

THE STRUCTURE AND EVOLUTION OF
INTERPLANETARY CORONAL MASS EJECTIONS
OBSERVED BY MESSENGER AND *VENUS EXPRESS*

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Dedicated to the memory of my grandmother, Ruth Marion Good

ABSTRACT

ICMEs observed by the MESSENGER and *Venus Express* spacecraft have been catalogued and analysed. The ICMEs were identified by smooth rotations of the B -field direction consistent with a flux rope structure, coinciding with an enhanced field strength. Thirty-five ICMEs were found in the surveyed MESSENGER data (~March 2007 to April 2012), and eighty-four ICMEs in the surveyed *Venus Express* data (May 2006 to December 2013). Ropes with northward leading edges were four times more common than ropes with southward leading edges, in agreement with a previously established solar cycle dependence. Ropes at low inclinations to the solar equatorial plane were four times more common than high-inclination ropes, possibly an observational effect. In addition, data from MESSENGER, *Venus Express*, STEREO and ACE were examined for multi-point signatures of the catalogued ICMEs. For spacecraft separations $<15^\circ$ in heliocentric longitude, the second spacecraft observed the ICME's rope in 82% of cases; this percentage fell to 49% for $15\text{--}30^\circ$ separations, to 18% for $30\text{--}45^\circ$ separations, and to 12% for $45\text{--}60^\circ$ separations. One ICME, observed by MESSENGER and STEREO-B while the spacecraft were radially aligned, has been analysed in detail. Few such radial observations of ICMEs have been reported previously. Force-free fitting indicates that the ICME's rope diameter increased with an $r_H^{0.94}$ dependence on heliocentric distance, and the axial B -field strength dropped with an $r_H^{-1.84}$ dependence, clear indications of expansion. Axial magnetic flux was conserved, suggesting that the rope underwent no significant erosion through reconnection. The change in the rope's angular width has been estimated via helicity conservation. The rope axis rotated by $\sim 30^\circ$ between the spacecraft towards the solar equatorial plane. A preliminary study of a larger number of radially-observed ICMEs indicates that rope rotations of this magnitude are not uncommon; such rotations would have important implications for space weather forecasting.

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A selected list of abbreviations and acronyms found in the text:

ACE	<i>Advanced Composition Explorer</i>
AU	Astronomical Unit
CIR	co-rotating interaction region
CME	coronal mass ejection
DOY	day of year
EUVI	<i>Extreme Ultraviolet Imager</i>
FIPS	<i>Fast Imaging Plasma Spectrometer</i>
GSE	Geocentric Solar Ecliptic
HCI	Heliocentric Inertial
HCS	heliospheric current sheet
HELCATS	<i>Heliospheric Cataloguing, Analysis and Techniques Service</i>
HI	<i>Heliospheric Imager</i>
HMF	heliospheric magnetic field
ICME	interplanetary coronal mass ejection
IMP	<i>Interplanetary Monitoring Platform</i>
ISEE	<i>International Sun-Earth Explorer</i>
LASCO	<i>Large Angle and Spectrometric Coronagraph</i>
MESSENGER, MES	<i>MErcury Surface, Space ENvironment, GEochemistry, and Ranging</i>
MHD	magnetohydrodynamic(s)
MVA	minimum variance analysis
NEAR	<i>Near Earth Asteroid Rendezvous</i>
OCM	orbital correction manoeuvre
PEA	post-eruption arcade
PLASTIC	<i>Plasma and Suprathermal Ion Composition</i>
RTN	Radial-Tangential-Normal
SE	solar equatorial
SEP	solar energetic particle

SIR	stream interaction region
SOHO	<i>Solar and Heliospheric Observatory</i>
STEREO	<i>Solar TERrestrial RElations Observatory</i>
STA, STB	STEREO-A, STEREO-B
SWEPAM	<i>Solar Wind Electron, Proton and Alpha Monitor</i>
UT	Universal Time
VEX	<i>Venus Express</i>
VSO	Venus Solar Orbital

Note that the full names of spacecraft and instruments are italicised in the text while their abbreviations are not. This follows the convention adopted in the *Solar Physics* journal, published by Springer.

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1 | Introduction

1.1. THESIS MOTIVATION

Coronal mass ejections (CMEs) are large-scale magnetic field and plasma structures that erupt from the solar atmosphere. These discrete structures propagate out into the heliosphere following their 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. CMEs – or rather, their interplanetary manifestations, ICMEs – are the major driver of space weather at the Earth.

Presented in this thesis is an analysis of ICMEs observed by the *MErcury Surface, Space ENvironment, GEochemistry, and Ranging* (MESSENGER; MES) spacecraft, and by the *Venus Express* (VEX) spacecraft. Both MES and VEX spent significant amounts of time in the solar wind where they observed a large number of ICMEs. The motivation for studying ICMEs observed by these spacecraft is threefold:

- (i) MES and VEX have offered the only sub-1 AU *in situ* observations of ICMEs available from the last decade (~2006 to 2015);
- (ii) the datasets provided by these spacecraft have not been systematically analysed for ICME signatures before, and represent a largely untapped resource for the study of ICMEs; and
- (iii) MES and VEX greatly expand the *in situ* observational coverage near the solar equatorial (SE) plane provided by spacecraft at 1 AU, greatly expanding the opportunities to perform multi-point studies of individual ICMEs.

In Chapter 2, the MES and VEX spacecraft are described in outline. In Chapter 3, a catalogue of ICMEs observed by the two spacecraft is presented and analysed. The catalogued ICMEs were identified by the presence of magnetic flux ropes, the coiled magnetic field structures that are observed in many ICMEs. Cataloguing large numbers of ICMEs allows statistical trends in ICME properties to be robustly determined. Trends in the catalogue have been compared and contrasted to those found in other selected ICME catalogues; comparisons are in particular made with catalogues of ICMEs observed by *Helios*, the ground-breaking mission that sent spacecraft to the inner heliosphere for the first time, during Solar Cycle 21. Chapter 3 is based upon a journal article published by the author in *Solar Physics* (Good and Forsyth, 2016).

Identifying opportunities to perform multi-point ICME studies has been a key motivation for this work. Single-spacecraft analysis, although useful, can only offer a limited view of an ICME's nature, local to the one-dimensional path sampled by the spacecraft during the ICME's passage. Multi-point observations, where two or more spacecraft observe an ICME *in situ*, give a more global view. How far do ICMEs typically extend near the SE plane? How often do two longitudinally separated spacecraft near the SE plane observe signatures of the same ICME? In which ways, and to what extent, do individual ICMEs evolve during their propagation in interplanetary space? These outstanding questions in the field of ICME research can only be answered through multi-point analysis, and are questions considered in this thesis.

In Chapter 4, an in-depth study of an ICME observed by two radially aligned spacecraft is presented. Such observations allow sampling of approximately the same region of an ICME at different heliocentric distances, allowing any evolution in that region to be discerned. Chapter 4 is based on an article published by the author in the *Astrophysical Journal* (Good *et al.*, 2015). A preliminary study of a larger number of radially observed ICMEs is described in Chapter 5.

In the remainder of this chapter, a concise introduction to heliospheric physics relevant to the proceeding chapters is presented. Included are descriptions of the solar wind, the heliospheric magnetic field, CMEs and ICMEs, and force-free magnetic fields.

1.2. THE SOLAR WIND

The solar wind is a continuous stream of ionised particles flowing radially away from the Sun in all directions. This particle flow is mostly composed of H^+ (~95% by mass) and He^{2+} (~4%), with a wide range of other ions in small abundances (~1% in total) also typically present (*e.g.*, Bame *et al.*, 1972, Ogilvie and Coplan, 1995). In addition to the ions, there is an electron component in the solar wind that brings about quasi-neutrality of charge. The solar wind plasma flows to the extremities of the solar system where it eventually comes into pressure balance with the plasma of the interstellar medium. The surface at which this balance occurs, the heliopause, envelops the volume of space known as the heliosphere. Within the heliosphere, the solar wind dominates the plasma environment.

The solar wind exists because of the remarkably high temperatures found in the solar corona. These temperatures, in excess of 1 million K, produce a large pressure gradient relative to interplanetary space that drives out the coronal material. Parker (1958) was the first to describe a hydrodynamic model of the corona and solar wind. Considering only the dominant H^+ component, and by assuming a steady state, the momentum balance within the corona is given by

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \rho \mathbf{g} \quad (1.1)$$

where $\mathbf{u}$, ρ and p are the flow velocity, mass density and pressure within the corona, respectively, and $\mathbf{g}$ is the gravitational acceleration due to the Sun's mass. The first term on the right-hand side of Eq. 1.1 corresponds to the outward-directed pressure gradient force, and the second term to the inward-directed gravitational force: these terms do not balance in the corona, hence the non-zero momentum flow term present on the left-hand side (*cf.* a hydrostatic system such as the Earth's atmosphere, where this term would be zero).

For a one-dimensional, spherically symmetric corona, Eq. 1.1 becomes

$$u_r \frac{du_r}{dr} = -\frac{1}{nm} \frac{d}{dr}(2nk_B T) - \frac{GM_S}{r^2} \quad (1.2)$$

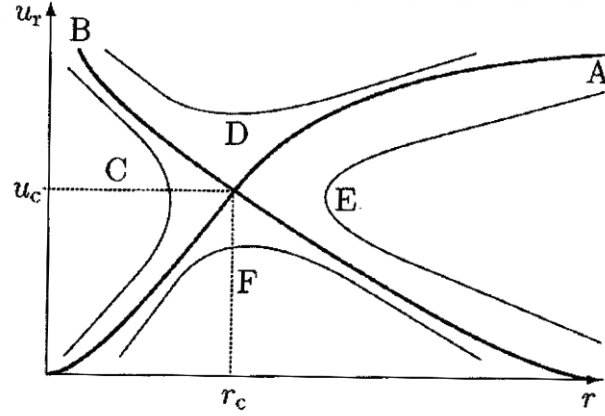


Figure 1.1. Six possible solutions to the Parker solar wind equation. Solution A most closely resembles the real solar wind – subsonic below the critical radius, and supersonic above. Taken from Kallenrode (2004).

where r is the radial distance from the solar surface, $n(r)$ and m are the number density and mass of H^+ ($\rho = nm$), respectively, $u_r(r)$ is the radial flow speed, T is the coronal temperature, G is the gravitational constant and k_B Boltzmann's constant. The electron pressure, equal to the pressure of the H^+ component, is accounted for by the factor of 2 in the pressure gradient term. By assuming that the corona is isothermal and applying the (steady-state) mass continuity condition, $r^{-2} d(r^2 \rho u_r)/dr = 0$, it may be shown that

$$\frac{1}{u_r} \frac{du_r}{dr} \left(u_r^2 - \frac{2k_B T}{m} \right) = \frac{4k_B T}{mr} - \frac{GM_S}{r^2} \quad (1.3)$$

Eq. 1.3 is known as the Parker solar wind equation. Fig. 1.1 shows six mathematically possible solutions to this equation: of these, Solution A most closely resembles the observed solar wind. Below a critical radius $r_c = GM_S m / 4k_B T$ (~ 5.8 solar radii), the solar wind speed is subsonic, *i.e.*, $u_r < u_c$, where the sound speed $u_c = (2k_B T/m)^{1/2}$; above this radius, the solar wind is supersonic, *i.e.*, $u_r > u_c$. Fig. 1.2 shows Solution A extended to the radius of the Earth for a range of coronal temperatures. Despite neglecting various complicating factors in its derivation – *e.g.*, magnetic fields, anisotropies of temperature and pressure, differing H^+ and electron temperatures, and

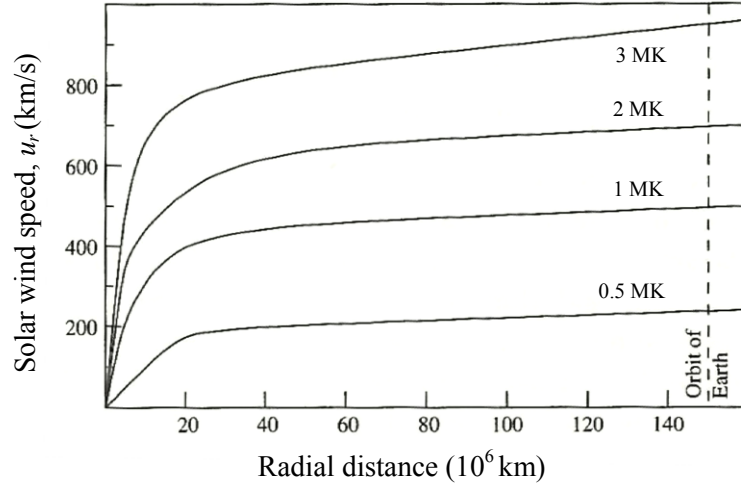


Figure 1.2. Solar wind speed as a function of radial distance from the Sun for a range of coronal temperatures. Adapted from a figure in Kallenrode, 2004.

the significant contribution made to the momentum transport by heavier ions – the form of Solution A is a reasonably accurate representation of the solar wind speed profile with distance from the Sun.

One important feature of the solar wind not accounted for in the basic Parker model is the existence in reality of two distinct solar wind plasma streams, namely, the ‘fast’ and ‘slow’ winds. The fast wind emerges from coronal holes, regions of open magnetic field in the corona. Coronal holes are usually confined to the Sun’s polar regions during the minimum phase of the 11-year solar activity cycle; during solar maximum, coronal holes often appear at much lower latitudes. The mean flow speed of the fast wind at 1 AU is $\sim 700 \text{ km s}^{-1}$, with an average ion density of $\sim 3 \text{ cm}^{-3}$ (e.g., Feldman *et al.*, 1977). The slow solar wind, in contrast, emerges from regions of closed magnetic field in the corona; around solar minimum, these closed field regions predominate near the heliomagnetic equator. The mean flow speed of the slow wind at 1 AU is $\sim 300 \text{ km s}^{-1}$, with an average ion density of $\sim 8 \text{ cm}^{-3}$. The slow wind is more turbulent than the fast, and more variable in speed, density and composition.

1.3. THE HELIOSPHERIC MAGNETIC FIELD

The coronal plasma exists in a low beta state (*i.e.*, the plasma's magnetic pressure exceeds its thermal pressure) and thus the dynamics of the corona are dominated by the coronal magnetic field. During solar minimum, the coronal field is quasi-dipolar in form – open field lines at the poles, closed field lines around the heliomagnetic equator. With increasing altitude in the corona, however, the dynamic pressure of the solar wind outflow becomes increasingly significant. Eventually, the solar wind dynamic pressure dominates and the frozen-in coronal field is dragged out with the solar wind. At around 2 solar radii (R_S) above the solar surface, the dragged-out field is largely radial. Fig. 1.3 shows how the coronal field (solid lines) becomes increasingly less dipolar (dashed lines) with distance from the solar surface, and how the closed loops around the equator are drawn out to form the streamer belt. The field continues to advect with the solar wind into the heliosphere, forming the heliospheric magnetic field (HMF).

The radially-outflowing solar wind and the HMF embedded within it do not co-rotate with the Sun. Since the footpoints of the magnetic field lines are anchored to the photosphere (the nominal surface of the Sun), the HMF is wound into an Archimedean spiral by the solar rotation. First modelled by Parker (1958), the eponymous Parker spiral is depicted in Fig. 1.4. The radial component of the field in Parker's spherically symmetric model is given by

$$B_r = B_0 \left(\frac{r_0}{r} \right)^2 \quad (1.4)$$

This inverse-square relationship follows from the conservation of magnetic flux required by Gauss's law, *i.e.*, $r^{-2} d(r^2 B_r)/dr = 0$. The radial distance r_0 gives the location of the source surface of the HMF. The magnetic field threading the source surface is purely radial with a magnitude of B_0 ; across the source surface, B_0 varies with latitude along lines of fixed longitude. The source surface is commonly placed at $2.5 R_S$ above the photosphere in many coronal and heliospheric field models.

Above the source surface, the HMF acquires a non-zero azimuthal component, B_ϕ . The azimuthal component is most easily derived by moving to a reference frame co-rotating with the Sun at the solar rotation speed, Ω . In such a frame, the solar wind

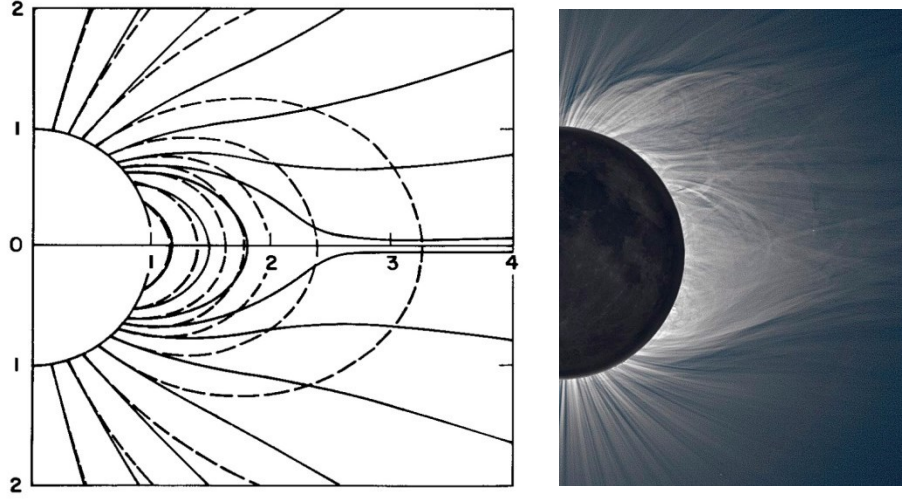


Figure 1.3. *Left panel.* The coronal field model of Pneuman and Kopp (1971). Solid lines show the coronal field, and dashed lines the dipolar field that would exist in the absence of the solar wind. At solar maximum, the coronal field structure is considerably more complex, although the field would be dragged out by the solar wind in a similar fashion. *Right panel.* An enhanced photographic image of the corona taken during a solar eclipse at solar minimum (obtained from www.zam.fme.vutbr.cz/~druck/eclipse, 26/07/16); bright regions correspond to the density enhancements found along flux tubes. There is a good qualitative match between the left and right panels.

speed also develops an azimuthal component, $v_\phi = -\Omega r \sin\theta$, where θ is the colatitude of the stream line. The negative sign indicates that the azimuthal component is oppositely directed to the solar rotation. This component is in addition to a constant radial speed component, v_r . As the field is frozen to the flow, the field lines trace out the same spiral pattern as the solar wind in the co-rotating frame. Thus, $B_\phi/B_r = v_\phi/v_r$, from which it follows that

$$B_\phi = -B_0 \frac{\Omega \sin\theta}{v_r} \frac{r_0^2}{r} \quad (1.5)$$

In contrast to the $1/r^2$ fall-off in the radial component, the azimuthal component falls with a more gradual $1/r$ dependence. The Parker spiral hence becomes more tightly wound with increasing heliocentric distance. The acute angle between the spiral field

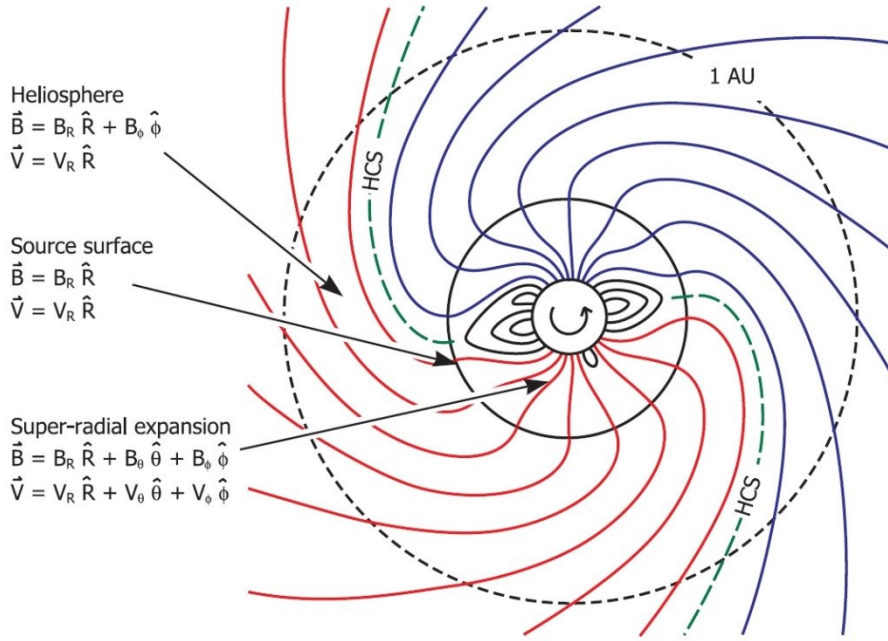


Figure 1.4. The Parker spiral in the solar equatorial (SE) plane. The red and blue spiral lines indicate sectors of opposite magnetic field polarity. The heliospheric current sheet (HCS) forms at the sector boundaries. Note that this sector structure arises in the SE plane because of the tilt between the heliomagnetic equatorial plane (co-planar with the x -axis in Fig. 1.3) and the SE plane. Taken from Owens and Forsyth (2013).

line and the radial direction is given by $\tan^{-1}(\Omega r \sin \theta / v_r)$; at the Earth, the spiral angle is $\sim 45^\circ$ for a typically observed solar wind speed of 400 km s^{-1} . As the solar wind flow (in the non-co-rotating frame) is entirely radial in Parker's model, there is no field component in the meridional θ direction.

Although the observed HMF direction often deviates from the Parker spiral direction over short timescales, there is a reasonably good match over long timescales, both in the ecliptic plane (*e.g.*, Ness and Wilcox, 1964) and at higher latitudes (Forsyth *et al.*, 2002). Owens and Forsyth (2013) present a recent review of various additions that have been made to the basic Parker model, which include, for example, differential rotation of the photospheric footpoints (Fisk, 1996).

Fig. 1.4 also depicts the heliospheric current sheet (HCS), which forms in

interplanetary space at the boundaries between sectors of oppositely directed magnetic field. Around solar minimum, the HCS originates at the cusp of the streamer belt (shown at $\sim 2.5 R_S$ on the x -axis of Fig. 1.3). In the simple quasi-dipolar picture, field lines directed away from the Sun predominate in one solar hemisphere, and field lines directed towards the Sun predominate in the other hemisphere. These anti-parallel field lines converge at the streamer belt cusp to form a magnetic neutral line across the disc of the Sun. The neutral line propagates out with the solar wind to produce the HCS.

As the rotation axis and magnetic dipole axis of the Sun are not aligned, the HCS takes the form of a rippled ‘ballerina skirt’ (Alfvén, 1977) rather than a simple flat sheet. Thus a spacecraft in the ecliptic plane (close to the solar equatorial plane) will cross the HCS multiple times during one solar rotation period.

1.4. CORONAL MASS EJECTIONS

1.4.1. *Solar origins*

The tilted dipole model of the Sun described above gives a good first-order approximation of the coronal magnetic field and the HMF at quiet times. However, the model does not capture the true complexity and dynamism, evident even during solar minima, of the coronal field and its extension into interplanetary space. Perhaps the most spectacular manifestation of this dynamism is the existence of coronal mass ejections (CMEs). As outlined at the opening of this chapter, CMEs are large-scale eruptions of magnetic flux and plasma from the Sun that are distinct from the regular solar wind outflow. CMEs are the biggest cause of deviation from the Parker models of the solar wind and HMF.

CMEs develop from regions of previously closed and stable magnetic field in the corona. Such field is located mostly around the streamer belt at solar minimum, but is more widespread across the solar surface towards solar maximum. The exact mechanism by which CMEs erupt is not fully understood, but must involve an imbalance between the stable, closed field and the corona’s tendency to expand (*e.g.*, Webb and Howard, 2012, and references therein). Chen (2011) reviews a number of the

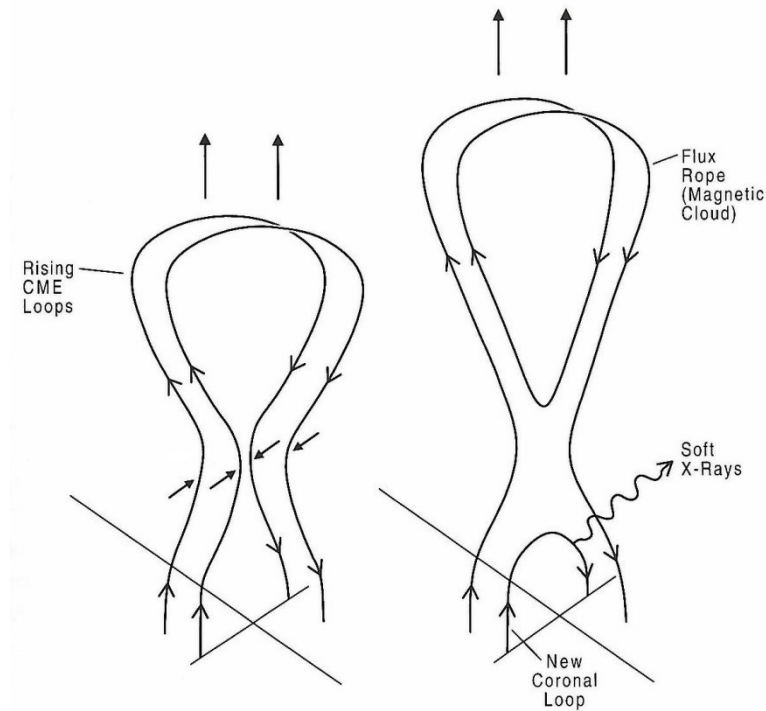


Figure 1.5. The flux rope formation model of Gosling (1993). Taken from Forsyth and Gosling (2001).

different CME launch models and their basis in observations.

Most models of CME development include the formation of magnetic flux ropes, either prior to or during the eruption process (Chen, 2011). Magnetic flux ropes consist of a series of nested, helical field lines wound around a central axis, where the pitch angle (*i.e.*, the angle between the field and axis directions) decreases as the axis is approached. These structures have long been observed *in situ* by interplanetary spacecraft (see Sect. 1.4.3).

Fig. 1.5 shows a mechanism for flux rope formation in the corona proposed by Gosling (1993), where the adjacent legs of different field loops become sheared and reconnect. Repeated occurrence of this process across multiple loops would produce a flux rope, with a new arcade of coronal loops forming beneath it. Such arcades, referred to as post-eruption arcades (PEAs), are often observed following the eruption of CMEs

(*e.g.*, Tripathi *et al.*, 2004).

Following their initiation, CMEs are accelerated upwards through the solar atmosphere. Again, this acceleration mechanism is not fully understood, but could involve reconnection jets beneath the magnetic core of the CME (*i.e.*, the flux rope) driving the CME away from the solar surface, or the solar wind outflow producing a drag force on the CME (Chen, 2011, and references therein).

1.4.2. Coronagraph observations

During the acceleration phase of their development, CMEs enter the coronagraph field of view. Coronagraphs produce white-light images of dense structures around the occulted disc of the Sun, where bright regions in the images correspond to regions of enhanced electron density. An example of a CME observed by a coronagraph is shown in Fig. 1.6 at successive stages of its emergence from the solar atmosphere. CMEs were first identified using coronagraphs (Tousey, 1973), and their classical definition – “an observable change in coronal structure that (1) occurs on a time scale between a few minutes and several hours and (2) involves the appearance of a new, discrete, bright, white-light feature in the coronagraph field of view” (Hundhausen *et al.*, 1984) – is based upon the coronagraph perspective.

The CME shown in Fig. 1.6 displays the commonly observed three-part structure of a bright front, dark cavity and bright core. The dark cavity is thought to contain the flux rope, with the bright front being a pile-up of coronal material ahead of the rope; the bright core corresponds to material from the blow-out of streamers and prominences that often coincides with CME eruption (*e.g.*, Howard *et al.*, 1985).

The *Large Angle and Spectrometric Coronagraph* (LASCO) on board the *Solar and Heliospheric Observatory* (SOHO) has provided near-continuous coronagraphic observation of the Sun since 1995, and has observed over ten thousand CMEs during this time. Based on the CDAW CME catalogue, which lists CMEs identified by eye in LASCO images, the rate of CME occurrence at the minimum of Solar Cycle 23 (May 1996 to Jan 2008) was ~ 0.5 per day, rising to ~ 6 per day at solar maximum (*e.g.*, Yashiro *et al.*, 2004).

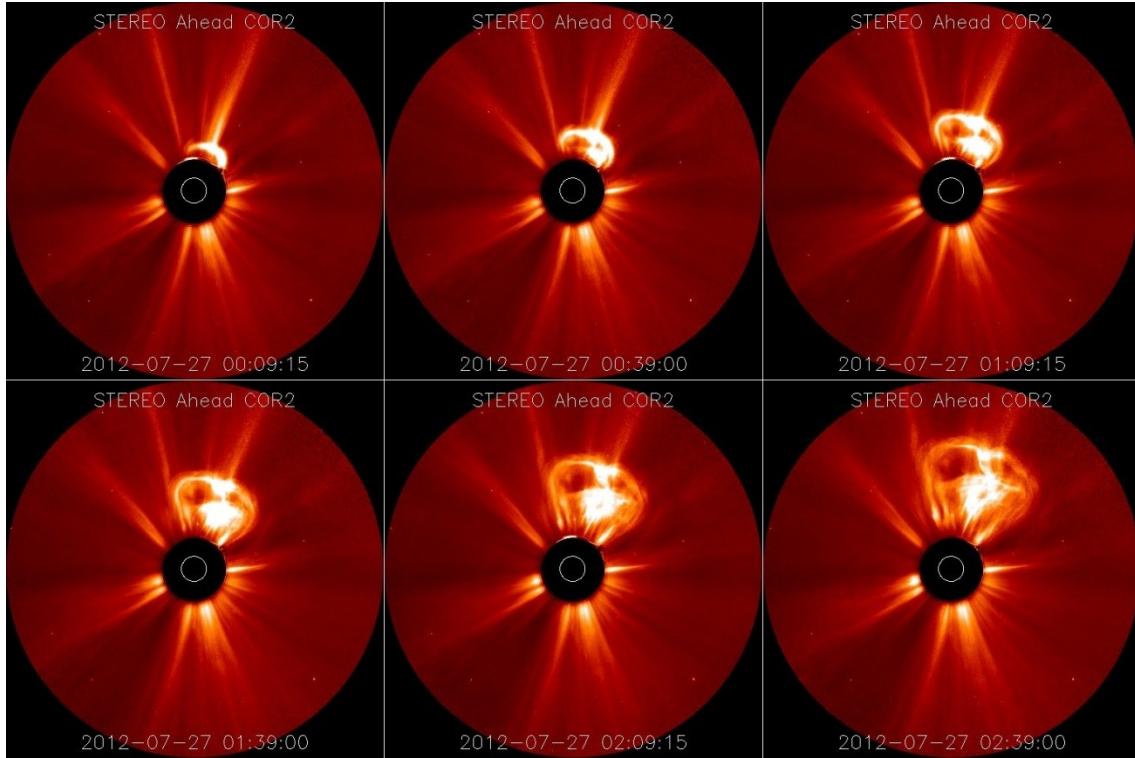


Figure 1.6. Evolution of a CME over 2.5 hours, observed by the COR2 coronagraph aboard the STEREO-A spacecraft. Images obtained from <http://stereo-ssc.nascom.nasa.gov>.

