On Modeling ICME Cross-Sections as Static MHD Columns

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Abstract
Solar coronal mass ejections are well-known to expand as they propagate through the heliosphere. Despite this, their cross-sections are usually modeled as static plasma columns within the magnetohydrodynamics (MHD) framework. We test the validity of this approach using in-situ plasma data from 151 magnetic clouds (MCs) observed by the WIND spacecraft and 45 observed by the Helios spacecraft. We find that the most probable cross-section expansion speeds for the WIND events are only \( \approx 0.06 \) times the Alfvén speed inside the MCs, while the most probable cross-section expansion speeds for the Helios events is \( \approx 0.03 \). MC cross-sections can thus be considered to be nearly static over an Alfvén crossing timescale. Using estimates of electrical conductivity arising from Coulomb collisions, we find that the Lundquist number inside MCs is high (\( \approx 10^{13} \)), suggesting that the MHD description is well justified. The Joule heating rates using our conductivity estimates are several orders of magnitude lower than the requirement for plasma heating inside MCs near the Earth. While the (low) heating rates we compute are consistent with the MHD description, the discrepancy with the heating requirement points to possible departures from MHD and the need for a better understanding of plasma heating in MCs.

Keywords Coronal mass ejections · Interplanetary-coronal mass ejections · Theory-magnetohydrodynamics (MHD)

1. Introduction
Coronal Mass Ejections (CMEs) are magnetised plasma structures erupting from the solar corona (Chen, 2011). Some of these CMEs have been sampled in-situ by several space-
craft, yielding detailed information on the CME plasma parameters along the line of intercept of the spacecraft. This has resulted in an extensive database of observations of the interplanetary counterparts of CMEs, which are called ICMEs (Zhang et al., 2007). The cross-sectional structure of ICMEs is typically modeled as a static plasma column, using the framework of magnetohydrodynamics (MHD) – this includes early works such as Lundquist (1951), Burlaga (1988) to works that are based on the Grad-Shafranov equation (Hu and Sonnerup, 2002; Möstl et al., 2009; Isavnin, Kilpua, and Koskinen, 2011) and similar formalisms (Nieves-Chinchilla et al., 2016, 2018a; Cid et al., 2002). This is similar in philosophy to analyzing the equilibrium of plasma columns in laboratory settings, e.g., Boyd and Sanderson (2003).

It is well known that ICMEs expand as they travel through the heliosphere, suggesting that they are dynamic, expanding structures (see, e.g., Bothmer and Schwenn, 1998; Vandas, Geranios, and Romashets, 2009; Gulisano et al., 2010). However, as mentioned above, ICME cross-sections seem to be quite well described as static plasma columns. It is therefore worth examining how the apparent success of such static models can be reconciled with the observation of expanding ICME cross-sections. This paper concentrates on the following broad areas:

1. Although ICME cross-sections are observed to expand, how do the expansion speeds compare with typical signal propagation speeds (such as the Alfvén speed) inside the plasma? If the expansion speeds are slow, the concept of a static column would be justified.
2. We check if the electrical conductivity of the medium is large (it is technically infinite in ideal MHD), which means that the magnetic diffusivity is very small. This is the basis for the well-known frozen-in condition for magnetic fields in MHD. The Lundquist number, which is the ratio of the magnetic diffusion timescale to the Alfvén crossing timescale, is a standard measure to quantify the goodness of the frozen-field assumption. The larger the Lundquist number, the better the validity of the MHD description.
3. An infinitely conducting plasma would be non-dissipative, in disagreement with expectations of plasma heating inside ICMEs. Having computed the electrical conductivity for item 2, we use an approximate estimate of the current density to calculate the Joule heating rate and compare it with inferred MC plasma heating rates.

The data we have used are explained in Section 2. From here on, we will restrict our attention only to the magnetic clouds (MCs) within the overall ICME structure. MCs are the magnetically well structured parts of ICMEs and their boundaries and expansion speeds are typically better defined. We compare the observed MC expansion speeds with Alfvén speed in Section 3. We evaluate the collisional conductivity and use it to evaluate the Lundquist numbers for MCs in Section 4. The conductivity is used to compute Joule heating rates in Section 5. Our overall conclusions on the applicability of the MHD paradigm to MCs and the caveats are presented in Section 6.

2. Data

We use in-situ data from three different spacecraft (WIND, Helios 1 and Helios 2) for our current study. The WIND ICME catalogue (wind.nasa.gov/ICMEindex.php) provides a sample of well-observed Earth-directed ICMEs as observed by the WIND spacecraft (Nieves-Chinchilla et al., 2018b, 2019) near the Earth. The magnetic clouds (MCs) associated with these ICMEs are classified into different categories depending upon how well the observed
plasma parameters fit the expectations of a static flux rope configuration. Of all the ICMEs observed between the years 1995 and 2015 listed on the WIND website, we first shortlist those that are categorized as F+ and Fr events. These events best fit the expectations of the flux rope model (Nieves-Chinchilla et al., 2016, 2018b). Fr events indicate MCs with a single magnetic field rotation between 90° and 180° and F+ events indicate MCs with a single magnetic field rotation greater than 180°. We further shortlist events that are neither preceded nor followed by other ICMEs or ejecta two days before and after the event under consideration, so as to exclude interacting CMEs. Our final shortlist comprises 151 ICMEs from the WIND catalogue.

We also use in-situ data from the 45 well observed MCs from Helios observations short-listed by Bothmer and Schwenn (1998). These 45 events, observed between December 1974 and July 1981, provide us with an opportunity to analyze ICMEs at heliocentric distances ranging from 0.3 AU to 1 AU. This composite dataset helps us to analyze the behavior of well observed MCs over a wide range of heliospheric distances. The shortlisted events from the WIND spacecraft are listed in Table A.1 while those from the Helios 1 and 2 spacecraft are listed in Table A.2.

3. How Good Is the Static Assumption for ICMEs?

ICME cross-sections are modeled as static plasma columns. However, it is clearly evident from observations that they expand as they propagate.

Our findings show how and why the static assumption is justified. The momentum equation for ideal MHD is given by

\[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla P + \frac{1}{4\pi \rho} (\nabla \times \mathbf{B}) \times \mathbf{B} + \frac{\mathbf{F}}{\rho},
\]

(1)

Here \(\mathbf{v}\), \(P\), and \(\rho\) are the bulk plasma velocity, pressure, and mass density, respectively. The second term on the right hand side (RHS) of Equation 1 represents the Lorentz self-force \((1/c) \mathbf{j} \times \mathbf{B}\), with \(\mathbf{j} \equiv (c/4\pi)(\nabla \times \mathbf{B})\) the current density. The last term on the RHS involving \(\mathbf{F}\) represents external forces such as gravity. If the system is in magnetohydrostatic equilibrium, the plasma velocity \(\mathbf{v} = 0\) (see, e.g., Section 14.3 in Choudhuri et al., 1998; Section 4.3 in Boyd and Sanderson, 2003). The gravitational attraction due to the Sun becomes negligible beyond a few solar radii above the photosphere, and \(\mathbf{F}\) can therefore be ignored (see Section 2 in Cargill, 2004). Equation 1 for magnetohydrostatic equilibrium therefore reduces to (Nieves-Chinchilla et al., 2016)

\[
\frac{1}{4\pi \rho} (\nabla \times \mathbf{B}) \times \mathbf{B} = \frac{1}{\rho} \nabla P.
\]

