RADIAL EVOLUTION OF A MAGNETIC CLOUD: *MESSENGER*, *STEREO*, AND *VENUS EXPRESS* OBSERVATIONS

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ABSTRACT

The *Solar Orbiter* and *Solar Probe Plus* missions will provide observations of magnetic clouds closer to the Sun than ever before, and it will be good preparation for these missions to make full use of the most recent in situ data sets from the inner heliosphere—namely, those provided by *MERcury Surface, Space ENVironment, GEOchemistry, and Ranging* (*MESSENGER*) and *Venus Express*—for magnetic cloud studies. We present observations of the same magnetic cloud made by *MESSENGER* at Mercury and later by *Solar TERrestrial RELations Observatory-B* (*STEREO-B*), while the spacecraft were radially aligned in 2011 November. Few such radial observations of magnetic clouds have been previously reported. Estimates of the solar wind speed at *MESSENGER* are also presented, calculated through the application of a previously established technique. The cloud’s flux rope has been analyzed using force-free fitting; the rope diameter increased from 0.18 to 0.41 AU (corresponding to an $r_H^{0.94}$ dependence on heliocentric distance, r_H), and the axial magnetic field strength dropped from 46.0 to 8.7 nT (an $r_H^{-1.84}$ dependence) between the spacecraft, clear indications of an expanding structure. The axial magnetic flux was ~ 0.50 nT AU² at both spacecraft, suggesting that the rope underwent no significant erosion through magnetic reconnection between *MESSENGER* and *STEREO-B*. Further, we estimate the change in the cloud’s angular width by assuming helicity conservation. It has also been found that the rope axis rotated by 30° between the spacecraft to lie close to the solar equatorial plane at *STEREO-B*. Such a rotation, if it is a common feature of coronal mass ejection propagation, would have important implications for space weather forecasting.

Key words: magnetic fields – solar wind – Sun: coronal mass ejections (CMEs) – Sun: heliosphere

1. INTRODUCTION

Coronal mass ejections (CMEs) are large-scale magnetic field and plasma structures that erupt from the solar atmosphere. These structures propagate out into the heliosphere from the Sun following eruption and when observed by spacecraft in situ, display magnetic field, plasma, and particle signatures distinct from those of other transient structures and the ambient flow of the solar wind.

Burlaga et al. (1981) coined the term *magnetic cloud* to describe particularly well ordered and coherent magnetic structures, later identified as a subset of CMEs, which are frequently observed by spacecraft in situ: a magnetic cloud is defined as a structure with (i) a magnetic field of magnitude above that of the average local interplanetary field that (ii) rotates smoothly through a large angle, embedded in (iii) a low beta plasma with (iv) a temperature lower than that of normally expanding solar wind.

Magnetic cloud signatures are relatively simple to understand and model compared to the often variable and disordered in situ signatures that are observed in other CMEs. Soon after the first identification of magnetic clouds, it was found that their ordered magnetic field topology is often approximated by the linear force-free flux rope (Goldstein 1983), a structure consisting of a series of nested, helical field lines wound around a central axis, with pitch angles that decrease as the rope axis is approached. Various flux-rope-based models have since been developed that can be fitted to magnetic field data, and which allow, for example, the rope axis orientation, radial width, and axis field magnitude of magnetic clouds to be estimated; Riley et al. (2004) and Al-Haddad et al. (2013) have compared the most commonly used models.

In this work, we present observations of a magnetic cloud observed by the *MERcury Surface, Space ENVironment, GEOchemistry, and Ranging* (*MESSENGER*) spacecraft (orbiting Mercury) at 0.44 AU and later by the *Solar TERrestrial RELations Observatory-B* (*STEREO-B*) spacecraft at 1.09 AU, when the two spacecraft were close to radial alignment in early 2011 November. Observations of this kind, with two radially aligned spacecraft separated in heliocentric distance, allow sampling of approximately the same region of the cloud and so allow any evolution that may have occurred within that region to be ascertained. We fit a commonly used force-free, constant- α flux rope model to the magnetic field data of the cloud at each location and consider how the rope orientation, size, and structure evolved during its propagation between the two points. The axial magnetic flux of the rope at the two spacecraft has also been estimated, as well as the helicity per unit flux rope length. Gómez-Herrero et al. (2015) have recently proposed a link between this magnetic cloud and a solar energetic particle (SEP) event observed at multiple spacecraft that occurred around the time of the cloud’s launch. This SEP event has previously been studied by Park et al. (2013) and Prise et al. (2014).

We also present observations of a magnetic cloud observed in the same time period by *Venus Express* while the spacecraft was at a 27° longitudinal separation from the *MESSENGER*–*STEREO-B* line. The arrival time of the cloud signatures at Venus, roughly midway between the arrival times at Mercury and 1 AU, would point to all three spacecraft having observed the same cloud.

Relatively few magnetic clouds observed by pairs of radially aligned spacecraft have been documented. To the best of our

knowledge, 10 such events have previously been reported where the two or more observing spacecraft were separated by less than 10° in heliographic inertial longitude and latitude and separated by more than ~ 0.2 AU in heliocentric distance (a distance over which appreciable evolution in the CME may be discerned, at least in the inner heliosphere). Burlaga et al. (1981) studied a magnetic cloud observed by *Helios 1* (at 1 AU) and the two *Voyagers* (both at 2 AU) while the spacecraft were around 10° from longitudinal alignment in 1978 January. Forsyth et al. (2006) briefly discuss the evolution of a magnetic cloud observed with an alignment of *Helios 2* (0.42 AU) and *IMP 8* (1 AU) in 1979 April. Leitner et al. (2007) described three further events from the *Helios* era that were well observed with alignments involving, respectively, *Helios 1* (0.87 AU), *IMP 8* (1 AU) and *Pioneer 11* (3.8 AU) in 1975 November; *Helios 2* (0.62 AU), *IMP 8* (1 AU), and the *Voyagers* (1.6 AU) in 1977 November; and *ISEE 3* (1 AU), *Voyager 2* (6.4 AU), *Voyager 1* (7.4 AU), and *Pioneer 11* (9.4 AU) over 1980 March to May.

