREO-B, with $\theta \sim 17^\circ$, $\phi \sim 259^\circ$, and $B_0 \sim 21$ nT. The impact parameter was large at both spacecraft, with a value of 0.6 at MESSENGER and 0.8 at STEREO-B, and the fits had low $\chi^2$ values of 0.03 at both spacecraft. The $\sim 70^\circ$ rotation in $\phi$ between MESSENGER and STEREO-B estimated from the flux rope fits is in agreement with the $B_R$ changes noted in the hodograms and underlines the likelihood that the $B_R$ difference between the two spacecraft are caused by rotation of the flux rope and not due to the spacecraft crossing location with respect to the flux rope axis. This provides an additional indication that the ICME structure underwent significant changes during propagation and that those changes involved an increase in complexity in the flux rope structure. Evidence of a complex structure at 1 au is also given by suprathermal electron data at STEREO-B, which shows only very short sections of bidirectional electrons inside the ME. Such characteristics are compatible with extended magnetic connectivity. We also note that at the Sun, EUVI-B observations of the CME source region hint toward the eruption of a right-handed flux rope (as indicated by the forward-S topology of pre-eruptive coronal loops in Figure 10(a)), although the lack of photospheric magnetic field measurements prevents an accurate estimation of the source region and flux rope magnetic properties, such as the helicity and initial orientation/flux rope type. Overall, the eruption of a right-handed flux rope is consistent with in situ estimates of a positive helicity flux rope at MESSENGER and STEREO-B as obtained from the force-free field fits.

4.2. Ruling Out Possible Factors Affecting Change in This ICME

In the above section, we presented significant differences in the ICME sheath duration, dynamic pressure, and flux rope orientation observed in situ between MESSENGER and STEREO-B. As discussed below, we can rule out two possible causes of these differences: 1) due to ICME flank arrival at MESSENGER versus center arrival at STEREO-B, and 2) due to interaction with other ICMEs in the propagation space.

To discuss point 1 above, we consider remote-sensing observations, along with the location angle derived from the flux rope fits, duration of the ICME, and WSA-ENLIL model simulations. An overview of the remote-sensing observations of the CME and its source region is provided in Figure 10. Based on STEREO EUVI-B images (Figure 10(a)–(c)), the CME under study erupted around 02:30 UT on December 26 from a source region located around $\theta \sim -11^\circ$ and $\phi \sim -165^\circ$ in Stonyhurst coordinates. The CME was later observed in the corona by the LASCO C2 and C3 instruments (starting at 03:12 UT and 03:48 UT, respectively), as well as by the COR2 instruments on board STEREO-A and STEREO-B (first observations at 03:24 UT and 03:55 UT, respectively). In the corona, the CME initial direction (as listed in the DONKI database) was toward $-134^\circ$ HEEQ longitude, and at this time STEREO-B was at $-151^\circ$ HEEQ and MESSENGER at 176° HEEQ. Thus, the CME most probably underwent a deflection of about 30° westward within the first solar radii of propagation. We conducted a reconstruction of the CME geometry and kinematics with the GCS model and multiple viewpoints (i.e., observations from LASCO, STEREO-A, and
STEREO-B (Figures 10(d)–(i)), which indicates that the CME in the corona was directed toward $-15^\circ$ HEEQ latitude and $-135^\circ$ HEEQ longitude, essentially confirming the DONKI-based longitude.