(2)

We note that Equation 2 can be obtained from Equation 1 if the plasma velocity \(\mathbf{v} = 0\) and/or if the material derivative of the plasma velocity \(D\mathbf{v}/Dt = \partial \mathbf{v}/\partial t + (\mathbf{v} \cdot \nabla) \mathbf{v} = 0\). In our context, magnetohydrostatic equilibrium refers to the first assumption \(\mathbf{v} = 0\). Equation 2 depicts the balance between the Lorentz force and the force due to the pressure gradient in the plasma. Early models (Burlaga, 1988; Lepping, Jones, and Burlaga, 1990) assumed that the flux rope is force-free (i.e., \(\mathbf{j} \times \mathbf{B} = 0\)), in which case the RHS of Equation 2 would be zero. Some later models, e.g., Möstl et al. (2009), Scolini et al. (2019), Nieves-Chinchilla et al. (2016) relax this force-free condition and assume the term \(\nabla P\) in the RHS of Equation 2 to be non-zero.
Figure 1  Examples of the linear fit of the solar wind speed ($v_{sw}$) profile inside the MC. Panels a and b describe event 53 of Table A.1 (WIND observations) and event 8 of Table A.2 (Helios observations), respectively. The red lines in the plots denote the linear fit. $v_s$ and $v_e$ are the speeds at the MC start ($t_s$; blue dotted line) and at the MC end ($t_e$; black dotted line), respectively as obtained from the linear fit. We compute the MC expansion speeds (Equation 3) using $v_s$ and $v_e$.

Figure 2  Histograms of $R_A$, the ratio of the MC expansion speed to the Alfvén speed (Equation 4), for the events listed in Tables A.1 (panel a) and A.2 (panel b).

For each of the ICMEs listed in Tables A.1 and A.2, we compute the expansion speed of the MC cross-section using (Nieves-Chinchilla et al., 2018b)

$$v_{exp} = \frac{1}{2} (v_s - v_e),$$

where $v_s$ and $v_e$ are the speeds at the start and at the end of the MC boundary, as obtained from a linear fit of the temporal profile of the solar wind speed (see Figure 1). The expansion speed we determine is only for the MC part of the overall ICME. This is primarily because only MC boundaries are well determined for the Helios events; we retain the same scheme for the WIND events for consistency. However, the expansion speed needs not be strictly zero for the static assumption (Equation 2) to be valid. If $|v_{exp}|$ is small in comparison with characteristic speeds, such as the Alfvén speed, the static approximation can be considered to be valid. The WIND ICME website (wind.nasa.gov/ICMEindex.php) provides a thorough time profile of the Alfvén speed $v_A$, using which we compute the following ratio:

$$R_A = \frac{|v_{exp}|}{(v_A)} ,$$

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where \( \langle v_A \rangle \) is the average Alfvén speed inside the MC. Our findings for \( R_A \) (Equation 4) for the WIND ICMEs (Table A.1) and the Helios ICMEs (Table A.2) are shown in Figure 2. The mean, median, and mode for \( R_A \) from the WIND events (panel a, Figure 2) are 0.29, 0.24, and 0.06, respectively. The mean, median, and mode of \( R_A \) for the Helios events (panel b, Figure 2) are 0.28, 0.25, and 0.03, respectively. With reference to point 1 in Section 1, we thus find that the expansion speeds of the magnetic clouds are far smaller than the Alfvén speeds inside them. In other words, MC boundaries are static (to a fairly good extent) over an Alfvén crossing timescale.

4. On MH in the MHD Description

The “magnetohydro” aspect of the MHD equations mandates that the medium is an infinitely conducting fluid. In turn, it implies that the magnetic diffusivity \( \to 0 \), which means that the magnetic field is frozen into the plasma. The Lundquist number, the ratio of the magnetic diffusion timescale to the Alfvén crossing timescale, is a measure of the goodness of this assumption. For an infinitely conducting plasma, the Lundquist number \( \to \infty \). In the following, we assess how well the MC plasma conforms to this expectation. In order to evaluate the Lundquist number in our situation, we need to know the conductivity of the MC plasma. The collisional timescales can be used to estimate the electrical conductivity. In evaluating the electrical conductivity, we restrict ourselves to Coulomb collisions and do not consider any anomalous effects such as scattering due to wave-particle interactions. The timescale for electrons to relax to a Maxwellian distribution following a small perturbation is given by (Huba, 2013)

\[
t_{ee} \approx 4 \times 10^4 \frac{T_e^{3/2}}{n \ln(\Lambda)}
\]

where \( T_e \) is the electron temperature in units of \( 10^4 \) K, \( n \) is the electron number density (assumed to be equal to the proton number density) in units of \( \text{cm}^{-3} \) and \( \ln(\Lambda) \) is the Coulomb logarithm (taken to be 20 for our study). While Equation 5 gives the electron collisional relaxation timescale in units of second, the proton collisional relaxation timescale would be a factor of \( \sqrt{m_p/m_e} \) larger and the electron-proton collisional thermalization timescale would be a factor of \( m_p/m_e \) larger (Sturrock, 1994). We do not have direct access to electron temperature measurements; the WIND and Helios databases only provide measurements of proton temperature. Some authors (Richardson, Farrugia, and Cane, 1997) suggest that the electron temperature exceeds the proton temperature by a factor \( \gtrsim 2 \) while some others (see, e.g., Osherovich et al., 1993) believe that this factor is in between 7 and 10. Furthermore, the ICME electrons often have a thermal core and non-thermal wings (Nieves-Chinchilla and Viñas, 2008). For the sake of concreteness, we assume that the electron temperature is 10 times the proton temperature. Ohm’s law for a magnetized plasma is generally written as

\[
j = \sigma_0 E_\parallel + \sigma_p E_\perp + \sigma_H (\hat{b} \times E)
\]