1.4.3. ICMEs and magnetic clouds

Beyond the coronagraph field of view, CMEs continue to propagate and expand into the heliosphere along with the solar wind. When observed by spacecraft *in situ*, CMEs are referred to as ICMEs; ICMEs display a set of signatures in magnetic field, plasma and particle data distinct from that of the ambient solar wind. A number of commonly observed ICME signatures are listed in Table 1.1.

Many ICMEs do not display all of the signatures in Table 1.1. Also, a number of these signatures may be associated with other phenomena. For example, enhanced B field magnitudes are a common feature of co-rotating interaction regions (CIRs), structures that are formed by the interaction of fast and slow solar wind streams (*e.g.*, Gosling and Pizzo, 1999).

Signature	Description
(B1) B rotation*	$\gg 30^\circ$, smooth
(B2) B enhancement*	$\gg 10$ nT in ejecta; compression in sheath
(B3) B variance decrease	
(B4) Boundary discontinuities	
(B5) HMF draping	
(B6) Low plasma beta (β)*	$\beta < 0.1$
(P1) Declining velocity profile	
(P2) Extreme proton density (n_p) decrease	$n_p \leq 1 \text{ cm}^{-3}$
(P3) Electron temperature (T_e) drop	$T_e < 60,000 \text{ K}$
(P4) Proton temperature (T_p) drop*	$T_p < 0.5 \times [\text{expected temperature}]; T_p \ll T_e$
(P5) Upstream forward shock	
(C1) Enhanced $\text{He}^{2+}/\text{H}^+$ ratio	$\text{He}^{2+}/\text{H}^+ > 0.08$
(C2) Elevated O charge states	$\text{O}^{7+}/\text{O}^{6+} > 0.01$
(C3) High Fe charge states	
(C4) Occurrence of He^+	$\text{He}^+/\text{He}^{2+} > 0.01$
(C5) Enhancements of Fe/O	
(C6) Enhancements of $^3\text{He}/^4\text{He}$	
(W1) Ion acoustic waves	
(S1) Bi-directional strahl electrons	
(S2) Bi-directional MeV ions	
(S3) Cosmic ray depletions (Forbush decreases)	Few % at $\sim 1 \text{ GeV}$
(S4) Bi-directional cosmic rays	

Table 1.1. The in situ signatures of an ICME observed at 1 AU. Magnetic field (B), plasma dynamics (P), plasma composition (C), plasma wave (W) and suprathermal particle (S) signatures are listed separately. Starred (*) table entries are the signatures of magnetic clouds. Expected temperature is an empirically derived estimate of solar wind temperature under normal conditions, as a function of solar wind speed and heliocentric distance (Lopez and Freeman, 1986). Adapted from a table in Zurbuchen and Richardson (2006).

When an ICME displays the starred signatures in Table 1, it may be described as a magnetic cloud. Burlaga *et al.* (1981) coined the term ‘magnetic cloud’ to describe particularly well ordered and coherent magnetic structures, later identified as a subset of ICMEs, that are frequently observed by spacecraft *in situ*: a magnetic cloud is formally 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 ICMEs. Soon after the first identification of magnetic clouds, it was found that their ordered magnetic field topology is often well approximated by the linear force-free flux rope (Goldstein, 1983). A cylindrically symmetric flux rope is shown in Fig. 1.7. 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 a number of these models.

Cane and Richardson (2003) found that around 15% of ICMEs observed near the SE plane at solar maximum are magnetic clouds, rising to 60% of ICMEs at solar minimum. At solar minimum, the streamer belt is often close to the SE plane – thus, if most radially propagating magnetic cloud flux ropes emerge from the closed fields of the streamer belt, it follows that more magnetic clouds will be observed near the SE plane at this time. Conversely, closed-field regions are found across a wider range of heliolatitudes at solar maximum, and so the magnetic clouds that emerge from them are less likely to intersect the SE plane.

It has been argued (*e.g.*, Russell *et al.*, 2005) that all ICMEs contain the low beta flux ropes of magnetic clouds, and that a spacecraft only observing other ICME signatures has followed a trajectory through the cloud that does not intersect the central flux rope region. This interpretation treats the magnetic cloud classification as an observationally dependent description, rather than a description of a physically distinct sub-population of ICMEs.

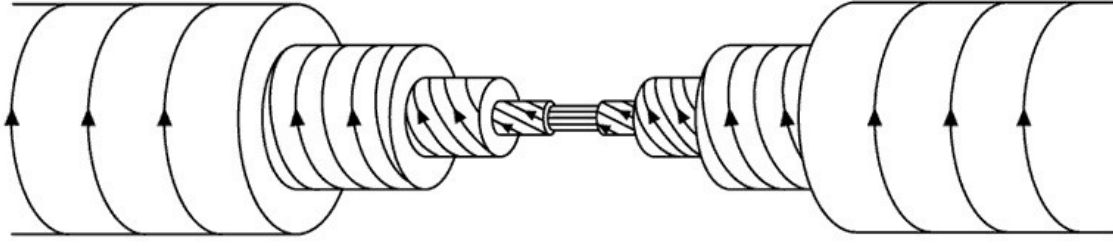


Figure 1.7. A cylindrically symmetric magnetic flux rope. Along the central axis of the rope, the field direction is aligned with the axis direction . Taken from Russell (1999).

1.4.4. Force-free fields

Many flux rope fitting techniques assume that the rope's magnetic field is force-free. Force-free fields are used to model a wide range of phenomena in space plasmas. The derivation that follows is adapted from a textbook treatment of force-free fields by Priest (1995).

In the magnetohydrodynamic force-free situation, where there is hydrostatic balance between the pressure gradients and gravity, the force balance

$$\mathbf{j} \times \mathbf{B} - \nabla p + \rho \mathbf{g} = \mathbf{0} \quad (1.6)$$

holds, where $\mathbf{j}$ is the current density. In low plasma beta structures such as magnetic clouds, the magnetic field component is dominant, such that

$$\mathbf{j} \times \mathbf{B} = \mathbf{0} \quad (1.7)$$

where the magnetic field is described as 'force-free'. Eq. 1.7 requires the magnetic field and current density to be parallel: thus $\mathbf{j}$ can be expressed as magnetic field multiplied by a scalar function of position, $\alpha(\mathbf{r})/\mu_0$, such that Ampère's law,

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} \quad (1.8)$$

may be re-written as

$$\nabla \times \mathbf{B} = \alpha(\mathbf{r}) \mathbf{B} \quad (1.9)$$

Taking the divergence of Eq. 1.9 and assuming a non-divergent B field yields

$$\mathbf{B} \cdot \nabla \alpha(\mathbf{r}) = 0 \quad (1.10)$$

This indicates that α is constant along a field line, and can only vary in the direction perpendicular to the field. Taking the curl of Eq. 1.9 yields

$$[\nabla^2 + \alpha^2(\mathbf{r}) + \nabla \alpha(\mathbf{r}) \times] \mathbf{B} = \mathbf{0} \quad (1.11)$$

If α is uniform, Eq. 1.11 simplifies to the Helmholtz equation,

$$(\nabla^2 + \alpha^2) \mathbf{B} = \mathbf{0} \quad (1.12)$$

The solution to this equation for a cylindrical flux rope geometry is described in Sect. 4.2.

2 | The MESSENGER and *Venus Express* spacecraft

Observations made by MESSENGER and *Venus Express* are central to the work presented in this thesis. The two spacecraft spent significant amounts of time in the solar wind despite their planetary focus, and offer the most recent *in situ* observations of the solar wind from the inner heliosphere. In this chapter, the mission objectives, instrument suites and orbits of both spacecraft are described. These descriptions follow a general introduction to fluxgate magnetometers. Magnetic field measurements from MES and VEX have been used most extensively in this work, and so the spacecraft's fluxgate magnetometers are described in greater detail. The sources of the MES and VEX data that have been used are given in Sect. 3.1.

2.1. FLUXGATE MAGNETOMETERS

In its most common form, a fluxgate magnetometer consists of a magnetically permeable, ring-shaped core and two coils of conducting wire. One coil is wound around the core (the 'drive' coil) and the other around the disc of the core (the 'sense' coil), as depicted in Fig. 2.1.

An alternating current is passed through the drive coil, which repeatedly magnetises and demagnetises the core in a periodic fashion. The symmetry of the core means that for each magnetic field component generated by one half of the core, an equal and opposite component is generated by the other half. These components cancel each other out in the absence of an external B -field, and no current is induced in the sense coil. This scenario is shown by the left-hand plots in Fig. 2.1.

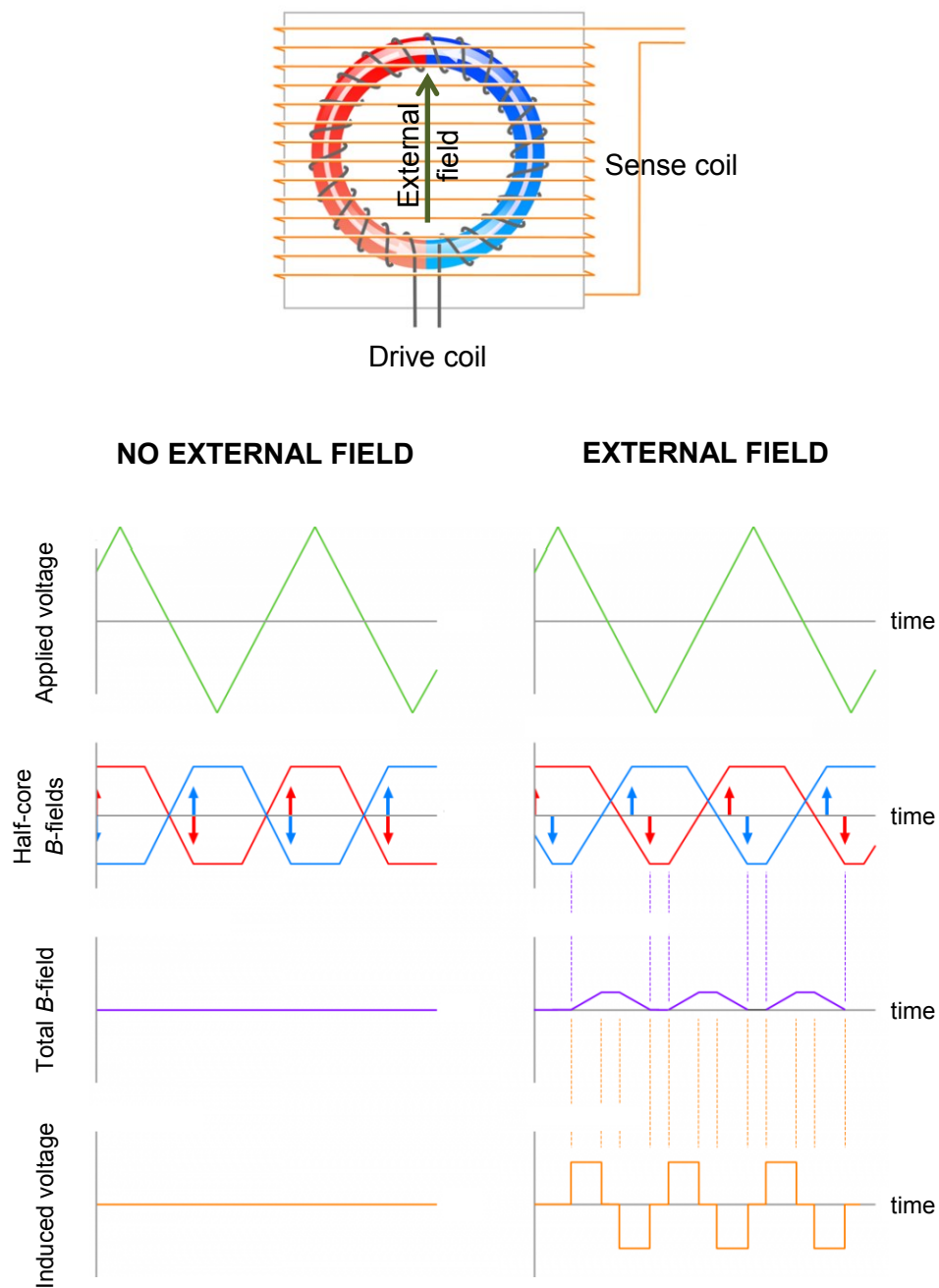


Figure 2.1. A ring-core fluxgate magnetometer (*depicted top*). The half-core B -fields (*red and blue lines*), total field (*lilac line*) and the induced voltage (*orange line*) produced by a driving voltage (*green line*) are shown, in both the absence and presence of an external B -field. Adapted from figures taken from www.carisma.ca, 26/07/16.

In the presence of an external field, the symmetry between the fields generated by the half-cores is broken. One half-core will have a field component that is parallel to the external field, and the other half-core will have a corresponding anti-parallel component. The half-core producing the parallel component will demagnetise later and the half-core producing the anti-parallel component will demagnetise sooner. Thus, during the time when demagnetisation occurs and the half-core polarities reverse, a net, time-varying magnetic field is produced by the core that induces a current in the sense coil. This situation is shown in the right-hand plots in Fig. 2.1.

The small, field-proportional voltage measured by the sense coil is at twice the frequency of the applied voltage. This voltage is sometimes fed back into the fluxgate as a dc voltage in order to null the core field, which can improve the linearity between the external field and induced voltage. (This mode of operation is described as ‘closed loop’.) Three orthogonal cores can be used to precisely determine the orientation of the external field vector in three dimensions.

2.2. MESSENGER

2.2.1. *Mission objectives and instrument suite*

NASA’s *ME*rcury *S*urface, *S*pace *EN*vironment, *GE*ochemistry, and *R*anging (MESSENGER; MES) spacecraft was launched in August 2004, and, following a ~6.5 year cruise phase, entered orbit around Mercury in March 2011. It was the first spacecraft to visit Mercury since *Mariner 10* in the 1970s, and the first to ever orbit the planet. MESSENGER’s primary mission period lasted from April 2011 to March 2012. This was followed by two extended mission periods. Upon the total depletion of its propellant in April 2015, MESSENGER impacted the surface of Mercury.

Solomon *et al.* (2001) describe the six science objectives of the MESSENGER mission, namely:

- (i) to investigate the high metal/silicate ratio found at Mercury, and its implications for planetary formation processes;
- (ii) to determine the geological history of Mercury;

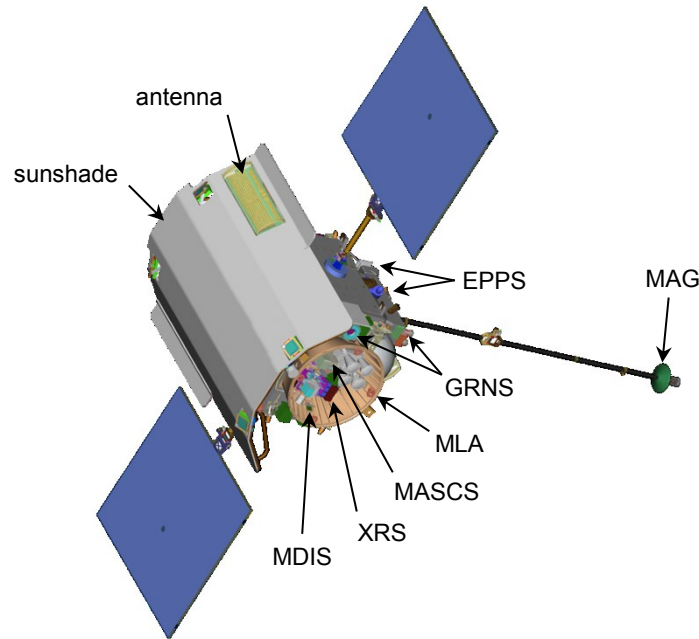


Figure 2.2. The MESSENGER spacecraft. The location of each of the instruments described in Table 2.1 is indicated. Image taken from messenger.jhuapl.edu, 26/07/16.

- (iii) to investigate the nature and origin of Mercury's intrinsic magnetic field;
- (iv) to investigate the structure and state of Mercury's core;
- (v) to identify the radar-reflective materials found at Mercury's poles; and
- (vi) to determine the dynamics and composition of Mercury's exospheric atmosphere.

Objective (iii) was the most significant with regard to the present work since it required MESSENGER to make many magnetospheric boundary crossings and to spend much time in the solar wind, where ICMEs were directly observable. The full suite of instruments carried by MESSENGER is described in Table 2.1, and the location of each instrument on the spacecraft is shown in Fig. 2.2.

MESSENGER carried a tri-axial, ring-core fluxgate magnetometer, MAG, mounted on a boom that extended 3.6 m from the spacecraft. The magnetometer had a coarse measurement range of $\pm 51,300$ nT at a 1.6 nT resolution that was used for pre-

Instrument	Description
<i>Energetic Particle and Plasma Spectrometer (EPPS)</i>	Composed of the Energetic Particle Spectrometer (EPS) that measured high energy electrons and ion distributions, and the Fast Imaging Plasma Spectrometer (FIPS) that measured low energy ion distributions (Bruce Andrews <i>et al.</i> , 2007)
<i>Gamma Ray and Neutron Spectrometer (GRNS)</i>	Produced elemental composition maps of Mercury's surface (Goldsten <i>et al.</i> , 2007)
<i>Magnetometer (MAG)</i>	A tri-axial fluxgate magnetometer that measured Mercury's intrinsic magnetic field (Anderson <i>et al.</i> , 2007)
<i>Mercury Atmospheric and Surface Composition Spectrometer (MASCS)</i>	Two grating spectrographs that analysed UV, visible and IR emission from Mercury's surface and exosphere (McClintock and Lankton, 2007)
<i>Mercury Dual Imaging System (MDIS)</i>	Two CCD cameras, a narrow-angle camera and a wide-angle camera used to map Mercury's surface (Edward Hawkins <i>et al.</i> , 2007)
<i>Mercury Laser Altimeter (MLA)</i>	A laser altimeter used to map the surface topography of Mercury (Cavanaugh <i>et al.</i> , 2007)
<i>Radio Science (RS)</i>	Used to precisely determine Mercury's gravitational field, as well as the location of the spacecraft (Srinivasan <i>et al.</i> , 2007)
<i>X-Ray Spectrometer (XRS)</i>	Used to map the elemental composition of Mercury's surface (Schlemm <i>et al.</i> , 2007)

Table 2.1. The eight instruments on board the MESSENGER spacecraft.

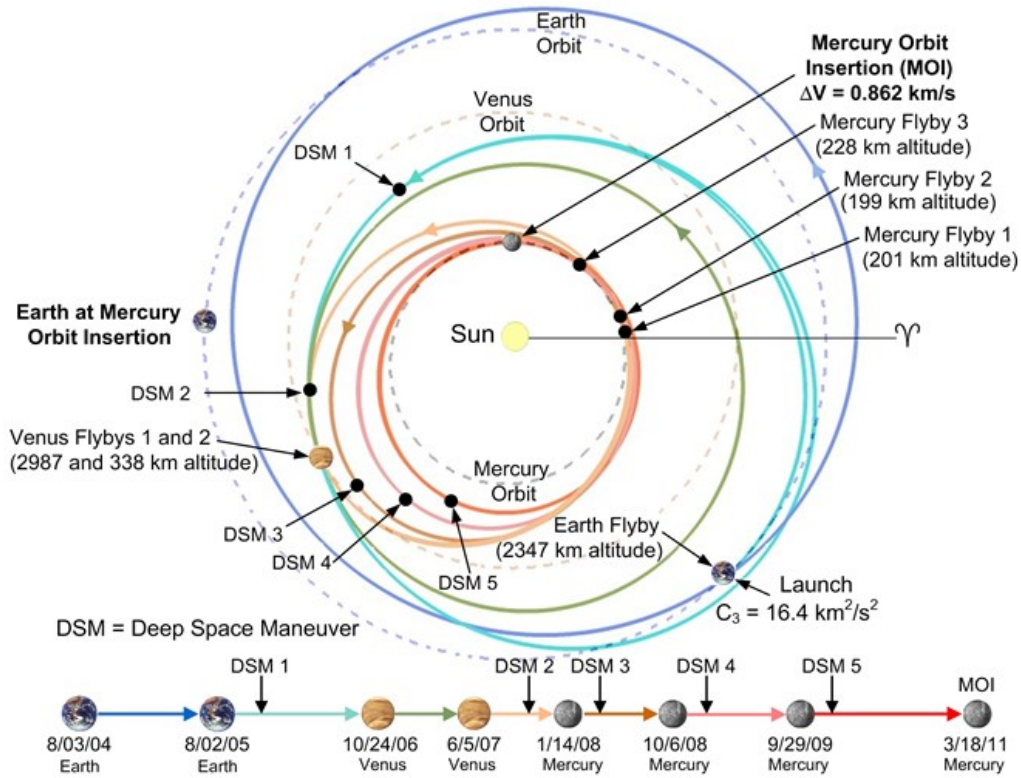


Figure 2.3. MESSENGER's cruise phase trajectory projected onto the ecliptic plane. Taken from messenger.jhuapl.edu, 26/07/16.

flight testing, and a fine measurement range of $\pm 1,530 \text{ nT}$ at a 0.047 nT resolution used for orbital-phase operations at Mercury. MAG had eleven sampling rates ranging from 0.01 Hz to 20 Hz ; eight-minute bursts of higher-resolution sampling were triggered by increased field fluctuations. MESSENGER was a magnetically clean spacecraft, with a fixed background field of less than a few nT and a variable field below 0.05 nT at least above 3 Hz identified at MAG's location on the boom. A detailed description of MESSENGER's MAG instrument is given by Anderson *et al.* (2007).

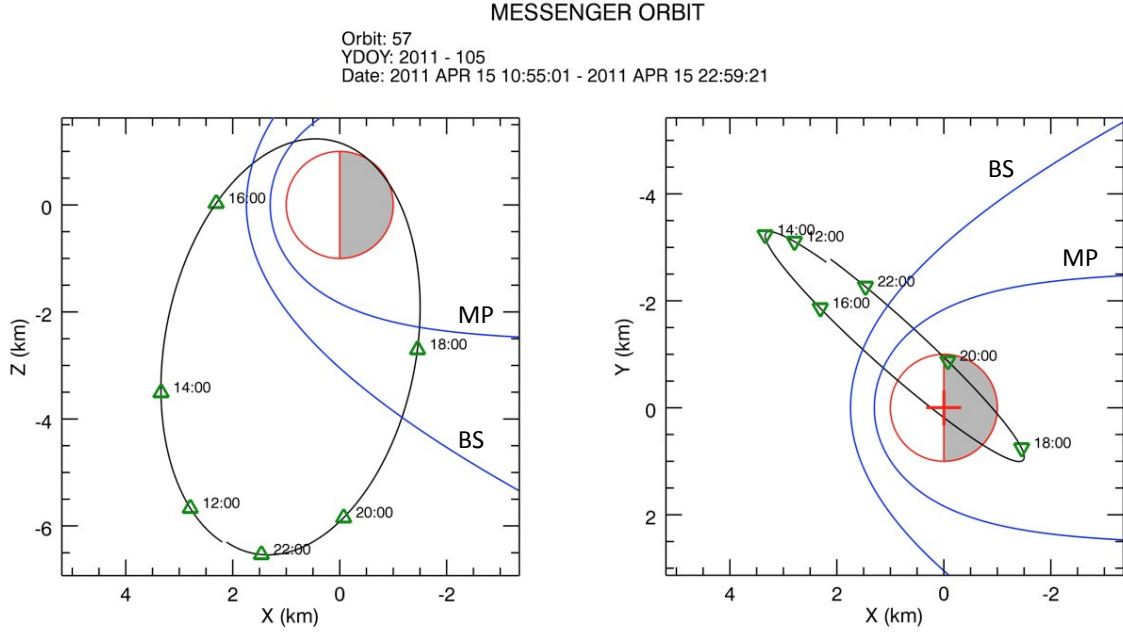


Figure 2.4. MESSENGER's 57th orbit of Mercury (*black ellipses*), early in the primary mission phase. X is parallel to the planet-Sun line, Z is parallel to the planet's spin axis, and Y completes the orthogonal set. The blue lines give the mean locations of the planetary magnetopause (MP) and bow shock (BS). Adapted from a figure taken from messenger.jhuapl.edu, 26/07/16.

2.2.2. Cruise phase and planetary orbits

The cruise phase trajectory of MESSENGER projected onto the ecliptic plane (*i.e.*, Earth's orbital plane) is shown in Fig. 2.3. Between launch on 3 August 2004 and planetary insertion on 18 March 2011, MES consecutively made one flyby of Earth, two flybys of Venus and three of Mercury. The flybys were used to perform gravity-assist manoeuvres that brought MES down to the heliocentric orbital distance of Mercury prior to planetary insertion. From mid-2007 onwards, the heliocentric latitude of MES relative to the SE plane did not exceed $\sim 3.4^\circ$.

At planetary insertion, MESSENGER entered into a highly eccentric orbit around Mercury. The initial periapsis of the orbit was at ~ 200 km above Mercury's surface, and the apoapsis at $\sim 15,193$ km; the orbital period was 12 hours. Numerous

orbital correction manoeuvres (OCMs) were performed during the primary mission phase (from insertion to 18 March 2012) to maintain these orbital characteristics. The periapsis was initially located at 60°N in latitude, and the orbital plane was inclined at 82.5° to Mercury's equatorial plane. The line connecting the periapsis and apoapsis of the orbit rotated clockwise around Mercury throughout the orbital mission. MES's eccentric orbit afforded clear views of the Caloris basin, a feature of interest on Mercury's surface close to the north pole.

MES's first, year-long extended mission began on 18 March 2012. On 16 and 20 April 2012, OCMs took place that brought the periapsis altitude to 278 km, the apoapsis altitude to 10,314 km, and the orbital period to 8 hours. Throughout the rest of the first extended mission, and the first fifteen months of the second extended mission (the two-year period from 18 March 2013), the periapsis altitude drifted steadily downwards. Four OCMs in the latter half of the second extended mission briefly stepped up the periapsis altitude, but the overall downward trend continued. The inevitable total depletion of MESSENGER's fuel precluded any further OCMs, and the spacecraft came to a controlled impact on Mercury's surface at 54°N , 210°E on 30 April 2015.

Fig. 2.4 depicts MESSENGER's orbit early in the primary mission phase. The orbital period at this time was 12 hours. The blue lines in the figure indicate the mean locations of the planet's magnetopause and bow shock; the figure indicates that MES spent a large majority of its time outside the magnetosphere during each orbit, where it made direct observations of the solar wind.

2.3. *VENUS EXPRESS*

2.3.1. *Mission objectives and instrument suite*

ESA's *Venus Express* (VEX) spacecraft was launched in November 2005, and, following a relatively short cruise phase of five months, entered orbit around Venus in April 2006. VEX was the first spacecraft to orbit Venus since NASA's *Magellan* spacecraft in the early 1990s. Although VEX's nominal mission ended in September

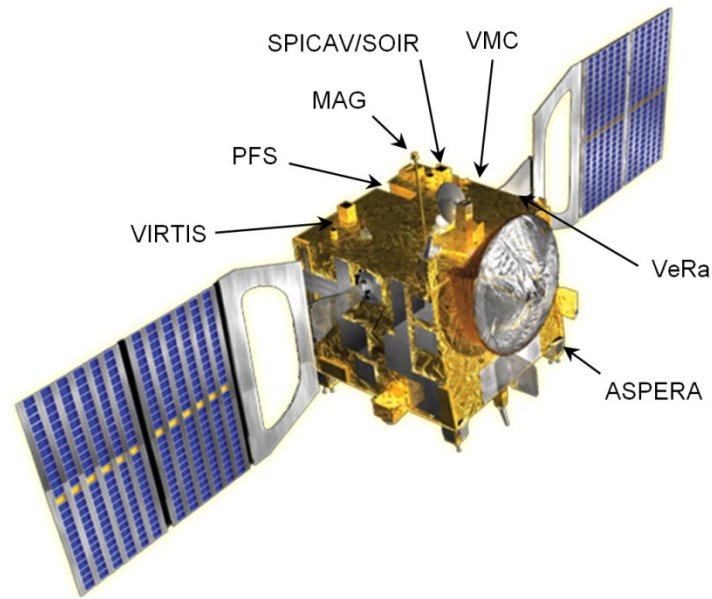


Figure 2.5. The *Venus Express* spacecraft. The location of each of the instruments described in Table 2.2 is indicated. Image taken from venus.wisc.edu, 26/07/16.

2007, the spacecraft's lifetime was extended by more than seven years to December 2014, when contact with the spacecraft was lost.

Titov *et al.* (2006) describe the scientific goals of the *Venus Express* mission. These included the investigation of:

- (i) the temperature profile of the Venusian atmosphere, particularly at lower altitudes;
- (ii) the detailed composition and chemistry of the Venusian atmosphere;
- (iii) the structure, composition and dynamics of Venus's thick cloud layer;
- (iv) the dynamics of Venus's atmosphere through detailed observation of wind velocities;
- (v) the atmosphere-solar wind interaction, and the subsequent atmospheric erosion; and
- (vi) the surface of Venus, via indirect measurements (*e.g.*, finding traces of volcanic activity through thermal mapping near the surface).

Instrument	Description
<i>Analyser of Space Plasma and Energetic Atoms</i> (ASPERA)	A range of neutral particle, ion and electron analysers used to study the solar wind-Venusian atmosphere interaction (Barabash <i>et al.</i> , 2007)
<i>Venus Express Magnetometer</i> (MAG)	Two tri-axial fluxgate magnetometers (one to detect the s/c field) used to measure Venus's induced field (Zhang <i>et al.</i> , 2007)
<i>Planetary Fourier Spectrometer</i> (PFS)	An infrared spectrometer used to study the Venusian atmosphere (Formisano <i>et al.</i> , 2006)
<i>SPectroscopy for Investigation of Characteristics of the Atmosphere of Venus</i> (SPICAV); <i>Solar Occultation at InfraRed</i> (SOIR)	A suite of UV and infrared spectrometers used for atmospheric studies at all altitudes (Bertaux <i>et al.</i> , 2007)
<i>Venus Radio Science Experiment</i> (VeRa)	Used radio signals to study Venus's surface, atmosphere, ionosphere and gravity field (Häusler <i>et al.</i> , 2006)
<i>Visible and InfraRed Thermal Imaging Spectrometer</i> (VIRTIS)	An imaging spectrometer that operated in the visible and infrared (Piccioni <i>et al.</i> , 2007)
<i>Venus Monitoring Camera</i> (VMC)	A miniature wide-angle CCD camera that imaged Venus at UV, visible and infrared wavelengths (Markiewicz <i>et al.</i> , 2007)

Table 2.2. The seven instruments on board the *Venus Express* spacecraft.

