Generic Magnetic Field Intensity Profiles of Interplanetary Coronal Mass Ejections at Mercury, Venus, and Earth From Superposed Epoch Analyses

Miho Janvier1, Reka M. Winslow2, Simon Good3, Elise Bonhomme1, Pascal Démoulin4, Sergio Dasso5,6, Christian Möstl7, Noé Lugaz2, Tanja Amerstorfer1, Elie Soubrié1, and Peter D. Boakes7

1Institut d’Astrophysique Spatiale, CNRS, Université Paris-Sud, Université Paris-Saclay, Orsay, France, 2Institute for the Study of Earth, Ocean, and Space, University of New Hampshire, Durham, NH, USA, 3Department of Physics, University of Helsinki, Helsinki, Finland, 4LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université Paris Diderot, Sorbonne Paris Cité, Meudon, France, 5Instituto de Astronomía y Física del Espacio, UBA-CONICET, Buenos Aires, Argentina, 6Departamento de Ciencias de la Atmosfera y los Océanos and Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Buenos Aires, Argentina, 7Space Research Institute, Austrian Academy of Sciences, Graz, Austria

Abstract
We study interplanetary coronal mass ejections (ICMEs) measured by probes at different heliocentric distances (0.3–1 AU) to investigate the propagation of ICMEs in the inner heliosphere and determine how the generic features of ICMEs change with heliospheric distance. Using data from the MErcury Surface, Space ENVironment, G EOchemistry, and Ranging (MESSENGER), Venus Express and ACE spacecraft, we analyze with the superposed epoch technique the profiles of ICME substructures, namely, the sheath and the magnetic ejecta. We determine that the median magnetic field magnitude in the sheath correlates well with ICME speeds at 1 AU, and we use this proxy to order the ICMEs at all spacecraft. We then investigate the typical ICME profiles for three categories equivalent to slow, intermediate, and fast ICMEs. Contrary to fast ICMEs, slow ICMEs have a weaker solar wind field at the front and a more symmetric magnetic field profile. We find the asymmetry to be less pronounced at Earth than at Mercury, indicating a relaxation taking place as ICMEs propagate. We also find that the magnetic field intensities in the wake region of the ICMEs do not go back to the pre-ICME solar wind intensities, suggesting that the effects of ICMEs on the ambient solar wind last longer than the duration of the transient event. Such results provide an indication of physical processes that need to be reproduced by numerical simulations of ICME propagation. The samples studied here will be greatly improved by future missions dedicated to the exploration of the inner heliosphere, such as Parker Solar Probe and Solar Orbiter.

1. Introduction
The Sun is the source of intermittent ejections of bulk plasma and magnetic field structures called coronal mass ejections (CMEs, see review in Webb & Howard, 2012). With space probes, these structures are observed as they propagate in the interplanetary medium. Interplanetary coronal mass ejections, or ICMEs (Kilpua et al., 2017) that have been detected by in situ instruments, are identified by a combination of plasma and magnetic field parameters (Jian et al., 2006; Klein & Burlaga, 1982; Wimmer-Schweingruber et al., 2006).

One or a combination of plasma characteristics different than the ambient solar wind (SW) can be observed in ICMEs. When ICME fronts propagate faster than the ambient SW, a shock forms, and the accumulated SW material between the shock and the ejecta is called the ICME sheath. In the sheath, the magnitudes of the density and the magnetic field increase, while the magnetic field variance is large. Behind the ICME sheath is a magnetically dominated region with less intense magnetic fluctuations than in the sheath, which we term magnetic ejecta (ME), similarly to Winslow et al. (2015, 2016). The subset of MEs that exhibit rotation in the azimuthal magnetic field component, and have proton temperatures and plasma β (ratio of the plasma thermal pressure to the magnetic pressure) values that are lower than the ambient SW, are termed magnetic clouds (hereafter MCs, Burlaga et al., 1981). These MCs are typically modeled with twisted magnetic field...
configurations or flux ropes (Al-Haddad et al., 2013; Dasso, 2009). Given that plasma parameters are not available from the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) and Venus Express missions, identifying MCs is not possible in these data, and thus we adopt the generic term ME to refer to the ICME substructure that is magnetically dominated. In this paper, we refer to an “ICME” as a set of two substructures: “sheath” and “ME,” whereas we note that another common convention termed these substructures “sheath” and “ICME.”

ICMEs propagate within the heliosphere and their arrival and consequences at the planets of the solar system can be tracked (e.g., see Cane et al., 2000; Prangé et al., 2004; Witassee et al., 2017). ICMEs are known to generate geomagnetic storms at Earth (e.g., Farrugia et al., 1997; Gosling, 1990; Lindsay et al., 1995; J. Zhang, et al., 2004), while ICME-related space weather events have been observed at Mercury (Slavin et al., 2014; Winslow et al., 2017) and Mars as well (Lee et al., 2017).

In Masías-Meza et al. (2016), the authors investigated how the generic profiles of ICMEs with well-defined MCs appear at 1 AU, using measurements of the SW transients by the ACE spacecraft. The authors used a superposed epoch analysis (SEA) to derive the generic profile of ICMEs at 1 AU. They found that this profile changed depending on the speed of ICMEs. By creating subgroups of ICMEs ranked with their speeds, they found that ICMEs with the slowest speeds have a symmetric generic magnetic field profile, while the subgroup with the fastest speeds have a nonsymmetric profile, with a stronger magnetic field in their front than in their rear. The symmetric profiles were interpreted as evidence of a relaxation mechanism taking place: as the magnetic field pressure within the MC tries to be in balance with the surrounding SW, one would expect a more symmetric profile with a lower propagation speed than an MC propagating faster than the SW, therefore accumulating a sheath with stronger magnetic field and plasma pressures (Liu et al., 2008). The presence of a strong sheath then implies surrounding conditions at the front and at the wake of the ME different from one another.

Investigating ICMEs seen at different distances can provide important information about how these structures behave during their propagation in the heliosphere and interact with different planets’ space environments (Bothmer & Schwenn, 1998; Good et al., 2015, 2018; Liu et al., 2005; Winslow et al., 2015).

A SEA, also known as a Chree analysis (Chree, 1914), provides a means to statistically analyze patterns in a time-varying parameter in a population of events. A classical SEA typically involves the use of a characteristic reference time, such as the event starting time, to align all the studied events to a common zero epoch time. Then, events are binned to a common set of time bins and averaged in each time bin to deduce a mean or median temporal profile. When the studied events also have clearly defined end times, the event timescales can be normalized (e.g., on a scale from 0 at the event start to 1 at the event end) as part of the SEA, prior to the binning and averaging. By averaging the profiles, the SEA reinforces the common features of the events. SEA is a well-established technique that is regularly used in a wide range of disciplines, including in the geophysics and space physics community; for example, it has been used to infer the generic properties of corotating/stream interaction region profiles in order to make comparisons with ICMEs (Yermolaev et al., 2017), and it has been used to analyze ICME substructures (Klein & Burlaga, 1982; Rodríguez et al., 2016; G. Zhang, & Burlaga, 1988).

It is important to note that the SEA technique should only be applied to a set of events with features that appear to show some ordering in time in the parameter used in the analysis. If applied to parameters without the same time ordering (e.g., the ICME north-south field component), significant features may be averaged out.

In the following, we investigate how the propagation away from the Sun affects the generic profile of ICMEs. For this study, we therefore consider three different samples of ICMEs observed at spacecraft positioned at different heliospheric distances. The observations made near Mercury’s orbit are provided by the MESSENGER mission and those made near Venus’s orbit are provided by the Venus Express mission; we also analyze events observed by the ACE spacecraft that were previously studied by Masías-Meza et al. (2016).

We first start in section 2 by describing the different data sets used in the paper and their characteristics. Since MESSENGER and Venus Express were planetary spacecraft that regularly crossed in and out of the magnetosphere and SW, identifying ICMEs using these spacecraft data sets has required more careful consideration. In section 3, we introduce the SEA technique before applying it to the different samples we have at the three different space missions. The results are shown in section 4, where we look at the SEA on the
whole data sets at different spacecraft, before searching for a method to create subcategories of events and the specific profiles of these subcategories in section 5. Discussions and conclusions are given in section 6.

2. Description of the Data Sets

In the present study, we use the data from three planetary missions, MESSENGER, Venus Express, and ACE. A brief description of the missions as well as their data sets is given below.

2.1. The MESSENGER Mission and Data

2.1.1. Description of the Data Set

The MESSENGER mission (Solomon et al., 2007) was launched on 3 August 2004 and terminated on 30 April 2015. After multiple flybys, the spacecraft reached Mercury for its orbit insertion on 18 March 2011. The Magnetometer (MAG; Anderson et al., 2007) onboard MESSENGER operated continuously after 2007. The sample rate was typically 2 s$^{-1}$ during the cruise phase. It has thus produced a database of interplanetary magnetic field (IMF) observations in the inner heliosphere in the heliocentric distance range of $0.3 < r < 0.6$ AU. After its orbit insertion around Mercury, due to its highly eccentric orbit, MESSENGER spent 40% to 85% of its time outside of Mercury's magnetosphere, in the SW. Although the MESSENGER payload included a plasma spectrometer (the Fast Imaging Plasma Spectrometer, FIPS; Andrews et al., 2007), the spacecraft was three axis stabilized and FIPS had a limited field of view that did not allow for the recovery of the SW density. SW speed and temperature could be derived from the measurements about 50% of the time that MESSENGER was in the SW (Gershman et al., 2012). ICMEs have been identified in MESSENGER data near Mercury's orbit since early January 2009 (Good & Forsyth, 2016). The orbital phase of the mission coincided with the ramp up to and the maximum of the solar cycle 24. This results in the number of ICMEs observed during MESSENGER's orbital phase (after 2011) being higher than that during the cruise phase.

MESSENGER magnetic field data are available on the Planetary Data System (https://pds.nasa.gov/) and were made accessible for this study through the HELCATS project (https://www.helcats-fp7.eu/; Möstl et al., 2017). Due to MESSENGER's crossing in and out of Mercury's magnetosphere during the orbital phase of the mission, the data needed to be cleaned, that is, the magnetospheric passages had to be removed to leave behind only interplanetary observations. For any given ICME, we have selectively included sections of data where MESSENGER is clearly outside of the magnetosphere, specifically, outside of the bow shock boundary. The magnetospheric boundaries move faster than the spacecraft, leading to MESSENGER crossing the bow shock multiple times, both before and after crossing the magnetosphere. In order to maximize the available data for the ICME profiles, we have identified all the bow shock crossings during each ICME event and have included all data sections outside of those boundaries, even sections of a few minutes in length. For details on identification of the bow shock boundary in the MESSENGER data the reader is referred to Winslow et al. (2013).