Thus, remote-sensing observations suggest the CME initial direction was more closely aimed toward STEREO-B than toward Mercury, raising the possibility that MESSENGER passed through the flanks of the ICME while STEREO-B passed through closer to the center, which could partly explain the larger differences between the observations at the two locations. However, from in situ observations, for a fully flank arrival, we would expect a $B_T$-dominant field with very little rotation in the magnetic field direction overall (Möstl et al. 2010, 2020), and a significantly longer duration ICME crossing than for a center arrival. In fact, at MESSENGER, we see a $B_T$-dominant field, with clear rotation in $B_N$, and a much shorter duration ICME crossing (even after accounting for expansion) than at STEREO-B. Based on these arguments, we can conclude that the ICME likely had a close to center arrival at STEREO-B and an in-between flank and center arrival at MESSENGER. This picture is further supported by the location angle $\lambda$ calculated at MESSENGER and STEREO-B based on results from the force-free fittings. We obtain $|\lambda| \sim 57^\circ$ at MESSENGER and $|\lambda| \sim 10^\circ$ at STEREO-B, suggesting that MESSENGER passed through closer to the flank of the ICME than STEREO-B, but not actually in the flank (which would be at $|\lambda| \sim 90^\circ$). This is in line with WSA-ENLIL simulation results shown in Figure 11. Overall, although the two spacecraft did not cross through the exact same portion of the ICME, it is also clear that MESSENGER did not cross through the flanks and the observational differences are too large to be explained by crossing location alone.

Regarding point 2) from above, coronal and heliospheric remote-sensing observations in the days before and after the CME eruption show little activity, and thus it is not likely that there were any other ICMEs in the propagation space that the ICME in question would have interacted with on its way to MESSENGER and STEREO-B. From STEREO COR2-A and COR2-B, the only other CME around this time (a small CME launched around 01:25 UT on December 25, i.e., the day before the CME in question) was heading toward STEREO-A and not STEREO-B. MESSENGER was directly in between STEREO-A and STEREO-B at this time, which implies that for this CME to have been in the propagation space of the ICME in question between MESSENGER and STEREO-B, this smaller, earlier event would have had to have been observed at MESSENGER. As there were no ICMEs observed at MESSENGER in the days prior to December 26, we can rule out this small CME having interacted with and caused the observed changes in the CME studied here by the time it reached STEREO-B.

4.3. Critical Factor Affecting This ICME: SIR

Although the $\sim30^\circ$ separation between the observing spacecraft could inherently introduce differences in the measured magnetic field, the differences observed (both in terms of sheath length, dynamic pressure, and magnetic field structure and complexity) are too large to be explained by just the separation alone. Similarly to the event showcased in

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**Figure 6.** Magnetic field data for the 2013 December 26 CME event measured in situ at MESSENGER on 2013 December 27. The colors are the same as in Figure 1. The vertical magenta lines denote the start time of the shock and ME, while the data interval shown ends at the end of the ME just after which MESSENGER re-enters Mercury’s magnetosphere. The data gap corresponds to MESSENGER’s passage through the magnetosphere.
Winslow et al. (2016), the ICME magnetic field is fairly simple at MESSENGER, but it is much more complex by the time it reaches STEREO-B.

We therefore use WSA-ENLIL data as described in Section 2 to contextualize the plasma environment through which the ICME propagated between Mercury and STEREO-B. WSA-ENLIL simulations (available at https://ccmc.gsfc.nasa.gov/database_SH/Camilla_Scolini_010421_SH_2.php) of the background solar wind and of the CME initialized with parameters from the DONKI catalog (Figure 11) show that there was an SIR, including the HCS, in the ICME’s propagation space from Mercury to STEREO-B at this time. In this case, the CME arrival time at MESSENGER and STEREO-B was modeled by ENLIL to occur about 7 and 20 hr earlier than observed, respectively. In this case, the error on the arrival time is therefore significantly larger than for the first CME event considered, and for this reason, the time steps chosen in Figure 11 are not matching the observed arrival times of the ICME at MESSENGER (Figure 6) and STEREO-B (Figure 7). Despite this discrepancy, key factors affecting the CME propagation and interaction with the ambient solar wind can be identified in Figure 11 and are further supported by simulations of the steady-state solar wind alone (available at https://ccmc.gsfc.nasa.gov/database_SH/Dan_Aksim_060419_SH_4.php, not shown here). In particular, the model predicts the SIR/HCS to have passed by Mercury by the time the ICME arrives there (left panel in Figure 11), while it predicts the SIR/HCS arrival at STEREO-B early on December 29 soon after the ICME arrival (right panel in Figure 11). We note that because here we are only interested in the time period of a few days between the CME eruption time and its arrival at 1 au, in the following we use the term “SIR” as we have no information about whether this specific stream interaction region was also a CIR, i.e., a corotating stream interaction region originated by a recurrent coronal hole and observed in situ over multiple solar rotations (Richardson 2018).