Mulligan et al. (1999) described two events observed when the *Wind* and *NEAR* spacecraft were separated by $5^\circ 4'$ and $1^\circ 2'$ in longitude and 0.28 and 0.18 AU in heliocentric distance, respectively, in 1997 November and December. The Bastille Day event of July 2000 was observed by *NEAR* (1.8 AU) and *ACE* (1 AU) while the spacecraft were at a $1^\circ 9'$ longitudinal separation (Mulligan et al. 2001; Russell et al. 2003). Skoug et al. (2000), Du et al. (2007), and Nakwacki et al. (2011) have presented in-depth studies of the same cloud that was observed with an alignment of *ACE* (1 AU) and *Ulysses* (5.4 AU) in 1998 March. More recently, Nieves-Chinchilla et al. (2013) have reported observations of a cloud seen at *MESSENGER* and *STEREO-B* while the spacecraft were aligned in 2009 August.

As well as describing an interesting individual event, this work seeks to highlight the viability of using post-planetary insertion data from *MESSENGER* and *Venus Express* to study CMEs and other heliospheric phenomena, given that both spacecraft still spent significant amounts of time in the solar wind after insertion. As long as care is taken when locating magnetospheric boundaries in the data, one can clearly discern the unperturbed solar wind intervals and the signatures of solar wind structures.

MESSENGER and *Venus Express* are particularly useful for performing CME studies that involve radial conjunctions of spacecraft, such as the one presented here. Given the orbital periods of the planets orbited by the spacecraft (88 days for Mercury and 225 days for Venus), radial conjunctions have frequently occurred between each spacecraft and others located at 1 AU (e.g., *ACE*, *Wind*, *STEREO-A* and *B*) and between the two spacecraft themselves, giving ample opportunity for the radial observation of CMEs. Moreover, studies involving radially aligned and inner-heliospheric spacecraft such as *MESSENGER* and *Venus Express* will be good preparation for the upcoming *Solar Orbiter* and *Solar Probe Plus* missions.

2. SPACECRAFT OBSERVATIONS

This work presents in situ observations from the *MESSENGER* (Solomon et al. 2001), *STEREO* (Kaiser 2005), and *Venus Express* (Titov et al. 2006) spacecraft. *MESSENGER* is a NASA planetary mission that entered Mercury's orbit in 2011 March following a 7 yr cruise phase. Launched in October 2006 and also a NASA mission, *STEREO* consists of a pair of spacecraft close to

Figure 1. Locations of the three inner planets and the *STEREO* spacecraft at 2011 November 5 00:00 UT.

the Earth's orbital path around the Sun, one (*STEREO-A*) running ahead of the Earth and the other (*STEREO-B*) falling behind; it offers a stereoscopic view of the inner heliosphere. ESA's *Venus Express* mission was launched in 2005 November and, following a short cruise phase, entered a 24 hr orbit of Venus in 2006 May.

Figure 1 shows the location of Mercury, Venus, Earth, and the two *STEREO* spacecraft on 2011 November 5 00:00 UT. The *MESSENGER* spacecraft (at Mercury) and *STEREO-B* were at distances of 0.44 AU and 1.09 AU from the Sun at this time, respectively.

The signatures of a magnetic flux rope were observed at *MESSENGER* from 00:43 UT on November 5 and lasted for approximately 16 hr. Figure 2 shows the magnetic field measurements taken during this period of time by the MAG instrument on board *MESSENGER* (Anderson et al. 2007), where the flux rope boundaries in the data are marked with vertical dashed lines. The data displayed have a time-averaged resolution of 10 s. The magnetic field components (second panel, in *RTN* coordinates), the angle of the field vector with the *R-T* plane (θ , third panel), and the angle from the *R* direction anticlockwise (looking from solar north) to the projection of the field vector onto the *R-T* plane (φ , fourth panel) all show the relatively smooth rotation of the field direction associated with a flux rope structure. The boundaries of the flux rope were estimated to lie at the start and end of this period of rotation. The trailing edge of the rope was identified with somewhat less certainty than the leading edge. As with many CME flux ropes, the magnetic field magnitude (first panel) was enhanced within the rope relative to the ambient solar wind. The enhanced field magnitude of a sheath driven ahead of the flux rope is also clearly displayed.

The smooth lines overlaying the data in the top four panels of Figure 2 are a flux rope model fit to the data, the results of which are described in the following section. Intervals in the data where the spacecraft traversed the foreshock and magnetosphere of Mercury (shown by the gray shaded regions) have been excluded from the plot.

The bulk plasma speed profile within the rope is presented in the bottom panel of Figure 2. The figure displays data from the Fast Imaging Plasma Spectrometer (FIPS; Andrews et al. 2007) on board *MESSENGER*, an instrument primarily designed to

Figure 2. Magnetic field magnitude (first panel), field components (second panel), field angles θ and φ (third and fourth panels, as defined in the text), and bulk plasma speed (fifth panel, where accessible; please refer to the text for details) observed by *MESSENGER*. The gray shaded regions show where the spacecraft was within the magnetosphere of Mercury.

study hot and subsonic ions in Mercury’s magnetosphere. Although the spacecraft’s radially directed sunscreen obscures the core of the solar wind velocity distribution from FIPS, some of the distribution can be sampled from the particles that carry a non-radial velocity component and that enter the FIPS instrument when the spacecraft is in the solar wind. Gershman et al. (2012) have developed a technique that extracts the bulk solar wind speed from these partial distributions, and the technique has been used to obtain the data shown in Figure 2. The figure shows that the rope leading edge, at a speed of around 700 km s^{-1} , was traveling considerably faster than the trailing edge, at around 450 km s^{-1} , a clear indication that the cloud was expanding. A declining speed profile such as this is another common in situ CME signature: Jian et al. (2006), for example, cataloged 230 CMEs observed in situ by *ACE* and

Wind between 1995 and 2004, of which only 17 ($\sim 7\%$) were not observed to be expanding.

