A robust estimation of the twist distribution in magnetic clouds

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ABSTRACT

Context. Magnetic clouds (MCs) are observed *in situ* by spacecrafts. The rotation of their magnetic field is typically interpreted as the crossing of a twisted magnetic flux tube, or flux rope, which was launched from the solar corona.

Aims. The detailed magnetic measurements across MCs allow to infer the flux rope characteristics. Still the precise spatial distribution of the magnetic twist is challenging, so debated.

Methods. In order to improve the robustness of the results, we perform a superposed epoch analysis (SEA) of a set of well observed MCs at 1 au. While previous work was done using the MC central time, now we use the result of a fitted flux rope model to select the time of the closest approach to the flux rope axis. This implies a precise separation of the in- and outbound regions and to coherently phase the observed signals. We also search for and minimise the possible biases such as magnetic asymmetry and a finite impact parameter.

Results. We apply the SEA to derive the median profiles both for the flux rope remaining when cross by the spacecraft and to recover the one present before erosion. In particular, the median azimuthal B component is nearly a linear function of the radius. More generally, the results confirm our previous ones realised without such deep analysis. The twist profile is nearly uniform in the flux rope core, with a steep increase at the border of the flux rope and with similar profiles in the in-/outbound. The main difference with our previous study is a largest twist by ∼ 20%.

Key words. Physical data and processes: magnetic fields, Sun: coronal mass ejections (CMEs), Sun: heliosphere

1. Introduction

Large-scale magnetic structures released from the solar corona have been observed since a long time with remote observations. These structures, known as coronal mass ejections (CMEs), are the main drivers for space weather effects at or near Earth. The *in situ* observations of CMEs in the interplanetary medium are known as interplanetary coronal mass ejections (ICMEs). About one third of ICMEs have the signatures defining a magnetic cloud (MC): enhanced magnetic field strength with respect to ambient values, a monotonic and high rotation of the magnetic field vector, and a low proton temperature (Burlaga et al. 1981). The observed coherent rotation in MCs is interpreted as the passage through the spacecraft of a large-scale twisted magnetic flux tube or flux rope (FR).

The twist profile inside the FR is still under discussion reaching to different conclusions. Some authors, e.g. Burlaga et al. (1998); Dasso et al. (2006); Lepping et al. (2011); Lanabere et al. (2020) and references therein, found that the magnetic twist profile is comparable to the one of the Lundquist model (Lundquist 1950). In this model the twist is nearly constant around the FR centre, increasing from the core outward, and reaching significant large values toward the FR boundary, and theoretically can diverge depending on where the end of the FR is defined.

Another used model to describe the interplanetary FRs is the Gold-Hoyle model, where the twist distributes uniformly along the radius of the FR (e.g., Farrugia et al. 1999; Dasso et al. 2003). Magnetic data are also least square fitted by various FR models. Since the assumed model defines the distribution of the twist, different authors using different models have found different twist distribution (e.g., Mulligan et al. 1999; Hidalgo et al. 2000; Cid et al. 2002; Nieves-Chinchilla et al. 2018).

In a recent study, and without assumption of a magnetic model for the FR, Lanabere et al. (2020) found that the twist in a typical MCs is distributed nearly uniformly in the FR core, and it increases towards the FR boundaries, i.e. they found the same expected behaviour for the twist as expected from the Lundquist model. Meanwhile, other authors supports the idea that FRs have a high twist core enveloped by a less twisted outer shell (*e.g.* Wang et al. 2018). A more detailed discussion about recent twist studies can be found in Lanabere et al. (2020); Florido-Llinas et al. (2020, and references therein)

Remote observations of CMEs show that their radial extension increases as they propagate away from the low corona. This expansion continues in the interplanetary space as deduced by *in situ* observations of the proton velocity (e.g. Démoulin et al. 2008; Gulisano et al. 2010; Regnault et al. 2020). This expansion creates an ageing effect with a FR growing in size, so with a weaker magnetic field, as the spacecraft crosses it. This in-

troduces a bias in the data by mixing space and time evolution. Démoulin et al. (2020) concluded that the expansion effect in the *in situ* measurements is not the main origin of the observed asymmetry in the magnetic field profile of MCs. Then, the effect of expansion on the deduced twist profile is expected to be weak.