The atmospheric focus of the *Venus Express* mission is clearly evident in these scientific aims. The fifth objective is most relevant to this work, since it required VEX to enter the solar wind during its planetary orbit. The full suite of instruments carried

by VEX is described in Table 2.2, and the location of each instrument on the spacecraft is shown in Fig. 2.5.

VEX carried a magnetometer instrument (MAG) in order to investigate fully the atmosphere-solar wind plasma interaction at Venus. This interaction gives rise to the induced magnetic field present at the planet (Venus does not have an intrinsic magnetic field). MAG consisted of two ring-core, tri-axial fluxgate magnetometers. The outboard fluxgate was placed at the tip of the 90 cm-long boom, while the inboard fluxgate was placed 10 cm from the spacecraft along the boom. This dual-sensor setup was designed to aid identification of any spacecraft-generated field overlapping the external field. The inboard and outboard sensors had default measurement ranges of ± 524 nT and ± 262 nT, respectively, at resolutions of 0.016 nT and 0.008 nT, respectively. The ranges of both sensors could be changed to anything between ± 32.8 nT and $\pm 8,388.6$ nT on command, at corresponding resolutions of between 0.001 and 0.128 nT. Both fluxgates measured the magnetic field at a cadence of 128 Hz. A detailed description of VEX's MAG instrument is presented by Zhang *et al.* (2007).

Unlike MESSENGER, *Venus Express* was not a magnetically clean spacecraft. This lack of magnetic cleanliness arose from the reuse in VEX of components from VEX's sister mission, *Mars Express*, which did not carry a magnetometer and which did not have strict magnetic cleanliness requirements. However, various techniques have been employed to clean the VEX MAG dataset so that its quality is at least comparable to that obtained from magnetically clean spacecraft (Zhang *et al.*, 2007; Pope *et al.*, 2011).

2.3.2. Cruise phase and planetary orbits

Venus Express was launched on 9 November 2005. Following a relatively direct and short-duration cruise phase in interplanetary space, VEX arrived at Venus on 11 April 2006. VEX initially entered into an eccentric polar orbit at a period of 9 days. A series of manoeuvres were executed between 15 April and 6 May 2006 that brought VEX into its quasi-polar operational orbit, which had a periapsis at 250 km above the planet's surface, an apoapsis at 66,000 km, and a period of 24 hours. The periapsis was located

at $\sim 80^\circ\text{N}$. Similarly to MESSENGER, VEX's highly eccentric orbit at a large apoapsis resulted in the spacecraft spending large intervals of time entirely in the solar wind.

This orbit was maintained until July 2009, when the periapsis was brought into a range of 185 – 300 km above the surface. The periapsis was further reduced to 130 km following the end of the extended scientific mission in May 2014, in preparation for a series of successful aerobraking operations that took place during June and July 2014. The reduced periapsis altitude resulted in a reduction in the orbital period to 22 hours 20 minutes, caused by an increase in atmospheric drag on the spacecraft.

The periapsis was raised to 460 km after the completion of the aerobraking campaign and VEX entered into a reduced science phase of operation. The periapsis altitude gradually reduced with the natural decay of the orbit. An attempt was made to raise the periapsis in November 2014, in order to prolong VEX's lifetime into 2015. However, the amount of remaining propellant was less than anticipated, and the subsequent failure of the manoeuvres led to the loss of contact with VEX on 28 November 2014. The VEX mission was officially brought to an end by ESA on 16 December 2014. The spacecraft is thought to have crashed to the surface of Venus some time in late January or early February 2015.

2.4. OTHER SPACECRAFT

In situ data from the *Advanced Composition Explorer* (ACE; Stone *et al.*, 1998) and the *Solar Terrestrial Relations Observatory* (STEREO; Kaiser, 2005) have also been used in this work. ACE, a NASA mission operational since December 1997, orbits the L1 point between the Sun and the Earth. Also forming part of a NASA mission, the twin STEREO spacecraft were launched in October 2006 and placed into heliocentric orbits at approximately 1 AU. One spacecraft, STEREO-A, leads the Earth in its orbit while the other, STEREO-B, lags behind; each has receded from the Sun-Earth line by about 22.5° per year since launch. The reader is referred to the relevant references above for detailed descriptions of these missions.

STEREO-A and STEREO-B, along with ACE at the Sun-Earth line, have offered *in situ* coverage at 1 AU across an unprecedented range of heliolongitudes. One

consequence of this enhanced coverage was that many of the ICMEs observed by MES and VEX in the inner heliosphere were later observed at 1 AU; such multi-point observations are central to the work presented in Chapters 3, 4 and 5.

2.4.1. *STEREO*

The STEREO spacecraft carry tri-axial ring-core fluxgate magnetometers (Acuña *et al.*, 2007), positioned 3m from the spacecraft buses on 4m-long booms. The magnetometers have a coarse measurement range of $\pm 65,536$ nT at a resolution of 2 nT, and a fine range of ± 512 nT with a 0.015 nT resolution. The coarse range was used in the earliest phase of the mission while the magnetometer operated in the Earth's magnetic field, and the fine range has been used during the main science phase of the mission, in the solar wind. The spacecraft return magnetic field measurements at time resolutions of 32 Hz ('Burst'), 8 Hz ('Normal') and 0.1 Hz ('Beacon'). Both STEREOs are magnetically clean, with the spacecraft's dc fields of less than 1–3 nT and variable fields of less than ~ 0.03 nT meeting the science requirements of the mission.

Each STEREO spacecraft also carries the *Plasma and Suprathermal Ion Composition* instrument (PLASTIC; Galvin *et al.*, 2008), an energy-mass spectrometer used to determine the elemental composition, ionic charge states and bulk flow parameters of significant solar wind ions. PLASTIC can measure the energies of ions between ~ 0.3 and 80 keV q^{-1} , and has a near-complete angular coverage in the ecliptic plane. The instrument returns a particle energy spectrum across the full energy range every 60 s. Solar wind plasma parameters derived from PLASTIC measurements are used in Chapters 3, 4 and 5.

2.4.2. *ACE*

ACE carries two ring-core tri-axial fluxgate magnetometers, each mounted on a separate boom 4.2m from the spacecraft centre (Smith *et al.*, 1998). Each magnetometer has eight measurement channels, of which the narrowest measures in the range ± 4 nT (at a resolution of ± 0.001 nT), and the broadest measures in the range $\pm 65,536$ nT (at a resolution of 16.0 nT), with magnetic field sampling rates of up to 24 Hz. ACE is a

magnetically clean spacecraft that provides magnetic field measurements accurate to 0.1 nT.

The ACE spacecraft carries multiple instrument packages for analysing the solar wind. In Chapters 3 and 5, measurements are used from the *Solar Wind Electron, Proton and Alpha Monitor* (SWEPAM; McComas *et al.*, 1998) on board ACE. SWEPAM's ion instrument (SWEPAM-I) provides energy spectra of protons and alpha particles with energies between 0.26 and 36 keV q^{-1} across all angles every 64 s, from which bulk flow parameters for the solar wind can be obtained.

3 | A catalogue of ICMEs observed by MESSENGER and *Venus Express*

In this chapter, a catalogue of ICMEs observed by the MESSENGER and *Venus Express* spacecraft is presented. Despite their primary focus as planetary missions, both spacecraft spent significant amounts of time in the solar wind, allowing observation of transient solar wind structures such as ICMEs. MES data spanning ~ 5 years have been examined for ICME signatures, including data from the spacecraft's cruise phase in interplanetary space and the first year it spent orbiting Mercury; similarly, VEX data spanning ~ 7.5 years have been examined, all of which was gathered while the spacecraft orbited Venus. This chapter is based upon the Good and Forsyth (2016) journal article published in *Solar Physics*.

Neither spacecraft carried dedicated instruments for analysing the dynamics and composition of the solar wind plasma, and so ICMEs have been identified by their magnetic field signatures alone. The identification criteria have been chosen such that the ICMEs identified may well be magnetic clouds also; the absence of temperature data precludes any definite magnetic cloud identifications.

MESSENGER and *Venus Express* offer the most recent *in situ* observations of ICMEs at sub-1 AU heliocentric distances. Given the lack of plasma and compositional data, a comprehensive analysis of the nature of the ICMEs encountered by MES and VEX is not possible, unlike in the case of the pioneering sub-1 AU *Helios* mission (*e.g.*, Bothmer and Schwenn, 1998; Liu *et al.*, 2005; Leitner *et al.*, 2007). However, much may be gleaned from the magnetic field measurements alone. In this work, the flux rope configurations for the catalogued ICMEs have been classified, and the occurrence of different configuration types has been related to the phase of the solar cycle. The

frequency at which ICMEs were observed by MES and VEX is also considered in terms of the solar cycle.

Perhaps the greatest value to be obtained from ICME observations by MES and VEX can be found in linking observations of individual events at these spacecraft to observations of the same events at 1 AU spacecraft. Taken together, MESSENGER, *Venus Express*, STEREO-A, STEREO-B and ACE/*Wind* offered unprecedented *in situ* coverage of interplanetary space near the solar equatorial (SE) plane, and unprecedented opportunities for multi-point ICME observations. For each ICME observed by MES and VEX, signatures of the same event at other spacecraft have been identified, where they existed. This analysis has been used to estimate the probability that two spacecraft will observe the same ICME as a function of the spacecraft's heliocentric longitudinal separation.

Other ICME catalogues have recently been compiled that use MESSENGER and *Venus Express* data. Winslow *et al.* (2015) list relatively fast ICMEs observed by MES after March 2011 that drove shocks, displayed an enhanced field magnitude and distorted Mercury's magnetosphere. Similarly, Vech *et al.* (2015) identify ICMEs observed by VEX that produced significant enhancements in the field magnitude of Venus's induced magnetosphere. Savani (2010) also lists ICMEs observed by VEX during the early phase of the mission.

Sect. 3.1 describes the data used in this study. The ICME identification criteria are described in Sect. 3.2, and the ICME catalogue is presented and analysed in Sect. 3.3.

3.1. SPACECRAFT DATA

This study makes use of magnetic field measurements made by MESSENGER's magnetometer (MAG; Anderson *et al.*, 2007). The data were obtained from the Planetary Plasma Interactions (PPI) node of the Planetary Data System (PDS) archive (ppi.pds.nasa.gov/index.jsp). Data at a time-averaged resolution of 10 seconds have been used; figures in this work displaying MESSENGER MAG measurements show data at this resolution.

The black-dotted line in Fig. 3.1 shows the heliocentric distance of MESSENGER with time, where the x -axis spans the full duration of the mission. The grey-shaded region in the lower half of the figure before March 2007 (marked with a vertical dotted line) highlights a period of time where data are largely unavailable or suspect. Grey-shaded regions in the lower half of the figure after March 2007 show data-gap intervals during the remainder of the cruise phase.

Fig. 3.1 also shows the interval of time covered by the MES ICME catalogue presented in this work. The catalogue primarily spans the time from when data became more regularly available, in March 2007, to the time, following planetary insertion, when MESSENGER's orbital period at Mercury changed from 12 to 8 hours in April 2012. The signatures used in this study to identify ICMEs (described in Sect. 3.2) were often heavily obscured by bow shock and magnetosphere traversals after April 2012 - three magnetosphere traversals per 24 hours from then onwards, compared to two crossings previously - and so data after this time have not been surveyed. Three additional events have been identified outside the primary catalogue window, two in May 2005 (during a brief period when data were available) and one clearly visible event in May 2012.

Data from VEX's magnetometer (MAG; Zhang *et al.*, 2006) have also been used in this study, obtained from ESA's Planetary Science Archive (PSA; sciops.esa.int/index.php?project=PSA&page=vex). A time-averaged data resolution of 4 seconds has been used; figures displaying VEX data in this work show data at this resolution. The heliocentric distance of VEX is shown by the red line in Fig. 3.1, and data gaps by (light) grey regions in the top half of the figure. Data are available for the entire period of time that VEX spent at Venus, although none are available from the cruise phase. The VEX ICME catalogue presented here spans the period from May 2006 to December 2013.

3.2. IDENTIFICATION CRITERIA

Three criteria were used to identify ICMEs in magnetometer data from MESSENGER and *Venus Express*, namely (i) relatively smooth, monotonic rotations of the magnetic

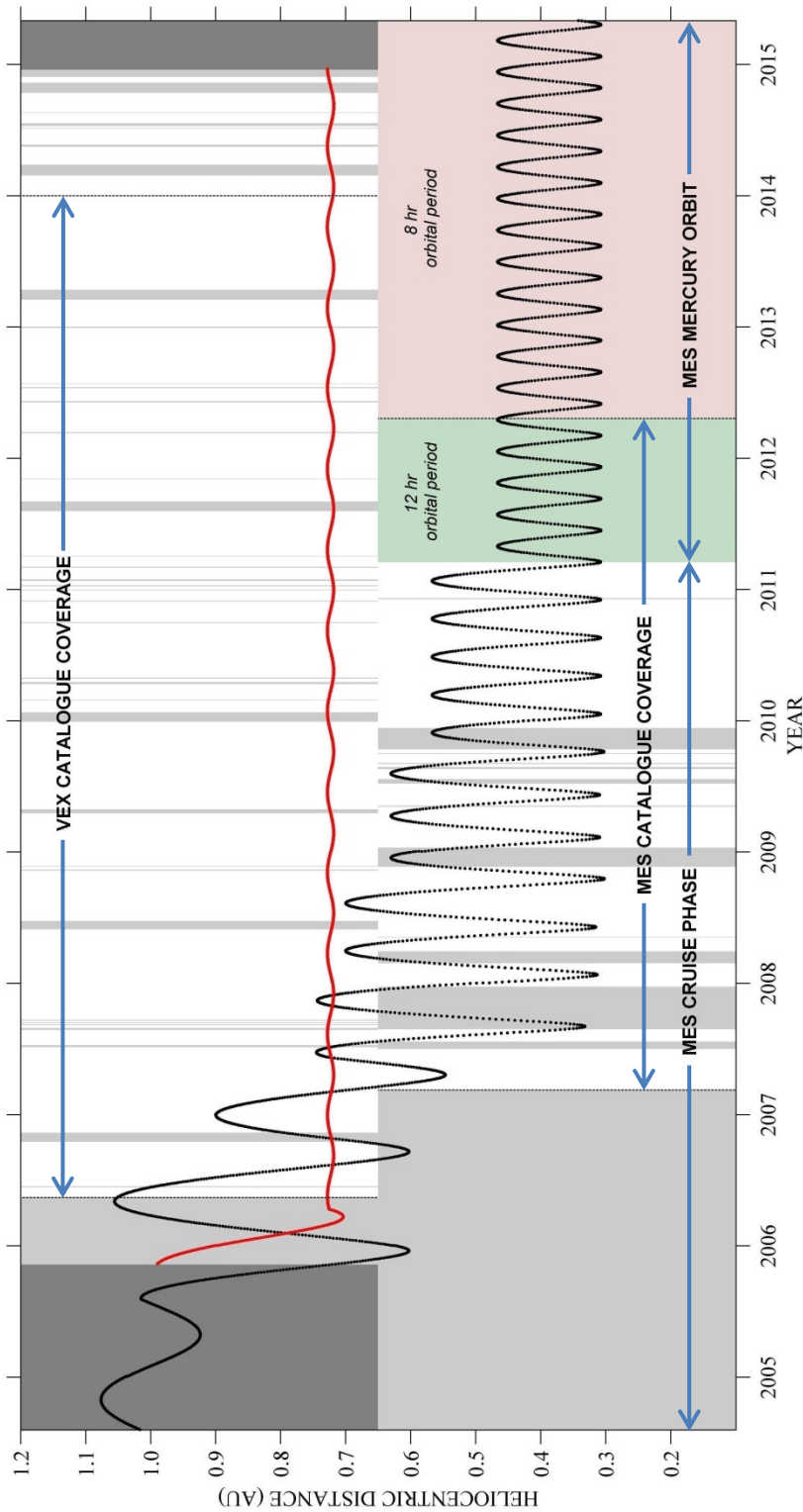


Figure 3.1. The heliocentric distances of MESSENGER (black-dotted line) and *Venus Express* (red line) with time. Vertical dotted lines bound the time period covered by the ICME catalogues. Regions shaded light grey in the top and bottom halves of the figure indicate times at which MAG data are unavailable at VEX and MES, respectively. The green-shaded region highlights the time when MES orbited Mercury with a period of 12 hours, and the red-shaded region with a period of 8 hours.

field direction, coinciding with (ii) an enhanced magnetic field strength relative to that of the ambient solar wind field, which (iii) lasts for a period no less than 4 hours (~ 0.17 days). These criteria are such that the ICMEs identified were possibly magnetic clouds also. The first two criteria are the magnetic field signatures of a magnetic cloud as originally described by Burlaga *et al.* (1981). The third criterion sets a different time threshold to that of Burlaga *et al.*, who specify a duration of ~ 1 day for the field enhancement and rotation. A 1-day threshold is suitable for identifying magnetic clouds at 1 AU but clouds observed closer to the Sun may be missed with such a threshold, since magnetic clouds are often smaller closer to the Sun (and hence spacecraft intersect them for shorter durations). Given that MESSENGER and *Venus Express* spent much of their time at heliocentric distances significantly under 1 AU, the duration threshold was reduced. The choice of a 4-hour minimum duration was somewhat arbitrary. The purpose of this criterion was to ensure that all large-scale flux ropes likely to be associated with CMEs were included in the catalogue, whilst ensuring that the smaller-scale, non CME-related flux ropes which pervade the solar wind were excluded (Moldwin *et al.*, 2000; Janvier *et al.*, 2014). Flux rope boundaries have been located at discontinuous features in the field components, between which the field magnitude was enhanced and the field direction rotated in a way consistent with the identification criteria. The adoption of flux rope signatures as an ICME identifier is also an effective way to exclude field enhancements associated with stream and co-rotating interaction regions (SIRs and CIRs), which do not show such a field configuration. No strict value was placed on the field enhancement factor relative to the solar wind in order to meet the second criterion.

Fig. 3.2 shows an example of an ICME observed by MESSENGER in January 2009, during the spacecraft's cruise phase. The boundaries of the ICME's flux rope are indicated with vertical dotted lines. The first panel displays the magnetic field magnitude. At its peak within the flux rope, the field magnitude was ~ 3.5 times the value it held in the ambient solar wind, clearly satisfying the second identification criterion.

The second panel shows the three components of the B -field, in RTN co-ordinates. The R direction in this spacecraft-centred co-ordinate system points radially

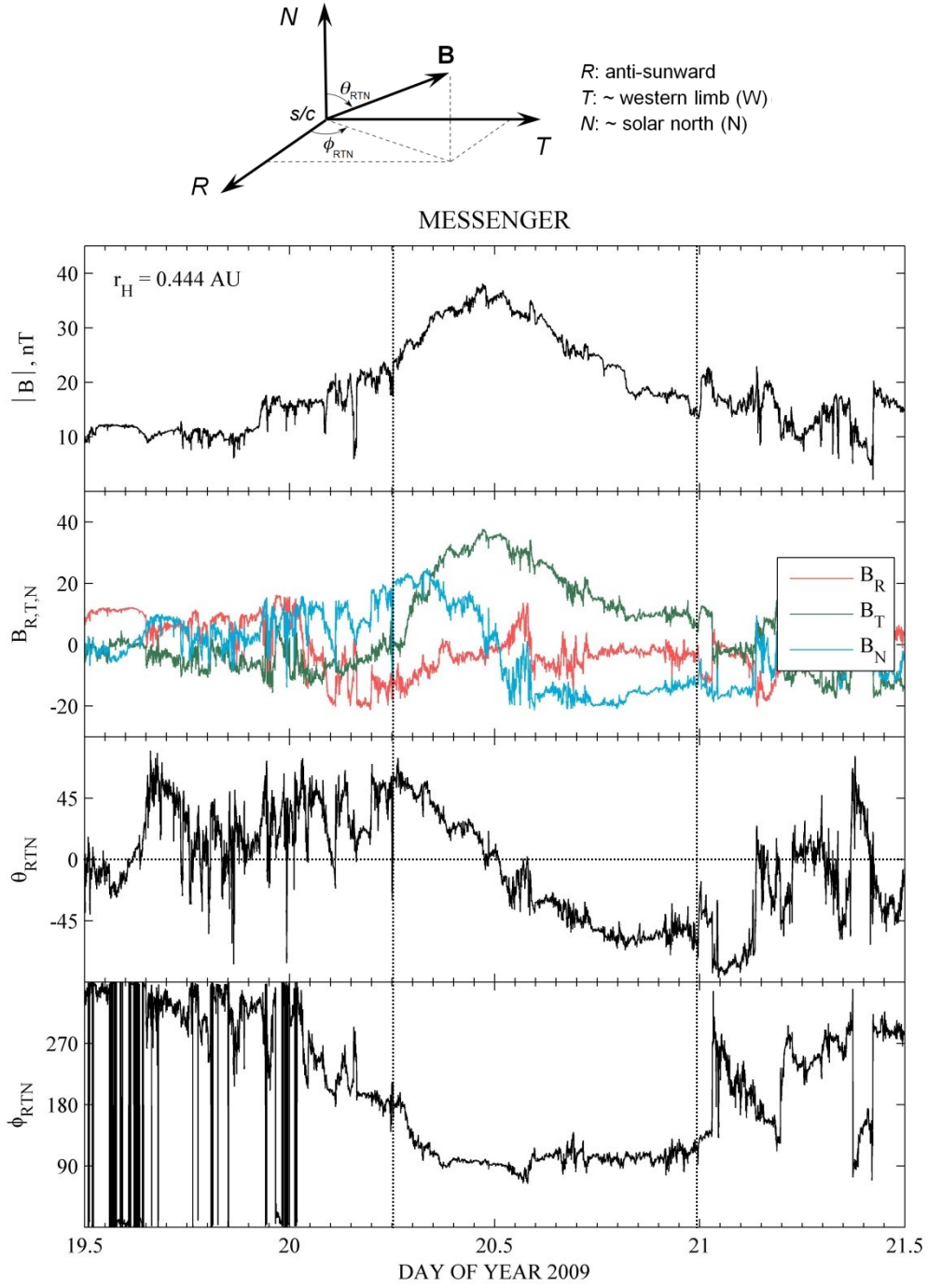


Figure 3.2. An ICME observed by MES during the spacecraft's cruise phase (event MES200901 in Table 3.1). The panels show the B -field magnitude, RTN components and field angles θ_{RTN} and ϕ_{RTN} , respectively. The NWS-configured flux rope is bounded by the dotted vertical lines. The ICME is a quality 1 event.

away from the Sun, T points in the direction of the vector product of R with the solar rotation axis, and N completes the right-handed set. The third panel shows the latitude angle of the B -field vector relative to the R - T plane, $\theta_{\text{RTN}} = \sin^{-1}(B_N/B)$; $\theta_{\text{RTN}} = 90^\circ$ indicates that the vector points in the $+N$ direction, $\theta_{\text{RTN}} = -90^\circ$ in the $-N$ direction. The fourth panel shows the angle between the projection of the B -field onto the R - T plane and the R direction, ϕ_{RTN} , such that

$$\phi_{\text{RTN}} = \begin{cases} \tan^{-1}(B_T/B_R), & \text{if } B_R > 0 \\ \tan^{-1}(B_T/B_R) + 180^\circ, & \text{if } B_R < 0 \text{ and } B_T \geq 0 \\ \tan^{-1}(B_T/B_R) - 180^\circ, & \text{if } B_R < 0 \text{ and } B_T < 0 \end{cases} \quad (3.1)$$

ϕ_{RTN} has been mapped to angles between 0 and 360° in Fig. 3.2. Thus, for a B -field vector laying in the R - T plane (*i.e.*, when $\theta_{\text{RTN}} = 0$), ϕ_{RTN} values of 0 , 90° , 180° and 270° correspond to the $+R$, $+T$, $-R$ and $-T$ directions, respectively.

Field rotations are easily discerned by plotting θ_{RTN} and ϕ_{RTN} : they show a relatively smooth and monotonic rotation of the B -field direction within the flux rope in Fig. 3.2 (satisfying the first identification criterion), over the course of 1.25 days (satisfying the third criterion). The discontinuities in the field components near the middle of the rope around day of year (DOY) 20.6 are consistent with the formation of a current sheet, suggesting that the flux rope cross section may have been flattened and non-circular (Owens, 2009). Note also the relatively gradual rise in the B -field strength ahead of the rope in Fig. 3.2, and the absence of any significant shock or discontinuity. Many ICMEs do not drive shocks at times close to solar minimum (such as when this event was observed), and so a shock-driving condition for identifying ICMEs has not been imposed.

Fig. 3.3 shows an ICME that did drive a shock. This event was observed by *Venus Express* in September 2006. The shock ahead of the flux rope (at $\sim$ DOY 253.6) is marked by a dashed line, and the flux rope boundaries by two dotted lines as in Fig. 3.2. The magnetic field components in the second panel are displayed 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.

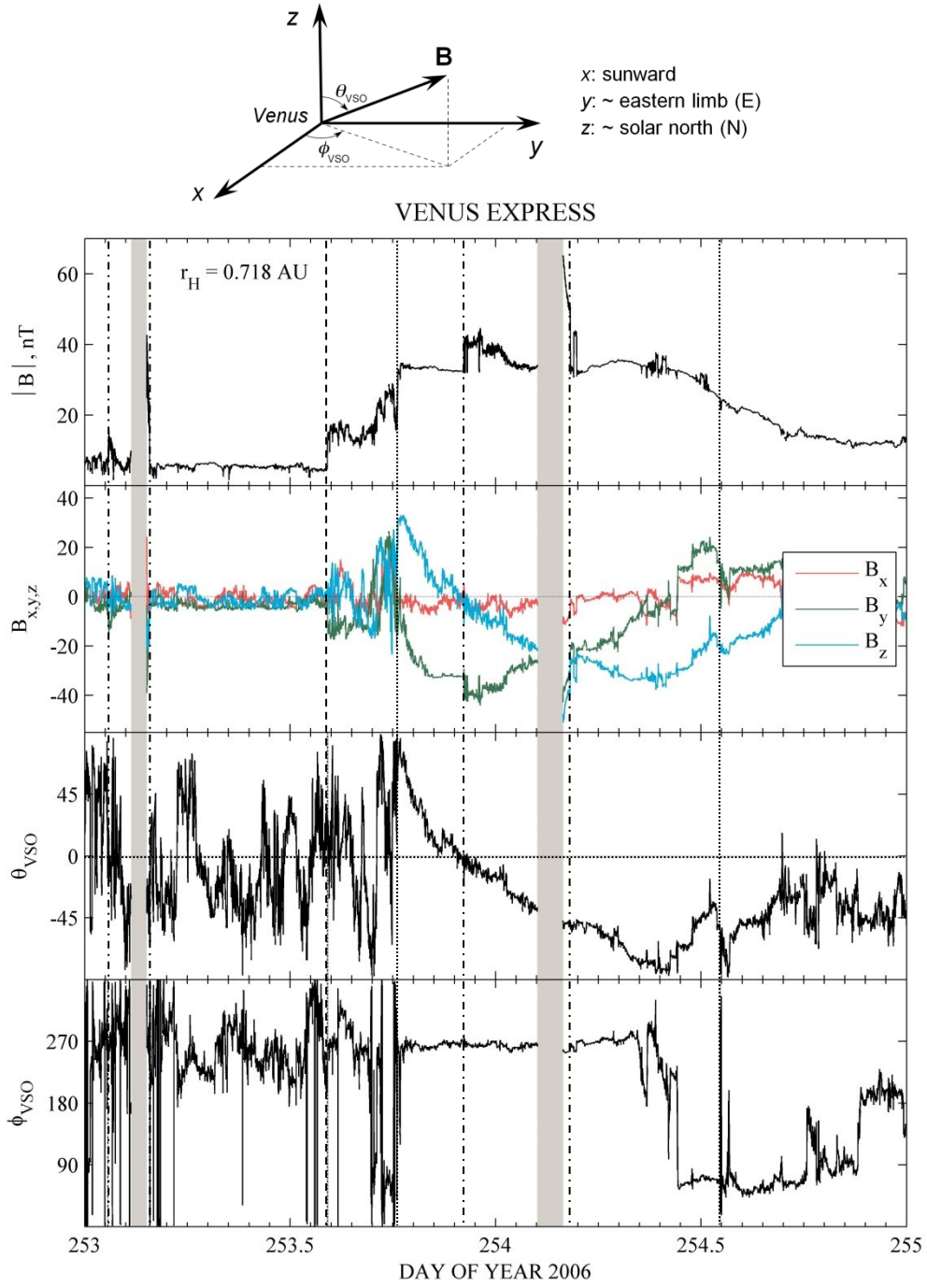


Figure 3.3. An ICME observed by VEX (event VEX200603). The panels show the B -field magnitude, components and field angles in VSO co-ordinates. Dotted lines show the flux rope boundaries, dash-dotted lines Venus bow shock crossings, and the dashed line a field discontinuity driven by the rope; grey-shaded regions show periods when the spacecraft was near or within Venus's induced magnetosphere. This quality 1 ICME has an NWS-configured rope.

θ_{VSO} and ϕ_{VSO} , shown in the third and fourth panels respectively, are equivalent to θ_{RTN} and ϕ_{RTN} in the RTN system. $\theta_{\text{VSO}} = 90^\circ$ indicates that the B -field points in the $+z$ direction, $\theta_{\text{VSO}} = -90^\circ$ in the $-z$ direction; when in the x - y plane, ϕ_{VSO} values of 0° , 90° , 180° and 270° indicate a vector pointing in the $+x$, $+y$, $-x$ and $-y$ directions, respectively. Data obtained by the spacecraft when it was close to the induced magnetosphere of Venus have been excluded from the plot; these intervals, which have been identified manually, are shaded grey. Bow shock crossings are indicated with dash-dotted lines.

The three ICME identification criteria were clearly met by this event: the field magnitude at the rope centre was enhanced by a factor of ~ 7 relative to the solar wind, and the field rotated relatively smoothly for ~ 0.8 days. Data obtained when the spacecraft was within the planet's magnetosheath – *i.e.*, the interval either side of the grey-shaded regions, up to the bow shock crossings – have been retained since the field rotations of the flux rope were still apparent in these intervals. Note that the enhanced field magnitude in these regions is a result of the bow shock crossings, and is not an intrinsic feature of the flux rope field.

Fig. 3.4 shows another ICME observed by *Venus Express*, in October 2011. Boundaries within the data are marked in the same way as for Fig. 3.3. Like the previous examples, this event clearly met the criteria for classification as an ICME, despite the flux rope boundaries being partly obscured in this case. VEX was close to Venus's induced magnetosphere during the arrival of the flux rope and so the leading edge was not directly observed. The trailing edge was observed at DOY 209.4, soon after the spacecraft made an outbound bow shock crossing. There is a large kink in ϕ_{RTN} near the rope centre, a result of significant discontinuities in the three field components in this region. Again, this points to the presence of a current sheet and non-circular flux rope cross section.