At 22:56 UT on November 6, approximately 46 hr after the arrival of the flux rope at *MESSENGER*, the same rope arrived at *STEREO-B*. The arrival times of the cloud at the two spacecraft are listed in Table 1. All of the defining signatures of a magnetic cloud were observed at *STEREO-B*, as displayed in Figure 3: an enhanced magnetic field magnitude (first panel), a relatively smooth rotation of the magnetic field direction (second to fourth panels), a low temperature (seventh panel), and plasma beta (eighth panel) were all present during the 43 hr passage of the structure over the spacecraft. Indeed, this is a particularly pristine example of a magnetic cloud. The extent of the cloud was determined by the period of smooth field rotation, in a similar fashion to the identification of the flux

Table 1Arrival Times, Speeds, and Flux Rope Model Parameters of the Magnetic Cloud at *MESSENGER* and *STEREO-B*

	<i>MESSENGER</i>	<i>STEREO-B</i>
Distance of s/c from Sun (AU)	0.44	1.09
Sheath arrival time	2011 Nov 4 15:09 UT	2011 Nov 6 05:09 UT
Flux rope arrival time	2011 Nov 5 00:43 UT	2011 Nov 6 22:56 UT
Flux rope end time	2011 Nov 5 17:05 UT	2011 Nov 8 17:49 UT
Leading edge speed (km s ⁻¹)	~700	620
Trailing edge speed (km s ⁻¹)	~450	410
H (force-free)	-1 (left handed)	-1 (left handed)
p (force-free)	0.02	0.01
χ^2 (force-free)	0.33	0.21
Rope axis orientation (MVA)	$\theta_R = -20^\circ \pm 13^\circ$,	$\theta_R = 3^\circ \pm 8^\circ$,
	$\varphi_R = 79^\circ \pm 20^\circ$	$\varphi_R = 126^\circ \pm 2^\circ$
Rope axis orientation (force-free)	$\theta_R = 26^\circ \pm 8^\circ$,	$\theta_R = -4^\circ \pm 1^\circ$,
	$\varphi_R = 84^\circ \pm 4^\circ$	$\varphi_R = 117^\circ \pm 2^\circ$
B_0 (nT) (force-free)	46.0	8.7
$S' = v_c \cdot t$ (AU)	0.18 ± 0.02	0.46 ± 0.05
S , flux rope cylinder diameter (AU)	0.18 ± 0.02	0.41 ± 0.05
Φ (nT AU ²)	0.49 ± 0.08	0.50 ± 0.11
H_M/L (nT ² AU ³)	1.02 ± 0.26	0.47 ± 0.16
L/S (nT ⁻² AU ⁻⁴ , H_M)	5.5 ± 1.9	5.2 ± 2.4

rope at *MESSENGER*. This identification is supported by the coincidence of low temperature and plasma beta. Both the magnetic field data (from *STEREO-B*'s IMPACT-MAG instrument; Acuña et al. 2007) and plasma data (from the PLASTIC-B instrument suite; Galvin et al. 2008) presented in Figure 3 are at a time-averaged resolution of 1 minute.

The declining speed profile (fifth panel) and low temperature that were observed are both signatures of an expanding structure. As at *MESSENGER*, the flux rope was preceded by a sheath of piled-up magnetic field and plasma. The overlying smooth lines in the first four panels are, as in Figure 2, a flux rope model fit to the data.

The spacecraft locations at the arrival time of the leading edge of the flux rope at each spacecraft were separated by 4:3 in heliocentric inertial (HCI) longitude and 6:8 in HCI latitude. This angular separation is small relative to the 40°–60° average angular width of CMEs observed in coronagraph images (Gopalswamy et al. 2010), and so we assume that (i) the same region of the magnetic cloud was sampled by the two spacecraft, (ii) the properties of the magnetic cloud (e.g., flux rope axis orientation) throughout this region are the same at any given time, and (iii) any differences observed in the cloud properties at the two spacecraft are due to an evolution in the properties of this region during propagation. We also assume that the cloud propagated radially away from the Sun between Mercury and 1 AU.

Figure 4 shows the magnetic field data within the cloud at *MESSENGER* overlapped with the corresponding field data from the cloud at *STEREO-B*. The field axes of the *MESSENGER* data (y-axes, right) in this figure have been contracted and the time axis (x-axis, top) expanded relative to the axes of the *STEREO-B* data such that a “best-fit” overlap of

the two data sets was obtained, with the constraint that the leading edges of the flux rope in both data sets (denoted by the vertical dashed line) overlap exactly. The contraction of the field axes and expansion of the time axis in this way factor out, respectively, the drop in field magnitude and increase in radial width that occurred during propagation, so that only the shapes of the corresponding field profiles are compared. The *MESSENGER* data have been scaled along the time axis by the same factor for the magnitude and all three field components.

The magnetic field data have been presented in this way to highlight the similarity of the field magnitude (first panel), tangential component (third panel), and normal component (fourth panel) profiles, and to support the assertion that the same structure was observed by the two spacecraft.

The time axis of the *MESSENGER* data has been scaled linearly to produce the overlap in Figure 4. Although this linear scaling shows a reasonably good correlation with the *STEREO-B* data, the flux rope itself may not in reality have expanded in a linear, self-similar fashion during its propagation.

3. ANALYSIS

Both minimum variance analysis (MVA) and force-free fitting have been applied to the flux rope intervals in the magnetic field data. MVA is a commonly used technique that involves finding the eigenvalues and eigenvectors of the covariance matrix of the field data, where the eigenvector associated with the intermediate eigenvalue will ideally correspond to the direction of the flux rope axis (Goldstein 1983). The model used for the force-free fitting is based on that described by Burlaga (1988) and Lepping et al. (1990). It assumes a cylindrically symmetric flux rope field configuration $\mathbf{B}$ that satisfies

$$\nabla^2 \mathbf{B} = -\alpha^2 \mathbf{B} \quad (1)$$

where α is a constant. The field component along the axial direction of the cylinder is given by

$$B_A = B_0 J_0(\alpha R) \quad (2a)$$

and the tangential component by

$$B_T = B_0 H J_1(\alpha R) \quad (2b)$$

where J_0 and J_1 are the zeroth- and first-order Bessel functions, respectively, H is the rope handedness, B_0 is the field strength along the axis, and R is the radial distance from the rope axis; the radial field component is zero. These solutions were first described by Lundquist (1950). The force-free condition ($\mathbf{j} \times \mathbf{B} = 0$) underpinning the model requires the magnetic pressure within the flux rope to be balanced by the tension of the coiled field lines.