Another important process that MCs experiment during their travel though the interplanetary medium is erosion, due to magnetic reconnection with the ambient solar wind (*e.g.* Dasso et al. 2006, 2007; Ruffenach et al. 2015). This erosion modifies the balance of magnetic flux present in the inbound compared to the outbound, as well as the estimated values of magnetic flux and helicity derived from *in situ* measurements (the inbound (outbound resp.) corresponds to the time series when the spacecraft is going nearer (away resp.) from the FR center). Moreover, the percentage of eroded magnetic flux is very case dependent, then this needs to be taken into account in MC studies. In particular from the analysis of two studied-cases, Pal et al. (2021) concluded that the erosion have significant effects on the obtained magnetic flux rope twist, as it is expected mainly due to the lack of its external part, which typically is highly twisted.

In a previous work, Lanabere et al. (2020) found the typical twist distribution inside MCs, using a superposed epoch analysis (SEA). The SEA is a classical technique used to enhance the common properties of a set of events while minimising the specificity of individual cases. A MC has a front and a rear boundary separated by a case dependent time interval. Then, in order to superpose the data of many MCs, their boundaries are first set to the same normalised time values within the selected events. Next, a SEA of a scalar quantity is carried out by taking the mean or the median of the cases. This defined a SEA time profile outlining the dominant characteristics of the MC selection (e.g. Masías-Meza et al. 2016). This can be generalised to ICMEs and to derive the probability distribution of the studied parameter versus time (Janvier et al. 2019; Regnault et al. 2020).

When a vector field is considered, such as the magnetic field, before performing the SEA, the data should be rotated to a common frame where the vector components have the same physical meaning for all the studied cases. Since MCs have a FR structure, the FR frame is the relevant frame, with the adding that all FRs need to be set to the same helicity sign so that the magnetic signals add up. Setting the same impact parameter sign is also needed. Then, a SEA of the axial and azimuthal components could be performed, from which a twist profile is derived (Lanabere et al. 2020). They apply this technique to a subset of MCs characterised by low asymmetry in the B profile to minimise its effect. It results in a typical twist profile which is nearly uniform in the FR core and which moderately increases towards the MC boundaries.

However, by using the MC boundaries for the SEA, Lanabere et al. (2020) do not consider the in-/outbound asymmetries typically present in MCs (e.g., those produced by the erosion). Then, such SEA mix MCs which have a different unbalance of magnetic flux in the in- and outbound. Said differently, the normalised time corresponding to the closest approach distance of the spacecraft to the FR axis, would be at a different location for each of the superposed MCs. This could especially affect the deduced azimuthal component profile, which is reversing at the FR axis, then this could impact on the deduced twist profile.

Démoulin et al. (2019) presented a new analysis of the results obtained by Lepping et al. (1990), with consequences on the interpretation of the FR boundaries. A reference time is defined for the minimum approach distance of the spacecraft to the fitted FR axis, which in general is different than the central MC time. In general this implies a different size of the FR in the in-

and outbound. Then, the same size can be selected on both sides in order to get a FR. This allows to superpose MC data limited to a FR extension with the closest approach time of FR axis for all cases located at the same time. Finally, this enhances the physical coherence of the superposed field components of the MC data.

The above improvements of the SEA of MC data is done in steps, as follows. In Sect. 2 we describe the data and the studied quantities. We define a method to assign a sign to the asymmetry factor reported in Lepping's catalogue so that the fitted FR is fully defined. In particular, this defined the central reference time corresponding to the FR axis for each studied MC. In Sect. 3 we implement the procedure developed by Démoulin et al. (2019) to define the radius of the FR remaining when crossed by the spacecraft and the radius of the non-eroded FR. Then, we present the SEA applied to different MCs subsets in order to analyse, then to minimise the identified biases present withinin the magnetic field components. Next, in Sect. 4 we present the SEA twist profiles of the eroded and non-eroded FRs. Finally, in Sect. 5 we present a summary and our conclusions.

2. Data and fitted flux rope model

2.1. Data

In this work we use Lepping et al. (2006) catalogue, which consists of a full description of more than 160 MCs observed by Wind spacecraft between 1995-2012. Lepping's catalogue is available at `https://wind.gsfc.nasa.gov/mfi/mag_cloud_S1.html`. This catalogue includes physical quantities that were estimated with the Lundquist's FR model fitted to the MC data (Lepping et al. 1990). In particular, we used the start and end time of the passage of Wind through the MCs, the FR orientation θ_L ϕ_L, the closest approach distance CA of Wind to the FR axis, the asymmetry factor asf, the FR radius R_0 (in au), and the magnetic helicity sign H. In this catalogue, each MC is classified into three different categories according to the fitting quality (Q_0), where $Q_0 = 1$ means that good fitting was obtained, $Q_0 = 2$ stands for fair quality, and $Q_0 = 3$ for poor quality, as defined in Appendix A of Lepping et al. (2006). We keep a set of 91 MCs of quality $Q_{1,2}$.