where \( j \) is the current density of the plasma, \( \hat{b} \) is the unit vector along \( B \), \( E_\parallel \) and \( E_\perp \) are the components of the electric field (\( E \)) in the directions parallel and perpendicular to the \( B \), respectively. The different electrical conductivities are (Sturrock, 1994):
\[
\sigma_0 = \frac{n e^2 t_{ee}}{m_e} \quad \text{isotropic conductivity,} \tag{7}
\]
\[
\sigma_P = \sigma_0 \frac{t_{ee}^{-2}}{t_{ee}^{-2} + \Omega^2} \quad \text{Pedersen conductivity,} \tag{8}
\]
\[
\sigma_H = \sigma_0 \frac{t_{ee}^{-1} \Omega}{t_{ee}^{-2} + \Omega^2} \quad \text{Hall conductivity,} \tag{9}
\]
where \( e \) is the electron charge in cgs units, \( m_e \) is the electron mass in g, \( t_{ee} \) (Equation 5) is the electron collisional timescale in second and \( \Omega \equiv q |B|/m_ec \) (where \( |B| \) with the magnitude of the magnetic field) is the electron gyrofrequency in Hz. The isotropic conductivity \( \sigma_0 \) is the effective conductivity in an unmagnetized plasma; in a magnetized plasma it denotes the conductivity along the magnetic field. The other two conductivities \( \sigma_P \) and \( \sigma_H \) are the conductivities perpendicular to the magnetic field. The Lundquist number is usually defined only with regard to the magnetic diffusivity arising from the isotropic conductivity \( \sigma_0 \). Accordingly, the isotropic magnetic diffusivity \( \eta_0 \) and the corresponding diffusion timescale are given as:
\[
\eta_0 = \frac{c^2}{4\pi \sigma_0}, \quad \eta_0 = \frac{L_{MC}^2}{\eta_0} \quad \text{(cgs units),} \tag{10}
\]
where \( L_{MC} \) denotes the diameter of the magnetic cloud. For WIND events, we use
\[
L_{MC} = 2 \times R_{cc}, \tag{11}
\]
where \( R_{cc} \) is the MC radius fitted using the circular-cylindrical (cc) flux-rope model (Hidalgo et al., 2002; Nieves-Chinchilla et al., 2016) and is available in the WIND ICME catalogue (wind.nasa.gov/ICMEindex.php). Since we do not have access to a quantity such as \( R_{cc} \) for the 45 Helios events (Table A.2), we define \( L_{MC} \) for these events as
\[
L_{MC} \equiv \int_{t_s}^{t_e} |v_{sw}(t)| \, dt. \tag{12}
\]
The quantity \( v_{sw}(t) \) denotes the solar wind velocity along the spacecraft trajectory, while \( t_s \) and \( t_e \) denote the start and end times of the MC, respectively (Figure 1). By way of checking the reliability of \( L_{MC} \) as defined in Equation 12, we use a ratio
\[
l_f = \frac{\int_{t_s}^{t_e} |v_{sw}(t)| \, dt}{2 \times R_{cc}} \tag{13}
\]
for the 151 WIND events (Figure 3). The mean, median, and mode of the histogram displayed in Figure 3 are 1.22, 1.06, and 1.01, respectively. In other words, \( l_f \approx 1 \) and \( L_{MC} \) as determined using Equation 12 is close to the value obtained by fitting a static flux rope model (Equation 11). This justifies our use of Equation 12 to calculate \( L_{MC} \) for the Helios events (Table A.2).

The Lundquist number is defined as
\[
S_0 = \frac{\langle t_{nl0} \rangle}{t_A}, \tag{14}
\]
where the Alfvén timescale is \( t_A \equiv L_{MC}/v_A \) and \( \langle \rangle \) denotes a temporal average inside the MC. We evaluate the Lundquist number defined in Equation 14 on the set of events listed
Figure 3  Histogram of $l_r$ (Equation 13).

Figure 4 Histograms of the Lundquist number $S_0$ (Equation 14) for the events listed in Table A.1 (panel a) and Table A.2 (panel b).

in Table A.1 (observed by the WIND spacecraft) and Table A.2 (observed by Helios 1 and 2 spacecraft). The mean, median, and mode of $S_0$ for the WIND events (panel a, Figure 4) are $9.8 \times 10^{13}$, $2 \times 10^{13}$, and $9 \times 10^{12}$, respectively. The mean, median, and mode of $S_0$ for the Helios events (panel b, Figure 4) are $3.4 \times 10^{14}$, $1.4 \times 10^{14}$, and $4.3 \times 10^{13}$, respectively. As noted earlier, we have assumed the electron temperature to be 10 times the proton temperature for these calculations. If instead the electron temperature is taken to be equal to the proton temperature, the numbers on the x-axis of Figure 4 would need to be multiplied by 0.03. Consequently, the mean, median and mode would also have to be multiplied by 0.03.

The main result is that the magnetic diffusivity arising out of the isotropic conductivity is small and the corresponding Lundquist number is therefore quite large. By comparison, the Lundquist number for laboratory Tokamak plasmas is $\gtrsim 10^7$ and that for plasmas in a magnetic reconnection experiment is $\lesssim 10^3$ (Ji et al., 1998). Based on this comparison, it is fair to conclude that MC plasmas adhere better (than laboratory plasmas) to the basic assumptions made in MHD. Since the electrons in ICMEs can be non-Maxwellian (Nieves-Chinchilla and Viñas, 2008), we note that transport coefficients such as the conductivity might be somewhat enhanced (Husidic et al., 2021).
5. Joule Heating of MC Plasma

We now turn our attention to the dissipation rate implied by collisional conductivity calculated in Section 4. In order to do this we need an estimate of the current density \( j \). The current density in ideal MHD is given by

\[
j = \frac{c}{4\pi} (\nabla \times \mathbf{B}). \tag{15}\]

In order to calculate \( j \), we would need to know the curl of the magnetic field. We have a time series of the vector magnetic field along the line of intercept for each event in our dataset. We can approximate the \( \nabla \) operator by

\[
\nabla \equiv \hat{x} \frac{\partial}{\partial x} + \hat{y} \frac{\partial}{\partial y} + \hat{z} \frac{\partial}{\partial z} = \hat{x} \frac{1}{v_{sw x}} \frac{\partial}{\partial t} + \hat{y} \frac{1}{v_{sw y}} \frac{\partial}{\partial t} + \hat{z} \frac{1}{v_{sw z}} \frac{\partial}{\partial t}, \tag{16}\]

where \( v_{sw x} \), \( v_{sw y} \), and \( v_{sw z} \) are the \( x \)-, \( y \)-, and \( z \)- components of the solar wind velocity, respectively. The idea employs the usual Taylor hypothesis, whereby we can write \( \partial / \partial x \to v_{sw x}^{-1} \partial / \partial t \) and so on. The temporal derivatives \( (\partial / \partial t) \) are evaluated numerically from the time series data. Since we have access to all components of \( \mathbf{B} \) and all components of \( \nabla \) (Equation 16), we can estimate \( \nabla \times \mathbf{B} \) and consequently the current density \( j \) (Equation 15) at least along the line of spacecraft intercept. The directions \( \hat{x} \), \( \hat{y} \), and \( \hat{z} \) refer to the Cartesian coordinate system used for measuring solar wind velocities and magnetic fields. For the WIND observations, they correspond to the geo-centered solar ecliptic (GSE) coordinate system (wind.nasa.gov/mfi_swe_plot.php), whereas for the Helios events, they correspond to the spacecraft-centered solar ecliptic (SSE) coordinate system (Di Matteo et al., 2019). The noise in the solar wind velocity measurements can introduce errors in our estimate of the current density; in particular, the \( y \)- and \( z \)- components of the solar wind velocity are found to be \( \approx 1.4 \) to \( 1.9 \) times noisier than the \( x \)- component. On the other hand, the magnitude of \( v_{sw x} \) is \( \approx 100 \) times larger than the other two components. Errors can also be introduced via the numerical differentiation process. Notwithstanding these caveats, this method offers a practical and reliable means of estimating the flux rope current, as we show herewith.