As ENLIL finds that the HCS arrives during the ICME passage at STEREO-B, and as differences of up to a couple of days have been reported between measured HCS crossings and simulated ones (e.g., Lee et al. 2009; Szabo et al. 2020), we turn our attention to the in situ data at MESSENGER and STEREO-B. From magnetic field data at Mercury, we find that the HCS crossing occurred sometime between December 22 and December 24, as MESSENGER was skimming the current sheet and switched from $+B_R$ IMF to $-B_R$ IMF in that time (in agreement with results from the WSA-ENLIL simulations).

Thus, by the time the ICME reached Mercury on December 27, the HCS was in the propagation space between Mercury and STEREO-B. From magnetic field data at Mercury, we find that the HCS crossing occurred sometime between December 22 and December 24, as MESSENGER was skimming the current sheet and switched from $+B_R$ IMF to $-B_R$ IMF in that time (in agreement with results from the WSA-ENLIL simulations).
Thus, it is clear from in situ data that the HCS arrived at both Mercury and STEREO-B before the ICME, and therefore, it is unlikely that the ICME interacted with it. The WSA-ENLIL model results are in agreement with this conclusion, also showing that the HCS was at the front of the SIR. It is important to mention that for this second case study, a suboptimal performance of the WSA-ENLIL model prediction of the solar wind structure in the region of interest is likely given that the photospheric magnetic field data used as input for such simulations are only updated in regions on the solar disk that are seen as front-sided from Earth (i.e., opposite to the direction of propagation of this ICME).

Given that we only have magnetic field data at MESSENGER and due to the frequent magnetospheric crossings of Mercury, it is not possible to determine when the SIR itself arrived there. However, the STEREO SIR database\(^5\) (Jian et al. 2019) lists an SIR start time at STEREO-B of 21:47 UT on December 31, ending at 17:38 UT on 2014 January 2, and there is no other SIR identified for more than six days before or after the ICME in question. This suggests that the SIR arrived at STEREO-B two days later than in the WSA-ENLIL simulation. It is also important to note that neither MESSENGER nor STEREO-B was exactly in the heliographic equatorial plane, whereas these simulation results are: this could have been an additional cause of these differences in modeled and observed arrival times.

Overall, based on the WSA-ENLIL simulation and the in situ data, we can infer the most likely scenario that the ICME caught up to and overtook the SIR between Mercury and STEREO-B, which is why the ICME arrived earlier than the SIR as seen in situ at STEREO-B. Furthermore, Salman et al. (2020) list the CME initial speed at \(\sim 1000\) km s\(^{-1}\), the transit speed from Sun to Mercury at \(\sim 770\) km s\(^{-1}\), and the transit speed from Mercury to STEREO-B at \(\sim 710\) km s\(^{-1}\). From STEREO-B data, we find that the SIR had a maximum speed of 540 km s\(^{-1}\), similar to the maximum in situ speed of the ICME at that location. Given that we know that the ICME had a nearly 200 km s\(^{-1}\) larger transit speed from Mercury to STEREO-B, we infer that the ICME was likely traveling significantly faster closer to Mercury than near STEREO-B, encountered the SIR and slowed down as it overtook it due to the substantial drag posed by the high-density stream. During this encounter, the ICME was significantly transformed from what was observed at Mercury to that observed at STEREO-B.