Wind spacecraft data are used in this study. In particular, we use data from the Magnetic Field Instrument (MFI) and the Solar Wind Experiment (SWE), with a temporal cadence of 60 s for MFI and 92 s for SWE. We downloaded them from `https://cdaweb.sci.gsfc.nasa.gov/pub/data/wind/mfi/mfi_h0` and `https://cdaweb.sci.gsfc.nasa.gov/pub/data/wind/swe/swe_h1/`, respectively. From these data we use the magnetic field magnitude and components in GSE coordinate system and proton wind speed component along the Sun-Earth direction.

The study of geometric and physical properties of MCs, such as asymmetry, magnetic flux and twist, is best defined in the local frame ($\hat{e}_x, \hat{e}_y, \hat{e}_z$), known as the orthonormal FR frame. The Z axis is defined by the FR axis direction oriented by the magnetic field direction in the central FR part. X and Y axis are orthogonal to the Z axis with the spacecraft trajectory contained in the X, Z plane. In the FR frame the magnetic field components are noted (B_x, B_y, B_z) and (b_x, b_y, b_z) when normalised by the magnetic field strength. The observed magnetic field components are rotated from GSE to the FR frame using Lepping's FR axis orientation (θ_L, ϕ_L). A study of the differences between Lepping's orientations and minimum variance (MV) orientations can be found in Lanabere et al. (2020). We showed that there are small
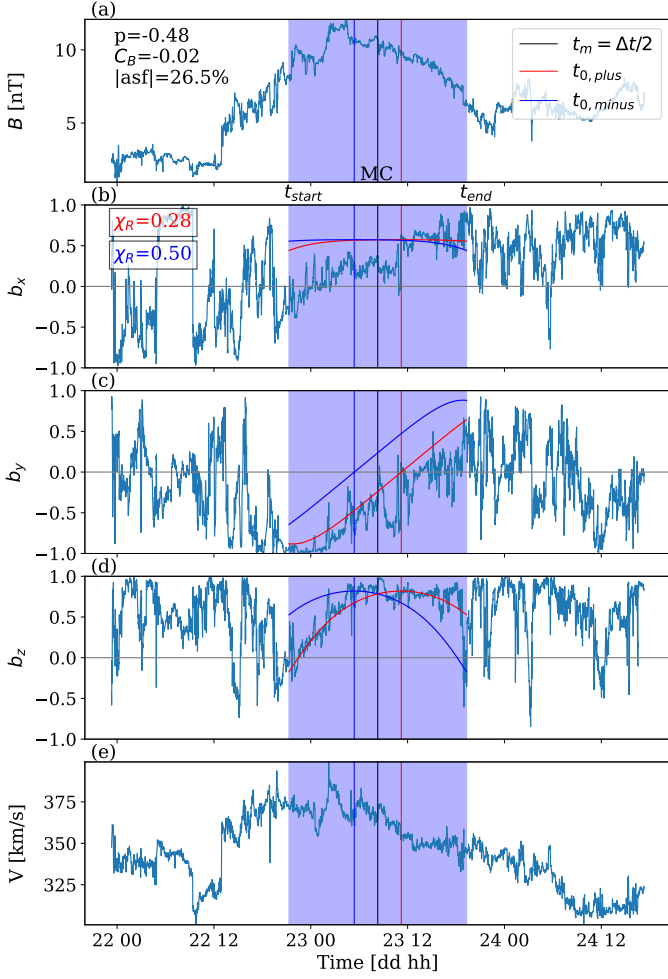
Fig. 1. Selection of the correct sign of asf for the MC observed on 22 August 1995. The MC region is shown with a blue background. (a) The magnetic field magnitude, (b,c,d) the magnetic field components, normalised to the field magnitude, in the FR frame. Two Lundquist solutions fitted to the observed magnetic fields components, with its origin set at $t_{0,\text{minus}}$ (blue) and $t_{0,\text{plus}}$ (red) is added in (b,c,d). (e) The observed velocity profile. The correct sign of asf is determined by the best fit represented by the lower χ_R value (Eq. 8). Here it is for $\text{sgn(asf)} = 1$ (red curves).

differences between MV and Lepping orientation for the set $Q_{1,2}$ (Pearson and Spearman correlation coefficients about 0.93 and 0.78 for θ and ϕ respectively) leading to comparable SEA profiles.