3.3. ANALYSIS

Table 3.1 lists details of the ICMEs found using magnetic field data from MESSENGER and *Venus Express*. Events in the tables are given a 3-part identification

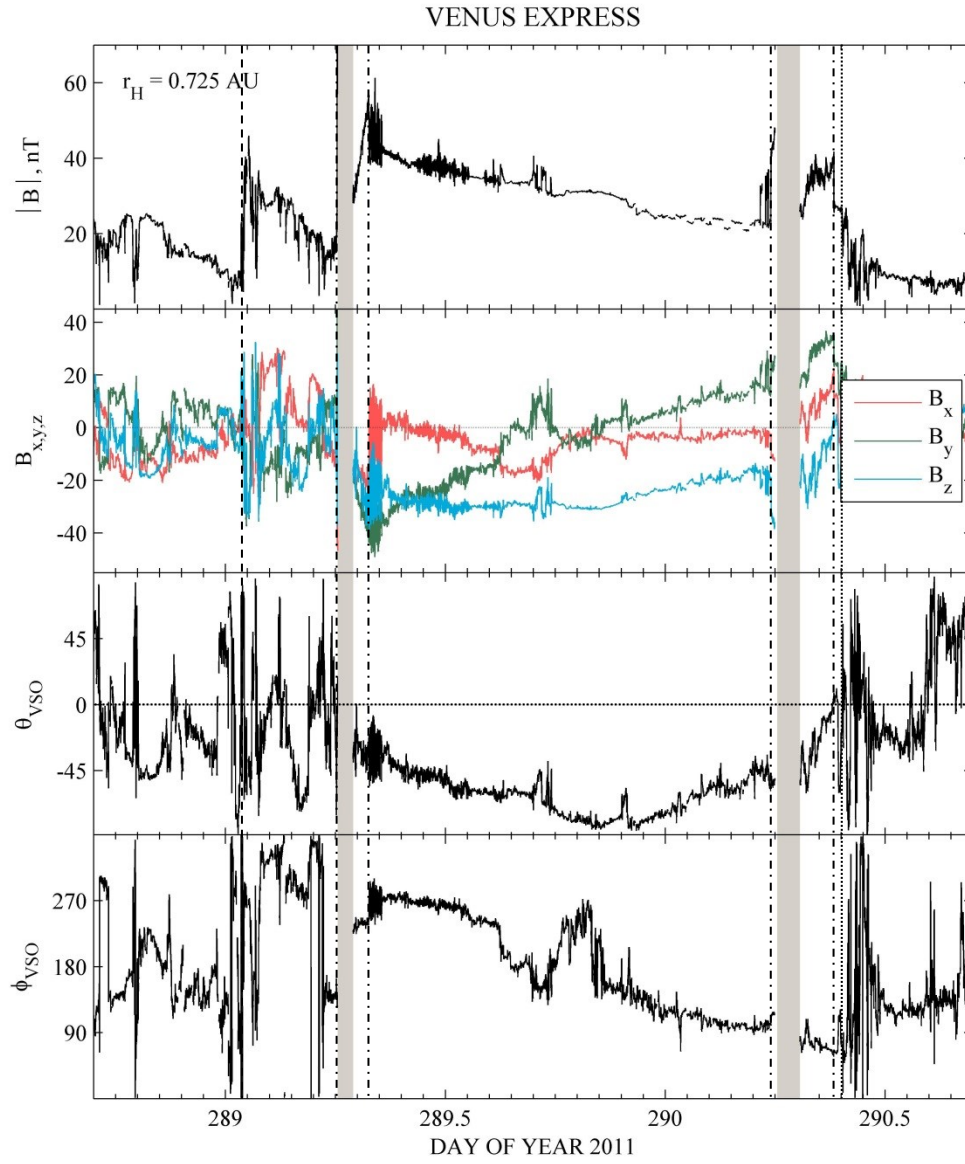


Figure 3.4. An ICME observed by VEX (event VEX201111). The panels and demarcation lines are as described in the caption to Figure 3. The ICME is a quality 2 event, with a WSE-configured rope.

number, based on the observing spacecraft ('MES' or 'VEX'), the year of the observation, and the chronology of the event relative to other events observed that year. For example, event MES201103 was the third ICME observed by MESSENGER in 2011. Where two events appear in close temporal proximity to each other in the data, each rope ID is given an 'a', 'b' ... *etc.* suffix.

For each ICME, the times at which the spacecraft observed the leading and trailing edges of the flux rope have been given. Trailing edges are not always straightforward to identify, particularly when only magnetic field data are available to make the identification: for some ambiguous cases, alternative trailing edge locations have been suggested. Where a boundary is obscured by a data gap or (more likely) by the spacecraft being out of the solar wind, a range of times within which the boundary would have been observed is given. The duration of the flux rope interval is also indicated, as well as the maximum field strength reached within the rope. Where the flux rope drove a shock or discontinuity, the time at which the shock or discontinuity was observed is given. Values in parentheses are less certain.

Each event observed by the spacecraft has been given a quality rating value of '1', '2', or '3', denoting events of high, intermediate and low quality, respectively. A quality 1 event is characterised by particularly smooth and low variance rotation, sharply defined flux rope boundaries, and few or no data gaps in its data time series. A quality 3 event is characterised by field rotations with higher than ideal variance (which are, nonetheless, still consistent with a flux rope structure), a weak field magnitude enhancement, or data gaps and obscured rope boundaries. Quality 2 events have some characteristics of both quality 1 and 3 events. Fig. 3.2 and 3.3 show examples of quality 1 events, and Fig. 3.4 presents a quality 2 event. The rating encompasses both the quality of the observations made by the spacecraft (*e.g.*, whether data gaps were present or rope boundaries observed) and the intrinsic quality of the ICME itself (*e.g.*, the degree of smoothness in the rotation, or the field enhancement factor relative to the solar wind.) There is inevitably a degree of subjectivity in rating events in this manner.

A small number of events have been included in the catalogues that only strictly meet two of the three identification criteria. These events are indicated by an asterisk (*) next to their ID numbers in Table 1. For example, event MES201201 (previously

studied by Rollett *et al.*, 2014) showed a very strong field magnitude enhancement over 0.43 days, with the relatively smooth rise and fall in the field magnitude often seen in magnetic clouds, but the field direction showed little rotation. In this case, the spacecraft could have intersected a leg of the ICME connecting the flux rope back to the Sun. Likewise, event VEX201007b (previously studied by Möstl *et al.*, 2012) displayed a large field magnitude enhancement with flux rope-like rotations, but its duration was only 0.14 days. This may have been a particularly fast ICME. Such events have been included since they are likely to be ICMEs despite failing to meet one of the criteria; the criteria that are met by these events are met unambiguously.

3.3.1. Event statistics

A total of 35 ICMEs found in the MESSENGER data and 84 ICMEs found in the *Venus Express* data are listed in Table 3.1. The number of ICMEs encountered by the two spacecraft in each year is given in Table 3.2, along with the mean heliocentric distances at which the ICMEs were observed, $\langle r_H \rangle$, and the mean maximum B-field strengths within the ICMEs' flux ropes, $\langle B_{\max} \rangle$. MESSENGER encountered events across the full range of heliocentric distances it covered during its cruise phase and subsequent insertion at Mercury; all of the events encountered by *Venus Express* were observed at ~ 0.72 AU, the heliocentric distance of Venus. The MESSENGER catalogue contains fewer events than the *Venus Express* catalogue, probably a reflection of the shorter timespan it covers compared to the VEX catalogue (see Sect. 3.1). Italicised event numbers in Table 3.2 indicate that data for that year are incomplete (*i.e.*, 2005 and 2007 for MESSENGER, and 2006 for VEX), or that the data have only been partly analysed (*i.e.*, 2012 for MESSENGER).

There is some limited evidence of a solar cycle dependence in the figures presented in Table 3.2. Comparing those years with largely complete datasets, it can be seen that fewer events were observed per year around the deep solar minimum of 2008 than in the declining phase of the previous cycle (Cycle 23) and the ascending phase of the current cycle (Cycle 24). There is also a general increase in $\langle B_{\max} \rangle$ from 2008 as solar maximum is approached. Note the increasing trend in $\langle B_{\max} \rangle$ observed by MESSENGER was partly an effect of the spacecraft's declining heliocentric distance

3. ICMEs OBSERVED BY MES AND VEX

Year/ Event #	r_H , AU	t_D , DOY	t_L , DOY	t_T , DOY	t_T (<i>alt.</i>), DOY	Duration, days	B_{max} , nT	Q	Rope type	H
MESSENGER										
MES...										
200501	0.925	128.513	128.668	129.126	129.939	0.458	31	1	NWS	L
200502	0.928	134.951	135.350	136.058	137.514	0.708	38	1	ENW	L
200701	0.587	-	124.873	126.040	126.248	1.167	23	2	NWS	L
200702	0.669	-	144.948	145.246	145.719	0.298	20	2	SWN	R
200703a	0.743	-	167.214	167.923	-	0.709	10	1	SWN	R
200703b	0.744	-	167.944	168.377	-	0.433	17	1	(WNE)	R
200801	0.692	-	97.728	98.051	-	0.323	26	1	WSE	L
200802	0.526	(260.074)	260.302	260.809	260.590	0.507	31	2	NES	R
200801	0.723	-	364.865	(365.207)	365.322	0.342	11	2	NWS	L
					to 365.403					
200901	0.444	-	20.253	20.996	21.030	0.743	38	1	NWS	L
200902	0.327	-	46.183	46.592	46.794	0.410	47	3	-	-
200903	0.371	-	51.817	52.014	-	0.197	40	3	NWS	L
200904	0.625	-	(223.688)	224.252	-	0.564	24	2	NES	R
200905	0.561	-	240.057	240.650	240.890	0.593	20	1	NWS	L
200906	0.343	-	266.580	267.287	-	0.707	37	2	NES	R
200907	0.439	-	360.690	361.765	-	1.075	24	2	(ENW)	L
201001	0.552	81.156	81.368	81.920	81.982	0.552	32	1	NWS	L
201002	0.562	-	170.445	170.993	-	0.548	31	2	-	-
201003	0.378	-	242.704	243.526	-	0.822	35	2	NES	R
201004	0.462	309.490	309.703	310.547	-	0.844	55	1	NES	R
201005	0.337	-	343.075	343.601	343.507	0.526	65	1	-	-
201006	0.365	347.178	347.489	347.698	-	0.209	54	2	-	-
201101	0.525	-	5.345	6.165	-	0.820	27	2	NES	R
201102	0.511	-	43.229	43.734	-	0.505	47	1	NES	R
201103	0.331	-	68.089	68.520	68.567	0.432	91	3	NWS	L
201104	0.407	139.493	139.698	140.2	-	0.624	?	3	-	-
					to 140.443					
201105	0.322	(156.147)	156.188	156.353	-	0.256	172	2	-	-
					to 156.534					
201106	0.460	288.352	288.470	289.266	-	0.796	90	1	WSE	L
201107	0.439	308.631	309.030	309.712	309.571	0.682	42	1	NWS	L

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201108	0.396	-	318.272	318.734	319.000	0.487	50	3	NWS	L
			to	to						
201109	0.374	-	318.445	318.957	-	0.742	56	3	-	-
			321.763	(322.600)						
			to							
			321.954							
201110	0.345	327.211	327.263	327.626	-	0.428	100	3	SEN	L
			to	to						
			327.452	327.945						
201111	0.424	364.686	364.884	365.389	-	0.505	65	2	-	-
201201*	0.320	67.211	67.257	(67.622	-	0.430	130	2	-	-
				to						
				67.751)						
201202	0.464	100.217	100.373	101.275	101.242	0.902	52	2	SEN	L
201203	0.310	-	146.349	147.475	-	1.126	101	2	SWN	R

Venus Express

VEX...										
200601	0.724	-	186.196	186.486	-	0.290	25	3	(NES)	R
200602	0.723	198.184	198.261	198.756	199.438	0.495	22	2	NWS	L
200603	0.718	253.591	253.762	254.547	254.695	0.785	36	1	NWS	L
200701	0.725	-	44.611	45.398	45.106	0.787	19	2	WNE	R
200702*	0.719	-	(117.370)	117.674	-	0.304	13	3	(NWS)	L
200703	0.719	-	126.202	126.870	-	0.635	13	2	NWS	L
			to							
			126.269							
200704	0.721	-	145.150	145.833	-	0.683	16	2	SWN	R
200705a	0.724	-	167.094	167.930	-	0.836	11	2	SWN	R
200705b	0.724	-	167.980	168.446	-	0.466	17	2	NES	R
200706	0.722	-	285.725	285.899	-	0.174	21	1	NWS	L
200707*	0.719	-	321.306	321.792	-	0.486	20	2	-	-
200708	0.719	-	341.756	343.614	342.626	1.858	19	2	NWS	L
200801*	0.723	-	364.865	(365.207)	365.322	0.342	11	2	NWS	L
					to					
					365.403					
200901	0.721	-	17.609	17.951	-	0.343	13	2	NWS	L
200902	0.725	(118.902)	118.996	120.214	-	1.051	14	3	NES	R
			to							
			119.331							
200903	0.727	-	136.901	137.682	137.800	0.781	14	2	NWS	L
200904	0.728	-	153.777	154.514	-	0.737	12	2	WNE	R
200905	0.728	-	158.249	158.607	-	0.358	12	1	NWS	L
200906	0.728	-	175.240	175.490	-	0.250	13	2	(NWS)	L

3. ICMEs OBSERVED BY MES AND VEX

200907	0.727	-	191.443	192.267	192.360	0.824	16	2	NWS	L
200908	0.723	-	221.436	221.803	-	0.367	17	2	NWS	L
200909	0.720	-	248.836	249.015	-	0.221	21	2	NES	R
				to 249.099						
200910	0.719	-	290.240	290.963	290.750	0.723	10	1	(SEN)	L
200911	0.722	-	325.410	325.666	326.716	0.256	13	1	NWS	L
201001	0.725	-	-62.652	63.150	-	0.498	29	2	NWS	L
201002	0.724	-	76.388	77.510	-	1.122	21	1	NES	R
201003	0.719	157.569	157.608	158.031	-	0.423	22	1	(ESW)	R
201004	0.720	-	166.973	168.072	-	1.099	14	2	-	-
201005	0.721	-	173.620	174.770	-	1.150	21	2	-	-
201006	0.722	-	180.360	180.959	-	0.599	14	2	-	-
201007a	0.726	213.612	213.966	214.247	-	0.281	27	2	NWS	L
201007b*	0.726	214.479	214.529	214.670	-	0.141	60	2	WSE	L
201007c	0.726	-	214.921	215.604	-	0.683	28	1	-	-
201008	0.727	222.159	222.522	222.885	-	0.363	27	1	WSE	L
201009*	0.727	-	224.930	(225.222)	-	0.292	9	3	-	-
201010*	0.728	-	251.461	251.773	-	0.312	11	2	-	-
201011	0.728	253.672	253.915	254.714	-	0.799	20	2	WSE	L
201012	0.719	-	344.845	345.923	345.708	1.078	19	2	-	-
201101	0.727	(77.866)	78.138	78.496	-	0.302	28	3	NWS	L
			to 78.248							
201102	0.727	81.369	81.728	82.764	-	1.037	18	2	-	-
201103	0.728	-	95.717	96.627	-	0.910	20	3	NES	R
201104	0.728	-	101.461	101.731	-	0.270	15	1	NWS	L
201105	0.728	-	107.319	107.762	-	0.443	16	2	-	-
201106a	0.728	-	110.286	110.917	111.074	0.631	16	3	NWS	L
					to 111.226					
201106b	0.728	-	111.472	112.477	-	1.005	17	2	NES	R
201107	0.727	139.874	(140.161)	140.759	-	0.598	27	2	NES	R
201108	0.724	156.562	156.634	156.938	-	0.304	59	1	-	-
201109	0.721	-	182.573	183.376	-	0.803	18	2	(NWS)	L
201110	0.723	-	274.050	274.613	-	0.563	16	2	SWN	R
201111	0.725	289.035	289.254	290.402	290.24	1.112	43	2	WSE	L
			to 289.326		to 290.383					
201112a	0.727	309.154	309.289	309.659	310.009	0.284	53	2	NES	R
			to 309.461							
201112b	0.727	-	310.077	311.132	-	1.055	14	2	NWS	L

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201113	0.728	(323.158)	323.319 to 323.451	324.138	-	0.753	40	2	(NES)	R
201114a	0.727	359.527	359.652	360.032	-	0.380	20	2	NES	R
201114b	0.727	-	(360.118)	360.943	360.699	0.581	31	3	ESW	R
201114c	0.727	-	361.097	361.654	-	0.557	20	2	NES	R
201201	0.724	-	16.931 to 17.253	18.091	-	0.999	42	3	SWN	R
201202	0.722	-	32.880	33.559	-	0.679	23	3	-	-
201203	0.721	-	43.259 to 43.319	43.564	43.574	0.275	22	3	-	-
201204	0.719	61.568	61.894	62.556	62.769	0.663	23	3	SWN	R
201205*	0.719	67.560	67.843	68.488	68.976	0.645	22	2	-	-
201206	0.722	(123.027)	123.634	125.064	-	1.430	19	2	NES	R
201207	0.727	-	167.810	168.353	168.367	0.543	88	1	NES	R
201208	0.728	-	189.847	190.043	-	0.261	30	3	NWS	L
201209*	0.728	200.693	200.994 to 201.235	201.697	-	0.582	15	2	-	-
201210	0.728	-	211.458	211.749	-	0.291	40	1	(NES)	R
201211	0.722	257.197	257.489	258.137	258.319	0.648	21	2	NES	R
201212	0.719	315.652	315.914	316.080	316.199	0.196	24	3	SWN	R
201213	0.719	318.450	318.730	319.269	-	0.539	31	1	WNE	R
201214	0.720	(330.043)	330.220	330.472	330.647	0.252	16	2	NES	R
201215	0.722	-	352.513	353.155	-	0.697	26	3	-	-
201301	0.725	8.391	8.642	9.825	-	1.183	29	1	WNE	R
201302	0.728	-	33.094	33.869	-	0.775	16	1	NES	R
201303*	0.728	-	48.455	48.869	-	0.413	13	2	SWN	R
201304	0.728	-	52.669	(52.861)	-	0.192	20	3	ENW	L
201305	0.728	65.557	65.983	66.485	67.193 to 67.317	0.502	28	3	-	-
201306	0.727	-	72.862	73.303	-	0.441	23	1	ENW	L
201307	0.722	117.610	118.073	(119.579)	-	1.506	19	2	SEN	L
201308*	0.721	201.421	201.882	202.741	-	0.859	13	3	-	-
201309	0.728	-	(261.487)	261.939	-	0.452	19	2	NES	R
201310	0.728	278.179	278.523	(279.624)	279.206	1.101	19	2	-	-
201311	0.727	(300.468)	301.076	302.212	-	1.136	44	1	(SEN)	L

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201312	0.723	334.188	334.583	335.667	-	1.084	24	1	NES	R
201313*	0.721	348.130	348.606	348.986	-	0.380	16	2	-	-

Table 3.1. The MESSENGER and Venus Express ICME catalogue:

Year/Event # - The event ID, which gives the year (YYYY) and event number (XX) in the format YYYYXX;

r_H – the heliocentric distance at which the event was observed;

t_D – the time at which the shock or discontinuity ahead of the flux rope, if present, was observed;

t_L – the time at which the leading edge of the flux rope was observed;

t_T – the time at which the trailing edge of the flux rope was observed;

$t_T(\text{alt})$ – an alternative possible arrival time for the flux rope trailing edge;

Duration – time difference between the leading and trailing edge arrivals;

$B_{\max}$ – maximum B -field strength within the flux rope;

Q – The event quality ('1', '2' or '3');

Rope type – The flux rope's configuration, according to the Bothmer and Schwenn classification system;

H – The rope's handedness ('L' or 'R');

Parenthesised table entries indicate significant uncertainty in the stated values.

Year	MESSENGER			<i>Venus Express</i>		
	# of events	$\langle r_H \rangle$, AU	$\langle B_{\max} \rangle$, nT	# of events	$\langle r_H \rangle$, AU	$\langle B_{\max} \rangle$, nT
2005	2	0.93	35	-		
2006	-			3	0.72	28
2007	4	0.69	18	9	0.72	18
2008	2	0.61	29	1	0.72	11
2009	7	0.44	33	11	0.72	14
2010	6	0.44	35	14	0.72	23
2011	11	0.41	74	18	0.73	26
2012	3	0.36	94	15	0.72	29
2013	-			13	0.73	22

Table 3.2. The ICME catalogue in summary. Italicized numbers indicate that that year’s dataset for the spacecraft in question is incomplete or has not been analysed in full.

during this period – ICME flux ropes closer to the Sun tend to have larger B -field magnitudes that subsequently fall as the ropes expand during propagation.

3.3.2. Flux rope orientations

A simple way to categorise ICME flux ropes is by their approximate configuration relative to the SE plane. This configuration may be described in terms of the rotation of the magnetic field vector as the rope traverses the spacecraft. Using the three-part notation developed by Bothmer and Schwenn (1998), which indicates the field directions of the successively observed leading edge, centre and trailing edge of the rope, the configurations of the ropes observed by MESSENGER and *Venus Express* have been determined; these configurations are listed in Table 3.1. The field directions are given in terms of the cardinal directions from the perspective of an observer looking towards the Sun, relative to the SE plane. For example, a rope designated ‘NWS’ has a predominantly northward leading edge field (*i.e.*, parallel to the solar rotation axis), a

westward field at the centre (*i.e.*, pointing towards the western limb of the Sun) and a southward field at the trailing edge (*i.e.*, anti-parallel to the solar rotation axis). These cardinal directions may be approximately related to the RTN and VSO field angles defined previously: $N \equiv \theta_{\text{RTN}} \sim \theta_{\text{VSO}} \sim 90^\circ$; $S \equiv \theta_{\text{RTN}} \sim \theta_{\text{VSO}} \sim -90^\circ$; $E \equiv [\theta, \phi]_{\text{RTN}} \sim [0^\circ, 270^\circ]$ and $[\theta, \phi]_{\text{VSO}} \sim [0^\circ, 90^\circ]$; and $W \equiv [\theta, \phi]_{\text{RTN}} \sim [0^\circ, 90^\circ]$ and $[\theta, \phi]_{\text{VSO}} \sim [0^\circ, 270^\circ]$. These approximations may reasonably be made because the orbital planes of MESSENGER and *Venus Express* never deviated significantly (at least on heliospheric scales) from the SE plane. Figures 3.2 and 3.3 show examples of NWS flux rope configurations, and Figure 3.4 an example of a WSE configuration.

Ropes which were poorly observed or with complex rotations that did not conform to a simple flux rope picture (around 25% of catalogued events) have not been categorised in this way. Some of these uncategorised events showed strongly radial fields with little rotation (*e.g.*, event MES201201); such events are sometimes described as ‘magnetic cloud-like’ (*e.g.*, Wu and Lepping, 2007). Others may have been ‘complex ejecta’, *i.e.*, structures consisting of multiple flux ropes, or ICMEs that were distorted through interactions with other ICMEs or the solar wind.

3.3.2.1. Northward vs. southward leading edges

The numbers of each configuration type observed by both spacecraft are summarised in Table 3.3. It has been found that, across both spacecraft, ropes with northward leading edges (NES or NWS) were observed around four times more often than ropes with southward leading edges (SEN or SWN). This finding is in agreement with the previously established rule that NES/NWS (SEN/SWN) magnetic clouds predominate from the late declining phase of an odd (even) numbered solar cycle to the rising phase of the next cycle (Bothmer and Schwenn, 1998; Mulligan *et al.*, 1998; Li and Luhmann, 2004; Huttunen *et al.*, 2005): all of the ICME flux ropes listed in this work were observed in either the declining phase of Cycle 23 or rising phase of Cycle 24. An analogous result was, for example, found by Bothmer and Schwenn in their study of magnetic clouds observed by *Helios* during the declining phase of Cycle 20 and rising

	MESSENGER	<i>Venus Express</i>	Total
A. Northward leading edge (NES, NWS)	16	42	58
B. Southward leading edge (SEN, SWN)	5	10	15
C. High inclination (WNE, WSE, ENW, ESW)	5	12	17
D. Left-handed (NWS, SEN, ENW, WSE)	15	31	46
E. Right-handed (NES, SWN, ESW, WNE)	11	33	44
F. Uncategorised (-)	9	20	29
A : B	3.2 : 1	4.2 : 1	3.9 : 1
[A and B] : C	4.2 : 1	4.3 : 1	4.3 : 1
D : E	1.4 : 1	0.9 : 1	1.0 : 1

Table 3.3. The distribution of ICME flux rope configurations observed by MESSENGER and *Venus Express*.

phase of Cycle 21, when SEN/SWN clouds were around three times more common than NES/NWS clouds.

The predominance of NES/NWS over SEN/SWN ropes may be a result of the global configuration of the solar magnetic field (Mulligan *et al.*, 1998). During the period of time studied, the solar northern hemisphere largely consisted of inward-directed magnetic field and the southern hemisphere of outward-directed field. If most flux ropes are thought to emerge from the streamer belt around the solar equator, as depicted in Fig. 3.5, then such a solar field topology would lead to the greater instances of NES and NWS ropes that were observed. Li *et al.* (2011) highlight some of the nuances in this interpretation.

3.3.2.2. High vs. low inclination to the SE plane

An imbalance also exists between the number of flux ropes observed with an east/west axis orientation (NES, SEN, NWS and SWN) and those with a north/south axis orientation (ENW, WNE, ESW and WSE): the former were observed about four times more frequently than the latter (see Table 3.3). This imbalance may in part be due to

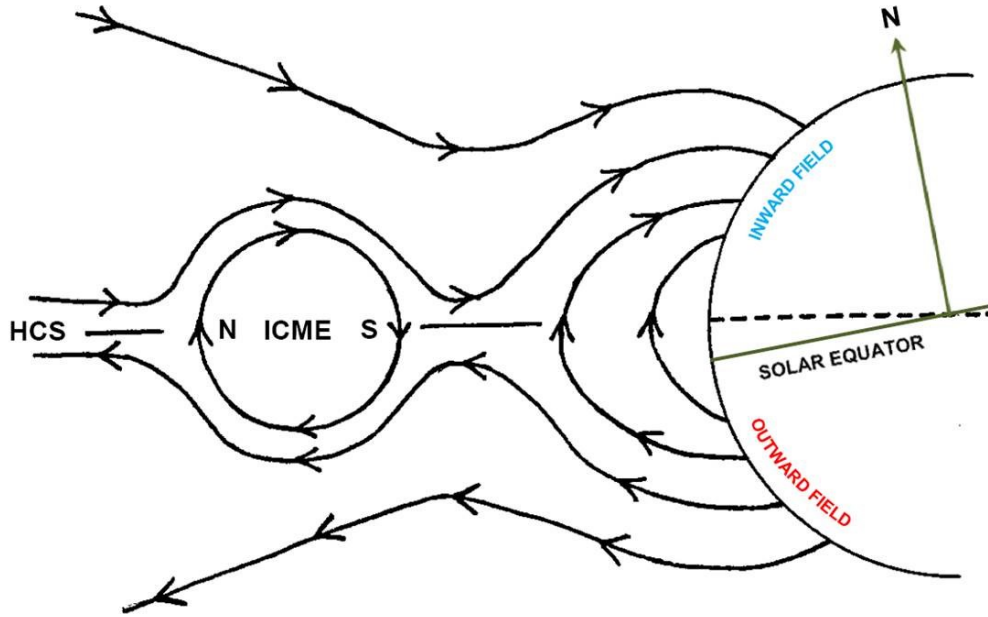


Figure 3.5. A configuration of the solar magnetic field that could explain the predominance of ICMEs with northward leading edges in the catalogue.

the relative likelihood of observation of each flux rope orientation. East/west-oriented ropes, with their axes at low inclinations to the SE plane, intersect a larger area of the SE plane close to which the observing spacecraft are found, and so are more likely to be observed. Conversely, north/south oriented ropes intersect a smaller area of the SE plane, and so are less likely to be observed. This interpretation assumes that ICME flux ropes are wider in the direction parallel to the flux rope axis than in the direction transverse to the rope axis.

Some have suggested that the east/west direction is a preferential direction for flux ropes observed in the heliosphere. Yurchyshyn (2008) and Isavnin *et al.* (2014), amongst others, suggest that ICME flux ropes can rotate during propagation to align with the local direction of the heliospheric current sheet, which often lies close to the SE plane. This rotation is discussed further in Sect. 4.3.

3.3.2.3. Left vs. right-handedness

Each flux rope configuration is associated with an intrinsic handedness. Handedness indicates the sense of field-line winding around the axis of the rope. NWS, SEN, ENW and WSE ropes are left-handed, and NES, SWN, ESW and WNE ropes are right-handed. It has been found that left-handed and right-handed flux ropes were observed in almost equal numbers (46 and 44, respectively) by MESSENGER and *Venus Express*. Given the solar-hemispherical ordering of ICME flux rope handedness (Rust, 1994), this result is to be expected.

3.3.3. Multi-point observations

For each of the MESSENGER events listed in Table 3.1, *in situ* data from *Venus Express*, STEREO-A (STA), STEREO-B (STB) and ACE have been examined for signatures of the same event. Likewise, *in situ* data from MESSENGER and the three 1 AU spacecraft have been examined for signatures of the *Venus Express* events. STEREO data have been obtained from the Space Physics Center of the UCLA Institute of Geophysics and Planetary Physics (aten.igpp.ucla.edu), and ACE data have been obtained from the ACE Science Center (www.srl.caltech.edu/ACE/ASC/index.html).

Data at each spacecraft have been examined at time windows within which the ICMEs observed at MESSENGER or *Venus Express* would be expected to arrive. For example, an ICME observed by MESSENGER at Mercury would have been likely to arrive at Venus 1 – 2 days later, and ~3 days later at 1 AU. Rigid search windows were not imposed in order to allow for particularly fast or slow events.

An event-by-event analysis is detailed in Table 3.4. It lists the heliocentric inertial (HCI) longitudes of MES (Θ_{MES}) and VEX (Θ_{VEX}) when they observed each of the ICMEs listed in Table 3.1, the HCI longitude of the other spacecraft at the expected arrival times of each ICME (Θ_x), the longitudinal separation between each spacecraft pair ($\Delta\Theta_x$), and the signature type observed at the second spacecraft. The longitudinal separations represent the angles within the SE plane subtended at the Sun by the spacecraft pairs. Latitudinal separations have been neglected.

3.3.3.1. Signature classification

Signatures within the search windows at the other spacecraft have been given one of the following three classifications:

- Flux rope signatures are present and likely to be associated with the ICME observed at MES or VEX (denoted ‘YY’ in Table 3.4)
- A shock or discontinuity with a significant B -field magnitude enhancement (without any flux rope signatures) is present and likely to be associated with the ICME observed at MES or VEX (denoted ‘Y’ in Table 3.4)
- No *in situ* signatures of an ICME are present, or, if present, are unlikely to be associated with the ICME observed at MES or VEX given coronagraph observations (denoted ‘N’ in Table 3.4)

Likelihood of association was assessed by considering expected arrival windows (as described in the second paragraph of this subsection) alongside coronagraph observations from LASCO (on board the SOHO spacecraft at L1), COR-2A, and COR-2B (on board STEREO-A and STEREO-B, respectively). A ‘YY’ or ‘Y’ classification has only been deemed likely if a single CME was launched from the Sun within a broad launch-time window, and if the apparent propagation direction of that CME - roughly estimated, from the vantage points of all three coronagraphs simultaneously - was towards both of the spacecraft in question. Greater emphasis was placed on coronagraph observations when determining associations for widely-spaced spacecraft ($> \sim 60^\circ$). A classification is parenthesised in Table 3.4 if:

- (i) the coronagraph observations are inconclusive (*e.g.*, if multiple CMEs are launched in similar directions around the same time); or
- (ii) the arrival time of the signature deviates significantly from what is expected.