The components of $\mathbf{B}$ were fitted to the magnetic field data at *MESSENGER* and *STEREO-B* using a χ^2 minimization procedure based on that performed by Lepping et al. (1990), where the axis orientation obtained from the MVA was used to initialize the minimization. The fits are shown by the smooth lines overlaying the second, third, and fourth panels of Figures 2 and 3. The model allows global parameters of a flux rope to be estimated from the magnetic field sampled along the arbitrary trajectory taken by the spacecraft through the rope. The free parameters of the model include B_0 , the rope axis orientation, and spacecraft impact parameter, p .

Figure 3. Magnetic field magnitude (first panel), field components (second panel), field angles θ and φ (third and fourth panels, as defined in the text), proton speed (fifth panel), proton density (sixth panel), proton temperature (seventh panel), and plasma beta (eighth panel) observed by *STEREO-B*. The red line overlaying the proton temperature data is the expected temperature (Lopez & Freeman 1986), an empirically derived quantity that estimates the temperature of normally expanding solar wind as a function of solar wind speed and distance from the Sun; the magnetic cloud plasma is cooler than would be expected for solar wind plasma of the same speed and heliocentric distance.

3.1. Flux Rope Handedness, B_0 , and Orientation

Table 1 summarizes the results of the MVA and force-free fitting. The force-free fits indicate that the ropes observed at the two spacecraft were both left-handed. A consistent handedness is a critical requirement for establishing that the spacecraft observed the same rope, given that the handedness of a flux rope cannot change. The force-free fitting also indicated that $B_0 \propto r_H^{-1.84}$ for this event, where r_H is the heliocentric distance from the Sun: B_0 dropped by a factor of 5.3 from 46.0 nT at *MESSENGER* to 8.7 nT at *STEREO-B*, a clear sign of expansion. The $r_H^{-1.84}$ dependence is in agreement with the statistical dependence of $r_H^{-1.64 \pm 0.40}$ found by Leitner et al.

(2007) for 130 clouds, most of which were observed during the *Helios* era.

The orientation of the flux rope axis at each spacecraft was also estimated using both analysis methods. The angles presented in Table 1 for these orientations are relative to the solar equatorial plane, where θ_R is the angle between the axis direction and the plane, and φ_R is the angle from the anti-sunward direction anticlockwise (looking from solar north) to the projection of the axis direction onto the plane. MVA gives $\theta_R = -20 \pm 10^\circ$, $\varphi_R = 79 \pm 20^\circ$ at *MESSENGER* and $\theta_R = 3 \pm 8^\circ$, $\varphi_R = 126 \pm 2^\circ$ at *STEREO-B*, compared to $\theta_R = 26 \pm 8^\circ$, $\varphi_R = 84 \pm 4^\circ$ at *MESSENGER* and $\theta_R = -4 \pm 1^\circ$, $\varphi_R = 117 \pm 2^\circ$ at *STEREO-B* from force-free fitting.

Figure 4. Magnetic field data at *MESSENGER* overlapped with the field data at *STEREO-B*.

The extent to which the three variance directions obtained from MVA are well defined may be determined by considering the ratios of the maximum eigenvalue (λ_1) and the minimum value (λ_3) to the intermediate value (λ_2). Commonly used criteria are those given by Siscoe & Suey (1972): for three well-defined variance directions to exist within a set of vectors, the conditions $\lambda_1/\lambda_2 > 1.37$ and $\lambda_3/\lambda_2 < 0.72$ should be met. The Siscoe and Suey conditions were met within the flux rope at both *MESSENGER*, where $\lambda_1/\lambda_2 = 1.9$ and $\lambda_3/\lambda_2 = 0.14$, and *STEREO-B*, where $\lambda_1/\lambda_2 = 2.4$ and $\lambda_3/\lambda_2 = 0.24$. When these conditions are met, the error in the variance directions is typically around 10° (Burlaga & Behannon 1982). These ratios indicate that at both spacecraft the minimum variance direction was fairly well defined relative to the intermediate, with less clear definition between the intermediate and maximum directions. Where λ_1 and λ_2 are similar, the flux rope axis may lie along the maximum rather than intermediate variance direction. (Briggs et al. (2011) present an example of this non-ideal case for a flux rope observed in the Martian magnetosphere.) This is not the case here, however: visual inspection of the data at *MESSENGER* and *STEREO-B* suggests that the flux rope axis would have lain close to the tangential direction ($\varphi = 90^\circ$) at both spacecraft, which is close to the intermediate variance directions obtained. Others (e.g., Sonnerup & Scheible 1998) apply the conditions of $\lambda_1/\lambda_2 > 10$ and $\lambda_3/\lambda_2 < 0.1$ for well-defined variance directions, conditions that are not met for the flux rope data at either spacecraft.

The impact parameters for both spacecraft were also estimated, from the force-free fitting. The impact parameter, p , is defined as the distance of closest approach made by the spacecraft to the flux rope axis divided by the rope radius, where a value of 0 indicates a spacecraft trajectory intersecting the rope axis and a value of 1 indicates a skimming encounter with the edge of the rope. The impact parameter was low at both *MESSENGER* and *STEREO-B* for this event, with values of 0.02 and 0.01, respectively. The accuracy of the flux rope parameters obtained from force-free fitting (e.g., Riley et al. 2004) and MVA (Gulisano et al. 2007) is greater for low impact parameter traversals such as these.

A measure of the “goodness of fit” of the force-free model is given by the final value of the χ^2 parameter used in the minimization procedure, which we (following the example of Lepping) define as

$$\chi^2 = \sum \left[(B_R - B_R^M)^2 + (B_T - B_T^M)^2 + (B_N - B_N^M)^2 \right] / N \quad (3)$$

where B_i ($i = R, T, N$) are the components of the measured magnetic field data, B_i^M ($i = R, T, N$) are the components of

the modeled data, and N is the total number of vectors in the sample. The fits to the *MESSENGER* data shown in Figure 2 and to the *STEREO-B* data in Figure 3 have χ^2 values of 0.33 and 0.21, respectively; ideally zero, χ^2 values less than unity correspond to relatively accurate fits, and values above two to relatively inaccurate fits (Lepping et al. 1990). Note that unit-normalized magnetic field vectors were used to calculate these χ^2 values.