2.1.2. Description of the ICME Catalogs

The list of MESSENGER ICMEs studied here comes from two catalogs. The first catalog of events is from Winslow et al. (2015), later completed until the end of the MESSENGER mission (Winslow et al., 2017), with a total of 69 ICMEs. The time interval (2011–2015) corresponds to the phase of the mission when MESSENGER was in orbit around Mercury. The authors selected ICMEs based on several criteria: having a clear interplanetary discontinuity seen as a step-function-like magnetic field increase followed by a sheath, a ME, and causing a visible distortion of Mercury’s magnetosphere (see details in Winslow et al., 2015). This implies that the catalog lists strong MEs that drove interplanetary shocks. However, the exact nature of the discontinuities (e.g., whether they were shocks or waves) could not be determined given the lack of key plasma parameters. Here the term “magnetic ejecta” is used to identify a strong and smooth magnetic field region, while a rotation (generally indicative of a flux rope, see section 1) is not always present.

The second catalog of events is from Good and Forsyth (2016). This list includes 36 magnetic clouds and ICMEs detected by MESSENGER during the period 2005–2012, therefore covering mostly the cruise phase. Note that out of these 36 events, only 20 events were within a reasonable distance of Mercury’s average orbit of 0.395 AU (a heliospheric distance range of 0.309 AU < r < 0.463 AU was selected), out of which 10 events were also found in the Winslow et al. (2015) catalog. Note that the small number of events in common is due to the fact that Good and Forsyth (2016) selected only well-defined magnetic clouds, that is, with a relatively clear and smooth rotation of the magnetic field direction, coinciding with a relatively enhanced field magnitude compared with the SW magnitude level, over a period of at least 4 or 5 hr. These signatures
Figure 1. Example of an interplanetary coronal mass ejection detected by MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) during the cruise phase, at distance $r = 0.462$ AU. The $x$ axis represents the time, while the $y$ axis represents the intensity of the magnetic field. The presence of a sheath is indicated by the yellow area, while the magnetic ejecta is bounded by the blue area. The black line traces the total magnetic field. The $B_T$ (in green) and partly $B_N$ (in blue) components show a coherent rotation, typical of an azimuthal/poloidal flux rope component, while $B_R$ (in red) and partly $B_N$ (in blue) show a stronger field in the central region than at the boundaries, again typical of the axial field component within a flux rope. This behavior indicates the presence of a flux rope.

2.1.3. Selecting Events

Out of these 79 ICMEs, some had the interplanetary shock or ME boundaries within Mercury’s magnetosphere while others had data gaps that were too large, so these events could not be used for the purposes of the present study. Overall, we constrained our data sample to 41 ICMEs that presented enough data within each substructure (at least ~60% of data coverage within the sheath/ME), had clear signatures of the sheath and ME, and had the boundaries of each substructure clearly defined. An example of an ICME detected at MESSENGER is shown in Figure 1, where we have represented a time series of the intensity of the magnetic field (the total magnetic field in black, $B_R$ in red, $B_T$ in green, and $B_N$ in blue). The shaded area in yellow indicates the presence of a sheath region, while the blue area indicates the presence of an ME. The ICME shown in Figure 1 corresponds to when MESSENGER was still in cruise phase (but with the spacecraft positioned at $r = 0.462$ AU, i.e., close to Mercury’s aphelion). Examples of ICMEs interacting with Mercury’s magnetosphere are given in Winslow et al. (2015) and Good et al. (2015).

2.2. The Venus Express Mission

2.2.1. Description of the Data Set

Venus Express (Titov et al., 2006; VEX in the following) was a European Space Agency (ESA) mission launched on 9 November 2005 and officially ended in December 2014. It was inserted in orbit around Venus on 11 April 2006. Similarly to the MESSENGER mission, VEX spent enough time in the SW during its orbit around the planet to allow the detection of ICMEs. The VEX MAG (T. L. Zhang et al., 2006) detected its first ICME in July 2006 and continued its sampling of SW structures up to the end of the mission. The orbital phase of the mission overlaps with the time interval of MESSENGER orbiting around Mercury, coincides with the solar minimum between cycles 23 and 24, and coincides with the ascending and maximum phases of cycle 24.

VEX’s MAG data used in the present study are available in the ESA’s Planetary Science Archive (at https://www.cosmos.esa.int/web/psa/venus-express), and were made accessible for this study through the HELCATS project. They correspond to a 1-min cadence sampling. The magnetic field was perturbed by magnetospheric crossings of the planet. Although Venus does not generate its own magnetosphere, an induced magnetic field arises from the interaction between the SW and the planet’s ionosphere. Then, each magnetospheric crossing was cleaned in order to render a solar-wind-only data set for ICME
analysis. On average, there is one magnetospheric crossing per 24 hr with a typical duration of 2.5 hr throughout the VEX data, while an ME is typically crossed in 14 hr.

### 2.2.2. Description of the ICME Catalogs

We used the VEX ICME catalog provided by Good and Forsyth (2016) where 84 events are listed, from 2006 to 2013. This catalog focuses on ICMEs that have a clear ME signature. This means that even though plasma parameters are not available from the mission, the authors identified time intervals where the magnetic field strength relative to that of the ambient SW field is enhanced for at least a period of 4 hr. While this may seem relatively short compared with the typical duration of ICMEs near Earth (approximately 1 day, see Table 1), this threshold was allowed to account for the expansion of ME as they move away from the Sun. The authors also inferred the presence of a magnetic cloud whenever there was a magnetic field rotation. However, the lack of plasma measurements for the VEX mission, as for MESSENGER, makes it impossible to define a proper magnetic cloud: we therefore only define ME for both of these two missions.

Since the data were cleaned for induced magnetospheric passes, the detection of the ICME substructure boundaries is not straightforward, and only 67 of the Good and Forsyth (2016) events were used in the analysis discussed in this paper. An example of an ICME found in the Venus Express data is shown in Figure 2. We identified 19 ICMEs that did not have a sheath region.

### 2.3. ACE Mission

The data collected at 1 AU are provided by the Advanced Composition Explorer (ACE; Stone et al., 1998). This spacecraft was launched on 25 August 1997 and has a stable orbit around the L1 libration point. The spacecraft provides a continuous coverage of SW parameters. Similarly to Masías-Meza et al. (2016), we use the 1-s time cadence IMF and 64-s time cadence plasma measurements from two of the instruments aboard the spacecraft (MAG and SWEPAM experiments, see McComas et al., 1998; Smith et al., 1998). The data from ACE are directly available online at [http://www.srl.caltech.edu/ACE/ASC/level2/](http://www.srl.caltech.edu/ACE/ASC/level2/).

For consistency and to make comparisons possible with the study of Masías-Meza et al. (2016), we choose to consider their list of the 42 events taken from their Table A1 (44 are listed in their paper; however, data are only available for 42 events in the ACE MAG database). These events correspond to ICMEs detected between 1998 and 2006 that have been flagged in the ICME list of Richardson and Cane (2010) as MCs, which Masías-Meza et al. (2016) crossed with the MC list from Lepping ([http://lepff1.gsfc.nasa.gov/mfi/mag_cloud_S1.html](http://lepff1.gsfc.nasa.gov/mfi/mag_cloud_S1.html); Lepping et al., 2006). Here all ICMEs are associated with the presence of a sheath and an associated shock. Note that here, all ICMEs have a well-defined MC, including the plasma characteristics (section 1) that can be observed because ACE SW plasma data are available. While this provides a bias for the ACE list (since most of the ICMEs at 1 AU do not have a clearly identified MC), the idea is to use ACE results as a guideline to get more understanding on how to analyze the superposed epochs for the MESSENGER and VEX ICMEs.

### 2.4. List of the Events With Revised Boundaries

The identification of ICME boundaries is highly dependent on the set of parameters used (i.e., plasma vs. magnetic field measurements) as well as on the authors making the identification: see, e.g., the study by ; Al-Haddad et al., 2013; Dasso et al., 2006; Richardson & Cane, 2004; Riley et al., 2004; Russell et al., 2005), where the authors analyzed this dependency. Thus, we have analyzed the times of the ICME boundaries
Figure 2. Example of an interplanetary coronal mass ejections detected by Venus Express. The format of the graph (x, and y-axis) as well as the choice of color for the lines are the same as in Figure 1. The coordinates for the magnetic field vector are expressed in Venus Solar Orbital (VSO) co-ordinates: x points from Venus towards the Sun, y from Venus in the direction opposite to the planet's orbital motion, and z completes the right-handed set. Here one of the magnetic field components ($B_x$ in red) shows an inversion of sign in the ME (blue-shaded area), while the two others are maximum near the center. They are the indication of the presence of a flux rope. The absence of data in the middle of the magnetic ejecta is due to the magnetospheric crossing.

again and have provided our assessments of the boundary times for MESSENGER, VEX, and ACE (see section 5.5). In catalogs of ICMEs detected by MESSENGER or VEX, the leading edge of the sheath was identified by an increase in the magnetic field intensity and the field variance. For ACE, the addition of plasma parameters provides another constraint in the definition of the boundaries of the ICME substructures. However, identifying the trailing edge for all these ICMEs is complicated, as plasma parameters and magnetic field components, when available, may not show a distinct transition when the spacecraft crosses the interface between the ME and the SW. Furthermore, events that are found in both Winslow et al. (2015) and Good and Forsyth (2016) MESSENGER catalogs do not necessarily give the same boundaries for the sheath and the ME. Our updated catalogs are made available in Appendix A.

3. The SEA
3.1. Normalization and Binning
We use the SEA in the following as a statistical method to determine averaged time profiles of physical parameters obtained in situ. Supposing that these physical parameters behave in a similar fashion, averaging time series from all events on a normalized timescale provides meaningful mean and median profiles. Doing so accentuates the typical features. The method used to prepare the data for the superposed epoch is the same as that in Masías-Meza et al. (2016).

In order to obtain a superposed epoch for all events, the time series data for each event is first normalized so that the sheath start time (or the discontinuity time) and the ME start and end times are all normalized to the same new time range. When defining the normalized timescale, one can freely choose the interval length for both the sheath or the ME. However, these two intervals are not independent from each other, as was shown in Masías-Meza et al. (2016), where the authors found that the interval size ratio between the physical length of the ME interval and the sheath was close to 3 for ACE data, meaning that the size of the ME was on average 3 times longer than the size of the sheath at 1 AU. Thus, we use two different time ranges as normalized times, one range for the sheath and another one for the ME.