An estimate of the average current carried by an MC can be calculated by

\[
\langle I \rangle = \langle j \rangle \times (\pi / 4) L_{MC}^2, \tag{17}\]

where the \( \langle \rangle \) denotes averaging over the MC. The mean, median, and mode of \( \langle I \rangle \) for the WIND events are \( 10^{11} \) A, \( 1.2 \times 10^{10} \) A, and \( 8 \times 10^8 \) A, respectively (panel a of Figure 5), while the mean, median, and mode of \( \langle I \rangle \) for the Helios events are \( 5.8 \times 10^{10} \) A, \( 3 \times 10^9 \) A, and \( 10^9 \) A, respectively (panel b of Figure 5). These numbers compare favorably with the estimate of \( \approx 10^9 \) A for the axial current carried by ICMEs near the Earth (Vršnak et al., 2019). Axial currents for flux rope CMEs closer to the Sun (in the LASCO’s field of view) are somewhat larger; they are of the order of \( 10^{10} \) A (Subramanian and Vourlidas, 2009). Our estimates of the axial current \( \langle I \rangle \) are thus in reasonable agreement with other independent calculations, lending support to our estimates of the current density \( j \) using Equations 15 and 16.
Figure 5 Histograms describing the average current (Equation 17) for the WIND (panel a) and Helios (panel b) events.

Figure 6 Histograms of the average Joule heating rate $D_r$ (Equation 18). Panel a refers to the events listed in Table A.1, while panel b refers to the events listed in Table A.2.

The average rate of energy dissipation per unit mass due to Joule heating inside the MC can be written as

$$D_r = \langle j^2 \rangle / \rho \sigma,$$

(18)

where $\langle \rangle$ denotes averaging inside the MC, $\sigma \equiv \sigma_0 + \sigma_P + \sigma_H$ (Equations 7 to 9) and $\rho = n(m_p + m_e)$ is the mass density, with $m_e$ and $m_p$ the electron mass, and proton mass, respectively, and $n$ the proton number density (assumed to be equal to the electron number density). For a MC composed by perfectly conducting plasma (i.e., $\sigma \rightarrow \infty$), the Joule heating rate would vanish.

However, the collisional conductivities computed in Section 4 suggest a finite Joule heating rate $D_r$ (Equation 18). We have plotted histograms of the Joule heating rate in units of $\text{J kg}^{-1} \text{s}^{-1}$ in Figure 6. We now compare this heating rate with expectations from ICME models. If magnetic clouds expanded adiabatically, their proton temperatures would likely be as low as a few K near the Earth (Chen and Garren, 1993). However, proton temperatures inside MCs are measured to be as high as $10^5$ K. This implies either that MCs remain magnetically connected to the solar corona with a very high thermal conductivity along the field (Chen and Garren, 1993) or that there is substantial plasma heating inside MCs (Kumar
Assuming that there is some kind of heating mechanism operating inside MCs, and using observations of the decrease in MC proton and alpha particle temperatures with heliocentric distance, Liu et al. (2006) estimate that the average required ICME heating rate at 1 AU is about 2550 J kg\(^{-1}\) s\(^{-1}\), of which 900 J kg\(^{-1}\) s\(^{-1}\) is accounted for by protons. By comparison, our estimates of the Joule heating rate inside MCs near the Earth are much smaller. The mean, median, and mode for the Joule heating rate for the WIND events (panel a, Figure 6) are 1.1, 6 × 10\(^{-4}\), and 8 × 10\(^{-6}\) J kg\(^{-1}\) s\(^{-1}\), respectively. The mean, median, and mode for the Joule heating rate for the Helios events (panel b, Figure 6) are 9 × 10\(^{-3}\), 1.3 × 10\(^{-6}\), and 2 × 10\(^{-8}\) J kg\(^{-1}\) s\(^{-1}\), respectively. In both cases, the mean value is biased by a few (∼11\% for WIND measurements and ∼6\% for Helios measurements) events. The inadequacy of Joule heating is the primary reason why turbulent dissipation and anomalous resistivity (which are clearly outside the purview of ideal MHD) are often invoked to account for proton heating (see, e.g., Liu et al., 2006; Verma, 1996).

6. Conclusions and Final Remarks

ICMEs are commonly modeled as static structures, in which the usual assumptions of magnetohydrodynamics are valid, but the plasma bulk velocity is zero (Equation 2). While this approach is widely adopted, we are not aware of a systematic study using a large sample of ICMEs which examines the validity of these assumptions. The early study by Klein and Burlaga (1982) mentions that magnetic cloud expansion speeds are expected to be ∼half the Alf\'ven speed in the ambient plasma, and some other studies (Lugaz et al., 2017, 2020) support this statement. While it seems that the Alf\'ven speed refers to the medium surrounding the ICME in these papers, Richardson and Cane (2010) refer to the Alf\'ven speed inside the ICME and state that “the mean expansion speed is around half the Alf\'ven speed based on the average ICME parameters”. Similarly, Zurbuchen and Richardson (2006) state: “The expansion speed \(v_{\text{exp}}\) is typically around half the Alf\'ven speed in the ICME”. It is also recognized that the ICME expansion speed should be less than the Alf\'ven speed in order for static ICME cross-section models, such as the ones using the Grad-Shafranov reconstruction technique, to be valid (Farrugia et al., 2020). In this paper, we use a sample of 151 ICMEs observed near the Earth by the WIND spacecraft and 45 MCs observed between 0.3 and 1 AU by the Helios spacecraft, to address the following questions (with a focus on the MC structures within the ICMEs):

1. ICMEs are observed to expand as they propagate, and yet their MC cross-sections are commonly modeled as static plasma columns. To what extent can the MC cross-sections be considered static?
2. Models of ICME and MC cross-sections assume the plasma to be a perfectly conducting fluid, which means that the Lundquist number (the ratio of the magnetic field diffusion timescale to the Alf\'ven timescale) should go to infinity. How large are the Lundquist numbers in the MC plasma?
3. How does the Joule heating rate in the ICME plasma compare with the required heating rate (as mandated by the observed proton temperatures), and what does this imply about departures from the ideal MHD assumptions?

The first question is addressed in Section 3, where we find that MC expansion speeds are typically much smaller than Alf\'ven speeds (Figure 2). Although MC expansion speeds only indicate the plasma velocities along the line of intercept by the spacecraft, our findings suggest that the timescales for signals to propagate from one end of the MC cross-section
to the other are much smaller than those over which the cross-section expands, broadly supporting the notion of a static structure. The ratio \( R_A \equiv |v_{\text{exp}}|/\langle v_A \rangle \) (Equation 3) has a mean of 0.29, a median of 0.24, and a mode of 0.06 for the WIND events in our sample, which are all observed at the position of WIND measurement. The mean, median, and mode of \( R_A \) for the Helios events are 0.28, 0.25, and 0.03, respectively. The Helios events are intercepted at various heliocentric distances, ranging from 0.3 to 1 AU. We note that the mean, median, and mode of \( R_A \) in all cases are below the frequently quoted value of 0.5.

The second question approaches the problem from a different perspective – one that is generally adopted in evaluating the suitability of the MHD approach for analyzing equilibrium configurations of plasma columns in laboratory settings. If the Lundquist number is large, it means that the plasma is effectively non-diffusive and the magnetic field is frozen-in; a key assumption of MHD. This question is addressed in Section 4. We use Coulomb collision timescales and the associated electrical conductivity to evaluate the Lundquist numbers and find that they are large (\( \gtrsim 10^{13} \)) (Figure 4). Another way of appreciating the significance of large Lundquist numbers in this situation is as follows (Boyd and Sanderson, 2003): the MHD description technically mandates an infinite magnetic Reynolds number \( (Re_m \equiv VL/\eta) \) where \( V \) is a representative macroscopic plasma velocity, \( L \) is a representative macroscopic length-scale and \( \eta \) is the magnetic diffusivity. However, for a static plasma column, \( V \rightarrow 0 \) and so the magnetic Reynolds number \( (Re_m) \) must also \( \rightarrow 0 \). The only way of legitimizing an MHD description is to show that the magnetic diffusivity is very small; in other words, to show that the diffusion timescale is larger than any other timescale of interest (in this case, the Alfvén timescale). Large Lundquist numbers essentially ensure this.