The error values given with the axis orientations in Table 1 were calculated by adjusting the location of the trailing edge of the flux rope (the identification of which is not unambiguous) to other plausible positions and repeating the MV and force-free analyses. These values should only be regarded as order-of-magnitude estimates of the error. They indicate that the MVA of the rope at *MESSENGER* was significantly more sensitive to the trailing edge location than the other fits. Note also that the error values associated with the force-free fit orientations given above do not capture any potential deviation from the linear force-free cylindrical flux rope model used for the fitting—any significant violation of these assumptions would lead to significant systematic error in the estimated orientations. Kahler et al. (2011) and Hu et al. (2014), among others, present evidence of limitations and inconsistencies in the Lundquist model.

3.2. Flux Rope Kinematics and Width

Table 1 also lists the measured speeds of the leading and trailing edges of the flux rope at both spacecraft. The leading edge underwent some slight deceleration between *MESSENGER* and *STEREO-B*, while the trailing edge speed remained roughly constant and equal to the solar wind speed behind the rope.

The width S' of the magnetic cloud in the radial direction may be defined as $v_c \cdot t$ (Gulisano et al. 2012), where v_c is the plasma speed measured at the center of the flux rope (i.e., where the modeled magnetic field strength is at its maximum) and t is the time taken by the spacecraft to traverse the rope. Unfortunately, *MESSENGER* did not observe the center of the flux rope during its passage because the spacecraft was not in the solar wind at this time, and so v_c could not be directly measured. However, given that the time at which the flux rope center would have arrived at Mercury is known—the time midway between the leading and trailing edges of the rope—it is possible to estimate the mean speed of the flux rope center between its arrival at Mercury and at *STEREO-B*. This mean speed was estimated to be 447 km s^{-1} , very close to the v_c value of 449 km s^{-1} measured at *STEREO-B*. It has therefore been assumed that the flux rope center moved at a roughly constant speed between the two spacecraft, and that the value of v_c at Mercury was equal to this speed.

S' was found to be $0.18 \pm 0.02 \text{ AU}$ at *MESSENGER* and $0.46 \pm 0.05 \text{ AU}$ at *STEREO-B*. These values are listed in Table 1. Given the magnetic cloud's expansion, S' can more accurately be described as the mean radial width of the cloud during the time spent by the spacecraft within the cloud, rather than as an instantaneous width.

S' corresponds to the distance of the path taken by the spacecraft through the magnetic cloud and does not account for the orientation of the flux rope. The radius of the cylindrical flux rope fitted to the data, S , was calculated to be $0.18 \pm 0.02 \text{ AU}$ and $0.41 \pm 0.05 \text{ AU}$ at *MESSENGER* and *STEREO-B*,

respectively, corresponding to a dependence of $r_H^{0.94}$ on heliocentric distance. This is in agreement with the statistical dependence of $r_H^{1.14 \pm 0.44}$ found by Leitner et al. (2007) and comparable to the $r_H^{0.96}$ dependence found by Russell et al. (2003) for the Bastille Day event.

Both estimates of the cloud's width clearly indicate that the cloud expanded along the radial direction during propagation between the two spacecraft. As with the rope orientation angles, the errors for the radial width values were estimated by adjusting the location of the trailing edge.

3.3. Magnetic Flux, Helicity, and Angular Width

The magnetic flux $\Phi = \int \mathbf{B} \cdot d\mathbf{A}$ that threaded the cross-sectional area A of the flux rope at both spacecraft has also been estimated, using parameters obtained from the force-free fitting. Assuming that A is circular and that the component of the magnetic field normal to A (i.e., the axial component) is given by Equation (2a), it may be shown that

$$\begin{aligned} \Phi &= 2\pi B_0 \int_0^{S/2} J_0(\alpha R) R dR \\ &= \frac{\pi J_1(\gamma)}{2\gamma} B_0 S^2 \sim 0.34 B_0 S^2 \end{aligned} \quad (4)$$

where γ is a constant equal to $\alpha S/2 \sim 2.405$, at which point J_0 falls to its first zero at the rope boundary. DeVore (2000) has derived an equivalent expression for the axial flux, as have Démoulin et al. (2002) and Dasso et al. (2006), among others. Taking S as the best estimate of the rope diameter (rather than S'), $\Phi = 0.49 \pm 0.08 \text{ nT AU}^2$ at *MESSENGER* and $\Phi = 0.50 \pm 0.11 \text{ nT AU}^2$ at *STEREO-B*. These figures suggest that the magnetic flux of the rope was largely conserved between 0.44 and 1.09 AU, and that the rope had undergone no appreciable erosion through magnetic reconnection during propagation, at least relative to the macroscopic scale of the cloud's width (see Lavraud et al. 2014, and references therein).

The magnetic helicity H_M within a volume V containing magnetic field $\mathbf{B}$ is defined as

$$H_M = \int \mathbf{A} \cdot \mathbf{B} dV, \quad (5)$$

where $\mathbf{A}$ is the vector potential of the magnetic field, such that $\mathbf{B} = \nabla \times \mathbf{A}$. Helicity is an invariant of MHD associated with twisted magnetic field structures such as flux ropes (Woltjer 1958). The launching of CMEs into the heliosphere is believed to be a key mechanism by which the Sun sheds helicity, preventing an endless buildup of this quantity in the solar corona.