Once the time series are normalized, the time intervals are divided by the same number of bins for each event. This is because each ICME does not have the same duration nor the same number of data points, so that by binning the data, we get the same number of data points for each event normalized on the same
timescale. In the present case, we impose 50 time bins for the sheath interval, while 150 bins are taken for the ME. The superposed epoch also includes an interval of SW prior to the arrival of the sheath with a duration twice that of the sheath, and a wake region with a duration equal to that of the ME. Then, the data from different events but of the same bin number are added together and the mean and median values of the magnetic field intensity in each bin are calculated. The data gaps are taken into account for each bin implying that the means and medians are computed with a variable number of cases along the normalized time.

3.2. The Size Ratio of ICME Substructures

The interval size ratio between the physical length of the ME interval and the sheath ratio may change depending on the ICME speed. However, it is on average similar for slow and fast ICMEs, as is shown in Figure 1 of Masías-Meza et al. (2016). Hence, since the superposed epoch aims at providing the most likely generic profile, it is important to use the typical interval size ratio when doing the normalization.

Since there are no continuous plasma parameters (and hence, continuous SW speed measurements) for MESSENGER and for VEX, the spatial size of the ME as well as the sheath cannot be inferred for events seen at these two spacecraft. Indeed, the velocity information is needed to transform the time range observed into an associated spatial size. We then estimated the size ratio of ICMEs at all spacecraft, including ACE, by comparing the time interval length for the sheath and the ME, rather than the actual physical size.

First, we calculated the median duration for all ICMEs that had both a sheath and an ME clearly defined in all MESSENGER, VEX, and ACE data. We use the median value because it is statistically more robust and resistant to outliers than the average value. The results are reported in Table 1 and are expressed in units of day. We find that on average, both the sheath and the ME have a smaller duration near Mercury (0.1 and 0.3 day, respectively) than near Earth (0.5 and 0.8 day, respectively). Assuming no large deceleration of ICMEs between Mercury’s orbit and 1 AU, this confirms the numerous studies that have shown that the magnetic substructure of ICMEs expands away from the Sun (e.g., Gulisano et al., 2010, 2012; Klein & Burlaga, 1982; Nakwacki et al., 2011, and references therein).

The ME to sheath duration ratio increases from Mercury to Earth. This is because the rate of size increase (i.e., expansion) is typically different between ME and sheaths. We find that between Mercury’s and Venus’s orbits, the sheath duration increases by a factor of 3, compared to 1.7-fold between Venus’s and Earth’s orbits. However, the duration of the ME increases by a factor of 2 between Mercury’s and Venus’s orbit, and 1.3-fold between Venus’s and Earth’s orbit. Both substructures see a bigger increase in duration between Mercury’s and Venus’s orbits compared with Venus’s and Earth’s orbits, which is expected since Venus is closer to Earth than it is to Mercury.

While both the sheath and ME expand in the SW away from the Sun, the longer duration of the sheath at 1 AU is interpreted as resulting from more SW piling up in the sheath from Mercury’s to Earth’s orbit. Indeed, if the ICME moves away from the Sun with a speed larger than the ambient SW, it will continue to accumulate a sheath by a “snow plow” effect. Then, the thickness of the sheath depends on both how much plasma and magnetic field is accreted/compressed from the pre-SW into the sheath and how much of it is able to escape toward the sides. This was shown with magnetohydrodynamic simulations by Siscoe and Odstrcil (2008): the authors showed that the SW piles up in front of ICMEs since it is unable to flow completely around the ejecta, due to the lateral expansion of ICMEs.

Furthermore, physical processes like magnetic reconnection at the rear of an ICME, due to an overtaking stream or another ICME, could also contribute to reducing the size of the ME with respect to an increasing sheath size. The study of Ruffenach et al. (2015) showed that the front and rear boundaries used to define the ejecta are chosen such that the duration of the flux rope is overestimated. Often, the ME might be reduced in size due to reconnection at the rear, even though it is still expanding overall. Such an erosion effect can however also take place at the front of the ME, therefore leading to the erosion of both the sheath region and the ME. As such, it seems more plausible that the increase of the sheath duration compared with that of the ME is due to a SW pileup as well as the dynamic expansion of the sheath.

3.3. Magnetic Field Correction for the Eccentricity of Mercury’s Orbit

ACE and VEX collect data at a roughly constant distance from the Sun due to the low eccentricity of Earth’s and Venus’s orbits. On the other hand, Mercury’s orbit is more eccentric than that of the other two planets, and as such, there is a variation in distance for the sample of data considered. This variation affects the measured ICME magnetic field intensity. It is well established that the magnetic field intensity within the
Figure 3. Superposed epoch analysis of the mean (black crosses) and median (red points) magnetic field intensity for all the ICMEs seen at (a) MESSENGER, (b) Venus Express (VEX), and (c) ACE. The yellow and blue regions are the sheath and the magnetic ejecta (ME) regions, respectively (a color convention kept for the superposed epoch plots). The number of studied interplanetary coronal mass ejections is indicated in the top left for the sheath, and top right for the ME. The normalized time (horizontal axis) is described in section 3.1. The vertical axis provides the field strength in nanoteslas. The colored arrows and vertical lines (yellow for MESSENGER, orange for VEX, and green for ACE) indicate the locations of the maxima in the median magnetic field profiles. The relative locations of the vertical lines show an asymmetry that is more pronounced at MESSENGER than at VEX and ACE. ICMEs = interplanetary coronal mass ejections; MESSENGER = MErcury Surface, Space ENvironment, GEochemistry, and Ranging; ACE = Advanced Composition Explorer.

ME decreases with distance away from the Sun as a power law (Bothmer & Schwenn, 1998; Gulisano et al., 2010; Kumar & Rust, 1996; Leitner et al., 2007; C. Wang, Du, & Richardson, 2005; Winslow et al., 2015). The multispacecraft study of Winslow et al. (2015) reports a fit of a power law to the data for the mean ME magnetic field of: $<B> = (7.5 \pm 1.2)r^{-1.95 \pm 0.19}$, where $B$ is expressed in nanoteslas and $r$ in astronomical unit. The value found in this study for $B$ at 1 AU is similar to the ones found by other authors (e.g., Y. Wang, Ye, et al., 2005), with a steeper radial dependence. In the following, the magnetic field intensity for all MESSENGER ICME events is normalized so as to consider the same distance from the Sun (taken as 0.37 AU) following the relationship found by Winslow et al. (2015).

4. Superposed Epoch Results of the Entire Data Sets at the Different Spacecraft

4.1. Magnetic Field Intensity Profiles at the Different Spacecraft

The results obtained for the SEAs at different spacecraft are shown in Figure 3, and the data for each superposed epoch have been put online (see all superposed epoch data: https://figshare.com/s/3e0394e629fbed907152). The top panel (a) shows the SEA of all ICMEs seen at Mercury, the middle one (b) of all ICMEs seen at VEX, and finally the bottom panel (c) of all the selected ICMEs seen at ACE. The number of events taken to obtain the superposed epochs is indicated in each graph. Note that the number...
Table 2
Median Values, as Well as the Mean and the Standard Deviation (in Brackets) of the Total Magnetic Field Intensities Within the Solar Wind, the Sheath, the ME, and the Wake for Each of the Superposed Epoch Obtained at MESSENGER, VEX, and ACE

| Substructures | MESSENGER | VEX | ACE |
|---------------|-----------|-----|-----|
| $B_{SW}$      | 23.0 (22.9 ± 1.4) | 7.2 (7.2 ± 0.4) | 6.1 (6.2 ± 0.3) |
| $B_{sheath}$  | 42.6 (42.9 ± 2.7) | 12.2 (12.3 ± 0.7) | 13.7 (13.4 ± 0.9) |
| $B_{ME}$      | 42.8 (42.1 ± 5.8) | 13.7 (13.8 ± 0.9) | 12.9 (12.5 ± 1.3) |
| $B_{wake}$    | 29.8 (29.8 ± 1.7) | 9.4 (9.3 ± 0.9) | 7.2 (7.7 ± 1.0) |

Note. ME = magnetic ejecta; MESSENGER = MErcury Surface, Space ENvironment, GEochemistry, and Ranging; VEX = Venus Express; ACE = Advanced Composition Explorer.

of events for the sheath and the ME is not the same. This is because in some cases, even though an ICME is clearly identified, either the sheath or the ME lacks enough data points so that these substructures do not enter into the averaging calculation for the superposed epoch. The timeline has been normalized so that $t_{\text{norm}} = 0$ corresponds to the discontinuity time, while on the vertical axis, we plot the magnetic field $B$ in nanotesla. The yellow-colored area corresponds to the sheath region, while the blue one corresponds to the ME region. The sheath duration is normalized to one time unit and the ME to three time units. This ratio, representative of the results found in section 3.2, is set at all spacecraft so as to provide a more straightforward comparison between the different averaged profiles.

In all these superposed epochs, the transition between the sheath and the ME region at $t_{\text{norm}} = 1$ is less clearly seen than the transition at $t_{\text{norm}} = 0$, but a change from a decreasing to an increasing total field is evident. The transition between the ME and the wake is somewhat continuous.

We quantified the median value of the magnetic field intensity within each of the substructures (sheath and ME) as well as the preceding SW and wake region for comparison, for each superposed epoch obtained at the three different spacecraft (Table 2). The values of the magnetic field intensities decrease from MESSENGER all the way to ACE, which is an expected result as discussed in section 3.2. The discontinuity jump, calculated using the ratio of the intensities between the sheath and the SW preceding the ICME, is 1.85 at MESSENGER, 1.70 at VEX, and 2.23 at ACE: the ratio therefore stays at comparable values. We also note that the ratio of the ME magnetic field intensity and that of the sheath is 1.01 at MESSENGER, 1.14 at VEX, and 0.94 at ACE, which is not that different from one spacecraft to another. Interestingly, for these events the average sheath and ejecta magnetic field strengths are quite similar.

Finally, the wake does not return to the same level of magnetic field intensity as the preceding SW after a time interval comparable to the ME interval (the ratio of magnetic field in the wake over that of the pre-ICME SW is 1.29 for MESSENGER, 1.31 for VEX, and 1.17 for ACE). This indicates that the passage of an ICME is felt much longer than just within the interval of the ICME disturbance. This effect was pointed out recently in the study by Temmer et al. (2017), who found that interplanetary space needs approximately 2 to 5 days at 1 AU to recover from the impact of ICMEs.