Flux ropes were identified at the other spacecraft by their magnetic field signatures in the same way as for the MESSENGER and *Venus Express* event cataloguing. The 1 AU spacecraft used in this analysis all carry instruments for analysing the solar wind

MESSENGER

MES ID	Θ_{MES}	STA?	Θ_{STA}	$\Delta\Theta_{\text{STA}}$	STB?	Θ_{STB}	$\Delta\Theta_{\text{STB}}$	ACE?	Θ_{ACE}	$\Delta\Theta_{\text{ACE}}$	VEX?	Θ_{VEX}	$\Delta\Theta_{\text{VEX}}$	VEX ID
200501	143.2	-	-	-	-	-	-	Y	151.9	8.7	-	-	-	-
200502	151.3	-	-	-	-	-	-	YY	158.6	7.3	-	-	-	-
200701	69.2	N	155.0	85.8	N	148.3	79.1	N	150.4	81.2	YY	81.0	11.8	200703
200702	112.4	N	174.9	62.5	N	165.3	52.9	N	168.6	56.2	YY	113.4	1.0	200704
200703a	145.2	N	197.8	52.6	N	184.6	39.4	N	189.5	44.3	YY	148.8	3.6	200705a
200703b	146.4	N	198.9	52.5	N	185.5	39.1	N	190.5	44.1	YY	150.4	4.0	200705b
200801	171.6	Y	147.1	24.5	N	99.0	72.6	N	122.9	48.7	N	261.9	90.3	-
200802	221.8	N	319.8	98.0	Y	245.4	23.6	N	280.6	58.8	N	164.3	57.5	-
200901	250.2	N	89.1	161.1	N	359.3	109.1	N	45.8	155.6	N	4.6	114.4	-
200902	27.8	N	117.3	89.5	YY	25.8	2.0	N	73.4	45.6	YY	49.9	22.1	-
200903	60.0	N	123.6	63.6	N	31.8	28.2	N	79.5	19.5	YY	56.4	3.6	-
200904	183.8	N	303.5	119.7	YY	194.1	10.3	N	245.3	61.5	N	331.3	147.5	-
200905	212.2	N	320.3	108.1	YY	207.8	4.4	YY	260.8	48.6	N	357.0	144.8	-
200906	298.0	N	348.3	50.3	N	230.7	67.3	Y	287.3	10.7	N	40.7	102.7	-
200907	256.0	N	86.5	169.5	YY	314.7	58.7	N	59.2	163.2	X	193.7	62.3	-
201001	205.1	N	174.2	30.9	N	35.8	169.3	N	107.5	97.6	N	328.6	123.5	-
201002	172.3	N	268.0	95.7	N	124.1	48.2	YY	193.5	21.2	N	111.0	61.3	-
201003	82.3	N	344.7	97.6	N	189.7	107.4	N	263.5	178.8	N	227.3	145.0	-
201004	246.6	N	54.7	168.1	YY	247.9	1.3	(N)	330.8	84.2	(N)	333.9	87.3	-
201005	53.7	N	89.1	35.4	N	276.7	137.0	N	3.9	49.8	YY	28.7	25.0	201012
201006	74.5	YY	93.3	18.8	N	280.2	154.3	N	7.9	66.6	N	35.2	39.3	-
201101	150.6	N	117.3	33.3	N	300.9	150.3	N	31.2	119.4	N	72.5	78.1	-
201102	226.6	N	155.9	70.7	N	335.2	108.6	N	68.9	157.7	N	134.1	92.5	-
201103	316.1	N	183.0	133.1	YY	0.1	44.0	N	95.2	139.1	N	174.0	142.1	-
201104	244.2	YY	257.9	13.7	N	70.9	173.3	N	164.9	79.3	YY	284.9	40.7	201107
201105	317.0	YY	273.9	43.1	N	86.0	129.0	N	179.1	137.9	YY	310.4	6.6	201108
201106	161.7	N	53.2	108.5	(Y)	208.5	46.8	N	308.6	146.9	YY	164.9	3.2	201111
201107	221.3	N	73.9	147.4	YY	225.6	4.3	N	328.5	107.2	YY	196.7	24.6	201112a
201108	251.7	N	84.4	167.3	N	234.1	17.6	N	338.5	86.8	N	214.1	37.6	-
201109	267.7	N	88.5	179.2	Y	237.5	30.2	N	342.5	74.8	YY	218.8	48.9	201113
201110	290.6	N	93.8	163.2	N	241.8	48.8	N	347.5	56.9	N	228.3	62.3	-
201111	128.0	Y	132.4	4.4	N	274.0	146.0	N	24.9	103.1	N	287.0	159.0	-
201201	31.8	N	202.3	170.5	N	335.2	56.6	Y	92.9	61.1	YY	34.5	2.7	201205

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201202	164.7	N	237.1	72.4	N	6.9	157.8	Y	125.8	38.9	N	88.1	76.6	-
201203	335.6	N	287.1	48.5	N	53.8	78.2	N	171.2	164.4	N	163.8	171.8	-

Venus Express

VEX ID	Θ_{VEX}	STA?	Θ_{STA}	$\Delta\Theta_{\text{STA}}$	STB?	Θ_{STB}	$\Delta\Theta_{\text{STB}}$	ACE?	Θ_{ACE}	$\Delta\Theta_{\text{ACE}}$	MES?	Θ_{MES}	$\Delta\Theta_{\text{MES}}$	MES ID
200602	313.0	-	-	-	-	-	-	N	206.8	106.2	-	-	-	-
200603	332.2	-	-	-	-	-	-	N	219.2	113.0	-	-	-	-
200604	62.6	-	-	-	-	-	-	N	273.3	149.3	-	-	-	-
200701	311.8	N	70.6	118.8	N	69.8	118.0	N	69.9	118.1	-	-	-	-
200702	68.0	N	145.7	77.7	N	140.0	72.0	N	141.7	73.7	Y	46.0	22.0	-
200703	81.0	N	155.0	74.0	N	148.3	67.3	N	150.4	69.4	YY	69.2	11.8	200701
200704	113.4	N	174.9	61.5	N	165.3	51.9	N	168.6	55.2	YY	112.4	1.0	200702
200705a	148.8	N	197.8	49.0	N	184.6	35.8	N	189.5	40.7	YY	145.2	3.6	200703a
200705b	150.4	N	198.9	48.5	N	185.5	35.1	N	190.5	40.1	YY	146.4	4.0	200703b
200706	337.9	Y	323.5	14.4	N	287.4	50.5	N	304.6	33.3	X	111.2	133.3	-
200707	34.4	N	359.7	34.7	N	319.4	75.0	N	339.5	54.9	X	156.6	122.2	-
200708	68.5	N	20.3	48.2	N	338.2	90.3	N	359.6	68.9	X	184.0	115.5	-
200801	329.3	N	66.2	96.9	YY	338.1	8.8	N	23.6	54.3	X	199.7	129.6	-
200901	359.8	N	86.0	86.2	YY	356.4	3.4	YY	42.9	43.1	N	238.5	121.3	-
200902	163.0	YY	192.5	29.5	N	98.0	65.0	N	145.1	17.9	N	203.9	40.9	-
200903	191.6	N	210.3	18.7	N	114.5	77.1	N	161.4	30.2	N	245.1	53.5	-
200904	218.5	YY	227.2	8.7	N	129.8	88.7	N	176.7	41.8	N	313.0	94.5	-
200905	224.8	Y	232.5	7.7	N	134.5	90.3	N	181.4	43.4	N	338.0	113.2	-
200906	251.7	N	250.5	1.2	N	150.1	101.6	N	197.6	54.1	N	74.5	177.2	-
200907	277.1	YY	268.6	8.5	N	165.4	111.7	N	213.7	63.4	X	124.4	152.7	-
200908	324.9	N	300.4	24.5	N	191.5	133.4	N	242.4	82.5	N	179.0	145.9	-
200909	9.9	YY	329.7	40.2	N	215.4	154.5	N	269.6	100.3	N	229.8	140.1	-
200910	76.4	(YY)	10.9	65.5	N	249.6	173.2	N	309.1	127.3	X	67.9	8.5	-
200911	133.1	(N)	48.0	85.1	N	281.1	148.0	N	345.0	148.1	X	173.2	40.1	-
201001	295.1	N	153.3	141.8	Y	15.9	80.8	N	87.4	152.3	N	165.8	129.3	-
201002	317.4	N	168.9	148.5	Y	30.8	73.4	N	102.5	145.1	N	193.2	124.2	-
201003	89.9	N	254.2	164.3	YY	111.6	21.7	N	181.2	91.3	N	144.7	54.8	-
201004	104.5	N	263.8	159.3	N	120.2	15.7	N	189.7	85.2	N	164.3	59.8	-
201005	115.9	N	271.2	155.3	YY	126.9	11.0	N	196.4	80.5	N	178.2	62.3	-
201006	125.5	N	277.6	152.1	Y	132.5	7.0	N	202.1	76.6	N	189.9	64.4	-

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201007a	179.9	N	313.5	133.6	YY	163.5	16.4	N	234.4	54.5	N	275.7	95.8	-
201007b	179.9	N	313.5	133.6	YY	163.5	16.4	YY	234.5	54.6	Y	275.7	95.8	-
201007c	181.5	N	314.5	133.0	YY	164.4	17.1	YY	235.4	53.9	N	279.7	98.2	-
201008	194.1	N	321.8	127.7	Y	170.6	23.5	N	242.1	48.0	N	312.9	118.8	-
201009	197.3	N	325.0	127.7	N	173.2	24.1	N	245.0	47.7	N	324.2	126.9	-
201010	238.4	N	351.9	113.5	N	195.8	42.6	YY	270.3	31.9	N	109.4	129.0	-
201011	243.2	N	355.0	111.8	Y	198.3	44.9	N	273.3	30.1	N	118.9	124.3	-
201012	28.7	N	89.1	60.4	N	276.7	112.0	N	3.9	24.8	YY	53.7	25.0	201005
201101	186.7	YY	191.4	4.7	N	8.0	178.7	N	103.2	83.5	N	5.8	179.1	-
201102	193.0	YY	194.5	1.5	N	10.9	177.9	N	106.2	86.8	N	31.1	161.9	-
201103	215.2	YY	209.2	6.0	N	24.7	169.5	Y	120.1	95.1	N	105.9	109.3	-
201104	223.1	YY	215.5	7.6	N	30.7	167.6	N	126.0	97.1	N	124.3	98.8	-
201105	232.6	(N)	220.8	11.8	N	35.7	163.1	N	131.0	101.6	N	143.8	88.8	-
201106a	237.3	YY	225.0	12.3	N	39.7	162.4	N	134.9	102.4	N	152.8	84.5	-
201106b	240.5	YY	227.1	13.4	N	41.7	161.2	N	136.8	103.7	N	158.6	81.9	-
201107	284.9	YY	257.9	27.0	N	70.9	146.0	N	164.9	120.0	YY	244.2	40.7	201104
201108	310.4	YY	273.9	36.5	N	86.0	135.6	N	179.1	131.3	YY	317.0	6.6	201105
201109	353.7	N	302.4	51.3	N	112.5	118.8	N	204.7	149.0	N	97.9	104.2	-
201110	141.0	N	36.6	104.4	N	194.9	53.9	N	292.7	151.7	N	113.8	27.2	-
201111	164.9	N	53.2	111.7	(Y)	208.5	43.6	N	308.6	143.7	YY	161.7	3.2	201106
201112a	196.7	N	73.9	122.8	YY	225.6	28.9	N	328.5	131.8	YY	221.3	24.6	201107
201112b	198.2	N	73.9	124.3	(N)	225.6	27.4	N	328.5	130.3	(N)	221.3	23.1	-
201113	218.8	N	88.5	130.3	Y	237.5	18.7	N	342.5	123.7	YY	267.7	48.9	201109
201114a	277.4	N	126.1	151.3	YY	268.7	8.7	(N)	18.8	101.4	N	102.3	175.1	-
201114b	277.4	N	127.2	150.2	YY	269.6	7.8	N	19.8	102.4	N	106.2	171.2	-
201114c	279.0	N	128.2	150.8	(YY)	270.4	8.6	N	20.8	101.8	N	110.1	168.9	-
201201	312.5	N	148.0	164.5	YY	287.3	25.2	N	40.1	87.6	N	175.8	136.7	-
201202	338.1	N	165.8	172.3	N	302.7	35.4	N	57.4	79.3	N	221.4	116.7	-
201203	354.1	N	177.2	176.9	N	312.7	41.4	N	68.6	74.5	N	255.7	98.4	-
201204	24.8	N	196.0	171.2	N	329.5	55.3	N	86.9	62.1	N	347.8	37.0	-
201205	34.5	N	202.3	167.8	N	335.2	59.3	Y	92.9	58.4	YY	31.8	2.7	201201
201206	125.4	N	261.6	136.2	N	29.7	95.7	YY	148.2	22.8	N	227.7	102.3	-
201207	195.5	N	308.2	112.7	N	73.9	121.6	YY	190.2	5.3	N	94.2	101.3	-
201208	230.3	N	331.1	100.8	N	95.9	134.4	YY	211.1	19.2	N	167.6	62.7	-
201209	247.7	(YY)	342.5	94.8	N	106.6	141.1	Y	221.5	26.2	N	198.1	49.6	-
201210	263.6	N	352.9	89.3	N	116.3	147.3	N	231.1	32.5	N	227.8	35.8	-
201211	336.9	(YY)	40.2	63.3	N	159.0	177.9	N	275.7	61.2	N	98.5	121.6	-
201212	72.4	(YY)	100.5	28.1	(N)	210.2	137.8	N	334.2	98.2	N	291.2	141.2	-
201213	77.2	YY	103.6	26.4	N	211.9	134.7	(YY)	336.2	101.0	X	306.9	130.3	-

3. ICMEs OBSERVED BY MES AND VEX

201214	95.1	YY	116.2	21.1	N	222.1	127.0	(Y)	348.3	106.8	(Y)	13.8	81.3	-
201215	132.3	X	140.2	7.9	(N)	241.8	109.5	N	11.5	120.8	YY	125.0	7.3	-
201301	165.9	YY	162.1	3.8	X	259.9	94.0	N	32.7	133.2	Y	192.7	26.8	-
201302	205.5	X	188.1	17.4	N	281.9	76.4	X	58.2	147.3	N	268.3	62.8	-
201303	229.2	N	203.9	25.3	(Y)	295.4	66.2	N	73.4	155.8	N	348.6	119.4	-
201304	237.1	N	209.1	28.0	N	299.9	62.8	N	78.5	158.6	N	20.2	143.1	-
201305	257.7	Y	222.8	34.9	Y	311.8	54.1	N	91.6	166.1	N	94.6	163.1	-
201306	268.8	N	230.2	38.6	N	318.3	49.5	N	98.7	170.1	N	121.7	147.1	-
201307	340.6	N	278.0	62.6	Y	1.1	20.5	N	143.1	162.5	N	256.3	84.3	-
201308	116.7	N	5.7	111.0	N	84.9	31.8	N	223.2	106.5	N	241.6	124.9	-
201309	210.7	N	66.6	144.1	N	141.7	69.0	N	120.6	90.1	X	156.6	54.1	-
201310	239.2	N	85.3	153.9	N	158.1	81.1	N	298.1	58.9	X	207.1	32.1	-
201311	274.1	N	108.3	165.8	(Y)	177.5	96.6	Y	320.0	45.9	YY	286.9	12.8	-
201312	326.7	N	142.7	176.0	N	205.9	120.8	YY	353.0	26.3	N	111.1	144.4	-
201313	350.8	N	158.4	167.6	N	218.7	132.1	YY	8.2	17.4	N	156.7	165.9	-

Table 3.4. Signatures of the ICMEs listed in Table 3.1 at other spacecraft, as a function of the HCI longitude of the other spacecraft, Θ_x , and as a function of the difference in longitude, $\Delta\Theta_x$, of the two observing spacecraft in question.

plasma; where a signature was observed at 1 AU, the *in situ* proton speed there has been compared to the mean speed between the two spacecraft (calculated from arrival times) as a further test of likelihood that the signature was associated with a particular ICME. *B*-field magnitude enhancements that appeared to be associated with SIRs or CIRs have been excluded when making a ‘Y’ classification. Entries in Table 3.4 marked ‘X’ indicate the presence of a significant data gap at the time when a signature would have been expected to appear. Italicised ‘YY’ entries in the VEX list indicate that the ICME’s flux rope was also observed by MES.

3.3.3.2. An example event

Fig. 3.6 shows an example of an ICME observed by MESSENGER (event MES201004 in Table 3.1) that was subsequently observed by STEREO-B. Magnetic field and plasma data (including bulk flow speed, density and temperature) from the cloud at STEREO-B are shown in Figure 3.7. The enhanced *B*-field magnitude and smooth field rotation characteristic of a magnetic cloud were present at both spacecraft; a magnetic cloud identification in this case is corroborated by the low plasma-beta (≤ 0.1) and temperature observed at STEREO-B. The two spacecraft were close to radial alignment around the time of observation, from 5 to 8 November 2010, with a separation of 1.3° in HCI latitude, 7.1° in HCI longitude and 0.61 AU in heliocentric distance. The cloud’s sheath arrived at MES at DOY 309.490 followed by the flux rope’s leading edge at DOY 309.703. Approximately 58 hours later, at DOY 312.119, the flux rope leading edge arrived at STEREO-B: the mean speed of the leading edge between the two spacecraft was thus $\sim 440 \text{ km s}^{-1}$, comparable to the measured *in situ* speed at STEREO-B. The profiles of the magnetic field components and direction angles observed within the rope were similar at the two spacecraft; the rope had an NES configuration at both spacecraft. There may have been some compression (or suppressed expansion) at the rear of the flux rope due to a faster-moving solar wind stream catching up with the cloud at STEREO-B; a solar wind compression region is evident immediately to the rear of the rope.

The most likely CME counterpart to this cloud appeared in the LASCO C2 field of view on DOY 307.525 (3 November 2010, 12:36 UT) at the eastern limb of the Sun

as viewed from L1. The CDAW CME catalogue (cdaw.gsfc.nasa.gov/CME_list) gives an estimated launch time from the solar surface of DOY 307.420 (November 3 2010, 10:05 UT) for this CME. The CME appeared as a halo in both the STEREO COR-2A and COR-2B fields of view. Taken together, the three sets of coronagraph observations suggest that the CME propagation direction was towards MES and STEREO-B. The estimated launch time and sheath arrival time at MES give a mean propagation speed of $\sim 415 \text{ km s}^{-1}$ between the Sun and MES, similar to the MES to STEREO-B speed.

There was an ICME-like B -field magnitude enhancement (without ‘YY’ flux rope field rotations) at VEX and ACE at $\sim$ DOY 311.3 and 312.4, respectively. VEX was at an 87° separation and ACE at an 84° separation from MES around this time. Arrival times alone suggest a possible association with the MES cloud. However, there was a second, Earth-directed CME appearing in the COR-2A -2B fields of view approximately 7 hours before the other CME, which may account for the VEX and ACE signatures. The signatures at VEX and ACE have therefore been given an ‘(N)’ classification – *i.e.*, some signatures were present that were unlikely to be associated with the ICME under consideration given the coronagraph observations, but coronagraph observations were not conclusive given that two CMEs were launched from the Sun at similar times in not dissimilar directions.

3.3.3.3. Statistical findings

Table 3.5 shows the number of each signature type observed, binned according to longitudinal separation in 15° -wide bins. The secondary signatures of all the ICMEs listed in Table 3.1 have been grouped together in this table. The numbers of each signature type are presented in the first three table rows; parenthesised values in these rows include the less certain signature associations.

The fractional distribution of each signature type within each bin is given in the bottom six rows, where P gives the distribution of the values without parentheses in rows 1 to 3, and P' the distribution of values with parentheses. Binomial standard errors are given for each fraction. Some columns do not sum to 1 due to rounding.

Figure 3.8 shows stacked bar plots of the fractional distributions in Table 3.5. Each bar is effectively normalised in height to the total number of spacecraft pairings

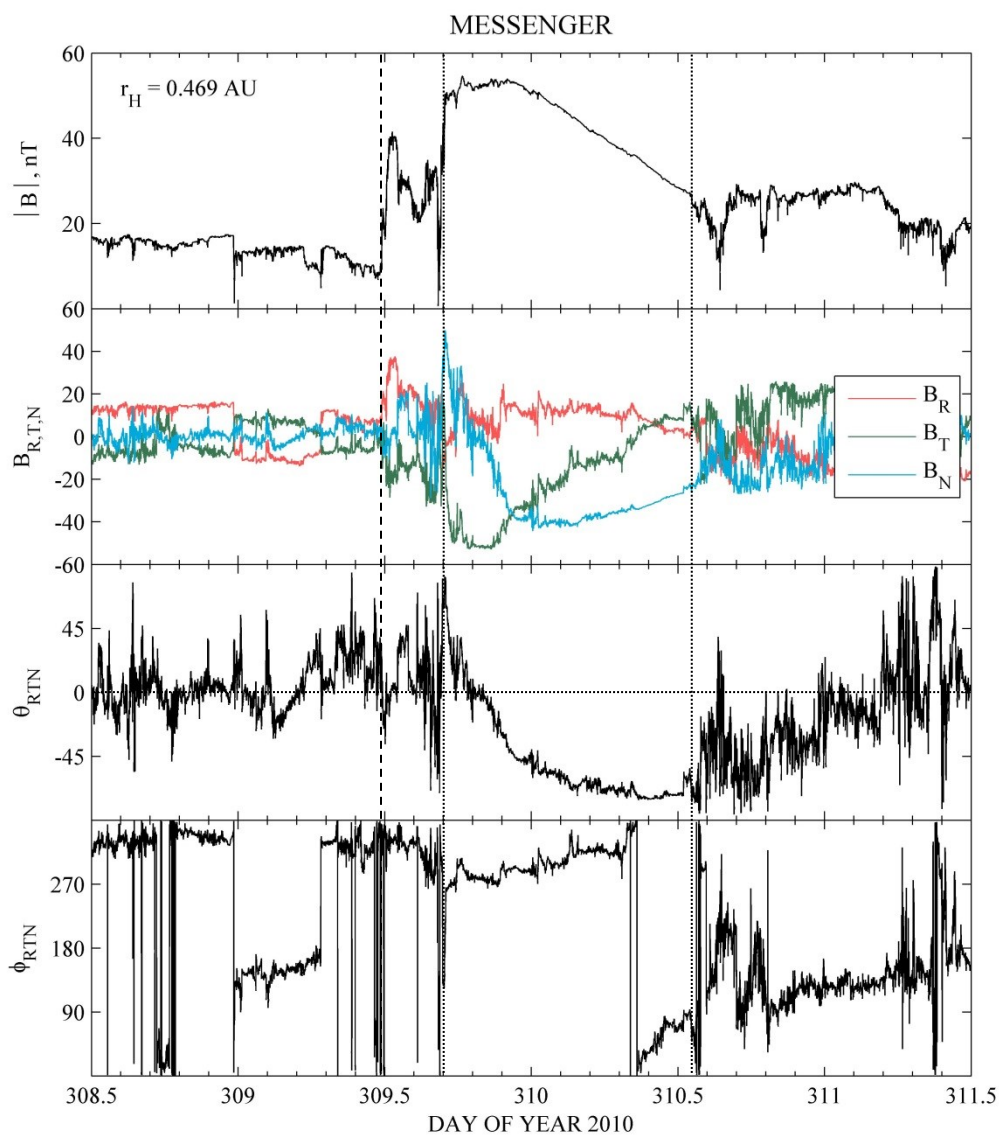


Figure 3.6. An ICME observed by MESSENGER (event MES201004) subsequently observed by STEREO-B (see Figure 3.7, opposite) while the spacecraft were close to radial alignment. The panels and demarcation lines are as described in Figs. 3.2, 3.3 and 3.4.

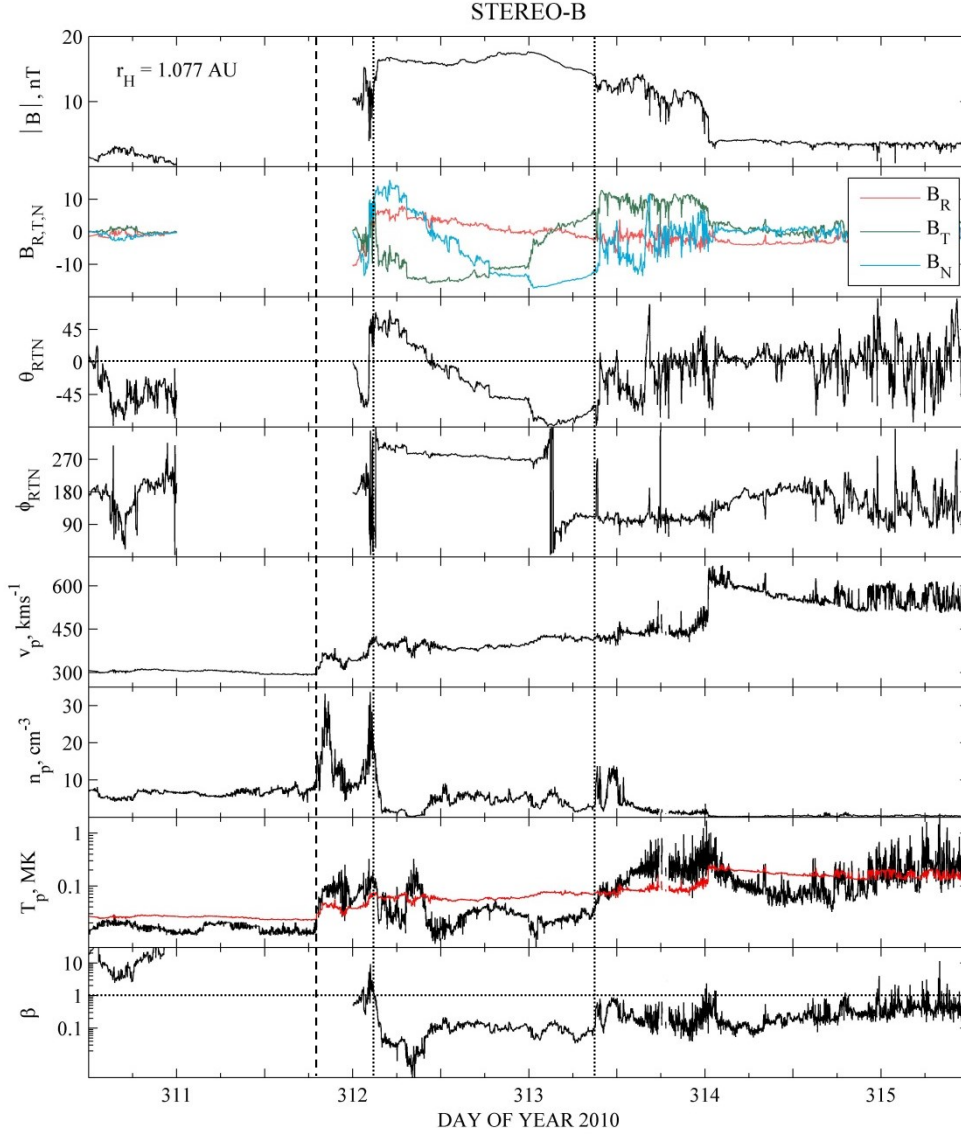


Figure 3.7. An ICME observed by STEREO-B, previously observed by MESSENGER (see Figure 3.6, opposite). The first four panels show magnetic field data in the same format as previous figures. The fifth to eighth panels show, respectively, the solar wind proton speed, proton density, proton temperature and plasma-beta. The red line overlaying the temperature data is the expected temperature (Lopez and Freeman, 1986), an empirically derived function of solar wind speed and heliocentric distance that predicts the temperature of normally-expanding solar wind. All of the magnetic field and plasma signatures of a magnetic cloud were present in this event. This cloud is clearly observed at both MES and STEREO-B.

Signature type	Spacecraft separation angle in the SE plane					
	0 - 15°	15 - 30°	30 - 45°	45 - 60°	60 - 75°	> 75°
Flux rope, 'YY'	32 (33)	19 (20)	7 (7)	5 (5)	0 (2)	0 (2)
Sheath, 'Y'	6 (6)	8 (8)	4 (5)	3 (4)	2 (3)	3 (6)
No signature, 'N'	1 (2)	12 (14)	28 (28)	35 (35)	33 (33)	215 (221)
$P['YY']$	0.82 ± 0.06	0.49 ± 0.08	0.18 ± 0.06	0.12 ± 0.05	0	0
$P['Y']$	0.15 ± 0.06	0.21 ± 0.06	0.10 ± 0.05	0.07 ± 0.04	0.06 ± 0.04	0.01 ± 0.01
$P['N']$	0.03 ± 0.03	0.31 ± 0.07	0.72 ± 0.07	0.81 ± 0.06	0.94 ± 0.04	0.99 ± 0.01
$P['YY']$	0.80 ± 0.06	0.48 ± 0.08	0.18 ± 0.06	0.11 ± 0.05	0.05 ± 0.04	0.01 ± 0.01
$P['Y']$	0.15 ± 0.06	0.19 ± 0.06	0.13 ± 0.05	0.09 ± 0.04	0.08 ± 0.04	0.03 ± 0.01
$P['N']$	0.05 ± 0.03	0.33 ± 0.07	0.70 ± 0.07	0.80 ± 0.06	0.87 ± 0.05	0.97 ± 0.01

Table 3.5. The numbers of each signature type observed at other spacecraft (MESSENGER or *Venus Express*, STEREO-A, STEREO-B, and ACE) associated with the ICMEs observed by MESSENGER and *Venus Express*, binned according to spacecraft separation.

within the corresponding bin; this number is indicated at the top of each bar. Figure 3.8(a) comprises the values without parentheses in Table 3.5, and Figure 3.8(b) the less certain, parenthesised values. Errors associated with the flux rope observations are displayed.

The trends in this figure are clear. As the spacecraft's longitudinal separation increased, the likelihood of the second spacecraft observing either the ICME's flux rope (bar components coloured blue) or sheath (coloured red) steadily dropped. At small angular separations, the second spacecraft almost always saw signatures of the same ICME's flux rope or sheath (95 or 97% of cases for separations between zero and 15°); conversely, a widely separated second spacecraft rarely saw any signature of the same ICME (1 or 4% of cases for separations greater than 75°).