For a constant- α , force-free cylindrical flux rope, $\mathbf{A} = \mathbf{B}/\alpha$; Démoulin et al. (2002) have shown that the helicity H_M per unit axial length of the flux rope L is given by

$$\frac{H_M}{L} = \frac{4\pi B_0^2}{\alpha} \int_0^{S/2} J_1^2(\alpha R) R dR \cong \frac{7}{80} B_0^2 S^3 \quad (6)$$

where the integral was calculated numerically. The final expression is given as a function of the rope diameter S , rather than as the function of radius presented by Démoulin et al. (2002). Taking B_0 and S as the best estimates of the axial field strength and rope diameter, respectively, H_M/L was equal to $1.02 \pm 0.26 \text{ nT}^2 \text{ AU}^3$ at *MESSENGER* and

Table 2

Times at which the Signatures of CMEs 1 and 2 Were First Observed by Various Instruments. WL—from Western Limb; EL—from Eastern Limb; GAP—a Large Preceding Gap in the Data; PEA—Post Eruption Arcade

	CME 1	CME 2
<i>STEREO-B</i> EUVI	2011 Nov 3 22:17 UT	2011 Nov 4 00:27 UT (PEA)
<i>STEREO-B</i> COR1	2011 Nov 3 22:26 UT (EL)	...
<i>STEREO-B</i> COR2	2011 Nov 3 22:54 UT (EL)	2011 Nov 4 01:55 UT (weak halo)
<i>STEREO-A</i> COR1	2011 Nov 3 22:20 UT (WL)	2011 Nov 4 00:45 UT (WL)?
<i>STEREO-A</i> COR2	2011 Nov 3 22:54 UT (WL)	2011 Nov 4 01:24 UT (WL)?
LASCO C2	2011 Nov 3 23:36 UT (halo) (GAP)	2011 Nov 4 01:25 UT (EL) (GAP)

$0.47 \pm 0.16 \text{ nT}^2 \text{ AU}^3$ at *STEREO-B*. Assuming that helicity is indeed a conserved quantity, the fall in H_M/L indicates that the magnetic cloud expanded along the axial direction during propagation between 0.44 and 1.09 AU.

It is impossible to determine the axial length L of the flux rope with the in situ observations that have been presented. However, it is possible to infer something about the angular width of the flux rope, Θ (i.e., the angle at the Sun spanned by the length of the flux rope axis). Again assuming that helicity is a conserved quantity, it is the case that

$$\left(\frac{H_M}{L}\right)_{MES} L_{MES} = \left(\frac{H_M}{L}\right)_{STB} L_{STB} \quad (7)$$

where the variables are at their values during the time of the cloud's observation by *MESSENGER* (*MES*) and *STEREO-B* (*STB*). Furthermore, assuming that L can be approximated as the arc of a circle such that $L = r_H \Theta$, it may be shown through substitution and rearrangement of Equation (7) that the ratio of the angular width of the flux rope at *STEREO-B* to the angular width at *MESSENGER* is given by

$$\begin{aligned} \frac{\Theta_{STB}}{\Theta_{MES}} &= \frac{(H_M/L)_{MES} r_{H,MES}}{(H_M/L)_{STB} r_{H,STB}} \\ &= \frac{B_{0,MES}^2 S_{MES}^3 r_{H,MES}}{B_{0,STB}^2 S_{STB}^3 r_{H,STB}}. \end{aligned} \quad (8)$$

This expression is found to equal ~ 0.89 using the parameters estimated for the flux rope, suggesting that the cloud spanned a somewhat smaller angular width at *STEREO-B* than at *MESSENGER*. We note that there is a large error associated with this ratio value arising from the S^3 dependence, limiting the certainty of any conclusions that may be drawn from it. However, this result is broadly in agreement with coronagraph observations, which indicate that CMEs tend to propagate and expand at roughly constant angular widths to fill cones (Zhao et al. 2002).

Equation (8) may be generalized to

$$\Theta_2 = \left(\frac{B_{01}^2 S_1^3 r_{H1}}{B_{02}^2 S_2^3 r_{H2}} \right) \Theta_1 \quad (9)$$

for observations made by any two spacecraft (denoted by subscripts 1 and 2). We note that this expression links parameters that could be estimated from remote observation (e.g., by *STEREO*'s Heliospheric Imagers)—namely, Θ , S , and r_H —with the magnetic field parameter B_0 . Further, in situ observations of the same flux rope by any two spacecraft

separated in heliocentric distance (regardless of their longitudinal separation) would satisfy Equation (9).

It is also possible, using the modeled parameters, to estimate the aspect ratio of the flux rope's length to radial width, L/S , as a function of H_M ; at *MESSENGER*, $L/S \sim (5.5 \pm 1.9) H_M \text{ nT}^{-2} \text{ AU}^{-4}$, and at *STEREO-B*, $L/S \sim (5.2 \pm 2.4) H_M \text{ nT}^{-2} \text{ AU}^{-4}$. If helicity is again assumed to be constant, the aspect ratio of the flux rope was approximately the same at each spacecraft. This result comes naturally from the conservation of axial flux found previously: from Equations (4) and (6) it may be shown that

$$L/S = (H_M/L)^{-1} S^{-1} H_M \sim B_0^{-2} S^{-4} H_M \sim \Phi^{-2} H_M. \quad (10)$$

Thus, for a constant- α , force-free cylindrical flux rope that conserves its axial flux and helicity, the aspect ratio of the rope's length to width would not change during propagation. Such a rope would also conserve its total number of average field line twists; a detailed discussion of the relationship between helicity and field line twist (i.e., the number of field line turns per unit length) is given by Hu et al. (2014). The relatively large errors associated with the L/S values given above arise from the Φ^{-2} dependency.

3.4. Coronagraph Observations, and in situ Signatures at Venus

The Large Angle and Spectrometric Coronagraph (LASCO) on board the *Solar and Heliospheric Observatory* (*SOHO*) spacecraft provides coronagraph images of the Sun taken from the L1 point on the Sun–Earth line (Brueckner et al. 1995). Two CMEs appeared in LASCO's field of view within a period of 2 hr around midnight of 2011 November 3, the time at which, given the measured in situ speeds, it is likely that the magnetic cloud observed in situ at *MESSENGER* and *STEREO-B* was launched from the Sun. Also, given their apparent propagation directions, one or both of these CMEs could have been observed in situ by *MESSENGER*, *Venus Express*, or *STEREO-B*.