4.2. Evolution of the Magnetic Field Asymmetry
At Mercury’s orbit, the ME total magnetic field increases and decreases shortly after the start of the ME. The profiles obtained at the other two spacecraft show that the start of the decrease is further away from the beginning of the ME than for MESSENGER. We note, however, that none of the superposed epoch profiles are completely smooth. This could be due to the variability of each profile and the relatively small number of similar profiles within the samples.

We found that for all spacecraft, the profiles of the ME show a peak in $|B|$, indicated with the yellow arrow and dashed lines in the MESSENGER data, orange in the VEX data, and green in the ACE data (Figure 3). The lines have been superposed on the results for all spacecraft to compare the position of the peaks for each spacecraft. This peak appears closer to the sheath for the MESSENGER data compared with the others and moves slightly toward the center of the ME for the VEX and ACE data. We also quantify this change in the symmetry of the profile by calculating the first moment of each of the curves delimited by the ME boundaries:
Figure 4. Superposed epoch for the 19 interplanetary coronal mass ejections (ICMEs) without a sheath detected by Venus Express. The magnetic ejecta region is indicated with the blue-shaded area. The plotting convention is the same as in Figure 3.

\[ \Delta t = \frac{1}{(t_{\text{rear}} - t_{\text{front}})} < B > \int_{t_{\text{front}}}^{t_{\text{rear}}} (t - t_{\text{rear}} + t_{\text{front}}) B(t) \, dt \]  \hspace{1cm} (1)

This first moment, written as \( \Delta t \) and expressed in units of time, is defined as the center of mass for 1-D distributions. It is a quantitative measure used here to quantify the asymmetry of the profile. This is a standard mathematical expression generally used for calculating the weighted mean position of a distribution of mass, or any quantity. It is a simple and robust measure of the asymmetry of a function. Other parameters such as distortion parameters can also be found in the literature (Nieves-Chinchilla et al., 2018). Considering only the superposed epoch profile of the ME for each spacecraft with a duration normalized to 1 (so that the beginning of the ME is at 0 and its end is at 1), we found that the first moment of the MESSENGER curve profile is situated at a distance 0.46 away from the beginning of the ME (0.04 from the center of the time interval), that for the VEX curve is at 0.48, and that for ACE is at 0.47 (respectively, 0.02 and 0.03 from the center of the time interval). The different locations of the first moments for each profile therefore follow the same trend as for the peaks. Quantifying the asymmetry, the comparison between all the superposed epochs at all the spacecraft does not give a clear indication of an evolution of an asymmetric total field profile with heliocentric distance.

Note also that the superposed epoch for the VEX data shows a second bump within the ME profile (Figure 3). Looking back at each individual case, we were not able to find a few specific events that could indicate why this bump is there. To check the stability of this bump, we removed several events and looked at their influence on the overall profile. By repeating this with different criteria (removing only outlier events, or removing events with a profile away from the average one, or removing events with structures within the ME), we confirmed that the bump is still present. We conclude that this second bump in the magnetic profile is not due to a small number of events, that is, outliers with a specific property.

4.3. ME Without Sheaths

We also selected events within the VEX sample that were not associated with any sheath (we found 19 cases). Note that since all ICMEs studied at MESSENGER and ACE have a sheath, we investigated the ME without sheaths in the VEX data only. We computed the superposed epoch for these cases, as shown in Figure 4. In this figure, the blue-shaded area represents the ME region, preceded and followed by the surrounding SW. Interestingly, the superposed epoch ME profile has a rounder profile than that of the ME preceded by a sheath region as was shown in Figure 3b. We calculated the asymmetry (as discussed above) and found that the first moment was located at 0.5, that is, at the center of the ME.

Following the results from Masías-Meza et al. (2016), slower ICMEs, which also tend to have weaker sheaths (in terms of the ratio between the SW and sheath magnetic field intensity value) display a symmetric profile for the ME substructure. This was interpreted as a consequence of a state in relaxation with the surrounding conditions and little interaction with the sheath. The ICMEs without sheaths showing a symmetric profile at the orbit of Venus extend the results from Masías-Meza et al. (2016) obtained at Earth’s orbit. When the sheath is nonexistent, the speed at which the structures are propagating is close to that of the SW. In such conditions, the magnetic field within the ME only needs to “adjust” to the surrounding environment without an extra higher total pressure in the sheath providing this symmetric profile.
5. SEAs Using Subcategories of ICMEs

In the following, we investigate in more detail the profiles obtained at each spacecraft by separating the samples into subgroups of ICMEs.

5.1. What Can Classifying ICMEs Reveal?

In Masías-Meza et al. (2016), the authors analyzed the generic magnetic field intensity profiles of ICMEs at 1 AU and the dependence of this profile with the average MC speeds. To do so, they created three subcategories of ICMEs classified with their speeds (low, medium, and high speed). They found that the MC inside ICMEs with the lowest speeds have a more symmetric profile with a less pronounced sheath, while the MCs propagating with a higher speed have a more asymmetric profile with a higher jump of $B$ at the shock preceding the sheath (see their Figure 3). They concluded that slow MC profiles can be interpreted as resulting from a relaxed force-free configuration, contrary to their faster counterparts. In the following, we investigate whether such differences between different categories of ICMEs can be observed closer to the Sun.

Classifying ICMEs with their average speed is not easy to do for the MESSENGER and the VEX data. First, the parameter is not readily available for both missions and for all cases. In some cases, it was possible to obtain limited SW speed data from MESSENGER’s FIPS instrument (e.g., see Figure 2 in Good et al., 2015); however, such data are not available for most ICME cases at MESSENGER. A short burst of density and speed measurements were made in the SW by VEX’s ASPERA-4 instrument once every 24 hr (e.g., see Figure 9 in Rouillard et al., 2009). However, the recovered speed data are very patchy and have considerably larger uncertainties associated with them than data obtained from dedicated SW plasma analyzers (as found on ACE, for example).

Therefore, we investigate in the following the possibility to use another parameter to rank the magnetic clouds in different categories that can correlate well with the speed. One straightforward possibility is to use the transit time from the Sun to estimate the average speed at Mercury and at Venus. The Winslow et al. (2015) list has an estimate of the speed based on the Sun-Mercury propagation, from the identification of the coronal CME causing the ME at MESSENGER. The speeds found for the set of data vary between 300 to 2,400 km/s. However, the associated CME has not been identified for all the events, so the transit speed can only be calculated for some of the events.

5.2. Sheath Magnetic Field Strength as Proxy for the ME Speed

Since the proton speed is available in the ACE 1 AU data, and since we only have the magnetic field intensities available at MESSENGER and VEX, we investigate in the following whether any correlation exists between the speed and the magnetic field intensity recorded within the different substructures.

We start by calculating the Pearson and Spearman correlation coefficients between the mean or the median value of the total magnetic field and the speed inside the sheath and inside the ME for each ICME seen at ACE. We find that it makes no difference whether we use the mean or the median values for this calculation, so we further proceed using the median values.

The results of four different correlation studies using ACE data are shown in Figure 5 with the Pearson and Spearman correlation coefficients in Table 3. The best correlation is found between the proton speed within the ME ($V_{ME}$) and within the sheath ($V_{sheath}$, Table 3). This result is expected: as the sheath is being driven by the ME, we indeed expect these substructures to propagate with similar speeds. Accordingly, a slightly lower correlation is present between $V_{ME}$ and $V_{sheath} - V_{SW}$, where $V_{SW}$ is the SW speed preceding the ICME (Figure 5a).

We then look at the correlations between the magnetic field intensities within the sheath $B_{sheath}$ (respectively within the ME, $B_{ME}$) with the speeds. The best correlation is found between $B_{sheath}$ and $V_{sheath} - V_{SW}$ (Figure 5b). We find that $B_{sheath}$ and $V_{ME}$ are moderately correlated having Pearson and Spearman correlation coefficients of 0.54 and 0.64, respectively (Figure 5c). $B_{ME}$ and $V_{ME}$ show poor or even no correlation with Pearson and Spearman correlation coefficients of 0.22 and −0.04, respectively (Figure 5d). These correlations are in agreement with the results found in Owens et al. (2005) for a larger sample of ICMEs at 1 AU, as well as the results of Liu et al. (2008) who showed that the flow speed and the magnetic field in the sheath correlates well with the speed of the ejecta.

Note here that we do not investigate the relation between the maximum magnetic field intensity in the ME and the ICME speeds. These were found to be moderately correlated: Richardson and Cane (2010) found...
that, at least for ICMEs with a magnetic cloud, the correlation coefficient is around 0.6 (see their Figure 11) while Möstl et al. (2014) later confirmed a relationship between the two (see their Figure 14). In our study, we mostly focus on correlations with median/mean quantities. This is because maximum values are not representative of the overall magnetic field behavior. Furthermore, maximum values for the magnetic field are not always found for VEX and MESSENGER data due to the magnetosphere crossings. We therefore choose a quantity that can be consistently studied with the different samples available to us and, moreover, which is statistically robust (as it is derived from an ensemble of points in contrast to a single point).

The correlation between $B_{\text{sheath}}$ and $V_{\text{ME}}$ means that, assuming this relationship also holds for ICMEs at Mercury and Venus, we now have a proxy for categorizing ICMEs with their speeds. In the following, we therefore define three categories of MESSENGER, VEX, and ACE ICMEs with weakest, medium, and strongest $B_{\text{sheath}}$ values, which we expect to be comparable to classifying the events by increasing the order of speed.

5.3. Superposed Epoch Profiles for Subcategories of ICMEs

The results of the SEA made for each of the categories and at each spacecraft is shown in Figure 6 for the MESSENGER data, Figure 7 for the VEX data, and Figure 8 for the ACE data.
Table 3
Pearson and Spearman Correlation Coefficients
Comparing the Median Total Magnetic Field B Within Each Substructures, B with the Median Proton Speed V, as Well as V for Each Substructure

| Parameters                  | Pearson | Spearman |
|-----------------------------|---------|----------|
| Bsheath vs. BME             | 0.37    | 0.26     |
| Vsheath vs. VME             | 0.92    | 0.93     |
| Vsheath − VSW vs. VME       | 0.77    | 0.80     |
| BME vs. VME                | 0.22    | −0.04    |
| Bsheath vs. VME             | 0.54    | 0.64     |
| BME vs. Vsheath             | 0.14    | −0.10    |
| Bsheath vs. Vsheath         | 0.46    | 0.60     |
| BME vs. Vsheath − VSW       | 0.18    | −0.02    |
| Bsheath vs. Vsheath − VSW   | 0.63    | 0.73     |

Note. The interplanetary coronal mass ejections are sampled at ACE with a 1-s time cadence. The highest correlations are indicated in bold.