The answer to the third question follows from Section 5; the large Lundquist numbers imply that resistive dissipation in the ICME plasma should be very small. This is certainly the case, especially in comparison with the plasma heating rate implied by the observed proton temperatures. Taken together, the answers to questions 1 to 3 generally offer strong support for magnetohydrostatic modeling of ICME cross-sections.

However, there are some caveats to this seemingly robust conclusion. The standard MHD description precludes any heating/dissipation at all. We have calculated the Joule dissipation rate in MCs arising out of electron Coulomb collisions and found it to be several orders of magnitude lower than the heating requirements implied by the observed proton temperatures. Assuming efficient electron-proton energy exchange, this argues for additional electron heating that cannot be accounted for by Coulomb collisions. Of course, protons could also be preferentially heated by processes such as turbulent fluctuations. Observations of intense plasma heating in ICMEs at heliocentric distances of a few \( R_\odot \) e.g., (Murphy, Raymond, and Korreck, 2011; Wilson et al., 2022) argue for localized electron heating (unlike the uniform Joule dissipation scenario we consider), perhaps in reconnection sites. The bulk ICME plasma could be heated via thermal conduction from these localized heating sites. Either way, it is clear that the enhanced energy dissipation required in ICMEs is “one significant departure” from the standard MHD description, which merits systematic study for a large sample of ICMEs. The conclusions from such a study could feed into dynamical models of Sun-Earth propagation and consequently on estimates of Earth arrival times.
Appendix A: Data Tables

A.1 Events from the WIND ICME Catalogue

Table A.1 The list of the 151 WIND ICME events we use in this study. The arrival date and time of the ICME at the position of the WIND measurement and the arrival and departure dates & times of the associated magnetic clouds (MCs) are taken from the WIND ICME catalogue (wind.nasa.gov/ICMEindex.php). The 15 events marked with asterisk (*) coincide with the near-Earth counterparts of 15 CMEs listed in Sachdeva et al. (2017).

| CME event number | CME Arrival date and time [UT] (1AU) | MC start date and time [UT] | MC end date and time [UT] | Flux rope type |
|------------------|--------------------------------------|-----------------------------|---------------------------|---------------|
| 1                | 1995 03 04 , 00:36                   | 1995 03 04 , 11:23          | 1995 03 05 , 03:06        | Fr            |
| 2                | 1995 04 03 , 06:43                   | 1995 04 03 , 12:45          | 1995 04 04 , 13:25        | F+            |
| 3                | 2010 06 30 , 09:21                   | 1995 06 30 , 14:23          | 1995 07 02 , 16:47        | Fr            |
| 4                | 1995 08 22 , 12:56                   | 1995 08 22 , 22:19          | 1995 08 23 , 18:43        | Fr            |
| 5                | 1995 09 26 , 15:57                   | 1995 09 27 , 03:36          | 1995 09 27 , 21:21        | Fr            |
| 6                | 1995 10 18 , 10:40                   | 1995 10 18 , 19:11          | 1995 10 20 , 02:23        | Fr            |
| 7                | 1996 02 15 , 15:07                   | 1996 02 15 , 15:07          | 1996 02 16 , 08:59        | F+            |
| 8                | 1996 04 04 , 11:59                   | 1996 04 04 , 11:59          | 1996 04 04 , 21:36        | Fr            |
| 9                | 1996 05 16 , 22:47                   | 1996 05 17 , 01:36          | 1996 05 17 , 11:58        | F+            |
| 10               | 1996 05 27 , 14:45                   | 1996 05 27 , 14:45          | 1996 05 29 , 02:22        | Fr            |
| 11               | 1996 07 01 , 13:05                   | 1996 07 01 , 17:16          | 1996 07 02 , 10:17        | Fr            |
| 12               | 1996 08 07 , 08:23                   | 1996 08 07 , 11:59          | 1996 08 08 , 13:12        | Fr            |
| 13               | 1996 12 24 , 01:26                   | 1996 12 24 , 03:07          | 1996 12 25 , 11:44        | F+            |
| 14               | 1997 01 10 , 00:52                   | 1997 01 10 , 04:47          | 1997 01 11 , 03:36        | F+            |
| 15               | 1997 04 10 , 17:02                   | 1997 04 11 , 05:45          | 1997 04 11 , 19:10        | Fr            |
| 16               | 1997 04 21 , 10:11                   | 1997 04 21 , 11:59          | 1997 04 23 , 07:11        | F+            |
| 17               | 1997 05 15 , 01:15                   | 1997 05 15 , 10:00          | 1997 05 16 , 02:37        | F+            |
| 18               | 1997 05 26 , 09:09                   | 1997 05 26 , 15:35          | 1997 05 28 , 00:00        | Fr            |
| 19               | 1997 06 08 , 15:43                   | 1997 06 09 , 06:18          | 1997 06 09 , 23:01        | Fr            |
| 20               | 1997 06 19 , 00:00                   | 1997 06 19 , 05:31          | 1997 06 20 , 22:29        | Fr            |
| 21               | 1997 07 15 , 03:10                   | 1997 07 15 , 06:48          | 1997 07 16 , 11:16        | F+            |
| 22               | 1997 08 03 , 10:10                   | 1997 08 03 , 13:55          | 1997 08 04 , 02:23        | Fr            |
| 23               | 1997 08 17 , 01:56                   | 1997 08 17 , 06:33          | 1997 08 17 , 20:09        | Fr            |
| 24               | 1997 09 02 , 22:40                   | 1997 09 03 , 08:38          | 1997 09 03 , 20:59        | Fr            |
| 25               | 1997 09 18 , 00:30                   | 1997 09 18 , 04:07          | 1997 09 19 , 23:59        | F+            |
| 26               | 1997 10 01 , 11:45                   | 1997 10 01 , 17:08          | 1997 10 02 , 23:15        | Fr            |
| 27               | 1997 10 10 , 03:08                   | 1997 10 10 , 15:33          | 1997 10 11 , 22:00        | F+            |
| 28               | 1997 11 06 , 22:25                   | 1997 11 07 , 06:00          | 1997 11 08 , 22:46        | F+            |
| 29               | 1997 11 22 , 09:12                   | 1997 11 22 , 17:31          | 1997 11 23 , 18:43        | F+            |
| 30               | 1997 12 30 , 01:13                   | 1997 12 30 , 09:35          | 1997 12 31 , 08:51        | Fr            |
| 31               | 1998 01 06 , 13:29                   | 1998 01 07 , 02:23          | 1998 01 08 , 07:54        | F+            |
| 32               | 1998 01 28 , 16:04                   | 1998 01 29 , 13:12          | 1998 01 31 , 00:00        | F+            |
| 33               | 1998 03 25 , 10:48                   | 1998 03 25 , 14:23          | 1998 03 26 , 08:57        | Fr            |
Table A.1 (Continued)