Cane *et al.* (1997) found qualitatively similar results in their study of ICME ejecta (including magnetic clouds) observed by *Helios 1*, *Helios 2* and IMP 8. They found few ejecta were observed by spacecraft pairs even at 40° separations or less, and hardly any at separations above 40°. However, they studied relatively few events, with

3. ICMEs OBSERVED BY MES AND VEX

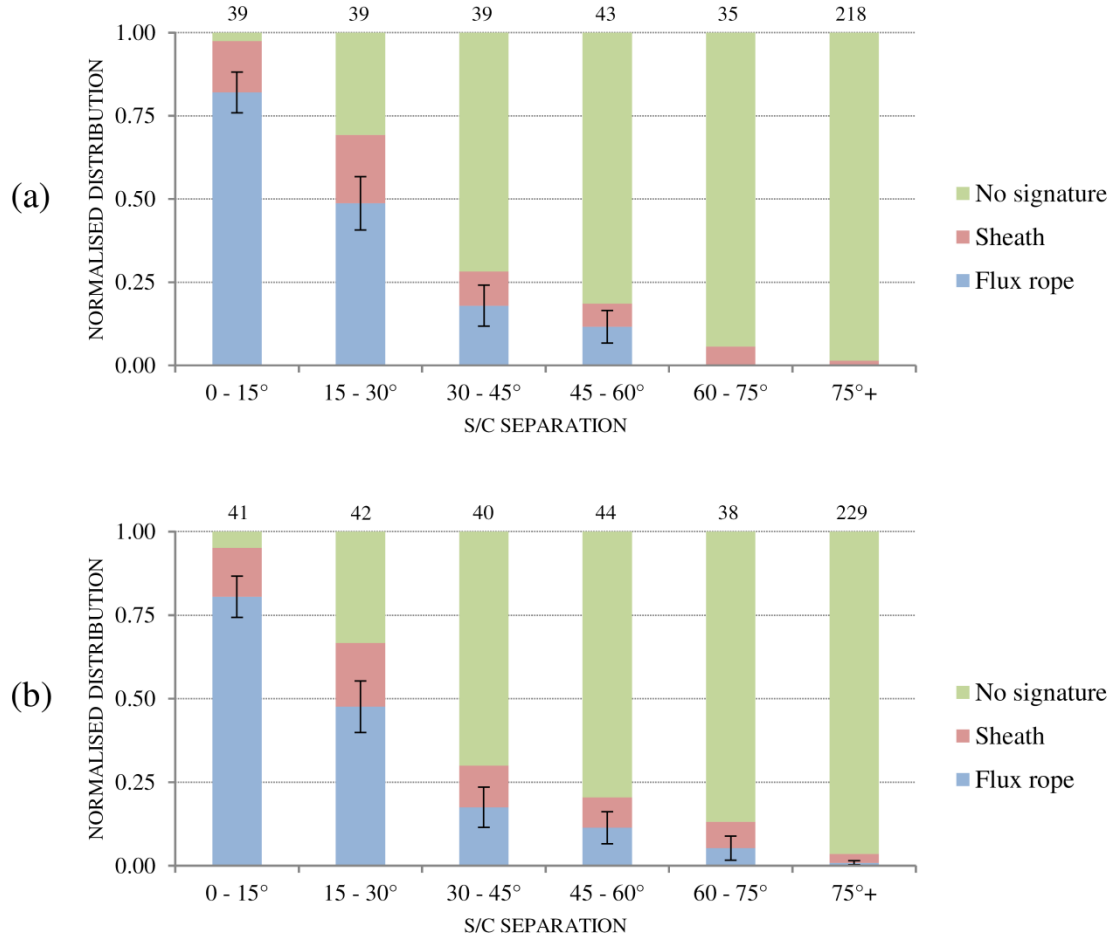


Figure 3.8. (a) Signatures of the ICMEs observed by MESSENGER and *Venus Express* at other spacecraft, as a function of spacecraft separation; (b) Same as (a), with the addition of less certain identifications.

spacecraft separations only up to 53°.

Bothmer and Schwenn (1998) present a comparable plot to that shown in Figure 3.8 (Fig. 12 in their work), based upon *Helios* and IMP/ISEE observations of magnetic clouds. Although they considered fewer events, their findings are broadly consistent with those presented here. Of the fifteen clouds they considered, eight were observed by two spacecraft at separations less than 40°, one at a separation between 50 and 60°, and

and none above 60° ; six clouds were only observed by a single spacecraft, all where the spacecraft separation was above 50° .

Figure 3.8 also shows that, at smaller spacecraft separations, ICME observations at the second spacecraft were more likely to be of the flux rope than of the sheath only. At the widest separations, conversely, it became more likely that the second spacecraft would miss the flux rope and encounter the sheath only. This finding is consistent with the notion that regions of solar wind disturbed by ICME propagation span a greater longitudinal extent than the ICME driving the disturbance, and that the shock or sheath region of an ICME extends beyond the flanks of the ICME's flux rope or ejecta (*e.g.*, Borrini *et al.*, 1982).

3.4. DISCUSSION

Magnetometer data from the MESSENGER and *Venus Express* spacecraft have been examined for the signatures of ICMEs. An enhanced B -field magnitude and smoothly rotating B -field direction consistent with a magnetic flux rope structure were the primary identification criteria. A total of 35 ICMEs observed by MESSENGER within a 5-year period and 84 ICMEs observed by *Venus Express* within a 7.5-year period have been identified. A number of these ICMEs are likely to have been magnetic clouds.

The flux rope within each ICME has been classified according to the observed magnetic field direction relative to the SE plane at its leading edge, centre, and trailing edge. It has been found that:

- (i) ICME flux ropes with northward leading edges were about four times more common than flux ropes with southward leading edges. This result is consistent with the findings of Bothmer and Schwenn (1998), Mulligan *et al.* (1998), Li and Luhmann (2004), and Huttunen *et al.* (2005); it may be an effect of the underlying, global configuration of the solar magnetic field (Mulligan *et al.*, 1998) during the ascending phase of Cycle 24, when magnetic field lines predominantly pointed inwards at the Sun's northern hemisphere and outwards at the Sun's southern hemisphere;

- (ii) ICME flux ropes with low inclinations to the SE plane were about four times more common than flux ropes at high inclinations. This may partly be due to an observational bias – ICME flux ropes at high inclinations are likely to intersect a relatively smaller area of the SE plane, and so are less likely to be observed;
- (iii) Left-handed ICME flux ropes were observed as frequently as right-handed flux ropes.

Multi-point observations for each of the catalogued ICMEs have been identified and classified. Data from MESSENGER, *Venus Express*, STEREO-A, STEREO-B and ACE were analysed, in conjunction with coronagraph observations. The results of this analysis are summarised in Table 3.5 and Figure 3.8. It has been found that:

- (iv) The percentage of cases where a pair of spacecraft observed the flux rope or sheath of the same ICME decreased steadily as the longitudinal separation of the spacecraft increased. Where two spacecraft were separated by 15° or less, both spacecraft observed the ICME's flux rope in 82% of cases. This percentage dropped to 49% for spacecraft separations of 15 to 30° , to 18% for separations of 30 to 45° , and to 12% for separations of 45 to 60° ;
- (v) As the separation of a spacecraft pair became greater, it became increasingly likely that the second spacecraft would observe the sheath of an ICME rather than the flux rope, in those cases where the second spacecraft encountered any signature of the event. This supports the idea that the sheath regions of ICMEs have greater longitudinal extents than the ejecta.

This analysis may be useful for those wishing to determine the likelihood that two spacecraft separated in longitude will observe the same ICME; based upon these results, for example, a spacecraft stationed at L5 – *i.e.*, at a 60° separation from the Sun-Earth line – would be expected to encounter any Earth-incident ICMEs in less than $\sim 10\%$ of cases. Results (iv) and (v) are consistent with those obtained from earlier comparable studies (*e.g.*, Cane *et al.*, 1997; Bothmer and Schwenn, 1998). However, the relatively large number of spacecraft-pair combinations considered in this analysis, made possible

by the relatively large number of spacecraft available, gives the results a greater statistical robustness than the equivalent results obtained from the *Helios*-era studies.

The validity of the multi-point analysis that has been performed depends on the validity of the associations that have been made between *in situ* signatures at different spacecraft. For smaller spacecraft separations, such associations are relatively straightforward to make; there is greater ambiguity in associating signatures at widely separated spacecraft. Heliospheric imaging, or a more sophisticated modelling of CME propagation directions from the coronagraph images, could be used to confirm or otherwise some of the signature associations that have been made, particularly in those cases where the spacecraft separation was wide (*e.g.*, $> 45^\circ$).

This work could be used as the basis for a number of further studies:

- The ICMEs listed in Table 3.1 could be analysed using flux rope fitting techniques (*e.g.*, Lundquist fitting; Burlaga, 1988) to give more precise axis orientations. The evolution of axis orientation with heliocentric distance could be determined (*e.g.*, Leitner *et al.*, 2007). However, some of the events listed (particularly those with obscured boundaries) would not be suited to such fitting;
- The event-by-event multi-point analysis presented in Table 3.4 could be recast in terms of the signature arrival or transit times. Such a reanalysis could be useful for constraining arrival times in MHD models of ICME propagation such as *Enlil* (Odstreil, 2003), or for constraining models that use STEREO's *Heliospheric Imager* observations to predict ICME arrival times (*e.g.*, Möstl *et al.*, 2014; Rollett *et al.*, 2014);
- Individual, multi-point-observed events from the catalogues could be analysed in greater detail. Although statistical averages of ICME characteristics are valuable, ICMEs show enough variability for case studies to be worthwhile. The multi-point analysis could be extended to study longitudinal variations in the signatures of individual events (*e.g.*, Farrugia *et al.*, 2011), or, where observing spacecraft were radially aligned, the radial evolution in events. Such a case study is presented in Chapter 4.

4 | The radial evolution of a magnetic cloud

In this chapter, observations of a magnetic cloud encountered by MESSENGER at 0.44 AU and later by STEREO-B at 1.09 AU are presented and analysed. At the time of observation, in November 2011, the two spacecraft were close to radial alignment. This fortuitous positioning allowed the spacecraft to sample approximately the same region of the cloud, so allowing the evolution that occurred within that region during propagation to be ascertained. This chapter is based upon the journal article published by Good *et al.* (2015).

A commonly used force-free, constant- α flux rope model has been fitted to the magnetic field data of the cloud at each location. Using parameters obtained from this fitting, changes that occurred in the cloud's flux rope orientation, size and structure during propagation between the two observation points have been considered. 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).

Also presented are observations of a magnetic cloud encountered in the same time period by *Venus Express*, while the spacecraft was at a 27° longitudinal separation from the MES – STEREO-B line. The arrival time of the cloud signatures at Venus, roughly mid-way between the arrival times at Mercury and 1 AU, would point to all three spacecraft having observed the same cloud.

Relatively few ICMEs or magnetic clouds observed by pairs of radially aligned spacecraft have been documented. To the best of the author's knowledge, ten 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 an ICME 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 January 1978. 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 April 1979. 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 November 1975; *Helios 2* (0.62 AU), IMP 8 (1 AU) and the *Voyagers* (1.6 AU) in November 1977; and ISEE 3 (1 AU), *Voyager 2* (6.4 AU), *Voyager 1* (7.4 AU) and *Pioneer 11* (9.4 AU) over March to May 1980.

Mulligan *et al.* (1999) described two events observed when the *Wind* and NEAR spacecraft were separated by 5.4° and 1.2° in longitude and 0.28 and 0.18 AU in heliocentric distance, respectively, in November and December 1997. The Bastille Day event of July 2000 was observed by NEAR (1.8 AU) and ACE (1 AU) while the spacecraft were at a 1.9° 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, which was observed by an alignment of ACE (1 AU) and Ulysses (5.4 AU) in March 1998. More recently, Nieves-Chinchilla *et al.* (2013) have reported observations of a cloud seen at MES and STEREO-B while the spacecraft were aligned in August 2009.

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 ICMEs 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.

MES and VEX are particularly useful for performing ICME 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; see Sect. 3.3.3) and between the two spacecraft themselves, giving ample opportunity for the radial observation of ICMEs. Moreover, studies involving radially aligned and inner-heliospheric spacecraft such as MES and VEX will be good preparation for the upcoming *Solar Orbiter* and *Solar Probe Plus* missions.

4.1. SPACECRAFT OBSERVATIONS

Fig. 4.1 shows the location of Mercury, Venus, Earth and the two STEREO spacecraft on 5 November 2011 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 hours. Fig. 4.2 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 seconds. The magnetic field components (second panel, in RTN coordinates), the angle between the field vector and 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 ICME flux ropes, the B -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 Fig. 4.2 are a flux rope model fit to the data, the results of which are described in Sect. 4.2. Intervals in

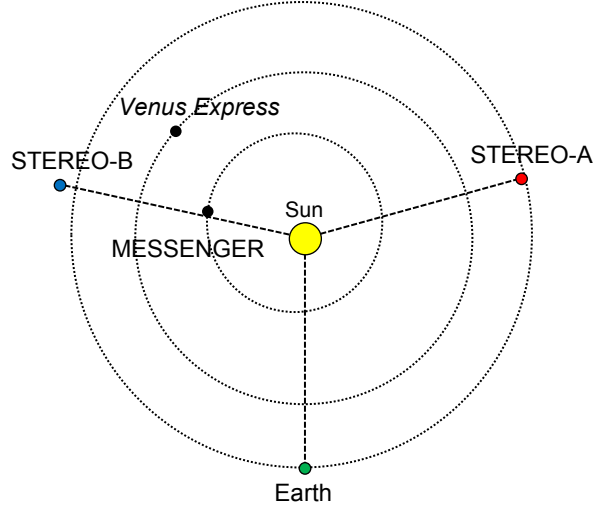


Figure 4.1. The locations of MESSENGER, *Venus Express* and the STEREO spacecraft at 00:00 UT on 5 November 2011, projected onto the ecliptic plane.

the data where the spacecraft traversed the foreshock and magnetosphere of Mercury (shown by the grey shaded regions) have been excluded from the plot.

The bulk plasma speed profile within the rope is presented in the bottom panel of Fig. 4.2. The figure displays data from the *Fast Imaging Plasma Spectrometer* (FIPS) (Andrews *et al.*, 2007) on board MESSENGER, an instrument primarily designed to study hot and subsonic ions in Mercury’s magnetosphere. Although the spacecraft’s radially-directed sunshade 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 which 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 Fig. 4.2. The figure shows that the rope leading edge, at a speed of around 700 km s^{-1} , was travelling 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* ICME signature - Jian *et al.* (2006), for example, catalogued 230 ICMEs observed *in situ* by ACE and *Wind* between 1995 and 2004, of which only 17 ($\sim 7\%$) were not observed to be expanding.

4. RADIAL EVOLUTION OF A MAGNETIC CLOUD

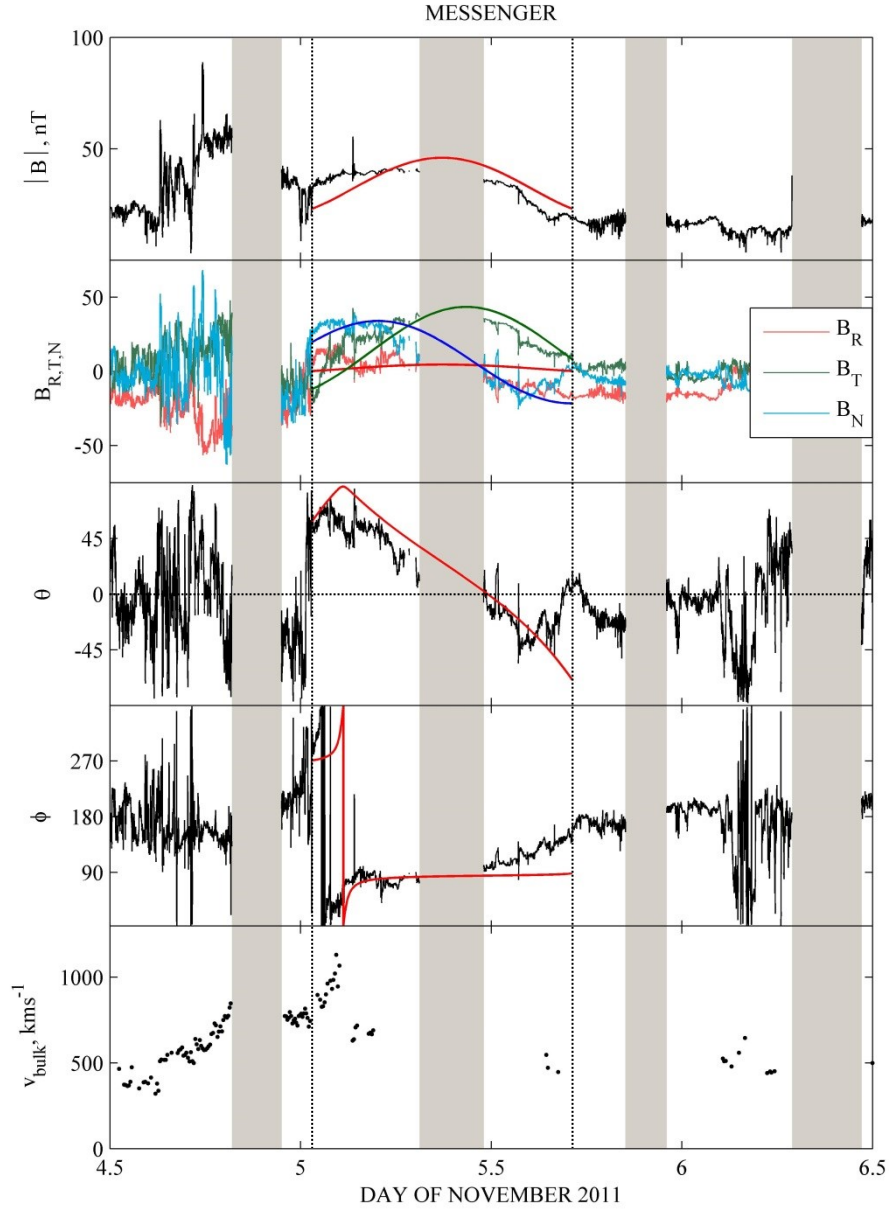


Figure 4.2. The magnetic field magnitude (first panel), field components (second panel), field angles θ and ϕ (third and fourth panels) and bulk plasma speed (fifth panel, where accessible; please refer to the text for details) observed by MESSENGER. The grey-shaded regions show where the spacecraft was within the magnetosphere of Mercury. The smooth lines displayed in the top four panels are a flux rope model fit to the data.

At 22:56 UT on 6 November, approximately 46 hours 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 4.1. All of the defining signatures of a magnetic cloud were observed at ST-B, as can be seen in Fig. 4.3: an enhanced B -field magnitude (first panel), a relatively smooth rotation of the B -field direction (second to fourth panels), a low temperature (seventh panel) and plasma beta (eighth panel) were all present during the 43-hour 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 duration of smooth field rotation, in a similar fashion to the identification of the flux rope at MES; 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; Acuna *et al.*, 2008) and plasma data (from the PLASTIC-B instrument suite; Galvin *et al.*, 2008) presented in Fig. 4.3 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 Fig. 4.2, 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 HCI longitude and 6.8° in HCI latitude. This angular separation is small relative to the 40 to 60° average angular width of CMEs observed in coronagraph images (Gopalswamy *et al.*, 2010). It has been assumed that:

- (i) the same region of the magnetic cloud was sampled by the two spacecraft;
- (ii) that the properties of the magnetic cloud (*e.g.*, flux rope axis orientation) throughout this region are the same at any given time;
- (iii) that any differences observed in the cloud properties at the two spacecraft are due to an evolution in the properties of this region during propagation; and
- (iv) that the cloud propagated radially away from the Sun between Mercury and 1 AU.

Fig. 4.4 shows the magnetic field data within the cloud at MESSENGER

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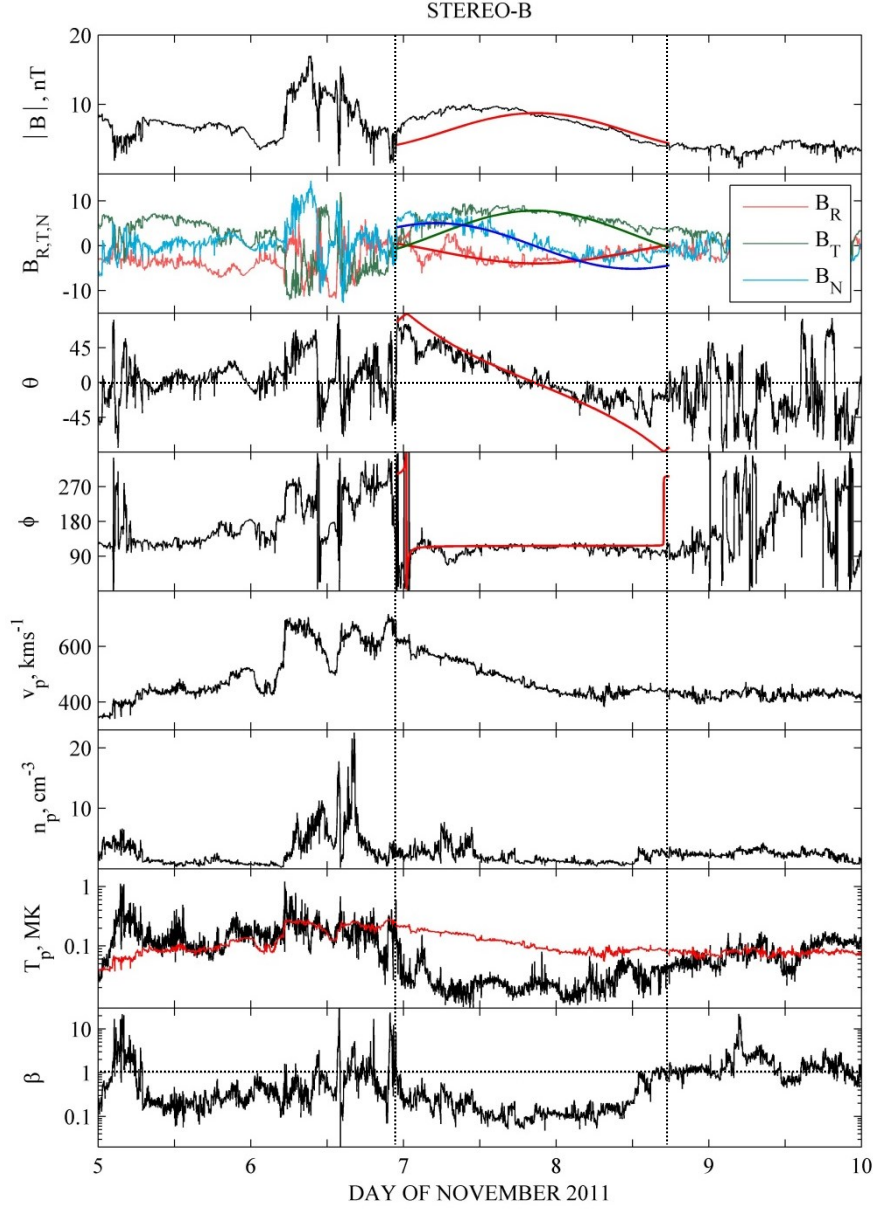


Figure 4.3. B -field magnitude (first panel), field components (second panel), field angles θ and φ (third and fourth panels), proton speed (fifth panel), proton density (sixth panel), proton temperature (seventh panel) and plasma beta (eighth panel) at STEREO-B. The red line overlaying the seventh panel is the expected temperature (Lopez and 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. The smooth lines in the top four panels are a flux rope model fit to the data.

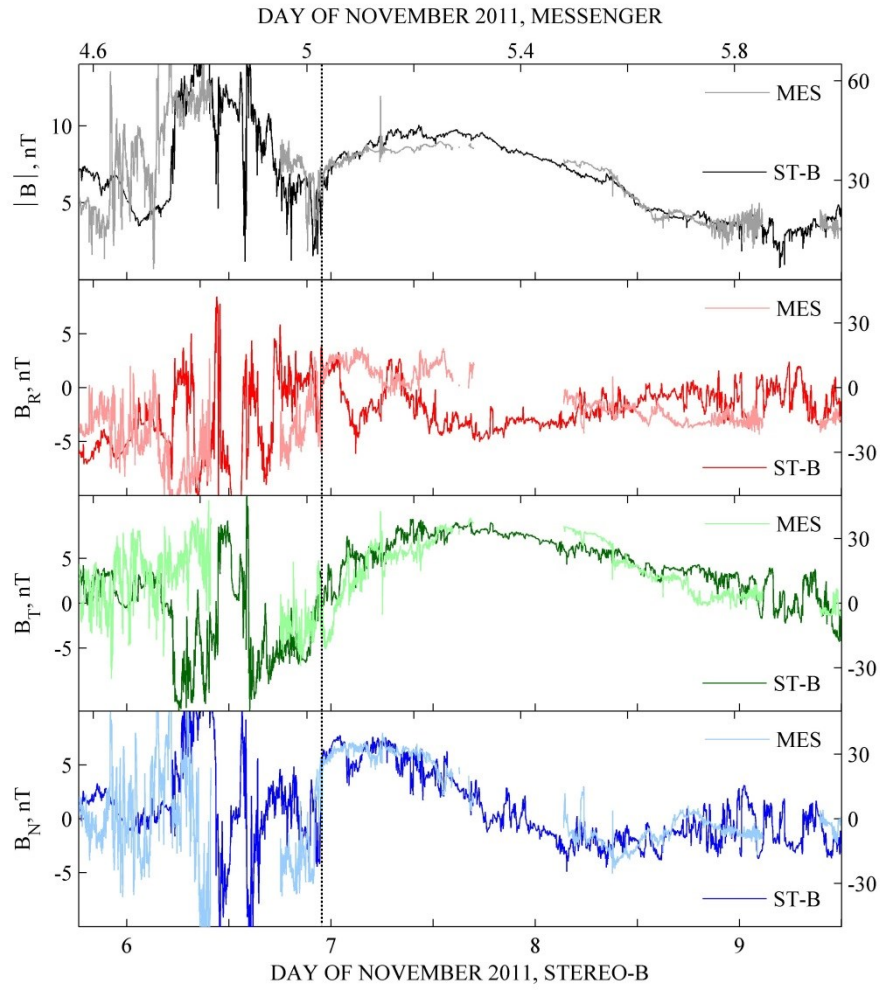


Figure 4.4. The magnetic field data at MESSENGER overlain with the field data at STEREO-B.

overlain with the corresponding field data from the cloud at STEREO-B. The field axes of the MES data (y -axes, right) in this figure have been contracted and the time axis (x -axis, top) expanded relative to the axes of the ST-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 factors 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 MES data has 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 MES data has been scaled linearly to produce the overlap in Fig. 4.4. Although this linear scaling shows a reasonably good correlation with the ST-B data, the flux rope itself may not in reality have expanded in a linear, self-similar fashion during its propagation.

4.2. 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 upon that described by Burlaga (1988) and Lepping *et al.* (1990); it assumes a cylindrically symmetric flux rope field configuration, $\mathbf{B}$, that satisfies

$$\nabla^2 \mathbf{B} = -\alpha^2 \mathbf{B} \quad (4.1)$$

where α is a constant. The derivation of this expression can be found in Sect. 1.4.4. The

field component along the axial direction of the cylinder is given by

$$B_A = B_0 J_0(\alpha R) \quad (4.2a)$$

and the tangential component by

$$B_T = H B_0 J_1(\alpha R) \quad (4.2b)$$

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 ($\mathbf{j} \times \mathbf{B} = \mathbf{0}$) 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 minimisation procedure based upon that performed by Lepping *et al.* (1990), where the axis orientation obtained from the MVA was used to initialise the minimisation. The fits are shown by the smooth lines overlaying the first four panels of Figs. 4.2 and 4.3. 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 .

4.2.1. Flux rope handedness, axial field and orientation

Table 4.1 summarises 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

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	MESSENGER	STEREO-B
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	-1 (left handed)	-1 (left handed)
p	0.02	0.01
χ^2	0.33	0.21
Rope axis orientation (MVA)	$\theta_A = -20 \pm 13^\circ$, $\varphi_A = 79 \pm 20^\circ$	$\theta_A = 3 \pm 8^\circ$, $\varphi_A = 126 \pm 2^\circ$
Rope axis orientation (force-free)	$\theta_A = 26 \pm 8^\circ$, $\varphi_A = 84 \pm 4^\circ$	$\theta_A = -4 \pm 1^\circ$, $\varphi_A = 117 \pm 2^\circ$
B_0 , nT	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

Table 4.1. Arrival times, speeds and flux rope model parameters of the magnetic cloud at MESSENGER and STEREO-B.

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 4.1 for these orientations are relative to the solar equatorial (SE) plane, where θ_A is the angle between the axis direction and the plane, and φ_A 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 $\theta_A = -20 \pm 10^\circ$, $\varphi_A = 79 \pm 20^\circ$ at MESSENGER and $\theta_A = 3 \pm 8^\circ$, $\varphi_A = 126 \pm 2^\circ$ at STEREO-B, compared to $\theta_A = 26 \pm 8^\circ$, $\varphi_A = 84 \pm 4^\circ$ at MES and $\theta_A = -4 \pm$

1° , $\varphi_A = 117 \pm 2^\circ$ at ST-B from force-free fitting.

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 and 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 MES, where $\lambda_1/\lambda_2 = 1.9$ and $\lambda_3/\lambda_2 = 0.14$, and at ST-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 and 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 and Scheible, 1998) apply the conditions of $\lambda_1/\lambda_2 > 10$ and $\lambda_3/\lambda_2 < 0.1$ for well-defined variance directions, conditions which are not met for the flux rope data at either spacecraft. These relatively strict criteria are more usually applied when determining plasma interface normals.

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 minimisation procedure, which may be (following the example of Lepping) defined as

$$\chi^2 = \sum [(B_R - B_R^M)^2 + (B_T - B_T^M)^2 + (B_N - B_N^M)^2] / N \quad (4.3)$$

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 modelled data, and N is the total number of vectors in the sample. The fits to the MES data shown in Fig. 4.2 and to the ST-B data in Fig. 4.3 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 normalised magnetic field vectors were used to calculate these χ^2 values.

The error values given with the axis orientations in Table 4.1 were calculated by adjusting the location of the trailing edge of the flux rope 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 MES 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), amongst others, present evidence of limitations and inconsistencies in the Lundquist model.

4.2.2. Flux rope kinematics and width

Table 4.1 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 MES and ST-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 centre of the flux rope (*i.e.*, where the modelled magnetic field strength is at its maximum), and t is the time taken by the spacecraft to traverse the rope. Unfortunately, MES did not observe the centre 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 centre would have arrived at Mercury is known – the time mid-way between the leading and trailing edges of the rope – it is possible to estimate the mean speed of the flux rope centre between its arrival at Mercury and at ST-B. This mean speed was estimated to be $447 \pm 6 \text{ km s}^{-1}$, very close to the v_c value of $449 \pm 2 \text{ km s}^{-1}$ measured at STEREO-B. It has therefore been assumed that the flux rope centre 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 MES and $0.46 \pm 0.05 \text{ AU}$ at ST-B. These values are listed in Table 4.1. Given the magnetic cloud's expansion, S' may 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 ± 0.02 and $0.41 \pm 0.05 \text{ AU}$ at MES and ST-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.