5.3.1. Profiles for Each Category
Overall, the same trend can be found between the different spacecraft: the superposed epoch profile with ICMEs with lower $B_{\text{sheath}}$ has a flatter profile (while still peaked) at all spacecraft, while the profiles from larger $B_{\text{sheath}}$ show a steeper decline in the magnetic field strength from the leading to the trailing edge of the ME. Note that while we used $B_{\text{sheath}}$ as a proxy to classify the ICMEs, we find that the three subcategories for ACE data show the same profiles as the ones found in Masías-Meza et al. (2016) when the classification was made on the speed within the ME, therefore justifying the use of $B_{\text{sheath}}$ as an ordering parameter.

For the small $B_{\text{sheath}}$ category, we find that the profile of the ME is more asymmetric at Mercury's orbit than it is at Earth's orbit with a peak of the profile close to the sheath for the MESSENGER data, while the peak is clearly at the center for ACE data, indicating an evolution toward an equilibrium. We provide below a quantification of this asymmetry.

5.3.2. Magnetic Field Intensities
As a next step, we compare the magnetic field intensities in all the substructures of the ICME superposed epoch and at all spacecraft. The results for the SW magnetic field intensities are reported in the first line in Table 4. We find a similar trend between the same categories at all spacecraft for the characteristics of the SW preceding the ICME: the magnetic field strength of the SW ($B_{\text{SW}}$) preceding ICMEs having large $B_{\text{sheath}}$ (i.e., faster ICMEs) is higher than the magnetic field strength of the SW preceding ICMEs having small $B_{\text{sheath}}$ (i.e., slower ICMEs). This is not simply a correlation between $B_{\text{SW}}$ and $B_{\text{sheath}}$ since the same trend was found with categories defined with $V_{\text{ME}}$ in Masías-Meza et al. (2016).

We next checked the ratio of the magnetic field intensities between the different substructures for each of the categories. The results are given in the second to fourth line in Table 4.

We find first that the ratio of the sheath magnetic field intensity and that of the pre-SW, $B_{\text{sheath}}/B_{\text{SW}}$, increases between the category "small" (with the lowest $B_{\text{sheath}}$) and category "large" (with the highest $B_{\text{sheath}}$), from 1.7 to 2.5 for the MESSENGER data, from 1.4 to 2 for the VEX data, and from 2 to 2.5 for the ACE data, as expected from the category selection.

We also find that the ratio $B_{\text{ME}}/B_{\text{sheath}}$ decreases from category small to category large for each of the spacecraft (from 1.1 to 0.8 for MESSENGER data, from 1.4 to 1.1 for VEX data, and from 1.4 to 0.7 for the ACE data). For both MESSENGER and ACE, we also find that the magnetic field intensity in the sheath region is larger than that inside the ME for the ICMEs within category large (Figures 6 and 8). This stronger sheath is consistent with the asymmetric magnetic field profile in the ME.

Finally, we also calculate the ratio of magnetic field intensities between the wake and the pre-ICME SW regions. We find that at all spacecraft, the ratio decreases (from 1.4 to 1.1 for the MESSENGER data, from 1.4 to 1.1 for the VEX data, and from 1.4 to 0.7 for the ACE data).
Figure 6. Superposed epoch of the total magnetic field for the MESSENGER data with three categories, where all the events are classified with increasing $B_{\text{sheath}}$ intensities. The yellow and blue regions are the sheath and the ME regions, respectively (a color convention kept for the superposed epoch plots). The black crosses (respectively red points) are the mean (respectively median) values over the number of studied interplanetary coronal mass ejections (indicated in the top left). The normalized time (horizontal axis) is described in section 4. The vertical axis provides the field strength in nanotesla. MESSENGER = MErcury Surface, Space ENvironment, GEochemistry, and Ranging.

to 1.1 as well for the VEX data, and from 1.7 to 0.9 for the ACE data). In other words, the SW magnetic field intensities pre- and post-ICMEs are more different for “slower” ICMEs than for “faster” ones. While ICMEs detected as fast at different spacecraft are ICMEs that are originally fast and that keep a higher speed relative to the ambient medium, slower ICMEs are ICMEs that are in a range from originally slow to fast events that have been slowed down by the SW, so as to become all slow ICMEs when observed in situ (see Masías-Meza et al., 2016). As such, the differences in the pre- and post-ICME SW characteristics for slow events could be due to initially faster ICMEs that have drastically been slowed down. For such cases, interactions with the SW (such as drag) could be accompanied with magnetic reconnection eroding the magnetic flux rope of the ejecta, leading to a larger wake dominated by this eroding mechanism and as such with different characteristics than the pre-ICME SW. Also, slow ICMEs are more likely to be overcome by a fast SW stream or a fast ICME. In such cases, the wake region would be disturbed by these structures, which furthermore could be compressed by the interaction (such an effect was shown in Rodriguez et al., 2016).

5.3.3. Asymmetry Parameter
We calculated the asymmetry parameter in the same way as section 4 (see equation (1)), the results being shown in the last line of Table 4. We find a similar tendency between the different categories for the MES-
Figure 7. Superposed epoch of the total magnetic field for the Venus Express data with three categories, where all the events are classified with increasing $B_{\text{sheath}}$ intensities. Same color convention as Figure 6.

SENGER and ACE data: the asymmetry parameter is negative as expected with a stronger field at the front. Its absolute value, which indicates the significance of the asymmetry, increases from 0.02 for the slower ICMEs to 0.07 for the faster ICMEs for MESSENGER, and from 0 (i.e. a central peak) to 0.05 for the ACE data. The superposed epoch profiles for VEX are less smooth, having more pronounced bumps than for MESSENGER and ACE. They also imply a different conclusion: we found approximately the same asymmetry parameter for all the ICME categories. However, when looking at Figure 7, one can see that the profiles for each category are qualitatively similar to that found for MESSENGER and ACE if we do not take into account the second (later) peak for medium and faster categories.

In summary, we find that the slower ICMEs have a more symmetric shape, with a peak closer toward the middle of the profile, while for faster ICMEs, the profile steepens, with a peak closer to the sheath.

We conclude that the slower MEs relax with increasing solar distance, which is related to the existence of a weaker sheath and a longer time to reach a given solar distance. In contrast, the fast MEs and their expansion drive a strong shock, then a strong sheath pressure builds up, which creates asymmetric conditions between the front and the rear of faster MEs. These events being still significantly faster than the overtaken SW, the sheath is expected to keep being built up to at least 1 AU. Also, slower ICMEs are more likely to be overtaken by fast streams or another CME, which creates a compression at the rear of the structure. This could affect the profile to make it more symmetric by creating an increase of the magnetic field intensity at the rear of the ME similar to that found at the beginning of the ME (fourth row of Table 4). Understanding such mechanisms will require further case studies and associated modeling.
5.4. Does Aging Impact the Profiles of ICMEs?

Comparing MESSENGER and ACE data means that we are comparing ICMEs at different “ages,” with the age of the structure corresponding to the time it has spent in the SW. Since the ICME takes a finite time to pass the observing spacecraft, the leading edge of the ICME is observed in a younger stage than the trailing edge.

One can estimate an average age difference between when the ICME starts (at the front of the ICME) and ends (at the rear of an ICME). The sampling at MESSENGER starts approximately 20 hr after the front of the ICME has left the coronal environment of the Sun. This has been estimated using the transit speed of all ICMEs seen departing the Sun in our sample and detected at MESSENGER near Mercury. The typical ME time duration in our MESSENGER sample is around 10 hr. This means that the observation of the rear of the ICME is made 30 hr after the structure has left the solar corona, when the ICME is 1.5 times older than the front.

Similarly, when a typical ICME arrives at ACE, its front part has left the Sun’s atmosphere approximately 3.5 days before. Since the typical ICME duration is estimated around 30 hr in our sample, this means that the rear part of the ICME is around 1.36 times older than its front, similar to what was found for MESSENGER.

In Démoulin et al. (2008) and Démoulin and Dasso (2009), the authors investigated models of ICME expansion and its consequences to understand the profiles of ICMEs. A spacecraft measures the magnetic field
Table 4

Values of the Magnetic Field Intensity in the Solar Wind and Ratio of Median Magnetic Field Intensities in Each Substructure for Each Subcategory of ICMEs Seen at Different Spacecraft and Classified With the Median Magnitude of Bsheath

| $B_{\text{sheath}}$ | MESSENGER | VEX | ACE |
|---------------------|-----------|-----|-----|
|                     | Small     | Medium | Large | Small | Medium | Large | Small | Medium | Large |
| $B_{\text{SW}}$ ($nT$) | 17.7      | 25.2 | 25.6 | 5.7 | 6.8 | 9.4 | 4.3 | 7.2 | 7.3 |
| $B_{\text{sheath}}/B_{\text{SW}}$ | 1.7 | 1.7 | 2.5 | 1.4 | 1.7 | 2 | 2 | 2 | 2.5 |
| $B_{\text{ME}}/B_{\text{sheath}}$ | 1.1 | 1 | 0.8 | 1.4 | 1.2 | 1.1 | 1.4 | 0.9 | 0.7 |
| $B_{\text{wake}}/B_{\text{sheath}}$ | 1.4 | 1.4 | 1.1 | 1.4 | 1.4 | 1.1 | 1.7 | 1.2 | 0.9 |
| Asymmetry parameter | $-0.02$ | $-0.04$ | $-0.07$ | $-0.02$ | $-0.01$ | $-0.02$ | 0 | $-0.03$ | $-0.05$ |

Note. ICMEs = interplanetary coronal mass ejections; MESSENGER = MErcury Surface, Space ENvironment, GEochemistry, and Ranging; VEX = Venus Express; ACE = Advanced Composition Explorer.

at different times across the encountered ICME. If the ICME is evolving during the crossing, for example, expanding, the observed data are mixing the spatial and temporal variations. The presence of an expansion implies a transformation of the observed field profile, because the younger front of the ICME is more compact than the older rear. This is detected as a higher magnetic field intensity at the front than at the back, as we found for the fast ICME category at all spacecraft. This effect is larger for larger ICMEs as they are observed during a longer time (for the same mean velocity value). However, Démoulin et al. (2008) showed that this effect was not significant enough to explain the asymmetry found in the ICME profiles at 1 AU.