| CME event number | CME Arrival date and time [UT] (1AU) | MC start date and time [UT] | MC end date and time [UT] | Flux rope type |
|------------------|-----------------------------|-----------------------------|-----------------------------|----------------|
| 34               | 1998 03 31 , 07:11          | 1998 03 31 , 11:59         | 1998 04 01 , 16:18         | Fr             |
| 35               | 1998 05 01 , 21:21          | 1998 05 02 , 11:31         | 1998 05 03 , 16:47         | Fr             |
| 36               | 1998 06 02 , 10:28          | 1998 06 02 , 10:28         | 1998 06 02 , 09:16         | Fr             |
| 37               | 1998 06 24 , 10:47          | 1998 06 24 , 13:26         | 1998 06 25 , 22:33         | F+             |
| 38               | 1998 07 10 , 22:36          | 1998 07 10 , 22:36         | 1998 07 12 , 21:34         | F+             |
| 39               | 1998 08 19 , 18:40          | 1998 08 20 , 08:38         | 1998 08 21 , 20:09         | F+             |
| 40               | 1998 10 18 , 19:30          | 1998 10 19 , 04:19         | 1998 10 20 , 07:11         | F+             |
| 41               | 1999 02 11 , 17:41          | 1999 02 11 , 17:41         | 1999 02 12 , 03:35         | Fr             |
| 42               | 1999 07 02 , 00:27          | 1999 07 03 , 08:09         | 1999 07 05 , 13:13         | Fr             |
| 43               | 1999 09 21 , 18:57          | 1999 09 21 , 18:57         | 1999 09 22 , 11:31         | Fr             |
| 44               | 2000 02 11 , 23:34          | 2000 02 12 , 12:20         | 2000 02 13 , 00:35         | Fr             |
| 45               | 2000 03 01 , 01:58          | 2000 03 01 , 03:21         | 2000 03 02 , 03:07         | Fr             |
| 46               | 2000 07 01 , 07:12          | 2000 07 01 , 07:12         | 2000 07 02 , 03:34         | Fr             |
| 47               | 2000 07 11 , 22:35          | 2000 07 11 , 22:35         | 2000 07 13 , 04:33         | Fr             |
| 48               | 2000 07 28 , 06:38          | 2000 07 28 , 14:24         | 2000 07 29 , 10:06         | F+             |
| 49               | 2000 09 02 , 23:16          | 2000 09 02 , 23:16         | 2000 09 03 , 22:32         | Fr             |
| 50               | 2000 10 03 , 01:02          | 2000 10 03 , 09:36         | 2000 10 05 , 03:34         | F+             |
| 51               | 2000 10 12 , 22:33          | 2000 10 13 , 18:24         | 2000 10 14 , 19:12         | Fr             |
| 52               | 2000 11 06 , 09:30          | 2000 11 06 , 23:05         | 2000 11 07 , 18:05         | Fr             |
| 53               | 2000 11 26 , 11:43          | 2000 11 27 , 09:30         | 2000 11 28 , 09:36         | Fr             |
| 54               | 2001 04 21 , 15:29          | 2001 04 22 , 00:28         | 2001 04 23 , 01:11         | Fr             |
| 55               | 2001 10 21 , 16:39          | 2001 10 22 , 01:17         | 2001 10 23 , 00:47         | Fr             |
| 56               | 2001 11 24 , 05:51          | 2001 11 24 , 15:47         | 2001 11 25 , 13:17         | Fr             |
| 57               | 2001 12 29 , 05:16          | 2001 12 30 , 03:24         | 2001 12 30 , 19:10         | Fr             |
| 58               | 2002 02 28 , 05:06          | 2002 02 28 , 19:11         | 2002 03 01 , 23:15         | Fr             |
| 59               | 2002 03 18 , 13:14          | 2002 03 19 , 06:14         | 2002 03 20 , 15:36         | Fr             |
| 60               | 2002 03 23 , 11:24          | 2002 03 24 , 13:11         | 2002 03 25 , 21:36         | Fr             |
| 61               | 2002 04 17 , 11:01          | 2002 04 17 , 21:36         | 2002 04 19 , 08:22         | F+             |
| 62               | 2002 07 17 , 15:56          | 2002 07 18 , 13:26         | 2002 07 19 , 09:35         | Fr             |
| 63               | 2002 08 18 , 18:40          | 2002 08 19 , 19:12         | 2002 08 21 , 13:25         | Fr             |
| 64               | 2002 08 26 , 11:16          | 2002 08 26 , 14:23         | 2002 08 27 , 10:47         | Fr             |
| 65               | 2002 09 30 , 07:54          | 2002 09 30 , 22:04         | 2002 10 01 , 20:08         | F+             |
| 66               | 2002 12 21 , 03:21          | 2002 12 21 , 10:20         | 2002 12 22 , 15:36         | Fr             |
| 67               | 2003 01 26 , 21:43          | 2003 01 27 , 01:40         | 2003 01 27 , 16:04         | Fr             |
| 68               | 2003 02 01 , 13:06          | 2003 02 02 , 19:11         | 2003 02 03 , 09:35         | Fr             |
| 69               | 2003 03 20 , 04:30          | 2003 03 20 , 11:54         | 2003 03 20 , 22:22         | Fr             |
| 70               | 2003 06 16 , 22:33          | 2003 06 16 , 17:48         | 2003 06 18 , 08:18         | Fr             |
| 71               | 2003 08 04 , 20:23          | 2003 08 05 , 01:10         | 2003 08 06 , 02:23         | Fr             |
| 72               | 2003 11 20 , 08:35          | 2003 11 20 , 11:31         | 2003 11 21 , 01:40         | Fr             |
| 73               | 2004 04 03 , 09:55          | 2004 04 04 , 01:11         | 2004 04 05 , 19:11         | F+             |
| 74               | 2005 05 15 , 02:10          | 2005 05 15 , 05:31         | 2005 05 16 , 22:47         | F+             |
Table A.1 (Continued)