4.2.3. *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 Eq. 4.2a, it may be shown that

$$\begin{aligned}\Phi &= 2\pi B_0 \int_0^{S/2} J_0(\alpha R) R dR \\ &= \frac{\pi J_1(\gamma)}{2\gamma} B_0 S^2 \sim 0.34 B_0 S^2\end{aligned}\tag{4.4}$$

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), amongst others. Taking S as the best estimate of the rope diameter (rather than S'), $\Phi = 0.49 \pm 0.08$ nT AU² at MESSENGER and $\Phi = 0.50 \pm 0.11$ nT AU² 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 (*cf.* Lavraud *et al.* 2014, and references therein).

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

$$H_M = \int \mathbf{A} \cdot \mathbf{B} dV\tag{4.5}$$

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 understood to be a key mechanism by which the Sun sheds helicity, preventing an endless build-up 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

$$\frac{H_M}{L} = \frac{4\pi B_0^2}{\alpha} \int_0^{S/2} J_1^2(\alpha R) R \, dR \cong \frac{7}{80} B_0^2 S^3 \quad (4.6)$$

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 MES and $0.47 \pm 0.16 \text{ nT}^2 \text{ AU}^3$ at ST-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

$$\left(\frac{H_M}{L}\right)_{\text{MES}} L_{\text{MES}} = \left(\frac{H_M}{L}\right)_{\text{STB}} L_{\text{STB}} \quad (4.7)$$

where the variables are at their values during the time of the cloud's observation by MES and ST-B. 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 Eq. 4.7 that the ratio of the angular width of the flux rope at ST-B to the angular width at MES is given by

$$\frac{\Theta_{\text{STB}}}{\Theta_{\text{MES}}} = \frac{(H_M/L)_{\text{MES}} r_{H, \text{MES}}}{(H_M/L)_{\text{STB}} r_{H, \text{STB}}} = \frac{B_{0, \text{MES}}^2 S_{\text{MES}}^3 r_{H, \text{MES}}}{B_{0, \text{STB}}^2 S_{\text{STB}}^3 r_{H, \text{STB}}} \quad (4.8)$$

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This expression is found to equal 0.89 ± 0.38 using the parameters estimated for the flux rope, suggesting that the cloud spanned a somewhat smaller angular width at ST-B than at MES. The 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 ICMEs tend to propagate and expand at roughly constant angular widths to fill cones (Zhao *et al.*, 2002).

Eq. 4.8 may be generalised to

$$\Theta_2 = \left(\frac{B_{01}^2 S_1^3 r_{H1}}{B_{02}^2 S_2^3 r_{H2}} \right) \Theta_1 \quad (4.9)$$

for observations made by any two spacecraft (denoted by subscripts 1 and 2). 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 Eq. 4.9.

It is also possible, using the modelled parameters, to estimate the aspect ratio of the flux rope's length to radial width, L/S , as a function of H_M ; at MES, $L/S \sim (5.5 \pm 1.9) H_M \text{ nT}^{-2} \text{ AU}^4$ and at ST-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 Eqs. 4.4 and 4.6, it may be shown that

$$L/S = (H_M/L)^{-1} S^{-1} H_M \sim B_0^{-2} S^{-4} H_M \sim \Phi^{-2} H_M \quad (4.10)$$

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.

4.2.4. *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 two hours around midnight of 3 November 2011, 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 3 November 2011 23:36 UT. This CME was also observed by both STEREO-A and -B's coronagraphs, emerging from the Sun's western limb as viewed from ST-A and from the eastern limb as viewed from ST-B. A significant brightening on the solar disc 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 the Earth). Park *et al.* (2013), Prise *et al.* (2014) and Gómez-Herrero *et al.* (2015) have presented extensive studies of this CME and its associated solar energetic particle signatures at 1 AU.

The second CME (CME 2) first appeared in LASCO's field of view on 4 November 01:25 UT at the Sun's eastern limb, and later as a weak halo in ST-B's COR2 coronagraph. A post eruption arcade was observed on the solar disc at a Carrington longitude of $\sim 59^\circ$, 25°N by ST-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 ST-A's COR1 and COR2 coronagraphs at around the same time.

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	CME 1	CME 2
STEREO-B EUVI	2011 Nov 3 22:17 UT	2011 Nov 4 00:27 UT (PEA)
STEREO-B COR1	2011 Nov 3 22:26 UT (EL)	-
STEREO-B COR2	2011 Nov 3 22:54 UT (EL)	2011 Nov 4 01:55 UT (weak halo)
STEREO-A COR1	2011 Nov 3 22:20 UT (WL)	2011 Nov 4 00:45 UT (WL)?
STEREO-A 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)

Table 4.2. The 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.

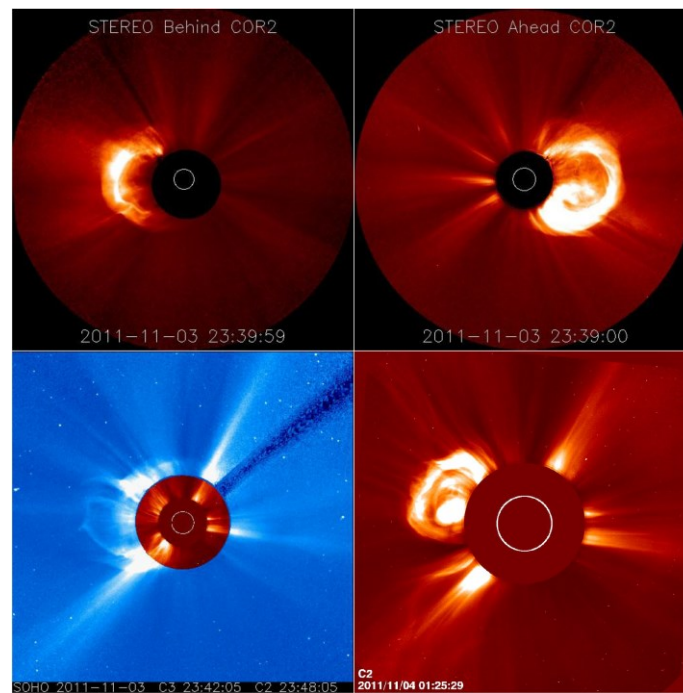


Figure 4.5. Coronagraph images of CME 1 (from STEREO in the top row, and LASCO bottom left) and CME 2 (LASCO, bottom right).

Table 4.2 summarises the times at which the signatures of CMEs 1 and 2 were first observed by the various instruments, and Fig. 4.5 shows a number of coronagraph images of the two CMEs.

Both CMEs are listed in the CDAW LASCO CME catalogue (cdaw.gsfc.nasa.gov/CME_list). Taking the catalogue’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 (Nov 3 21:30 UT for CME 1 and Nov 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 4 November 16:05 UT and CME 2 on 5 November 00:24 UT. The expected arrival time of CME 2 is closer to the actual *in situ* arrival time of 5 November 00:43 UT, and so it is more likely that CME 2 is the 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. Using the non-linear speeds given by the CDAW catalogue produce 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 MES and ST-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 centred 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 and Cane (1993), for example, have previously found that magnetic shock drivers such as flux ropes have a maximum longitudinal extent of 100° . Furthermore, the statistical analysis presented in the previous chapter suggests that such a wide flux rope would be very rare (as indicated by Table 3.5 and Fig. 3.8).

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

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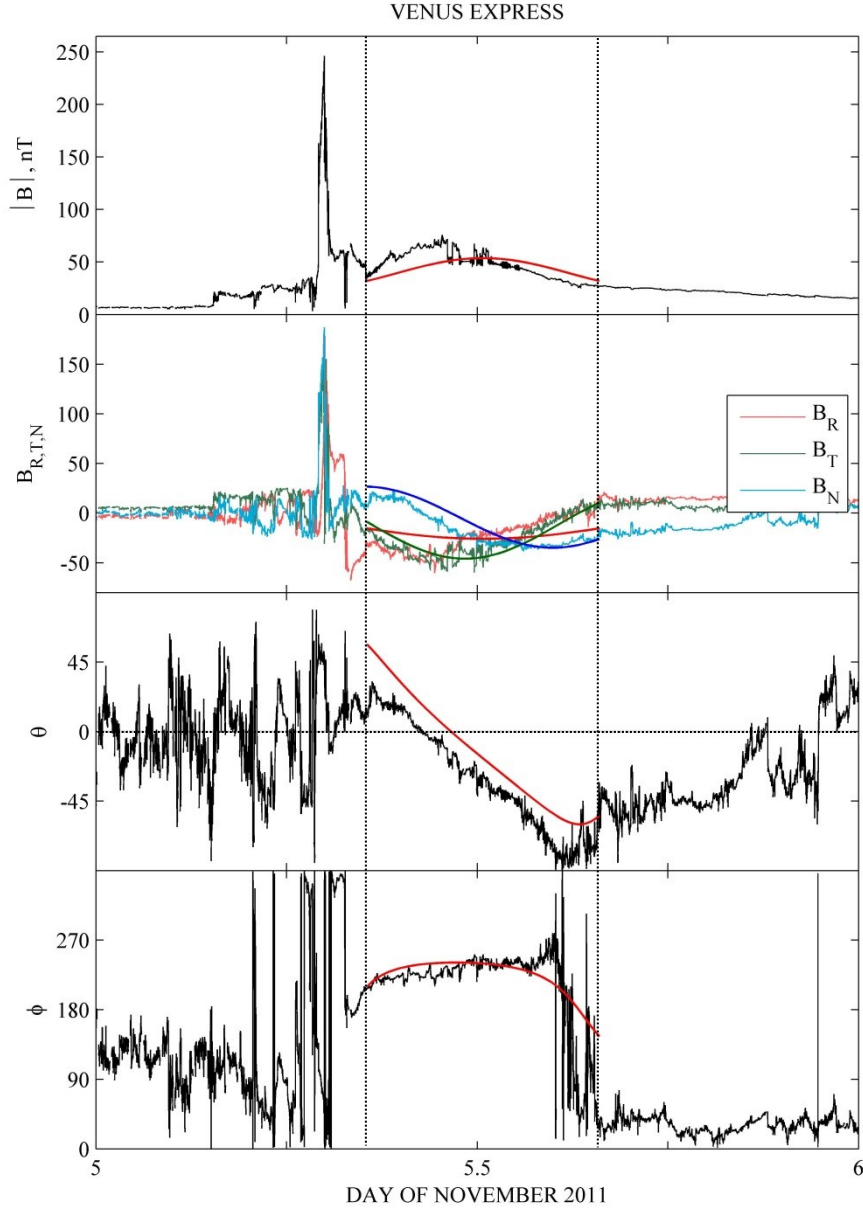


Figure 4.6. The magnetic field magnitude (first panel), field components (second panel), and field angles θ and ϕ (third and fourth panels, as defined in the text) observed by *Venus Express*. The flux rope interval, as in Figs. 4.2 and 4.3, is marked by the vertical dashed lines. Note the enhanced field 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. The smooth lines overlaying the data show a right handed flux rope fit to the data.

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 $\sim \theta_A = -20^\circ$, $\varphi_A = 278^\circ$ and impact parameter of 0.47; however, this fit is right handed, in contrast to the left-handedness of the rope at MESSENGER 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 ($\sim \theta_A = -50^\circ$, $\varphi_A = 264^\circ$, $\lambda_1/\lambda_2 = 3.6$, $\lambda_3/\lambda_2 = 0.098$).

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 $\sim \theta_A = -3^\circ$, $\varphi_A = 170^\circ$ 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, 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 Fig. 4.6. The front half of the flux rope was observed while the spacecraft was within Venus's magnetosheath but ostensibly 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 ICME flux ropes can often be discerned and analysed in the *Venus Express* data despite the spacecraft's regular forays into the planetary magnetosphere. Note that no magnetic cloud signatures were observed at either ACE or STEREO-A around the time of these events.

4.3. 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. Signatures of the same magnetic cloud observed by MESSENGER and STEREO-B while the spacecraft were close to radial alignment with the Sun in November 2011 have been analysed and presented. 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 analysed using force-free fitting and MVA. During propagation between 0.44 and 1.09 AU, the force-free fitting indicates that:

- 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;
- 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;
- the axis of the flux rope rotated by $\sim 33^\circ$ in longitude and $\sim 30^\circ$ in latitude θ_A towards 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, MVA may be a less accurate analysis method for determining the axis orientation of this rope compared to the force-free fitting.

Further, by assuming that the magnetic cloud's helicity was conserved, it has been inferred that:

- the cloud's axial length L increased during propagation;
- the cloud's angular width Θ at STEREO-B was 0.89 ± 0.38 times its value at MESSENGER, broadly in agreement with a cone model of CME expansion. A simple expression has been derived (Eq. 4.9) 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;
- the ratio of the cloud's length to width remained roughly constant, and it has been shown how this is a natural consequence of the axial flux and helicity conservation.

The magnetic cloud's apparent rotation is significant. It has been hypothesised 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 fourteen ICME 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) towards 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 (observed in coronagraph images, within a few R_S of the Sun) of CMEs from high to low latitudes, driven by fast solar wind emerging from coronal holes (Cremades and Bothmer, 2004).

The solar source of the magnetic cloud studied here had a Carrington longitude

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of $\sim 59^\circ$, 25°N during Carrington rotation 2116. The corresponding Wilcox Solar Observatory coronal field map (<http://wso.stanford.edu/>) at $2.5 R_\odot$ indicates that the neutral line in the vicinity of this source location was North-South aligned, very different to 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 $2.5 R_\odot$ 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 ICMEs observed by radially aligned spacecraft could be analysed in order to determine whether rotation of the flux rope axis towards 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 ICMEs, 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. A preliminary study of a larger number of ICME flux ropes observed by radially aligned spacecraft is presented in Chapter 5.

5 | Nineteen ICMEs observed by radially aligned spacecraft: a preliminary study

In Chapter 3, a large catalogue of flux-rope ICMEs observed by MESSENGER and *Venus Express* was presented and analysed. One of these ICMEs, observed by MES and later by STEREO-B while the two spacecraft were radially aligned with the Sun, was examined in detail in Chapter 4. In this chapter, a larger number of such radially observed events are analysed: the ICMEs' kinematic behaviour, changes in the apparent flux rope orientations between the observing spacecraft, and the nature of the ICMEs' expansion as determined by a dimensionless coefficient, are all considered. One aim of this analysis is to begin placing the observational study of the radial evolution of individual ICMEs on a more statistical footing, something that has not been previously attempted.

5.1. EVENT LIST

Table 5.1 lists nineteen cases where flux rope signatures of the same ICMEs were observed by pairs of radially aligned spacecraft in the solar wind. In each instance, the spacecraft closer to the Sun was either MES or VEX, and the spacecraft further away was STEREO-A, STEREO-B or ACE (or VEX, in some of the cases where MES was the inner spacecraft). Only one of the spacecraft pairs happened to include ACE: it is perhaps for this reason that few of these events have been studied before, since more consideration is usually paid to Earth-directed ICMEs.

The events listed in Table 5.1 were found as part of a more general multi-point analysis described in Chapter 3, and form the subset of events from Table 3.5 where the

radial separation between the observing spacecraft, Δr , exceeded 0.1 AU and the HCI longitudinal separation was less than 12° . Below a separation of ~ 0.1 AU, spacecraft pairs were effectively making coincident observations of an ICME, and so pairs at these separations have been excluded from this analysis. Most observing spacecraft pairs were separated by much more than this minimum radial distance. It has been assumed that spacecraft at longitudinal separations of 12° or below were sufficiently close to alignment for them to have sampled approximately the same region of a radially-propagating ICME; also, setting an upper separation limit of 12° allowed a reasonably large number of events to be included in the study. As in the previous multi-point analysis, latitudinal separations between the spacecraft have been neglected since they were always small.

Some ICMEs have not been included in Table 5.1 despite being observed by spacecraft pairs that met the criteria described above. These include event VEX201114, which consisted of a succession of closely spaced flux ropes for which the boundaries were difficult to precisely match at the two observing spacecraft. Events VEX201005, MES200904 and MES200903 have also been discounted because their signatures at the outer spacecraft in each case were particularly weak; the flux rope signatures of MES200903 at the second spacecraft (VEX in this instance) were also heavily obscured by a magnetosphere traversal.

5.2. CHANGE IN FLUX ROPE ORIENTATION

By assuming a particular global structure, the global parameters of flux ropes can be estimated from single spacecraft observations. One important parameter common to most of these structures is the orientation of the flux rope's central axis relative to a particular reference plane. This parameter can, for example, be used to link flux ropes observed *in situ* to the structure of features remotely observed on the solar surface (*e.g.*, filaments and post-eruption arcades; see discussion in Sect. 4.3). Knowledge of an ICME's flux rope orientation – and the extent to which the orientation changes during propagation – can also allow for better predictions of the strength and arrival time of southward-directed magnetic field at the Earth, a key parameter of geoeffectiveness.

Alignment #	s/c 1 event	$r_{s/c1}$ AU	s/c 2	$r_{s/c2}$ AU	Δr , AU	s/c 1			s/c 2		
						Year	t_L , DOY	t_R , DOY	Year	t_L , DOY	t_R , DOY
										Δt , days	
MES ...											
1	200701	0.587	VEX	0.719	0.132	2007	124.873	126.040	2007	(126.235)	126.870
2	200902	0.327	STB	1.003	0.676	2007	46.183	(46.592)	2007	(49.779)	50.469
3	200905	0.561	STB	1.084	0.523	2009	240.057	240.650	2009	242.826	243.351
4	201004	0.462	STB	1.077	0.615	2010	309.703	310.547	2010	312.119	313.378
5	201105	0.322	VEX	0.724	0.402	2011	156.188	(156.444)	2011	156.635	156.938
6	201106	0.460	VEX	0.725	0.265	2011	288.470	289.266	2011	(289.290)	290.402
7	201107	0.439	STB	1.086	0.647	2011	309.030	309.712	2011	310.956	312.742
8	201201	0.320	VEX	0.728	0.408	2012	67.257	(67.686)	2012	67.843	(68.488)
VEX ...											
9	200801	0.723	STB	1.026	0.303	2008	364.865	(365.432)	2008→09	366.152	1.037
10	200901	0.721	STB	1.015	0.294	2009	17.608	17.951	2009	19.075	19.627
11	200904	0.728	STA	0.956	0.228	2009	153.777	(154.514)	2009	(154.156)	(155.893)
12	200907	0.727	STA	0.957	0.230	2009	191.443	192.267	2009	192.963	194.234
13	201101	0.727	STA	0.958	0.231	2011	(78.204)	78.496	2011	78.983	79.429
14	201102	0.727	STA	0.957	0.230	2011	81.728	82.764	2011	82.289	84.045
15	201103	0.728	STA	0.957	0.229	2011	95.717	(96.627)	2011	96.403	97.853
16	201104	0.728	STA	0.957	0.229	2011	101.461	101.731	2011	(101.988)	102.433
17	201207	0.727	ACE	1.016	0.289	2012	167.810	168.353	2012	168.920	169.488
18	201215	0.722	MES	0.420	0.302	2012	(352.513)	(353.210)	2012	350.892	(351.828)
19	201301	0.725	STA	0.960	0.235	2013	8.642	9.825	2013	9.444	10.720
											1.276

Table 5.1. (*previous page*) Parameters of ICMEs observed by radially aligned spacecraft pairs. Note that for all alignments apart from alignment 18, s/c 1 is the inner spacecraft, *i.e.*, the spacecraft closer to the Sun.

Minimum variance analysis (MVA) has been used to estimate orientations of a number of the ICMEs observed by the spacecraft alignments listed in Table 5.1. For each ICME considered, the orientation has been found at each of the observing spacecraft independently. The results of this analysis are presented in Table 5.2. MVA is a widely used technique for estimating flux rope axis directions: it assumes an approximately cylindrical flux rope geometry, where the axis direction coincides with the direction of intermediate variance in the magnetic field data. This relatively simple technique is described in more detail in Sect. 4.2.

Events selected for MVA from Table 5.1 had clearly defined boundaries that could be matched at both spacecraft, with qualitatively similar field rotation patterns in θ_B and ϕ_B . Events where the rope’s magnetic field profile was heavily obscured at one of the spacecraft (*e.g.*, at MES for alignment 18), where the field rotation patterns at the two spacecraft were markedly different (*e.g.*, alignment 16) or where the field direction only changed by a small amount (*e.g.*, alignment 8, where ϕ_B only changes by $\sim 10^\circ$ through the rope), were not analysed.

Table 5.2 gives the latitude angles, θ_A , and longitude angles, ϕ_A , of the axis directions relative to the SE plane. ϕ_A corresponds to the angle anti-clockwise from the sunward direction to the projection of the axis vector onto the SE plane, when viewed from a northerly direction; θ_A corresponds to the angle between the axis vector and the SE plane, ranging from 90° for a northward-pointing vector to -90° for a southward-pointing vector. The Cartesian axis direction vectors used to obtain these angles were found in the various co-ordinate systems of the magnetic field data (RTN for MESSENGER and STEREO, VSO for *Venus Express*, and GSE for ACE; see Sect. 3.2 for the definitions of these co-ordinate systems); the orientation of these vectors relative to the SE plane were then determined. The RTN to SE transformation is only a function of the spacecraft’s heliocentric inertial latitude, θ_{HCL} , at the time of observation;

Alignment #	s/c 1					s/c 2					$\Delta\theta_A$	$\Delta\varphi_A$	ψ
	θ_A	φ_A	λ_1 / λ_2	λ_3 / λ_2	Data gap?	θ_A	φ_A	λ_1 / λ_2	λ_3 / λ_2	Data gap?			
1	60	319	4.41	0.39	N	46	325	1.69	0.44	N	-14	6	14
2*	-16	68	3.39	0.17	N	22	179	6.74	0.67	N	37	111	115
3	17	264	3.63	0.23	N	-20	256	4.36	0.09	N	-36	-8	38
4	-47	108	2.58	0.10	N	-23	87	3.33	0.02	N	25	-20	29
5*	-74	290	3.33	0.07	Y (41%)	-28	161	3.20	0.23	N	46	-129	73
6	-41	129	2.03	0.19	Y (32%)	-37	103	2.57	0.21	Y (15%)	4	-26	21
7	-20	258	1.95	0.14	Y (29%)	9	305	2.42	0.24	N	29	47	55
9	-39	260	5.88	0.18	Y (13%)	-31	289	4.07	0.13	N	9	29	25
10	-4	221	5.45	0.60	N	-28	280	7.47	0.38	N	-24	59	61
12	29	266	3.66	0.39	Y (9%)	-36	252	6.59	0.34	N	-65	-13	66
14*	36	85	4.09	0.58	Y (18%)	2	27	3.78	0.34	N	-34	-58	63
17*	63	98	3.17	0.04	Y (14%)	-22	99	1.53	0.07	N	-85	0	85
19	67	341	3.38	0.11	Y (11%)	67	359	2.47	0.06	Y (18%)	0	18	7
Mean:											-8 ± 11	1 ± 16	50 ± 9
Mean, un-starred fits:											-8 ± 10	10 ± 10	35 ± 7

Table 5.2. Orientations of flux ropes observed by pairs of radially aligned spacecraft. Starred alignments indicate questionable orientation estimates. The axis latitude and longitude angles (φ_A and θ_A , respectively) at each spacecraft are given, as well the changes in these quantities. The angle ψ is the angle between the axes in the plane in which the two axes are coplanar.

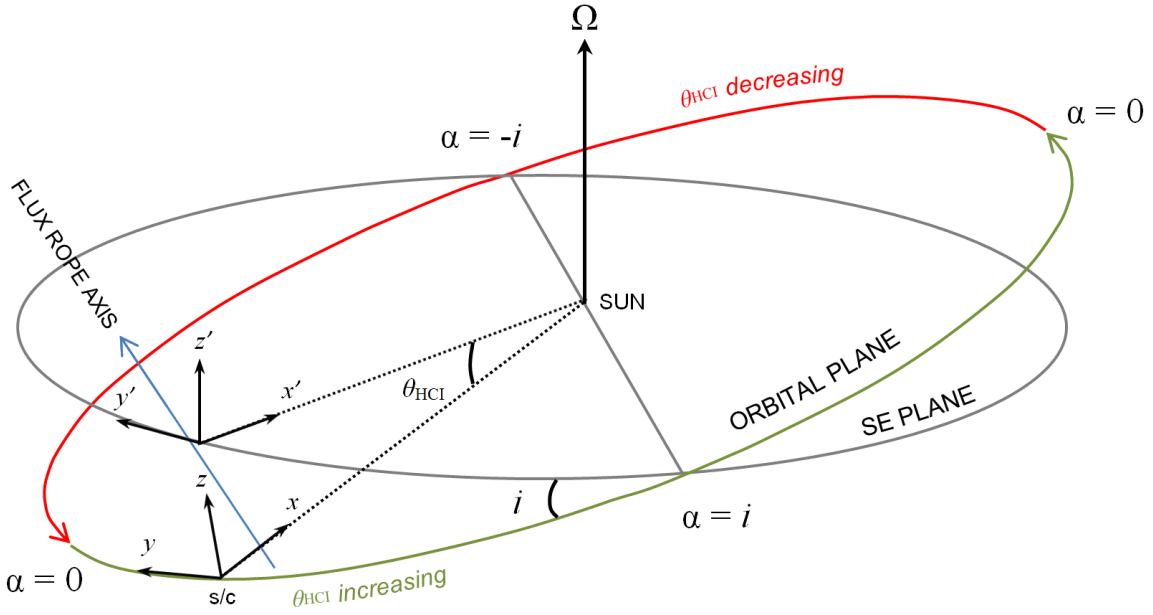


Figure 5.1. A visualisation of the orbital plane $(x y z)$ to SE $(x y z)'$ transformation given by Eq. 5.2.

$$\mathbf{a}' = \begin{pmatrix} \cos \theta_{\text{HCI}} & 0 & \sin \theta_{\text{HCI}} \\ 0 & 1 & 0 \\ -\sin \theta_{\text{HCI}} & 0 & \cos \theta_{\text{HCI}} \end{pmatrix} \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \mathbf{a} \quad (5.1)$$

where $\mathbf{a}$ is the original Cartesian axis direction in RTN co-ordinates, and $\mathbf{a}'$ is the axis direction relative to the SE plane, such that x' points to the Sun (*cf.* R , which points away from the Sun), z' is parallel to the solar rotation axis and y' completes the right-handed set. The equivalent transformation from any plane (*e.g.*, Venus's orbital plane or the ecliptic) inclined by angle i to the SE plane is given by

$$\mathbf{b}' = \begin{pmatrix} \cos \theta_{\text{HCI}} & 0 & \sin \theta_{\text{HCI}} \\ 0 & 1 & 0 \\ -\sin \theta_{\text{HCI}} & 0 & \cos \theta_{\text{HCI}} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{pmatrix} \mathbf{b} \quad (5.2)$$

where $\alpha = \pm i \cos [\sin^{-1}(\theta_{\text{HCI}} / i)] = \pm i [1 - (\theta_{\text{HCI}} / i)^2]^{1/2}$; α is positive when θ_{HCI} is increasing at the time of observation, and negative when θ_{HCI} is decreasing. This

transformation, illustrated in Fig. 5.1, involves an additional rotation about the x -axis of the original co-ordinate system. It is here assumed that x points towards the Sun, as in the VSO and GSE co-ordinate systems (unlike R in the RTN system).

Table 5.2 also lists the difference in latitude angle, $\Delta\theta_A$, and longitude angle, $\Delta\varphi_A$, of the flux rope axes between the spacecraft in each alignment. The non-zero values obtained suggest that the flux ropes rotated during propagation. The amount of rotation in the flux rope axis implied by these values varies considerably from event to event: some showed relatively little apparent rotation (*e.g.*, the ICMEs observed by alignments 1, 6 and 19) whilst others rotated quite significantly (*e.g.*, the ICMEs observed by alignments 2, 5, 14 and 17).

In the latter case, some of the large apparent rotations may be due to systematic error. Variance directions in a dataset are not always clearly defined and so there may be ambiguity between two or more of the variance directions (such a situation can arise when the eigenvalue ratios, λ_1/λ_2 and λ_3/λ_2 , approach unity; see Sect 4.2.1 for further details). At the outer spacecraft in alignments 2 and 14, visual examination of the flux rope data suggests that the axis directions would lie closer to the minimum (rather than intermediate) variance directions obtained from the MVA. At the inner spacecraft in alignment 17, a data gap sits near the centre of the rope (approximately where $\theta_B \sim 0^\circ$), which may be skewing the estimated θ_A value. Closer inspection of the flux rope data at both spacecraft in alignment 5 suggests the presence of complex, non-flux rope rotations which may not be suited to MVA; coupled with a large gap in the rope data at the inner spacecraft, the large $\Delta\theta_A$ and $\Delta\varphi_A$ values are likely to be inaccurate. Alignments 2, 5, 14 and 17 have been starred in Table 5.2 to indicate the questionable validity of the MVA in these cases.

Across all events listed in Table 5.2, the mean values of $\Delta\theta_A$ and $\Delta\varphi_A$ were $-8 \pm 11^\circ$ and $1 \pm 16^\circ$, respectively; for the better (*i.e.*, un-starred) MVA fits, these values were $-8 \pm 10^\circ$ and $10 \pm 10^\circ$, respectively. The fact that these values are close to zero suggests that, on average, there was no preferential direction to the rotation; θ_A and φ_A were equally likely to increase or decrease during propagation, in approximate terms. The uncertainty quoted for each value (as for all similar average values presented in this chapter) is the standard error of the mean. The absolute separation angle between the

axes, ψ , is also listed in Table 5.2 for each pair; the mean value of ψ was $50 \pm 9^\circ$ across all events, and $35 \pm 7^\circ$ for the better fits. The significance of these values is discussed in Sect. 5.5.

5.3. DIMENSIONLESS EXPANSION RATE

Gulisano *et al.* (2010) define a dimensionless expansion rate, ζ , for magnetic cloud flux ropes,

$$\zeta = \Delta v \, r / \Delta t \, v_C^2 \quad (5.3)$$

where Δv is the linearly extrapolated difference in speed between the leading and trailing edges of the flux rope, r is the heliocentric distance of the rope, Δt is the time taken for the rope to pass over the observing spacecraft, and v_C is the speed at the mid-point of the rope. Gulisano *et al.* postulate that ζ is a constant for all magnetic clouds not significantly perturbed by solar wind interactions, and which are thus able to expand freely in the solar wind. The constancy of ζ arises from the theory that ICME expansion is primarily driven by the drop in the ambient solar wind pressure with heliocentric distance (Démoulin and Dasso, 2009); since this pressure drop is uniform, the expansion of ICMEs should be similarly uniform.