We found, in our limited sample, that the aging is similar at Mercury to what it is at Earth: ICMEs take around 3 times longer to propagate from the Sun to Earth than to Mercury, but also take 3 times longer to be sampled at Earth than at Mercury, in agreement with a comparable nondimensional expansion rate found in the inner heliosphere (with the HELIOS missions, Gulisano et al., 2010) and at 1 AU. Then, we conclude that the aging effect likely does not have an important effect on the asymmetry profile seen at Mercury. More precisely, at Mercury as at 1 AU, the aging effect is expected to create a significant asymmetry in $B$ between the front and the rear of the ME only within very large ICMEs expanding faster than usual.

Table A1

Table of ICMEs Seen at MESSENGER

| Event number | Year of event | Discontinuity$^a$ | ME$^b$ leading edge | ME$^b$ trailing edge | $r_H^m$/AU | Catalog reference$^d$ |
|--------------|---------------|-------------------|--------------------|---------------------|------------|------------------------|
| 1            | 2009          | 19                | 20                 | 06:04:19            | 20         | 23:54:14               | G          |
| 2            | 2009          | 45                | 46                 | 04:23:31            | 46         | 14:12:28               | G          |
| 3            | 2009          | 51                | 51                 | 19:36:28            | 52         | 00:20:09               | G          |
| 4            | 2009          | 266               | 266                | 13:55:12            | 267        | 06:53:16               | G          |
| 5            | 2009          | 360               | 360                | 16:33:36            | 361        | 18:21:36               | G          |
| 6            | 2010          | 242               | 242                | 22:00:00            | 243        | 12:37:26               | G          |
| 7            | 2010          | 309               | 309                | 18:00:00            | 310        | 13:07:40               | G          |
| 8            | 2010          | 342               | 343                | 02:55:00            | 343        | 15:40:00               | G          |
| 9            | 2010          | 347               | 347                | 11:44:09            | 347        | 16:45:07               | G          |
| 10           | 2011          | 68                | 68                 | 02:08:09            | 68         | 12:28:48               | G          |
| 11           | 2011          | 139               | 139                | 16:45:07            | 140        | 02:00:00               | G, W       |
| 12           | 2011          | 155               | 155                | 16:15:46            | 156        | 00:43:24               | W          |
| 13           | 2011          | 156               | 156                | 04:29:45            | 156        | 06:10:00               | G, W       |
| 14           | 2011          | 159               | 159                | 06:45:00            | 159        | 10:06:41               | W          |
| 15           | 2011          | 172               | 172                | 21:30:00            | 173        | 14:55:00               | W          |
| 16           | 2011          | 265               | 265                | 12:46:24            | 265        | 21:41:37               | W          |
| 17           | 2011          | 278               | 278                | 06:02:02            | 278        | 12:32:19               | W          |
| 18           | 2011          | 288               | 288                | 13:30:00            | 289        | 06:23:02               | G, W       |
| 19           | 2011          | 364               | 364                | 21:12:57            | 365        | 09:19:52               | G, W       |
Table A1 (continued)

| Event number | Year of event | Discontinuity DOY | Discontinuity time | ME\(^a\) leading edge DOY | ME leading edge time | ME trailing edge DOY | ME trailing edge time | \(r_s^b\) AU | Catalog reference | Reference |
|--------------|--------------|-------------------|--------------------|--------------------------|----------------------|---------------------|---------------------|------------|-----------------|-----------|
| 20           | 2012         | 2                 | 18:28:13           | 2                        | 19:54:10             | 2                   | 22:50:00           | 0.434      | W               | W         |
| 21           | 2012         | 2                 | 22:55:00           | 3                        | 00:42:00             | 3                   | 04:53:00           | 0.434      | new             | new       |
| 22           | 2012         | 3                 | 04:52:48           | 3                        | 07:53:57             | 3                   | 12:40:37           | 0.436      | W               | W         |
| 23           | 2012         | 37                | 23:30:03           | 38                       | 00:49:59             | 38                  | 09:08:51           | 0.415      | W               | W         |
| 24           | 2012         | 64                | 10:34:41           | 64                       | 14:36:30             | 64                  | 19:00:00           | 0.309      | W               | W         |
| 25           | 2012         | 64                | 20:00:00           | 64                       | 22:30:00             | 65                  | 12:30:00           | 0.309      | new             | new       |
| 26           | 2012         | 65                | 12:28:50           | 65                       | 13:15:39             | 65                  | 15:15:00           | 0.311      | W               | W         |
| 27           | 2012         | 67                | 04:37:44           | 67                       | 06:10:53             | 67                  | 14:52:41           | 0.315      | G, W            | G, W      |
| 28           | 2012         | 71                | 05:34:10           | 71                       | 06:31:14             | 71                  | 10:00:00           | 0.331      | W               | W         |
| 29           | 2012         | 264               | 18:29:00           | 264                      | 19:17:00             | 264                 | 21:18:00           | 0.426      | W               | W         |
| 30           | 2013         | 248               | 13:39:59           | 248                      | 15:15:35             | 248                 | 22:54:41           | 0.416      | W               | W         |
| 31           | 2013         | 299               | 11:07:22           | 299                      | 13:21:07             | 299                 | 23:15:00           | 0.349      | W               | W         |
| 32           | 2013         | 300               | 12:35:00           | 300                      | 15:00:00             | 301                 | 01:53:06           | 0.344      | W               | W         |
| 33           | 2013         | 302               | 11:14:46           | 302                      | 11:14:46             | 302                 | 19:10:55           | 0.334      | W               | W         |
| 34           | 2014         | 24                | 03:25:19           | 24                       | 04:25:10             | 24                  | 08:15:00           | 0.340      | W               | W         |
| 35           | 2014         | 27                | 18:37:50           | 27                       | 19:55:25             | 28                  | 00:00:00           | 0.323      | W               | W         |
| 36           | 2014         | 208               | 16:01:06           | 208                      | 19:10:14             | 209                 | 06:06:00           | 0.309      | W               | W         |
| 37           | 2014         | 245               | 08:00:31           | 245                      | 08:27:50             | 245                 | 12:38:52           | 0.454      | W               | W         |
| 38           | 2014         | 348               | 08:55:29           | 348                      | 09:52:29             | 348                 | 17:19:15           | 0.463      | W               | W         |
| 39           | 2015         | 80                | 09:42:02           | 80                       | 11:28:46             | 80                  | 15:03:10           | 0.439      | W               | W         |
| 40           | 2015         | 97                | 23:30:30           | 98                       | 02:01:56             | 98                  | 06:16:39           | 0.351      | W               | W         |
| 41           | 2015         | 104               | 16:05:39           | 104                      | 17:41:27             | 104                 | 22:27:30           | 0.318      | W               | W         |

Note. ICMEs = interplanetary coronal mass ejections; MESSENGER = MERCury Surface, Space ENvironment, GEochemistry, and Ranging; DOY = day of year; ME = magneti ejecta; AU = astronomical unit. 
\(a\)This is either a disturbance or a shock. \(b\)ME stands for magnetic ejecta. \(c\)Heliospheric distance of the s/c in astronomical unit. \(d\)“G” stands for Good et al. (2015). “W” stands for Winslow et al. (2015).

5.5. Are Superposed Epoch Analyses Robust to the Definition of ICME Boundaries?

Defining the boundaries of ICMEs is difficult (see section 3.2). On the one hand, it is highly dependent on the availability of different sets of data (e.g., plasma and magnetic field parameters) that can help to consider wider criteria and guide the eye when defining the different substructures of ICMEs. On the other hand, defining boundaries can also depend from one person to another, as these boundaries are not objectively and clearly defined. To check the robustness of the SEA, we checked whether the results were consistent from one catalog of boundaries to another.

As described in section 2, we first used the catalogs already available for the MESSENGER, VEX, and ACE ICMEs, and we had a second look at all of the events listed. While the disturbance start is relatively easy to define, as the transition between the pre-ICME SW and the sheath is clear, the transition between the sheath and the ME, as well as the transition between the ME the post-ICME SW, are both more difficult to define. In this second check, we reassessed the boundaries by eye and then compared our results. We then constructed a list of ICMEs with the boundaries defining the shortest ME found between the different coauthors of this paper, as well as a list with the less restrictive boundaries. The reason for choosing the shortest durations for the ME is to be the most conservative in terms of defining the ME. When applying the superposed epoch technique, we found very little difference between the superposed epochs built from the two different lists, therefore showing that the method is robust and is not impacted by the fluctuations linked with the subjective definition of boundaries. This means that the results of the SEA were not strongly dependent on the exact choice of the boundaries. The list presented in Appendix A is the most conservative (most restrictive) list of ICME boundaries.
Table A2
Table of ICMEs Seen at Venus Express