| CME event number | CME Arrival date and time [UT] (1AU) | MC start date and time [UT] | MC end date and time [UT] | Flux rope type |
|------------------|--------------------------------------|----------------------------|---------------------------|---------------|
| 75               | 2005 05 20, 04:47                   | 2005 05 20, 09:35          | 2005 05 22, 02:23         | F+            |
| 76               | 2005 07 17, 14:52                   | 2005 07 17, 14:52          | 2005 07 18, 05:59         | Fr            |
| 77               | 2005 10 31, 02:23                   | 2005 10 31, 02:23          | 2005 10 31, 18:42         | Fr            |
| 78               | 2006 02 05, 18:14                   | 2006 02 05, 20:23          | 2006 02 06, 11:59         | F+            |
| 79               | 2006 09 30, 02:52                   | 2006 09 30, 08:23          | 2006 09 30, 22:03         | F+            |
| 80               | 2006 11 18, 07:11                   | 2006 11 18, 07:11          | 2006 11 20, 04:47         | Fr            |
| 81               | 2007 05 21, 22:40                   | 2007 05 21, 22:45          | 2007 05 22, 13:25         | Fr            |
| 82               | 2007 06 08, 05:45                   | 2007 06 08, 05:45          | 2007 06 09, 05:15         | Fr            |
| 83               | 2007 11 19, 17:22                   | 2007 11 20, 00:33          | 2007 11 20, 11:31         | Fr            |
| 84               | 2008 05 23, 01:12                   | 2008 05 23, 01:12          | 2008 05 23, 10:46         | Fr            |
| 85               | 2008 09 03, 16:33                   | 2008 09 03, 16:33          | 2008 09 04, 03:49         | Fr            |
| 86               | 2008 09 17, 00:43                   | 2008 09 17, 03:57          | 2008 09 18, 08:09         | Fr            |
| 87               | 2008 12 04, 11:59                   | 2008 12 04, 16:47          | 2008 12 05, 10:47         | Fr            |
| 88               | 2008 12 17, 03:35                   | 2008 12 17, 03:35          | 2008 12 17, 15:35         | Fr            |
| 89               | 2009 02 03, 19:21                   | 2009 02 03, 01:12          | 2009 02 04, 19:40         | Fr            |
| 90               | 2009 03 11, 22:04                   | 2009 03 12, 01:12          | 2009 03 13, 01:40         | F+            |
| 91               | 2009 04 22, 11:16                   | 2009 04 22, 14:09          | 2009 04 22, 20:37         | Fr            |
| 92               | 2009 06 03, 13:40                   | 2009 06 03, 20:52          | 2009 06 05, 05:31         | Fr            |
| 93               | 2009 06 27, 11:02                   | 2009 06 27, 17:59          | 2009 06 28, 20:24         | F+            |
| 94               | 2009 07 21, 02:53                   | 2009 07 21, 04:48          | 2009 07 22, 03:36         | Fr            |
| 95               | 2009 09 10, 10:19                   | 2009 09 10, 10:19          | 2009 09 10, 19:26         | Fr            |
| 96               | 2009 09 30, 00:44                   | 2009 09 30, 06:59          | 2009 09 30, 19:11         | Fr            |
| 97               | 2009 10 29, 01:26                   | 2009 10 29, 01:26          | 2009 10 29, 23:45         | Fr            |
| 98               | 2009 11 14, 10:47                   | 2009 11 14, 10:47          | 2009 11 15, 11:45         | Fr            |
| 99               | 2009 12 12, 04:47                   | 2009 12 12, 19:26          | 2009 12 14, 04:47         | Fr            |
| 100              | 2010 01 01, 22:04                   | 2010 01 02, 00:14          | 2010 01 03, 09:06         | Fr            |
| 101              | 2010 02 07, 18:04                   | 2010 02 07, 19:11          | 2010 02 09, 05:42         | Fr            |
| 102*             | 2010 03 23, 22:29                   | 2010 03 23, 22:23          | 2010 03 24, 15:36         | Fr            |
| 103*             | 2010 04 05, 07:55                   | 2010 04 05, 11:59          | 2010 04 06, 16:48         | Fr            |
| 104*             | 2010 04 11, 12:20                   | 2010 04 11, 21:36          | 2010 04 12, 14:12         | Fr            |
| 105              | 2010 05 28, 01:55                   | 2010 05 29, 19:12          | 2010 05 29, 17:58         | Fr            |
| 106*             | 2010 06 21, 03:35                   | 2010 06 21, 06:28          | 2010 06 22, 12:43         | Fr            |
| 107*             | 2010 09 15, 02:24                   | 2010 09 15, 02:24          | 2010 09 16, 11:58         | Fr            |
| 108*             | 2010 10 31, 02:09                   | 2010 10 30, 05:16          | 2010 11 01, 20:38         | Fr            |
| 109              | 2010 12 19, 00:35                   | 2010 12 19, 22:33          | 2010 12 20, 22:14         | Fr            |
| 110              | 2011 01 24, 06:43                   | 2011 01 24, 10:33          | 2011 01 25, 22:04         | Fr            |
| 111*             | 2011 03 29, 15:12                   | 2011 03 29, 23:59          | 2011 04 01, 14:52         | Fr            |
| 112              | 2011 05 28, 00:14                   | 2011 05 28, 05:31          | 2011 05 28, 22:47         | F+            |
| 113              | 2011 06 04, 20:06                   | 2011 06 05, 01:12          | 2011 06 05, 18:13         | Fr            |
| 114              | 2011 07 03, 19:12                   | 2011 07 03, 19:12          | 2011 07 04, 19:12         | Fr            |
| CME event number | CME Arrival date and time [UT] (1AU) | MC start date and time [UT] | MC end date and time [UT] | Flux rope type |
|-----------------|-------------------------------------|-----------------------------|---------------------------|---------------|
| 115*            | 2011 09 17 , 02:57                 | 2011 09 17 , 15:35         | 2011 09 18 , 21:07        | Fr            |
| 116             | 2012 02 14 , 07:11                 | 2012 02 14 , 20:52         | 2012 02 16 , 04:47        | Fr            |
| 117             | 2012 04 05 , 14:23                 | 2012 04 05 , 19:41         | 2012 04 06 , 21:36        | Fr            |
| 118             | 2012 05 03 , 00:59                 | 2012 05 04 , 03:36         | 2012 05 05 , 11:22        | Fr            |
| 119             | 2012 05 16 , 12:28                 | 2012 05 16 , 16:04         | 2012 05 18 , 02:11        | Fr            |
| 120             | 2012 06 11 , 02:52                 | 2012 06 11 , 11:31         | 2012 06 12 , 05:16        | Fr            |
| 121*            | 2012 06 16 , 09:03                 | 2012 06 16 , 22:01         | 2012 06 17 , 11:23        | F+            |
| 122*            | 2012 07 14 , 17:39                 | 2012 07 15 , 06:14         | 2012 07 17 , 03:22        | Fr            |
| 123             | 2012 08 12 , 12:37                 | 2012 08 12 , 19:12         | 2012 08 13 , 05:01        | Fr            |
| 124             | 2012 08 18 , 03:25                 | 2012 08 18 , 19:12         | 2012 08 19 , 08:22        | Fr            |
| 125*            | 2012 10 08 , 04:12                 | 2012 10 08 , 15:50         | 2012 10 09 , 17:17        | Fr            |
| 126             | 2012 10 12 , 08:09                 | 2012 10 12 , 18:09         | 2012 10 13 , 09:14        | Fr            |
| 127*            | 2012 10 31 , 14:28                 | 2012 10 31 , 23:35         | 2012 11 02 , 05:21        | F+            |
| 128*            | 2012 11 12 , 22:12                 | 2012 11 13 , 08:23         | 2012 11 14 , 08:09        | F+            |
| 129*            | 2013 03 17 , 05:21                 | 2013 03 17 , 14:09         | 2013 03 19 , 16:04        | Fr            |
| 130*            | 2013 04 13 , 22:13                 | 2013 04 14 , 17:02         | 2013 04 17 , 05:30        | F+            |
| 131             | 2013 04 30 , 08:52                 | 2013 04 30 , 12:00         | 2013 05 01 , 07:12        | Fr            |
| 132             | 2013 05 14 , 02:23                 | 2013 05 14 , 06:00         | 2013 05 15 , 06:28        | Fr            |
| 133             | 2013 06 06 , 02:09                 | 2013 06 06 , 14:23         | 2013 06 08 , 00:00        | F+            |
| 134             | 2013 06 27 , 13:51                 | 2013 06 28 , 02:23         | 2013 06 29 , 11:59        | Fr            |
| 135             | 2013 09 01 , 06:14                 | 2013 09 01 , 13:55         | 2013 09 02 , 01:56        | Fr            |
| 136             | 2013 10 30 , 18:14                 | 2013 10 30 , 18:14         | 2013 10 31 , 05:30        | Fr            |
| 137             | 2013 11 08 , 21:07                 | 2013 11 08 , 23:59         | 2013 11 09 , 06:14        | Fr            |
| 138             | 2013 11 23 , 00:14                 | 2013 11 23 , 04:47         | 2013 11 23 , 15:35        | Fr            |
| 139             | 2013 12 14 , 16:47                 | 2013 12 15 , 16:47         | 2013 12 16 , 05:30        | Fr            |
| 140             | 2013 12 24 , 20:36                 | 2013 12 25 , 04:47         | 2013 12 25 , 17:59        | F+            |
| 141             | 2014 04 05 , 09:58                 | 2014 04 05 , 22:18         | 2014 04 07 , 14:24        | Fr            |
| 142             | 2014 04 11 , 06:57                 | 2014 04 11 , 06:57         | 2014 04 12 , 20:52        | F+            |
| 143             | 2014 04 14 , 10:20                 | 2014 04 21 , 07:41         | 2014 04 22 , 06:12        | Fr            |
| 144             | 2014 04 29 , 19:11                 | 2014 04 29 , 19:11         | 2014 04 30 , 16:33        | Fr            |
| 145             | 2014 06 29 , 04:47                 | 2014 06 29 , 20:53         | 2014 06 30 , 11:15        | Fr            |
| 146             | 2014 08 19 , 05:49                 | 2014 08 19 , 17:59         | 2014 08 21 , 19:09        | F+            |
| 147             | 2014 08 26 , 02:40                 | 2014 08 27 , 03:07         | 2014 08 27 , 21:49        | Fr            |
| 148             | 2015 01 07 , 05:38                 | 2015 01 07 , 06:28         | 2015 01 07 , 21:07        | F+            |
| 149             | 2015 09 07 , 13:05                 | 2015 09 07 , 23:31         | 2015 09 09 , 14:52        | F+            |
| 150             | 2015 10 06 , 21:35                 | 2015 10 06 , 21:35         | 2015 10 07 , 10:03        | Fr            |
| 151             | 2015 12 19 , 15:35                 | 2015 12 20 , 13:40         | 2015 12 21 , 23:02        | Fr            |
### A.2 Events from the Helios Observation