### 5. Summary and Conclusions

In this work, we have presented a study of two ICMEs observed at Mercury and 1 au by spacecraft in longitudinal conjunction. Our interest was driven by the following question:

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\(^5\) Available at https://stereo-ssc.nascom.nasa.gov/pub/ins_data/impact/old_level3/LanJian_STEREO_SIR_List.txt.
what causes the drastic alterations observed in some ICMEs during propagation, and why do other ICMEs remain relatively unchanged? The two ICMEs under study presented major differences in their evolutionary behavior, with the first one propagating in a relatively self-similar manner, while the second one underwent significant changes in its properties. The in-depth analysis of the ICME magnetic field and plasma properties at Mercury and at 1 au together with considerations on the size evolution of sheaths and MEs with heliocentric distance, as well as simulations of the solar wind and the ICME performed with the WSA-ENLIL + cone model, allowed us to reconstruct the propagation scenario of the two events between Mercury and 1 au and to identify the critical factors controlling their evolution during propagation. The main results can be summarized as follows:

1. The first case study (CME launched from the Sun on 9 July 2013) was a relatively simple ICME observed during a period of near-perfect conjunction (∼3° of longitudinal separation) exhibiting little change in its global structure between Mercury and 1 au. This long-duration ICME presented similar signatures at the two spacecraft locations, such as clear boundaries between the sheath and ME, relatively similar sheath-to-ME ratio at both locations, sheath dynamic pressure values following typical scaling laws, clear bidirectional electrons throughout the whole ME at 1 au, and little change in the fitted flux rope parameters (e.g., handedness, orientation, classification) for the ME at ACE compared to MESSENGER.

2. The second event (CME launched from the Sun on 2013 December 26) was a case where significant changes in the ICME properties and structure were observed between Mercury and 1 au. Although not observed in perfect conjunction, the longitudinal separation between the two spacecraft (∼30°) was not enough to explain the large differences observed in situ at the two locations, especially because we were able to rule out a flank hit at both spacecraft. At MESSENGER, the ICME presented simple characteristics consistent with typical ICME properties at this heliocentric distance. At STEREO-B, on the other hand, a much more complex structure was observed: first, it proved to be complicated to define the boundaries between the sheath and the ME; the sheath duration was also significantly more extended than at MESSENGER, both in absolute terms and with respect to the ejecta duration; and the dynamic pressure in the sheath at STEREO-B was also much greater than what could be expected from the application of simple scaling laws. Finally, bidirectional electrons, a typical proxy used to identify MEs within ICMEs, were largely missing at STEREO-B, indicating that sufficient magnetic reconnection occurred between the ME and the surrounding solar wind to completely alter the magnetic connectivity of the ICME structure. In addition, we reported significant changes in the fitted flux rope parameters (e.g., orientation, classification) for the ME at STEREO-B compared to MESSENGER, indicating a large rotation in the azimuthal direction of the flux rope axis, further underlining that reconnection in the ME took place during propagation. All of this indicated increased complexity of the very nature of the ICME during propagation through interplanetary space.

3. For both events, we could rule out any interaction with other ICME structures in interplanetary space, as indicated by remote-sensing and in situ instrument data. For the first case study, we were able to exclude the presence of other solar wind transients (e.g., SIRs, HCS) in the ICME propagation space, therefore providing evidence that ICME structures (e.g., magnetic flux ropes, sheaths) remain approximately self-similar during propagation if no interaction with other transients in the solar wind occur. For the second case study, WSA-ENLIL simulations revealed the presence of an SIR and HCS propagating between Mercury and STEREO-B around the same time as the ICME. From these simulations, in situ data, and timing considerations we found that the HCS was ahead of the ICME and it is unlikely that the
ICME could have interacted with it between Mercury and 1 au; however, the SIR was in between Mercury and 1 au at the right time for the ICME to have caught up to it, interacted with it, and overtaken it due to the ICME’s faster speed. This interaction with the high-density stream is what caused the large increase in dynamic pressure and sheath duration from MESSENGER to STEREO-B, and the substantial rotation in flux rope orientation. Based on these results, we can conclude that the large changes observed in the ICME structure of this event between MESSENGER and STEREO-B were most likely due to the interaction with the SIR and not due to any other dominant factor.