| Event number | Year of event | Discontinuity\(^a\) DOY | Discontinuity\(^a\) time | ME\(^b\) leading edge DOY | ME leading edge time | ME trailing edge time | \(\rho_{\| H}^c\) AU |
|--------------|---------------|--------------------------|---------------------------|--------------------------|----------------------|----------------------|------------------|
| 1            | 2007          | 44                        | 04:48:00                  | 44                       | 14:40:16             | 45                   | 09:33:13         | 0.725            |
| 2            | 2007          | 117                       | 00:14:24                  | 117                      | 08:52:48             | 117                  | 16:10:33         | 0.719            |
| 3            | 2007          | 126                       | 00:43:12                  | 126                      | 08:24:00             | 126                  | 20:52:48         | 0.719            |
| 4            | 2007          | 144                       | 19:12:00                  | 145                      | 03:36:00             | 145                  | 19:59:31         | 0.721            |
| 5            | 2007          | 167                       | 02:15:21                  | 167                      | 02:15:21             | 167                  | 17:16:48         | 0.724            |
| 6            | 2007          | 167                       | 22:19:12                  | 167                      | 23:31:12             | 168                  | 10:42:14         | 0.724            |
| 7            | 2007          | 285                       | 17:24:00                  | 285                      | 18:43:12             | 285                  | 21:34:33         | 0.722            |
| 8            | 2007          | 321                       | 04:19:12                  | 321                      | 07:20:38             | 321                  | 19:00:28         | 0.719            |
| 9            | 2007          | 341                       | 18:08:38                  | 342                      | 03:44:38             | 343                  | 14:44:09         | 0.719            |
| 10           | 2008          | 364                       | 16:13:26                  | 364                      | 20:45:36             | 365                  | 04:58:04         | 0.723            |
| 11           | 2009          | 17                        | 13:33:36                  | 17                       | 14:36:14             | 17                   | 22:49:43         | 0.721            |
| 12           | 2009          | 118                       | 21:38:52                  | 119                      | 14:24:00             | 120                  | 05:08:09         | 0.725            |
| 13           | 2009          | 136                       | 10:19:12                  | 136                      | 21:37:26             | 137                  | 16:22:04         | 0.727            |
| 14           | 2009          | 153                       | 16:04:48                  | 153                      | 18:38:52             | 154                  | 12:20:09         | 0.728            |
| 15           | 2009          | 158                       | 05:58:33                  | 158                      | 05:58:33             | 158                  | 14:34:04         | 0.728            |
| 16           | 2009          | 175                       | 04:33:36                  | 175                      | 05:45:36             | 175                  | 11:45:36         | 0.728            |
| 17           | 2009          | 191                       | 07:59:31                  | 191                      | 10:37:55             | 192                  | 06:24:28         | 0.727            |
| 18           | 2009          | 221                       | 09:15:50                  | 221                      | 10:27:50             | 221                  | 19:16:19         | 0.723            |
| 19           | 2009          | 290                       | 05:45:36                  | 290                      | 05:45:36             | 290                  | 23:06:43         | 0.719            |
| 20           | 2009          | 325                       | 09:50:24                  | 325                      | 09:50:24             | 325                  | 15:59:02         | 0.722            |
| 21           | 2010          | 62                        | 04:37:03                  | 62                       | 15:39:27             | 63                   | 03:35:51         | 0.725            |
| 22\*         | 2010          | 74                        | 15:36:00                  | 74                       | 15:36:00             | 75                   | 12:28:48         | 0.724            |
| 23           | 2010          | 75                        | 18:57:36                  | 76                       | 09:18:34             | 77                   | 12:14:15         | 0.724            |
| 24           | 2010          | 157                       | 13:39:21                  | 157                      | 14:35:31             | 158                  | 00:44:38         | 0.719            |
| 25           | 2010          | 166                       | 14:09:36                  | 166                      | 23:21:07             | 168                  | 01:43:40         | 0.72             |
| 26           | 2010          | 173                       | 14:52:48                  | 173                      | 14:52:48             | 174                  | 18:28:48         | 0.721            |
| 27           | 2010          | 180                       | 00:57:36                  | 180                      | 08:38:24             | 180                  | 23:00:57         | 0.722            |
| 28           | 2010          | 213                       | 14:41:16                  | 213                      | 23:11:02             | 214                  | 05:55:40         | 0.726            |
| 29           | 2010          | 214                       | 11:29:45                  | 214                      | 12:41:45             | 214                  | 16:04:48         | 0.726            |
| 30           | 2010          | 214                       | 19:42:14                  | 214                      | 22:06:14             | 215                  | 14:29:45         | 0.726            |
| 31           | 2010          | 222                       | 03:48:57                  | 222                      | 12:31:40             | 222                  | 21:14:24         | 0.727            |
| 32           | 2010          | 224                       | 22:19:12                  | 224                      | 22:19:12             | 225                  | 05:19:40         | 0.727            |
| 33           | 2010          | 251                       | 11:03:50                  | 251                      | 11:03:50             | 251                  | 18:33:07         | 0.728            |
| 34           | 2010          | 253                       | 16:07:40                  | 253                      | 21:57:36             | 254                  | 17:08:09         | 0.728            |

All events in the catalogs can also be categorized depending on the quality of the data, most specifically on how easy it is to define an ICME. Indeed, some events cannot be fully sampled by MESSENGER or VEX because of magnetospheric crossings. Also, since the superposed epoch technique averages different events, it is important to check whether outliers in our sample (e.g., time series corresponding to higher-than-average magnetic field intensities) can affect the results. Although not shown here, we did a careful analysis removing different events to check the robustness of the results. Since on average we only found up to four outlier events, the superposed epoch profiles, were not affected by the removal of these outliers. As such, the technique is robust to a few outliers and in previous sections, the results are presented with the whole data set (Appendix A) for each spacecraft sample.
### Table A2 (continued)

| Event number | Year of event | Discontinuity<sup>a</sup> DOY | Discontinuity time | ME<sup>b</sup> leading edge DOY | ME leading edge time | ME trailing edge DOY | ME trailing edge time | \( \Phi_H \) c AU |
|--------------|---------------|-------------------------------|---------------------|-------------------------------|---------------------|---------------------|---------------------|------------------------|
| 35           | 2011          | 81                            | 08:51:21            | 81                            | 17:28:01            | 82                  | 18:20:44            | 0.727                  |
| 36           | 2011          | 101                           | 10:26:24            | 101                           | 11:03:50            | 101                 | 17:32:38            | 0.728                  |
| 37           | 2011          | 107                           | 07:39:21            | 107                           | 07:39:21            | 107                 | 18:17:16            | 0.728                  |
| 38           | 2011          | 111                           | 11:19:40            | 111                           | 11:19:40            | 112                 | 11:26:52            | 0.728                  |
| 39           | 2011          | 139                           | 20:58:33            | 140                           | 03:51:50            | 140                 | 18:12:57            | 0.727                  |
| 40           | 2011          | 156                           | 05:16:48            | 156                           | 08:38:24            | 156                 | 22:30:43            | 0.724                  |
| 41           | 2011          | 182                           | 11:31:12            | 182                           | 13:45:07            | 183                 | 09:01:26            | 0.721                  |
| 42           | 2011          | 273                           | 23:16:48            | 274                           | 03:36:00            | 274                 | 14:42:43            | 0.723                  |
| 43           | 2011          | 289                           | 00:50:24            | 289                           | 06:05:45            | 290                 | 09:38:52            | 0.725                  |
| 44           | 2011          | 359                           | 12:38:52            | 359                           | 15:38:52            | 360                 | 00:46:04            | 0.727                  |
| 45           | 2011          | 360                           | 23:16:48            | 361                           | 02:19:40            | 361                 | 15:41:45            | 0.727                  |
| 46           | 2012          | 32                            | 16:48:00            | 32                            | 21:07:37            | 33                  | 13:24:48            | 0.722                  |
| 47           | 2012          | 61                            | 13:37:55            | 61                            | 21:26:38            | 62                  | 13:21:04            | 0.719                  |
| 48           | 2012          | 67                            | 13:26:24            | 67                            | 20:13:12            | 68                  | 11:42:43            | 0.719                  |
| 49           | 2012          | 123                           | 00:38:52            | 123                           | 15:12:57            | 125                 | 01:32:09            | 0.722                  |
| 50           | 2012          | 200                           | 16:37:55            | 200                           | 23:51:21            | 201                 | 16:43:40            | 0.728                  |
| 51           | 2012          | 211                           | 09:50:24            | 211                           | 10:59:31            | 211                 | 17:58:33            | 0.728                  |
| 52           | 2012          | 257                           | 04:43:40            | 257                           | 11:44:09            | 258                 | 03:17:16            | 0.722                  |
| 53           | 2012          | 315                           | 15:38:52            | 315                           | 21:56:09            | 316                 | 01:55:12            | 0.719                  |
| 54           | 2012          | 318                           | 10:48:00            | 318                           | 17:31:12            | 319                 | 06:27:21            | 0.719                  |
| 55           | 2012          | 330                           | 01:01:55            | 330                           | 05:16:48            | 330                 | 11:19:40            | 0.72                   |
| 56           | 2013          | 8                             | 09:23:02            | 8                             | 15:24:32            | 9                   | 19:47:32            | 0.725                  |
| 57           | 2013          | 33                            | 02:15:56            | 33                            | 02:15:56            | 33                  | 20:51:38            | 0.728                  |
| 58           | 2013          | 48                            | 10:55:20            | 48                            | 10:55:20            | 48                  | 20:50:47            | 0.728                  |
| 59           | 2013          | 52                            | 16:03:21            | 52                            | 16:03:21            | 52                  | 19:55:12            | 0.728                  |
| 60           | 2013          | 65                            | 13:22:04            | 65                            | 23:35:48            | 66                  | 11:38:06            | 0.728                  |
| 61           | 2013          | 72                            | 20:41:16            | 72                            | 20:41:16            | 73                  | 07:15:36            | 0.727                  |
| 62           | 2013          | 117                           | 14:38:24            | 118                           | 01:45:07            | 119                 | 13:53:45            | 0.722                  |
| 63           | 2013          | 201                           | 10:06:14            | 201                           | 21:10:04            | 202                 | 17:47:02            | 0.721                  |
| 64           | 2013          | 261                           | 11:41:16            | 261                           | 11:41:16            | 261                 | 22:32:09            | 0.728                  |
| 65           | 2013          | 278                           | 04:17:45            | 278                           | 12:33:07            | 279                 | 14:58:33            | 0.728                  |
| 66           | 2013          | 334                           | 04:30:43            | 334                           | 13:59:31            | 335                 | 16:00:28            | 0.723                  |
| 67           | 2013          | 348                           | 03:07:12            | 348                           | 14:32:38            | 348                 | 23:39:50            | 0.721                  |

Note. This table is added to the list of Good et al.; DOY = day of year; ME = magnetic ejecta; AU = astronomical unit.

<sup>a</sup>This either a disturbance or a shock.  
<sup>b</sup>ME stands for magnetic ejecta.  
<sup>c</sup>Heliospheric distance of the s/c in astronomical unit.

### 6. Conclusion

This paper presents a comparison between statistical studies performed using magnetic field data from different spacecraft, namely, MESSENGER, VEX, and ACE. These three spacecraft sampled ICMEs at different distances from the Sun, from the orbit of Mercury (≈0.4), to that of Venus (0.72 AU) and Earth (1 AU). The conclusions are listed below.