**Table A.2** The list of 45 magnetic clouds (MCs) shortlisted by Bothmer and Schwenn (1998) using *in-situ* data from the Helios 1 and 2 spacecraft for the period December 1974–July 1981. The columns show the year, duration, heliocentric distance, and the spacecraft by which observed the MC.

| Magnetic Cloud serial number | Year | Time duration (Days, Hours) | Heliocentric distance (AU) | Observed by |
|------------------------------|------|----------------------------|---------------------------|-------------|
| 1                            | 1975 | 7 00 – 10                  | 0.92                      | Helios 1    |
| 2                            |      | 63,64 16 – 05              | 0.39                      | Helios 1    |
| 3                            |      | 92 06 – 16                 | 0.48                      | Helios 1    |
| 4                            |      | 313 03 – 18                | 0.81                      | Helios 1    |
| 5                            |      | 321 06 – 18                | 0.87                      | Helios 1    |
| 6                            | 1976 | 90 09 – 21                 | 0.47                      | Helios 2    |
| 7                            |      | 187 03 – 21                | 0.98                      | Helios 1    |
| 8                            | 1977 | 29,30 10 – 10              | 0.95                      | Helios 1    |
| 9                            |      | 76 05 – 20                 | 0.71                      | Helios 2    |
| 10                           |      | 78,79 22 – 08              | 0.57                      | Helios 1    |
| 11                           |      | 159,160 18 – 13            | 0.86                      | Helios 1    |
| 12                           |      | 240,241 14 – 10            | 0.84                      | Helios 1    |
| 13                           |      | 268,269 14 – 12            | 0.57                      | Helios 1    |
| 14                           |      | 35 14 – 00                 | 0.75                      | Helios 1    |
| 15                           | 1978 | 3,4 15 – 17                | 0.95                      | Helios 1    |
| 16                           |      | 4,5 08 – 10                | 0.94                      | Helios 2    |
| 17                           |      | 6 01 – 13                  | 0.95                      | Helios 2    |
| 18                           |      | 17 01 – 23                 | 0.98                      | Helios 2    |
| 19                           |      | 29,30 12 – 01              | 0.98                      | Helios 2    |
| 20                           |      | 37,38 16 – 16              | 0.98                      | Helios 2    |
| 21                           |      | 46,47 14 – 20              | 0.95                      | Helios 1    |
| 22                           |      | 47,48 03 – 09              | 0.95                      | Helios 2    |
| 23                           |      | 61,62 01 – 01              | 0.87                      | Helios 1    |
| 24                           |      | 92 02 – 07                 | 0.61                      | Helios 2    |
| 25                           |      | 114 12 – 19                | 0.32                      | Helios 2    |
| 26                           |      | 189,190 22 – 22            | 0.94                      | Helios 1    |
| 27                           |      | 292,293 01 – 14            | 0.47                      | Helios 1    |
| 28                           |      | 358,359 15 – 15            | 0.85                      | Helios 2    |
| 29                           |      | 363,364 09 – 14            | 0.85                      | Helios 1    |
| 30                           | 1979 | 58,59 15 – 15              | 0.96                      | Helios 1    |
| 31                           |      | 62 09 – 17                 | 0.94                      | Helios 1    |
| 32                           |      | 93 02 – 18                 | 0.68                      | Helios 2    |
| 33                           |      | 129 06 – 12                | 0.30                      | Helios 2    |
| 34                           |      | 148,149 23 – 07            | 0.43                      | Helios 1    |
| 35                           |      | 305 03 – 19                | 0.50                      | Helios 1    |
| 36                           | 1980 | 82,83 17 – 12              | 0.92                      | Helios 1    |
| 37                           |      | 90 01 – 15                 | 0.88                      | Helios 1    |
| 38                           |      | 162,163 17 – 01            | 0.41                      | Helios 1    |
### Table A.2  (Continued)

| Magnetic Cloud serial number | Year | Time duration Days | Hours | Heliocentric distance (AU) | Observed by |
|------------------------------|------|--------------------|-------|---------------------------|-------------|
| 39                           | 172  | 02 – 20            |       | 0.53                      | Helios 1     |
| 40                           | 175  | 05 – 17            |       | 0.57                      | Helios 1     |
| 41                           | 231  | 00 – 18            |       | 0.97                      | Helios 1     |
| 42                           | 117,118 | 09 – 03          |       | 0.79                      | Helios 1     |
| 43                           | 131,132 | 15 – 03          |       | 0.66                      | Helios 1     |
| 44                           | 146,147 | 03 – 07           |       | 0.48                      | Helios 1     |
| 45                           | 170  | 03 – 09            |       | 0.34                      | Helios 1     |

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### Declarations

#### Disclosure of Potential Conflicts of Interest

The authors declare that they have no conflicts of interest.

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