Assuming that ICME expansion is driven by the solar wind pressure drop, the radial width of an ICME, S , may be expressed as

$$S = S_0 (r / r_0)^m \quad (5.4)$$

where the ICME has width S_0 at heliocentric distance r_0 , and m is a constant; the ICME size is simply a function of heliocentric distance. Following the derivation presented by Gulisano *et al.*, Δv for an unperturbed ICME is given by

$$\Delta v \sim \frac{dS}{dt} = \frac{dS}{dr} \frac{dr}{dt} = m \frac{S}{r} v_C \quad (5.5)$$

Thus, $m \sim \zeta$ for unperturbed ICMEs.

Alignment #	s/c 2	$v_{L,2}$ kms ⁻¹	$v_{C,2}$ kms ⁻¹	$v_{T,2}$ kms ⁻¹	Δv_2 kms ⁻¹	R^2	Linear proportion	ζ
2*	STB	369	328	286	83	0.75	0.79	1.95
3*	STB	338	315	291	47	0.49	0.66	1.46
7	STB	607	468	329	279	0.96	0.76	1.34
10	STB	356	337	318	39	0.87	1.00	1.09
12	STA	332	302	272	59	0.89	0.71	0.85
13	STA	498	472	447	51	0.77	1.00	0.85
14	STA	689	550	412	277	0.83	1.00	0.86
15	STA	540	493	446	94	0.74	1.00	0.44
17*	ACE	547	393	238	309	0.95	0.42	6.22
19	STA	487	444	398	90	0.69	0.70	0.59

Table 5.3a. Directly calculated ζ values at the outer spacecraft. Starred alignments indicate that the estimated ζ values are questionable.

Alignment #	s/c 1	Mean speed, s/c 1 $\rightarrow$ s/c 2		<i>in situ</i> speed at s/c 1, extrapolated				$\zeta_{v=\text{const}}$	$\zeta_{v\text{extrap}}$	$\zeta_{v=\text{const}} / \zeta$	$\zeta_{v\text{extrap}} / \zeta$
		$\langle v_L \rangle$, kms ⁻¹	$\langle v_T \rangle$, kms ⁻¹	$v_{L,1}$ kms ⁻¹	$v_{T,1}$ kms ⁻¹	$v_{C,1}$ kms ⁻¹	Δv_1 kms ⁻¹				
2*	MES	325	302	281	317	299	-36	1.07	-0.56	0.5	-0.3
3*	MES	338	335	337	379	358	-42	0.78	-0.54	0.5	-0.4
7	MES	582	370	556	411	483	145	1.42	0.69	1.1	0.5
10	VEX	347	304	338	290	314	48	1.24	1.77	1.1	1.6
12	VEX	262	202	192	133	163	60	1.00	3.44	1.2	4.0
13	VEX	513	429	529	410	470	118	0.98	2.32	1.2	2.7
14	VEX	710	311	731	210	470	521	1.11	2.86	1.3	3.3
15	VEX	578	323	615	201	408	414	0.54	3.45	1.2	7.8
17*	VEX	451	441	354	644	499	-290	4.65	-2.70	0.7	-0.4
19	VEX	508	455	528	512	520	16	0.48	0.06	0.8	0.1

Table 5.3b. Estimated ζ values at the inner spacecraft.

5.3.1. Direct estimation at the outer spacecraft

Table 5.3a lists ζ values for a number of the ICMEs observed by the spacecraft pairs listed in Table 5.1. Since ζ is a function of Δv and v_C , it could only be directly calculated at spacecraft where *in situ* plasma velocity data were available, *i.e.*, at the 1 AU spacecraft. Δv and v_C in each case were estimated by fitting a straight line to the linear bulk plasma speed profile within the flux rope boundaries. The speeds at the leading and trailing edges of the rope (v_L and v_T , respectively; $\Delta v = v_L - v_T$), and at the rope mid-point (v_C) were taken from the linear fits. For events where the speed profiles were not linear at the leading or trailing edges, the fits to the linear regions of data were extended to the rope edges, and the extrapolated edge speeds were used to calculate Δv . An example linear fit is shown in Fig. 5.2. Any non-linear behaviour in the speed at the rope edges was likely due to interactions with the solar wind; an ICME is only described as ‘perturbed’ (following the Gulisano *et al.* definition) if less than $\sim 75\%$ of the speed profile is linear. Table 5.3a gives the proportion of the flux rope speed data that was linear for each event.

In a similar fashion to the flux rope orientation analysis, events in Table 5.3a have been starred where the ζ value is questionable. For instance, the ICME observed by STB in alignment 3 had only a weakly linear speed profile, with an R^2 value of 0.49; as a further example, the event observed by ACE in alignment 17 was heavily perturbed, with only 42% of its rope speed profile being linear. The high ζ value in this latter case cannot be directly compared to the values for the other ICMEs, which are unperturbed (or only weakly so) and expand freely.

The mean value of ζ for the un-starred events in Table 5.3a is 0.86 ± 0.11 , comparable to the value of 0.91 ± 0.23 found by Gulisano *et al.* in their study of *Helios* magnetic clouds. It is also compatible with results obtained by Liu *et al.* (2005) and Bothmer and Schwenn (1998), who found m values of 0.92 ± 0.07 and 0.78 ± 0.12 , respectively, from their direct measurements of ICME radial widths.

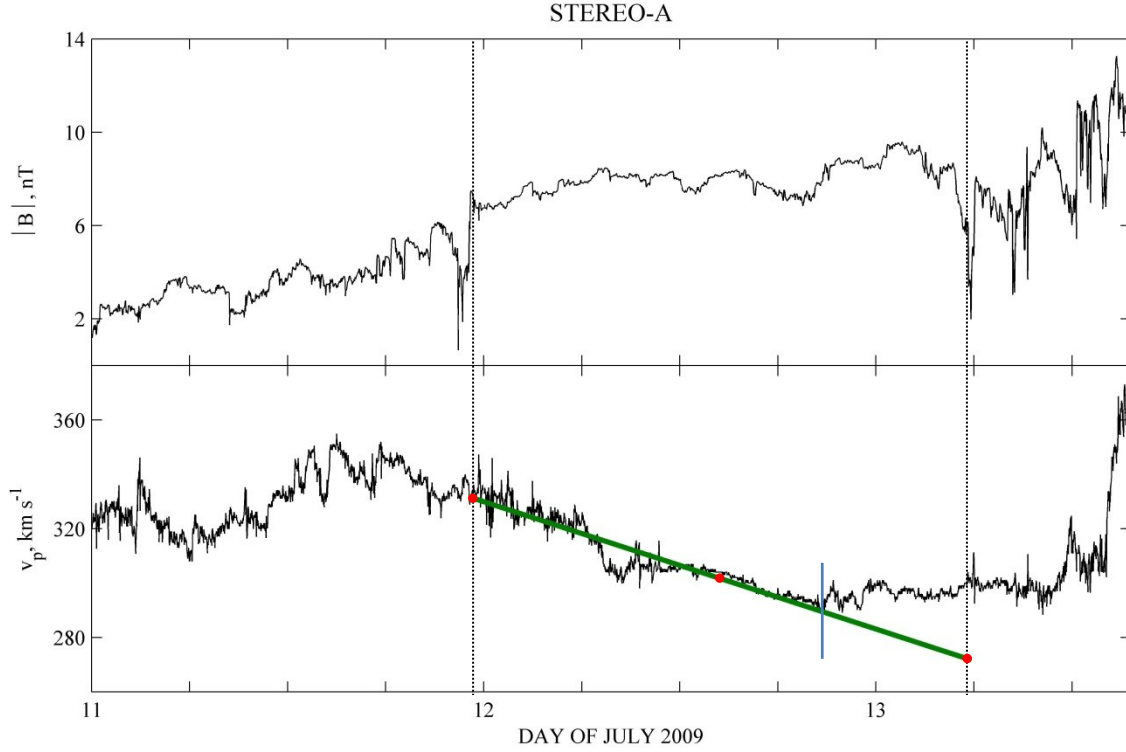


Figure 5.2. A linear fit (*green line*) to the speed data from the outer spacecraft (STA) of alignment 12. The flux rope boundaries are shown by the vertical dashed lines. The fit has been made to the linear speed data within the flux rope, *i.e.*, the data between the rope’s leading edge and the blue vertical line in the second panel; the fit has been extrapolated back to the rope’s trailing edge. The R^2 value of the fit is 0.89. Red dots show the points on the linear fit at which values of v_L , v_C and v_T were taken. This linear fitting technique was developed by Gulisano *et al.* (2010).

5.3.2. Extrapolation at the inner spacecraft

The values of ζ listed in Table 5.3a were directly calculated at the outer spacecraft in each of the alignments studied. Given the lack of plasma data, similar direct calculations of ζ were not possible at the inner spacecraft (MES or VEX). However, it is possible to estimate ζ values by making assumptions about the *in situ* speed of the ICMEs at the inner spacecraft. As far as the author is aware, only Nakwacki *et al.*

(2011) have previously estimated ζ values of the same ICME at different stages in its propagation.

For each of the alignments where ζ was calculated directly at the outer spacecraft, two different approaches have been taken to extrapolate ζ values at the inner spacecraft:

- (i) The speed profiles of the ICMEs were assumed to be constant, such that the v_C and Δv values measured *in situ* at the outer spacecraft were the same at the inner spacecraft. Δt and r were directly obtained at the inner spacecraft. The resulting expansion rate values, $\zeta_{v=\text{const}}$, are listed in Table 5.3b;
- (ii) The mean propagation speeds of the leading and trailing edges between the two spacecraft in each pair were estimated, by finding the transit times of the edges. These speeds are listed in Table 5.3b as $\langle v_L \rangle$ and $\langle v_T \rangle$, respectively. By assuming that the propagation speed profiles were linear, the *in situ* speeds of the leading edges at the inner spacecraft were estimated to equal $2\langle v_L \rangle - v_L$, where v_L is the *in situ* speed at the outer spacecraft; the trailing edge speeds at the inner spacecraft were similarly estimated. Thus v_C and Δv at the inner spacecraft were obtained. The resulting expansion rate values, ζ_{vextrap} , are listed in Table 5.3b.

The mean value of $\zeta_{v=\text{const}}$ for the un-starred alignments was equal to 0.97 ± 0.13 , similar to the mean expansion rate value at the outer spacecraft. Considering events individually, $\zeta_{v=\text{const}}$ was marginally higher (~ 10 to 20%) than the corresponding expansion rates at the outer spacecraft for six out of the seven un-starred alignments. Although these small differences are comparable in size to the error of the mean, it is possible that assuming constant speeds gives underestimates of $\Delta v/v_C^2$ at the inner spacecraft.

In contrast, the mean value of ζ_{vextrap} for the un-starred events was equal to 2.08 ± 0.50 , considerably higher than the mean value at the outer spacecraft. The relatively large error comes from the large spread in values found across the event list. Moreover, there is no good match between $\zeta_{v=\text{const}}$ and the expansion rate at the outer spacecraft for

any of the alignments individually: in most cases, the rate values are markedly different at each spacecraft. The approach used to find $\zeta_{v=\text{extrap}}$ appears to break down entirely for the three starred cases, where Δv becomes negative. Such a result is clearly invalid.

5.4. ARRIVAL SPEED VS. TRANSIT SPEED

A simple yet revealing exercise is to compare the mean transit speeds of the ICMEs' leading edges with their instantaneous speeds on arrival at the outer spacecraft. This comparison has been made for the subset of ICMEs listed in Table 5.3b; the transit speed and arrival speed for each ICME are listed in Table 5.4. Note that the actual arrival speeds as measured *in situ* at the outer spacecraft have been used here, rather than the linearly extrapolated leading edge speeds used in Sect 5.3. The arrival speeds, v_2 , versus the transit speeds, $\langle v \rangle$, are plotted in Fig. 5.3. A linear fit to the data is shown by the blue line in Fig. 5.3, while the dotted line shows where $v_2 = \langle v \rangle$. The best fit line does not deviate significantly from the dotted line, suggesting that the ICMEs propagated at approximately constant speeds.

However, it is notable that the best fit line sits slightly above the $v_2 = \langle v \rangle$ line at lower speeds, and beneath it at higher speeds – this suggests that the ICMEs with low transit speeds were accelerating to higher speeds, and ICMEs with high transit speeds were decelerating. The intersection of the two lines in Fig. 5.3 is at around 500 km s^{-1} , the approximate mean speed of the solar wind near the SE plane; ICMEs with transit speeds below this intersection point generally accelerated, while those above it tended to decelerate. It has previously been established that CME-ICME propagation speeds tend towards the ambient solar wind speed by Lindsay *et al.* (1999): in their study, Lindsay *et al.* found a similar break-point speed, where CMEs observed with speeds below 500 km s^{-1} were observed at higher speeds *in situ*, and CMEs with speeds above 500 km s^{-1} were observed at lower speeds *in situ*.

Alignment #	mean transit speed, km s^{-1}	arrival speed at s/c 2, km s^{-1}
2	325	342
3	338	327
7	582	618
10	347	361
12	262	330
13	513	498
14	710	700
15	578	524
17	451	511
19	508	472

Table 5.4. The mean transit speeds of the leading edges of ten ICME flux ropes observed by pairs of radially aligned spacecraft, and the *in situ* leading edge speeds on arrival at the outer spacecraft.

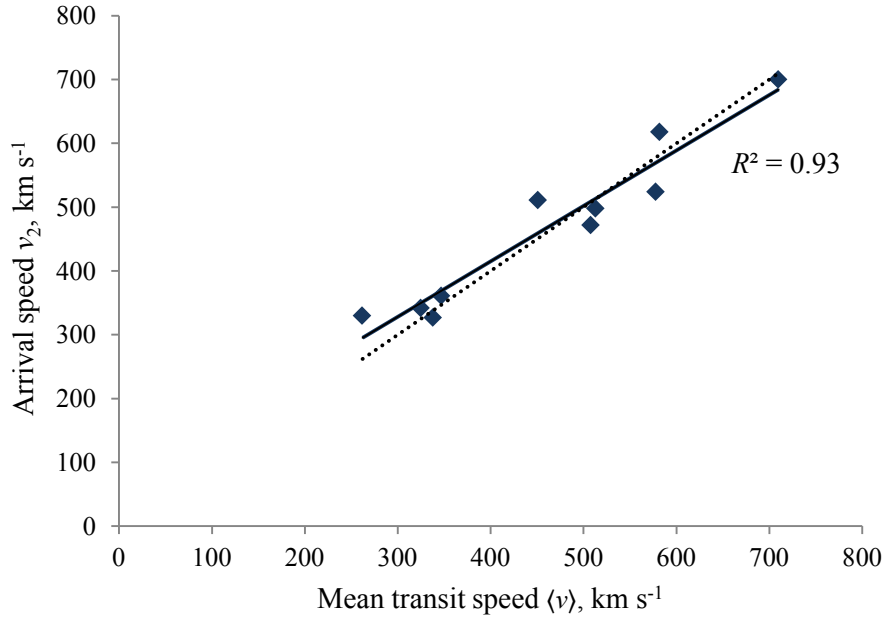


Figure 5.3. A plot of the values presented in Table 5.4. The blue line is a linear best fit to the data, and the dotted line corresponds to $v_2 = \langle v \rangle$.

5.5. DISCUSSION

For the nine ICMEs analysed where there was a good match in magnetic field signatures at the observing spacecraft, and where the MVA gave sensible flux rope orientations that were in agreement with the data, the difference between the axis direction at the inner and outer spacecraft, ψ , had a mean value of $35 \pm 7^\circ$. The mean spacecraft separation distance over which the apparent axis rotations occurred was ~ 0.36 AU; considering the ICMEs individually, there was a weak positive correlation between the rotation magnitude and propagation distance.

In order to determine the accuracy of the rotation estimates, it is important to consider the accuracy of the MVA. The Siscoe and Sweeney (1972) conditions (as defined in Sect. 4.2.1) were met at all of the spacecraft, suggesting that the intermediate variance directions were accurate to $\sim 10^\circ$. However, the Siscoe and Sweeney conditions do not indicate how accurately the intermediate variance direction represents the direction of a flux rope's axis. Gulisano *et al.* (2007) have demonstrated that the accuracy of MVA when determining flux rope axes is dependent on the impact parameter, p ; a p value of 0 indicates that the observing spacecraft intersected the rope axis, and a value of 1 indicates that the spacecraft skimmed the outer surface of the rope. By performing MVA on synthetic flux rope data for a range of p values, Gulisano *et al.* found that the angular deviation between the true and MVA-estimated axis orientation, η , is a quadratic function of p given by

$$\eta = ap^2 + bp + c \quad (5.5)$$

where $a = 17$, $b = 3.2$ and $c = 0.39$. Thus, for example, η has a value of $\sim 2^\circ$ when $p = 0.2$, of $\sim 6^\circ$ when $p = 0.5$, and $\sim 17^\circ$ when $p = 0.9$. One could imagine an extreme scenario where $p = 0.9$ at both of the aligned spacecraft, and the η -errors at each spacecraft acted in exactly opposite directions. Without any rotation in the flux rope axis, the apparent rotation would be $\sim 34^\circ$ (similar to the mean ψ value of 35°).

However, such a scenario is highly unlikely. Even if the η -errors were oppositely directed, p values as high as 0.9 are uncommon. For example, in their study

of 90 magnetic clouds, Lepping and Berdichevsky (2000) found over three quarters of events were observed with $p \leq 0.5$. Lepping and Berdichevsky ascribe this to a selection bias: flux rope encounters at low p are more easily identifiable. (Russell and Mulligan (2002), on the other hand, present evidence that the preponderance of low p observations is due to flattening in the flux rope shape normal to the radial direction.) Moreover, high p -value observations, where the spacecraft makes a more skimming encounter with the flux rope far from the central axis, would show much less field rotation than was observed in the events included in this analysis. If one assumes, for instance, a more typical average p value of 0.5 for the analysed events, the maximum possible η error associated with the ψ values listed in Table 5.2 would be $\sim 12^\circ$. In almost all cases ψ exceeded this value, leaving the distinct possibility that there was a large component to the calculated axis rotations with a physical origin. In order to better quantify the η errors, Lundquist fitting could be used to estimate the p values for each set of observations.

The analysis could be further extended by considering the ICMEs and their apparent rotations in more detail on an individual basis. Some ICMEs showed large apparent rotations (*e.g.*, the event observed by alignment 12, where $\psi = 66^\circ$) whilst others showed little rotation (*e.g.*, the event observed by alignment 19, where $\psi = 7^\circ$) that could be entirely due to errors in the MVA. The amount of rotation could be linked to the ambient solar wind conditions and the configuration of the local interplanetary magnetic field. For example, nearby fast or slow solar wind streams may have interacted with the propagating ICMEs to drive the flux rope rotations. Such an analysis would be difficult to perform with in situ data alone, however – remote observations of the solar wind (*e.g.*, from STEREO’s *Heliospheric Imager*) and the solar surface, and modelling input (*e.g.*, from *Enlil*), could help to give a more complete picture of the environment in which the ICMEs propagated.

The dimensionless expansion factor, ζ , was also estimated for a number of the ICMEs studied. These ICMEs were largely unperturbed by solar wind interactions. The mean of the ζ values directly calculated at the outer spacecraft for the better observed events was 0.86 ± 0.11 , comparable to the results of others. It indicates that,

on average, the radial widths of ICMEs expand almost linearly with propagation distance from the Sun.

Gulisano *et al.* (2010) suggest that ζ has approximately the same value for all unperturbed ICMEs. If this is correct, then individual ICMEs should hold the same ζ value throughout their propagation in interplanetary space. By assuming that the ICMEs propagated at constant speeds, and that the ICMEs maintained a constant speed difference between their leading and trailing edges, ζ values were estimated at the inner observing spacecraft: the resulting mean value of 0.97 ± 0.13 is similar to that obtained at the outer spacecraft, and supports Gulisano *et al.*'s findings. It is notable that the differences in the ζ values for individual events are smaller than the spread in values found across different events.

It is not clear why the second approach taken to estimate ζ at the inner spacecraft, where variable *in situ* speed profiles at the inner spacecraft were linearly extrapolated, appears to fail so comprehensively. It may be the case that the propagation speed profiles are not linear. It may also be incorrect to assume that the spacecraft in each pair sampled exactly the same edges of the flux ropes – there may have been some non-radial component to the propagation, or some non-negligible longitudinal variations in the flux rope structure over small angles. Global rotation of the flux ropes, as suggested by the previous analysis, could also lead to the spacecraft sampling different regions of the ICMEs. If any of these factors were significant, the second approach used to extrapolate ζ would be invalid.

In Sect. 5.4, the mean leading edge transit speeds of ten of the ICME flux ropes were compared to their instantaneous speeds on arrival at the outer spacecraft. As shown in Fig. 5.3, the transit and arrival speeds were similar for most of the ICMEs, suggesting that the ICMEs propagated with approximately constant speeds. However, there is some limited evidence of acceleration by ICMEs with transit speeds below $\sim 500 \text{ km s}^{-1}$, and deceleration of ICMEs with transit speeds above $\sim 500 \text{ km s}^{-1}$. This would support the findings of Lindsay *et al.* (1999), who found that CMEs with speeds (estimated through the analysis of coronagraph images) below 500 km s^{-1} had ICME counterparts with higher speeds (directly observed *in situ*), while CMEs with speeds above 500 km s^{-1} had ICME counterparts at lower speeds.

6 | Conclusion

An examination of the structure and evolution of interplanetary coronal mass ejections observed by MESSENGER and *Venus Express* has been presented in this thesis. Despite their primary role as planetary missions, both MES and VEX spent significant amounts of time in the solar wind where they observed a large number of ICMEs. The two spacecraft have provided the only *in situ* observations of ICMEs at sub-1 AU heliocentric distances from the last decade. Although the datasets from MES and VEX are not ideal for heliospheric studies – routinely available solar wind plasma data is lacking, and there are regular gaps in the interplanetary magnetic field data where the spacecraft were close to or within the magnetospheres of the planets they orbited – the analysis of these datasets has proved to be a fruitful exercise.

The flux rope configurations of the catalogued ICMEs show a clear ordering: ropes at low inclinations to the SE plane were around four times more common than highly inclined ropes, and ropes with northward leading edges were around four times more common than ropes with southward leading edges. The latter finding is likely to be an imprint of the dominant dipolar component (south to north) of the solar magnetic field during the ascending phase of Cycle 24, when the ICMEs were observed. This result is in agreement with studies of ICME flux ropes observed at sub-1 AU heliocentric distances during previous cycles.

Multi-point *in situ* analysis has been used to determine the probability that two spacecraft near the SE plane will both observe the flux rope of the same ICME as a function of the spacecraft's angular separation. For separations of 15° or less, both spacecraft observed flux rope signatures in 82% of cases; for much wider separations of between 45° and 60° , this probability fell to 12%. Above separations of 75° , the second

spacecraft had a negligible probability of observing the flux rope. It was also found that the likelihood of a second spacecraft only observing an ICME's sheath and not its flux rope increased with spacecraft separation. The findings suggest a maximum flux rope extent in the SE plane of $\sim 75^\circ$, and suggest that ICME sheath regions have greater longitudinal extents in the SE plane than the flux ropes that produce them. The relatively large number of spacecraft used in this analysis (MES, VEX, ACE and the two STEREOs), in addition to the relatively large number of ICMEs considered, has allowed multi-point observation probabilities to be estimated more precisely than in any previous studies.

A worthwhile extension to this analysis would be to determine the distribution of ICME longitudinal widths compatible with the distribution shown in Fig. 3.8. One could imagine using a simple Monte Carlo-type simulation of ICMEs with varying width and random propagation direction, where a record of the ICME 'hit rate' at two or more locations is used to build up a synthetic distribution comparable to Fig. 3.8. The ICME width distribution that best replicates Fig. 3.8 could thus be found. It would be interesting to compare this *in situ*-derived distribution to the well-established latitudinal distribution of CME widths observed in coronagraph images. Other possible applications of the multi-point analysis are suggested in Sect. 3.4.

Perhaps the greatest value to be obtained from the MES and VEX datasets is found in using them alongside other *in situ* datasets as in the analysis described above, and alongside the wide range of other contemporaneous heliospheric datasets available. The *Heliospheric Cataloguing, Analysis and Techniques Service* (HELcats) project, a collaboration between a number of European institutions that seeks to standardise and co-ordinate the unprecedented wealth of heliospheric observations gathered during the STEREO era, has fully incorporated the ICME catalogue presented in this work into its own products. Inclusion in the HELcats project will hopefully lead to the wider dissemination and use of the catalogue.

A detailed multi-point analysis of a particularly pristine magnetic cloud was presented in Chapter 4. The magnetic cloud was observed by MESSENGER and STEREO-B during a fortuitous radial alignment of the spacecraft in November 2011. Observation by radially aligned spacecraft allows sampling of approximately the same

region of an ICME or cloud at different stages in its propagation, and allows any evolution in that region to be discerned. Few such observations have been reported previously, or studied in as much depth. Much of our current understanding of how ICMEs' *in situ* characteristics evolve during propagation has been inferred from the statistical properties of different ICME populations observed at different heliocentric distances. Tracking the evolution of individual ICMEs deepens that understanding.

The cloud's flux rope was fitted with the constant- α , force-free Lundquist model. The fitting indicated that the flux rope's diameter increased with an $r_H^{0.94}$ dependence on heliocentric distance, r_H , and that the axial magnetic field strength dropped with an $r_H^{-1.84}$ dependence. Both findings represent direct evidence of an individual magnetic cloud's expansion. The axial magnetic flux, estimated from parameters derived from the fitting, was found to be conserved: this suggests that the cloud underwent little erosion through magnetic reconnection during its propagation from 0.44 to 1.09 AU. By assuming that the magnetic helicity of the flux rope was also conserved, it has been found that the length of the rope cylinder increased, and that the heliocentric angle spanned by that length did not change appreciably. The length-to-width ratio of the flux rope was approximately constant ($5.5 \pm 1.9 \text{ nT}^{-2} \text{ AU}^{-4} H_M$ at MES, and $5.2 \pm 2.4 \text{ nT}^{-2} \text{ AU}^{-4} H_M$ at STB) and it has been shown in Eq. 4.10 how this finding is a natural consequence of axial flux and helicity conservation.

The orientation of the flux rope axis was also determined from the force-free fitting, and appeared to change by $\sim 30^\circ$ in latitude between the two spacecraft. It has been suggested (*e.g.*, Yurchyshyn, 2008; Isavnin *et al.*, 2014) that ICME flux ropes can rotate towards alignment with the local orientation of the HCS. A preliminary study of a larger number of multi-point, radially-observed ICME flux ropes presented in Chapter 5 indicated a similar mean rotation in the events analysed, where MVA was used to determine the flux rope axis orientations. Error analysis suggests that the apparent rotations observed in the ICMEs cannot be accounted for by systematic errors in the MVA associated with large impact parameters, leaving the possibility that some of the rotations were due, at least in part, to physical rotations of the flux rope axes.

Any rotation by ICMEs during their passage through interplanetary space would have implications for space weather forecasting. It is conceivable that a future space

weather mission would involve placing an *in situ* monitor well upstream of the Earth (*i.e.*, much closer to the Sun than the L1 point), in order to give advanced warning of potentially geoeffective solar transients (*e.g.*, Eastwood *et al.*, 2015). Observations of the B -field strength, southward field component and speed of an Earth-directed ICME at this monitoring station could be used to forecast the ICME's geoeffectiveness on arrival at the Earth. Such a forecast would need to account for any radial expansion, field strength decrease, deceleration and solar wind interaction by the ICME during its transit between the monitor and Earth. Rotation, if it is indeed a significant phenomenon, would also need to be considered since it would change the arrival time and magnitude of any geoeffective southward field.

The dimensionless ICME expansion rate, ζ , was also determined for a number of the ICMEs listed in Chapter 5. By assuming that the propagation speed and speed difference between the leading and trailing edges of the flux rope were constant, it was found that the value of ζ was approximately constant for individual ICMEs at different stages in the propagation, and also approximately the same for different ICMEs. This supports the findings of Gulisano *et al.* (2010), who postulated that ζ is a constant for all expanding ICME flux ropes not significantly perturbed by solar wind interactions.

The apparent radial constancy of ζ could be a useful finding for space weather forecasting. Knowledge of an (unperturbed) ICME's ζ value, along with an estimate of its radial width at a monitoring point upstream of the Earth, would allow the ICME's width at 1 AU to be predicted (via Eq. 5.4, where $m \sim \zeta$). A forecast of the radial width would allow the duration of any geomagnetic activity to be estimated more accurately.

A comparison between the arrival speeds and mean transit speeds of ten of the ICMEs observed by radially aligned spacecraft is also included in Chapter 5. To the best of the author's knowledge, an analysis such as this, involving radially aligned spacecraft pairs, has not previously been performed. The arrival and transit speeds were comparable for most of the events studied, suggesting that ICMEs at sub-1 AU heliocentric distances propagate through interplanetary space at approximately constant speeds. However, there was some indication that ICMEs with mean transit speeds below 500 km s^{-1} weakly accelerated while ICMEs with mean transit speeds above 500 km s^{-1} weakly decelerated. It may be the case that the ICME speeds were moving

towards the ambient solar wind speed, which has an average value of $\sim 500 \text{ km s}^{-1}$ near the SE plane. A similar result was found by Lindsay *et al.* (1999), who compared the speeds of CMEs with their ICME counterparts. Observations of a larger number of events would be required to confirm this finding.

The work presented in Chapters 4 and 5 could be extended in a number of ways. The more detailed analysis applied to the November 2011 cloud could similarly be applied to some of the ICMEs identified in Chapter 5, in order to determine whether the characteristics of the November 2011 cloud are typical or not. The significance of magnetic reconnection could also be considered in greater depth. High resolution magnetic field and plasma data, available at the 1 AU spacecraft, could be examined for reconnection signatures at the leading and trailing edges of the flux ropes. In a substantial statistical study, Ruffenach *et al.* (2015) found that 30% of selected magnetic cloud boundaries observed at 1 AU displayed reconnection signatures; it would be worthwhile to determine whether a similar proportion of the flux rope boundaries identified in Chapter 5 showed such signatures. It would also be worthwhile to determine whether there is any correlation between the presence of reconnection signatures at 1 AU and a drop in the estimated axial flux between the inner and outer spacecraft. If flux rope erosion via reconnection during interplanetary transit is indeed a significant phenomenon (contrary to the November 2011 example), then it would have implications for space weather forecasting in a similar fashion to any flux rope rotations: reconnection would lead to an unwinding of the rope that could alter its structure considerably.

Further study of ICMEs observed by radially aligned spacecraft will also be good preparation for the upcoming *Solar Probe Plus* (Fox *et al.*, 2015) and *Solar Orbiter* (Müller *et al.*, 2013) missions, due to launch in July and October 2018, respectively. This new generation of inner heliospheric spacecraft will provide *in situ* observations of ICMEs and magnetic clouds from closer to the Sun than ever before. Moreover, both spacecraft will have trajectories that bring them into alignment with 1 AU spacecraft on numerous occasions. Hopefully they will encounter some ICMEs at these times.

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