Ultimately, the analysis of more events will be needed to provide definitive conclusions on all the possible causes and on

Figure 10. Overview of the remote-sensing observations of the 2013 December 26 CME. (a) EUVI-A image of the CME source region in the 195 Å filter on December 25, 19:25 UT, before the eruption. The skew of some coronal loops, marked by the yellow dotted lines, suggests a positive helicity region. (b) EUVI-A full disk image in the 195 Å filter on December 26, 03:56 UT, after the eruption. Bright post-eruptive arcades (b) and flare ribbons (c) are clearly visible in the source region. (d)–(i): base-difference white-light coronal images of the CME as seen by STEREO-B COR2 (left), SOHO LASCO C3 (middle), and STEREO-A COR2 (right) around December 26, 04:08 UT. The CME is visible as a bright feature. Panels (d), (e), and (f) show the plain images, while in panels (g), (h), and (i) the GCS wireframe is overplotted (in green).
Figure 11. WSA-ENLIL model simulated heliospheric conditions for the 2013 December 26 CME event at MESSENGER and STEREO-B, at three time steps: (a) at 00 UT on 27 December 2013, just after the ICME reached MESSENGER; (b) at 12 UT on 27 December 2013, during the ICME propagation from MESSENGER to STEREO-B; and (c) at 00 UT on 28 December 2013, just after the ICME reached STEREO-B. In the simulation, the HCS and SIR had reached Mercury prior to the ICME arrival (a), propagated in the ICME propagation space between MESSENGER and 1 au (b), and eventually reached STEREO-B after the ICME had passed by (c). We note that the snapshots have been chosen to illustrate the interaction between the CME and the HCS and SIR/HS in the WSA-ENLIL simulation, and therefore, they do not necessarily match the observed arrival time of the ICME at MESSENGER (Figure 6) and STEREO-B (Figure 7).

the frequency of drastic alterations in ICME structures during propagation. So far, the capability to extend such an in-depth analysis to a larger set of events has been challenging because of the extremely limited number of ICMEs exhibiting clear in situ flux rope signatures and observed at different radial distances by multiple spacecraft in longitudinal conjunction. However, while MESSENGER data have been extensively explored and analyzed with respect to ICME conjunction events (Salman et al. 2020; Lugaz et al. 2020b), in the near future a statistical analysis over a larger set of events will likely benefit from new data from the Parker Solar Probe (Fox et al. 2016), Solar Orbiter (Müller et al. 2020), and potentially BepiColombo (Benkhoff et al. 2010) missions.

Support for this work was provided by NSF grant AGS1622352. R.M.W. acknowledges support from NASA grants NNX15AW31G and 80NSSC19K0914, and NSF grant AGS1622352, as well as partial support from the NASA STEREO Quadrature grant. C.S. acknowledges the NASA Living With a Star Jack Eddy Postdoctoral Fellowship Program, administered by UCAR’s Cooperative Programs for the Advancement of Earth System Science (CPAESS) under award No. NNX16AK22G. N.L. acknowledges support from NASA grants 80NSSC17K0556, 80NSSC20K0431, and 80NSSC20K0700.

All the data analyzed in this study are publicly available. MESSENGER data are available on the Planetary Data System (https://pds.jpl.nasa.gov), while STEREO data are available on the Space Physics Data Facility’s Coordinated Data Analysis Web (https://cdaweb.sci.gsfc.nasa.gov). Simulation results have been provided by the Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center through their public Runs on Request system (http://ccmc.gsfc.nasa.gov). The CCMC is a multiagency partnership between NASA, AFMC, AFOSR, AFRL, AFWA, NOAA, NSF, and ONR. The ENLIL model was developed by D. Odstrčil at the University of Colorado at Boulder.

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