- We first investigated the typical duration of the ME and the sheath. We found that this duration increases with solar distance for both substructures due to their expansion when the ICME moves away from the Sun, while the ratio of the duration of the ME over that of the sheath decreases from MESSENGER to ACE. We propose that, as ICMEs continue their propagation away from the Sun, the sheath size increases due to the accretion of overtaken plasma and magnetic field. This could be investigated more quantitatively with mission data that provide in situ measurements of the speed.
Table A3
Table of ICMEs Seen at ACE

| Event number | Year of event | Discontinuity a | Discontinuity b | ME b leading edge | ME leading edge | ME trailing edge |
|--------------|---------------|-----------------|-----------------|-------------------|----------------|-----------------|
|              |               | DOY time        | DOY time        | DOY time          | DOY time       | DOY time        |
| 1            | 1998          | 63 10:55:12     | 63 14:19:25     | 65 05:00:57       | 65 05:00:57    | 123 16:30:43    |
| 2            | 1998          | 121 21:25:55    | 122 11:31:12    | 123 16:30:43      | 123 16:30:43   | 123 16:30:43    |
| 3            | 1998          | 267 23:13:55    | 268 09:25:55    | 269 12:25:55      | 269 12:25:55   | 269 12:25:55    |
| 4            | 1998          | 291 19:01:55    | 292 04:07:12    | 292 13:07:40      | 292 13:07:40   | 292 13:07:40    |
| 5            | 1998          | 312 04:20:38    | 313 00:25:55    | 314 00:25:55      | 314 00:25:55   | 314 00:25:55    |
| 6            | 1999          | 49 02:05:15     | 49 16:17:45     | 50 11:16:48       | 50 11:16:48    | 50 11:16:48    |
| 7            | 1999          | 106 10:39:21    | 106 19:14:51    | 107 20:15:21      | 107 20:15:21   | 107 20:15:21    |
| 8            | 1999          | 220 17:39:50    | 221 19:58:04    | 222 15:57:36      | 222 15:57:36   | 222 15:57:36    |
| 9            | 2000          | 42 23:11:01     | 43 16:17:45     | 43 23:16:48       | 43 23:16:48    | 43 23:16:48    |
| 10           | 2000          | 51 20:38:24     | 52 08:55:39     | 53 10:56:37       | 53 10:56:37    | 53 10:56:37    |
| 11           | 2000          | 175 12:21:36    | 176 07:16:47    | 177 19:16:19      | 177 19:16:19   | 177 19:16:19    |
| 12           | 2000          | 210 05:42:43    | 210 20:06:43    | 211 09:07:12      | 211 09:07:12   | 211 09:07:12    |
| 13           | 2000          | 224 18:04:19    | 225 06:16:18    | 226 02:16:19      | 226 02:16:19   | 226 02:16:19    |
| 14           | 2000          | 261 16:56:38    | 262 01:01:55    | 262 17:02:24      | 262 17:02:24   | 262 17:02:24    |
| 15           | 2000          | 277 00:08:38    | 277 16:14:52    | 278 13:14:51      | 278 13:14:51   | 278 13:14:51    |
| 16           | 2000          | 302 09:02:51    | 302 20:09:36    | 303 21:08:38      | 303 21:08:38   | 303 21:08:38    |
| 17           | 2000          | 311 09:12:57    | 311 22:09:27    | 312 17:24:00      | 312 17:24:00   | 312 17:24:00    |
| 18           | 2001          | 94 14:13:55     | 94 18:01:40     | 95 07:20:37       | 95 07:20:37    | 95 07:20:37    |
| 19           | 2001          | 101 13:21:21    | 102 07:30:43    | 102 17:29:45      | 102 17:29:45   | 102 17:29:45    |
| 20           | 2001          | 111 15:30:14    | 111 23:30:43    | 113 00:30:14      | 113 00:30:14   | 113 00:30:14    |
| 21           | 2001          | 118 04:30:43    | 119 01:30:43    | 119 12:30:14      | 119 12:30:14   | 119 12:30:14    |
| 22           | 2001          | 147 14:13:55    | 148 11:13:55    | 149 09:12:57      | 149 09:12:57   | 149 09:12:57    |
| 23           | 2001          | 304 12:47:31    | 304 19:59:01    | 306 09:00:00      | 306 09:00:00   | 306 09:00:00    |
| 24           | 2002          | 107 10:20:38    | 108 02:15:21    | 109 01:14:52      | 109 01:14:52   | 109 01:14:52    |

- We applied the superposed epoch method to obtain generic ICME magnetic field intensity profiles, which provides insights on their typical features, as they are enhanced by the averaging method. The method was applied to all events in each sample (section 4). We quantified the change in the asymmetry of profiles and found a slightly higher asymmetry at Mercury compared to the other two heliospheric locations (Venus and Earth).

- The SEA shows that at any distance from the Sun, the magnetic field intensity in the wake (the SW region following the ICME within the same time scale of the ME) does not fully recover the properties of the pre-ICME SW. This is in agreement with the finding by Temmer et al. (2017) that the SW has a long recovery period after the passage of an ICME.

- By separating ICMEs without a sheath in the Venus Express data, we found that the ME had a symmetric profile. This is coherent with the conclusion made at 1 AU of Masías-Meza et al. (2016) who showed that slow ICMEs tend to have a weaker sheath and a more symmetric profile.

Due to the strong variability in the ICME profiles at each spacecraft, we decided to investigate how to create subcategories of ICMEs. Because the speed is only partially available for MESSENGER and VEX, we used $B_{\text{sheath}}$, the median magnetic field intensity in the sheath, which appears to be a good proxy of the ME speed based on ACE results. We assume that this result also applies to the MESSENGER and VEX ICMEs, and these results are backed up by the ACE data for which the in situ proton velocity is available (Masías-Meza et al., 2016). The results of the superposed epoch for each categories of ICMEs at each spacecraft are listed below:

- The SW magnetic field intensity level in front of ICMEs is weaker (respectively higher) for weak (respectively strong) $B_{\text{sheath}}$ ICMEs. This could be due to the solar origin of the ICMEs, where ICMEs with strong
Table A3 (continued)

| Event number | Year of event | Discontinuity^a DOY | Discontinuity time | ME^b leading edge DOY | ME leading edge time | ME trailing edge DOY | ME trailing edge time |
|--------------|---------------|----------------------|--------------------|-----------------------|----------------------|----------------------|----------------------|
| 25           | 2002          | 109                  | 08:03:50           | 110                   | 11:28:19             | 111                  | 14:28:19             |
| 26           | 2002          | 143                  | 10:09:07           | 143                   | 22:20:38             | 144                  | 16:20:38             |
| 27           | 2002          | 213                  | 04:19:12           | 213                   | 10:49:26             | 213                  | 21:48:57             |
| 28           | 2002          | 213                  | 22:17:45           | 214                   | 08:06:43             | 214                  | 20:06:43             |
| 29           | 2003          | 79                   | 04:14:51           | 79                    | 11:32:37             | 79                   | 21:31:39             |
| 30           | 2003          | 229                  | 13:40:48           | 230                   | 10:16:19             | 231                  | 04:16:19             |
| 31           | 2003          | 324                  | 07:27:50           | 324                   | 10:51:36             | 325                  | 01:20:38             |
| 32           | 2004          | 94                   | 09:00:00           | 95                    | 00:59:02             | 96                   | 13:59:31             |
| 33           | 2004          | 204                  | 09:50:24           | 204                   | 14:13:55             | 204                  | 20:13:55             |
| 34           | 2004          | 208                  | 22:23:31           | 209                   | 01:35:02             | 209                  | 11:35:31             |
| 35           | 2004          | 242                  | 09:30:14           | 242                   | 19:17:45             | 243                  | 19:41:44             |
| 36           | 2004          | 312                  | 17:55:39           | 313                   | 04:14:24             | 313                  | 16:26:24             |
| 37           | 2005          | 140                  | 01:59:31           | 140                   | 06:00:00             | 141                  | 03:59:02             |
| 38           | 2005          | 163                  | 06:44:38           | 163                   | 16:14:37             | 164                  | 05:55:40             |
| 39           | 2005          | 165                  | 17:49:55           | 166                   | 04:13:26             | 167                  | 08:13:55             |
| 40           | 2005          | 198                  | 00:33:07           | 198                   | 12:57:36             | 199                  | .1229977             |
| 41           | 2005          | 364                  | 23:19:39           | 365                   | 13:53:43             | 1                   | 10:19:12             |
| 42           | 2006          | 348                  | 13:48:00           | 348                   | 21:36:00             | 349                  | 19:36:27             |

Note. ICMEs = interplanetary coronal mass ejections; ACE = Advanced Composition Explorer; DOY = day of year; ME = magnetic ejecta.
^a This either a disturbance or a shock. ^b ME stands for magnetic ejecta.

B_{sheath} originate from regions of the Sun where the magnetic fields of both the ICME and the pre-ICME are strong.

- The magnetic fields in the sheath region and in the ME are higher for fast ICMEs compared with slow ICMEs. This could be due to the shock compression, as well as the dynamic pressure due to the ME behind which are both higher in fast events (e.g., Manchester et al., 2005). This then increases the magnitude of the magnetic field, which evolution is not fully transmitted to the ME (both substructures being out of equilibrium).
- The SW magnetic field intensities post-ICMEs are larger than the pre-ICME ones especially for the slower ICMEs. This difference between slow and fast ICMEs may be linked with a more frequent and stronger interaction with an overtaking SW for slow ICMEs.
- The ME profiles are more symmetric for slow ICMEs (i.e., with a weaker B_{sheath}), while those classified as faster (i.e., with a stronger B_{sheath}) have a sloped profile and a larger asymmetry, with a larger magnitude of the magnetic field at the front than at the rear of the ME.

The category of ICMEs classified as faster with the B_{sheath} proxy are probed when they are younger than their slower counterparts. Having spent less time in the SW, they had less time to adjust the conditions within the ICMEs with the surrounding SW. In other words, these structures are less relaxed and therefore are expected to display a less symmetric magnetic field profile, which is what we have found for each category of fast ICMEs at the three spacecraft. On the other hand, the interaction with the sheath is stronger for the faster events, which also contributes to the asymmetry.

The present study provides insights on the evolution of the profiles of selected similar subsets of ICMEs at different heliospheric distances. The mechanisms behind the different profiles we have found, especially with regard to the speed of ICME propagation, will need to be investigated. Especially, MHD codes simulating the ICME propagation within the inner heliosphere will be invaluable in understanding the conditions needed to recover the results we have found with in situ data. Furthermore, future missions such as ESA’s Solar Orbiter and NASA’s Parker Solar Probe will be essential in completing catalogs of in situ detected ICMEs and in providing new data sets necessary to investigate the evolution of ICMEs in the interplanetary medium.
Appendix A: Tables of ICMEs seen at MESSENGER, Venus Express, and ACE

We present in the following the catalogs of ICME events seen at the different spacecraft. Table A1 is our catalog of ICMEs seen at MESSENGER, Table A2 ICMEs seen at Venus Express, and Table A3 the 42 ICMEs seen at ACE and studied in Masías-Meza et al. (2016).

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