The first of the two CMEs (CME 1) appeared as a halo in LASCO C2 from 2011 November 3 23:36 UT. This CME was also observed by both *STEREO-A*'s and *STEREO-B*'s coronagraphs, emerging from the Sun's western limb as viewed from *STEREO-A* and from the eastern limb as viewed from *STEREO-B*. A significant brightening on the solar disk is seen by *STEREO-B*'s Extreme Ultraviolet Imager (EUVI) close to the solar equator and eastern limb just prior to CME 1's entry into the coronagraph field of view, which could be the site from which the CME was launched. Taking all of these observations into consideration, it may be inferred that the halo seen in LASCO was back-sided (i.e., propagating away from Earth).

Figure 5. Coronagraph images of CME 1 (from *STEREO* in the top row, and *LASCO* bottom left) and CME 2 (*LASCO*, bottom right).

Park et al. (2013), Priše et al. (2014), and Gómez-Herrero et al. (2015) have presented extensive studies of this CME and its associated SEP signatures at 1 AU.

The second CME (CME 2) first appeared in *LASCO*'s field of view on November 4 01:25 UT at the Sun's eastern limb, and later as a weak halo in *STEREO-B*'s COR2 coronagraph. A post-eruption arcade was observed on the solar disk at a Carrington longitude of $\sim 59^\circ$, 25° N by *STEREO-B*'s EUVI just before the coronagraph observations of CME 2. A CME (which may be CME 2) was also seen to emerge from the western limb in *STEREO-A*'s COR1 and COR2 coronagraphs at around the same time. Table 2 summarizes the times at which the signatures of CMEs 1 and 2 were first observed by the various instruments, and Figure 5 shows a number of coronagraph images of the two CMEs.

Both CMEs are listed in the CDAW *LASCO* CME catalog (cdaw.gsfc.nasa.gov/CME_list). Taking the catalog's linear plane-of-sky speeds for the two CMEs (756 km s^{-1} for CME 1 and 991 km s^{-1} for CME 2), the estimated launch times for the CMEs (November 3 21:30 UT for CME 1 and November 4 00:10 UT for CME 2), and assuming that the CMEs propagated at constant speed, CME 1 would be expected to arrive at *MESSENGER* on November 4 16:05 UT and CME 2 on November 5 00:24 UT. The expected arrival time of CME 2 is closer to the actual in situ arrival time of November 5 00:43 UT, and so we suggest that CME 2 is the most likely counterpart to the magnetic cloud observed at *MESSENGER* and *STEREO-B*. Furthermore, it would be expected, given that the *MESSENGER*–*STEREO-B* line lay relatively close to the plane of sky as seen from *LASCO* at this time, that the plane-

of-sky speed should be comparable to the in situ leading edge speed (assuming little or no deceleration): this is indeed the case for CME 2. We note that using the nonlinear speeds given by the CDAW catalog produces comparable estimated arrival times and would lead to a similar conclusion to the one drawn above. This conclusion is in contrast to that reached by Gómez-Herrero et al. (2015), who link the magnetic cloud observed by *MESSENGER* and *STEREO-B* to CME 1. Such a linkage would suggest that the minimum longitudinal extent of the magnetic cloud's flux rope was 100° , since the active region from which CME 1 was launched lay 50° in longitude from *STEREO-B*. (This estimate of the minimum longitudinal extent assumes that the CME launch was centered at and symmetric about the active region.) As Gómez-Herrero et al. point out, a minimum span of 100° would make the flux rope particularly wide in longitudinal extent; Richardson & Cane (1993), for example, have previously found that magnetic shock drivers such as flux ropes have a maximum longitudinal extent of 100° .

The signatures of a flux rope were also observed at *Venus Express* from 08:31 UT on November 5, between the arrival times of the flux rope at *MESSENGER* and *STEREO-B*. *Venus Express* was at a 27° longitudinal separation from the *MESSENGER*–*STEREO-B* line at this time. Given that CMEs often have an angular width greater than 30° , it is quite possible that all three spacecraft observed the same magnetic cloud. The best force-free fit of the rope at *Venus Express* (with a χ^2 value of 0.18) gives an axis orientation of $\sim \theta_R = -20^\circ$, $\varphi_R = 278^\circ$, and impact parameter of 0.47; however, this fit is right-handed, in contrast to the left-handedness of the rope at *MESSENGER*.

Figure 6. Magnetic field magnitude (first panel), field components (second panel), and field angles θ and φ (third and fourth panels, as defined in the text) observed by *Venus Express*. The flux rope interval, as in Figures 2 and 3, is marked by the vertical dashed lines. Note the enhanced field strength within the magnetosphere ahead of the magnetic cloud, peaking at above 200 nT (compared to a typical field of ~ 40 nT): this compression of the magnetosphere was likely driven by the ram pressure of the impacting cloud. A right-handed flux rope fit is shown overlaying the data.

and *STEREO-B*. Such a disparity in handedness is not possible within a single magnetic cloud and suggests that a different cloud was observed by *Venus Express*. The axis orientation for this fit is comparable to that obtained from MVA ($\sim \theta_R = -50^\circ$, $\varphi_R = 264^\circ$, $\lambda_1/\lambda_2 = 3.6$, $\lambda_3/\lambda_2 = 0.098$).

However, there are signs of degeneracy in the force-free fitting of the rope at Venus. It is possible to obtain a somewhat lower quality, left-handed fit (with a χ^2 value of 0.26). This fit has an axis orientation of $\sim \theta_R = -3^\circ$, $\varphi_R = 170^\circ$, and impact parameter of 0.64. Such an orientation, near as it is to the sunward direction, is close to the limit at which the model can operate accurately. (The model breaks down entirely for sunward- or anti-sunward-oriented rope axes.) A relatively

large impact parameter such as this also tends to limit the accuracy of the model.

In summary, the arrival times of the cloud at each spacecraft unquestionably point to all three spacecraft having observed the same cloud; the best Lundquist fit of the cloud that can be obtained at Venus does not agree with this conclusion. However, given the ambiguity in the cloud fitting at Venus, we suggest that the results obtained from this fitting should be treated with caution. A more sophisticated model may be required to accurately model the cloud signatures at Venus.

The magnetic field data of the cloud taken by *Venus Express*'s MAG instrument (Zhang et al. 2006) are shown in Figure 6. The front half of the flux rope was observed while the

spacecraft was within Venus’s magnetosheath but reasonably good force-free fits could still be made across the full extent of the rope. As with the post-planetary insertion data for *MESSENGER*, heliospheric structures such as CME flux ropes can often be discerned and analyzed in the *Venus Express* data despite the spacecraft’s regular forays into the planetary magnetosphere.

We note that no magnetic cloud signatures were observed at either *ACE* or *STEREO-A* around the time of these events.

4. CONCLUSION AND DISCUSSION

Much of what is currently understood about magnetic cloud evolution during propagation has been inferred from the statistics of different clouds observed at different heliocentric distances, rather than the tracking of individual events. We have presented and analyzed signatures of the same magnetic cloud observed by *MESSENGER* and *STEREO-B* while the spacecraft were close to radial alignment with the Sun in 2011 November—such a rarely obtained set of radial observations has allowed the radial evolution of an individual magnetic cloud to be determined.

The flux rope of the cloud at the two spacecraft has been analyzed using force-free fitting and MVA. During propagation between 0.44 and 1.09 AU, the force-free fitting indicates that:

1. the cloud’s radial width increased by a factor of ~ 2.3 (corresponding to a dependence of $r_H^{0.94}$ on heliocentric distance) and axis magnetic field strength decreased by a factor of ~ 5.3 (a dependence of $r_H^{-1.84}$). This constitutes direct observational evidence, from the same region of the same magnetic cloud at two different heliocentric distances, of magnetic cloud expansion in the radial direction;
2. the magnetic flux that threaded the cross-sectional area of this cloud was conserved at the macroscopic scale, suggesting that at least some magnetic clouds may undergo little erosion through magnetic reconnection and retain their field topology during propagation beyond the orbit of Mercury;
3. and the axis of the flux rope rotated by $\sim 33^\circ$ in longitude and $\sim 30^\circ$ in latitude toward the solar equatorial plane ($\theta = 0^\circ$), suggesting that magnetic clouds may undergo significant rotation during propagation in interplanetary space. Given its apparent higher sensitivity to the location of the trailing edge of the flux rope at *MESSENGER*, as well as some questions of how well the variance directions in the data are defined, we suggest that the MVA is a less suitable analysis method for determining the axis orientation of this rope compared to the force-free fitting.

Furthermore, by assuming that the magnetic cloud’s helicity was conserved, we have inferred the following.

1. The cloud’s axial length L increased during propagation.
2. The cloud’s angular width Θ at *STEREO-B* was ~ 0.89 its value at *MESSENGER*, broadly in agreement with a cone model of CME expansion. A simple expression has been derived (Equation (9)) that relates the angular widths, radial widths, and axial field strengths of a magnetic cloud at two different heliocentric distances. This expression may be useful for linking in situ and remote observations of magnetic clouds.

3. The ratio of the cloud’s length to width remained roughly constant, and we have shown that this is a natural consequence of the axial flux and helicity conservation.

The magnetic cloud’s apparent rotation is significant. It has been hypothesized that the axes of magnetic clouds align with the local heliospheric current sheet (HCS) during their propagation through the heliosphere. Yurchyshyn (2008) studied the orientations of post-eruption arcade/coronagraph CME pairs and the corresponding magnetic clouds at 1 AU: where there was a difference between the corresponding orientations, it was found that the magnetic clouds tended to be aligned with the coronal neutral line, which forms the base of the HCS in the corona. Assuming that the neutral line gives at least a rough indication of the local HCS orientation at 1 AU, this finding supports the hypothesis that magnetic cloud axes rotate to align with the HCS.

Isavnin et al. (2014) have used coronagraph images to estimate the orientation of 14 CME flux ropes up to a heliocentric distance of 30 solar radii (R_S) and propagated these ropes to 1 AU with an MHD model, using in situ observations of the corresponding cloud at 1 AU as a model constraint. The model gave an estimate of the flux rope orientation all along its trajectory from the Sun to 1 AU and indicated that the ropes underwent significant rotation above 30 R_S ($\sim 20^\circ$ in θ for some cases) toward the solar equatorial plane and HCS. It has also been suggested (Forsyth et al. 2006) that this flattening of the cloud axis is linked to the global, systematic deflection of CMEs from high to low latitudes, driven by fast solar wind emerging from coronal holes (Cremades & Bothmer 2004).

The solar source of the magnetic cloud studied here had a Carrington longitude of $\sim 59^\circ$, 25° N during Carrington rotation 2116. The corresponding Wilcox Solar Observatory coronal field map (<http://wso.stanford.edu/>) at 2.5 R_S indicates that the neutral line in the vicinity of this source location was north–south aligned, very different from the magnetic cloud orientation observed in situ (which was approximately east–west aligned at *STEREO-B*). It may be the case that, in this instance, the neutral line at 2.5 R_S is a poor indicator of the HCS orientation at 0.44 and 1.09 AU, where the magnetic cloud was observed in situ. Moreover, neither *MESSENGER* nor *STEREO-B* crossed the HCS around the time of the magnetic cloud’s passage, suggesting that the cloud propagated through a region of the heliosphere away from the HCS. It is therefore difficult to associate the rotation observed in this cloud with HCS orientation.

Other clouds observed by radially aligned spacecraft could be analyzed in order to determine whether rotation of the flux rope axis toward the solar equatorial plane (or HCS) is a common phenomenon. A better understanding of such rotation could lead to better predictions of the geoeffectiveness of earthbound CMEs, given that such rotation would change the intensity and duration of southward magnetic fields impacted on the Earth’s magnetosphere. The magnetic cloud described here is one of the closest observed to the Sun to have been subsequently tracked along a radial line to a greater heliocentric distance: the upcoming *Solar Orbiter* and *Solar Probe Plus* missions will offer ample opportunity to make similar radially aligned observations from even closer to the Sun, and further studies that make full use of the *MESSENGER* and *Venus Express* data sets will be good preparation for these future missions.

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