We quantify the asymmetry of the $B(t)$ profile as in Lanabere et al. (2020) with the barycenter of the magnetic field intensity:

$$C_B = \frac{\int_0^{\Delta t} (t/\Delta t - 1/2)\, B(t)\, dt}{\int_0^{\Delta t} B(t)\, dt} \qquad (1)$$

where the observed MC is set in the time interval $[0, \Delta t]$. The factor $(t/\Delta t - 1/2)$ defined the time fraction to the MC central time. $C_B = 0$ for any symmetric $B(t)$ profile around the central time, while $C_B < 0$ (resp. $C_B > 0$) when the magnetic field is stronger on the inbound (resp. outbound) side. Finally, the magnitude of $|C_B|$ measures the importance of the asymmetry.

2.2. Definition of asf sign

The fit of the Lundquist's model to the magnetic data provides the time when the spacecraf was the closest from the axis of the best fitted FR. The asymmetry factor (asf) reported in Lepping's catalogue, provides information about how far is the center of the observed MC time interval with respect to the closest approach time. However, only the absolute value of asf is provided. In this section we define a procedure to retrieve the sign of asf. Fig. 1 shows the procedure applied to an example, the MC observed on 22 August 1995.

The absolute value of the asymmetry factor ($|asf|$) provided in Lepping's catalogue (Lepping et al. 2006) allows to compute the time of the closest approach as,

$$t_0 = \Delta t/2(1 \pm |asf|/100)\,. \qquad (2)$$

We added the absolute value to asf to reinforce that Lepping provides only positive values. Then, Eq. (2) results $t_0 = \Delta t/2$ when the closest approach of the FR axis is at the centre of the time interval (asf = 0%), and $t_0 \neq \Delta t/2$ otherwise. We note the two possible values for t_0 in Eq. (2) with the minus and plus signs as $t_{0,\text{minus}}$ and $t_{0,\text{plus}}$, respectively. These two options are shown in Fig. 1 as blue and red vertical lines for $t_{0,\text{minus}}$ and $t_{0,\text{plus}}$, respectively.

The linear force-free field model with cylindrical symmetry (Lundquist 1950) is used to fit the observed MC data (blue background in Fig. 1). In cylindrical coordinates $(\hat{\mathbf{e}}_r, \hat{\mathbf{e}}_\theta, \hat{\mathbf{e}}_z)$, this model writes

$$\boldsymbol{B}_L(R) = B_0\, J_1(\alpha R)\, \hat{\mathbf{e}}_\theta + B_0\, J_0(\alpha R)\, \hat{\mathbf{e}}_z \qquad (3)$$

where J_0 and J_1 are the ordinary Bessel functions of order 0 and 1 respectively, while B_0 and α are the two free parameters of the model.

In order to fit the Lundquist's model to the observed magnetic field components in the FR frame, the time t needs to be converted into the spatial coordinate X with its origin set at where the minimum approach distance occurs ($X(t_o) = 0$, $X < 0$ for the inbound branch, and $X > 0$ for the outbound one),

$$X(t) = (t - t_0) \langle V \rangle \cos \lambda\,, \qquad (4)$$

where $\langle V \rangle$ is the mean solar wind speed of the MC and $\lambda = \sin^{-1}(\cos \phi_L \cos \theta_L)$ is the location angle measured from the plane $(\hat{\mathbf{y}}_{\text{GSE}}, \hat{\mathbf{z}}_{\text{GSE}})$ towards the MC axis as defined by Janvier et al. (2013). Next, the signed distance to the FR axis, along the spacecraft trajectory inside the FR, is computed as

$$R = \text{sgn}(X)\sqrt{X^2 + (pR_0)^2}\,, \qquad (5)$$

where p is the impact parameter defined as $p = CA/100$ and R_0 is the FR radius from Lepping's table defined by the first zero of $J_0(\alpha R)$ (i.e., R_0 such that $J_0(\alpha R_0) = 0$).

For each option of the time of the closest approach (i.e. $t_{0,\text{minus}}$ or $t_{0,\text{plus}}$) we computed the normalised Lundquist solution

$$\boldsymbol{b}_L(R) = \frac{J_1(\alpha R)}{\sqrt{J_1^2(\alpha R) + J_0^2(\alpha R)}}\, \hat{\mathbf{e}}_\theta + \frac{J_0(\alpha R)}{\sqrt{J_1^2(\alpha R) + J_0^2(\alpha R)}}\, \hat{\mathbf{e}}_z\,. \qquad (6)$$

Next, the cylindrical magnetic field components are transformed to the orthonormal FR frame $(\hat{\mathbf{e}}_x, \hat{\mathbf{e}}_y, \hat{\mathbf{e}}_z)$. We recall that $\hat{\mathbf{e}}_x$ is in the plane defined by the spacecraft trajectory and the FR axis $(\hat{\mathbf{e}}_z)$. The Lundquist model writes

$$\boldsymbol{b}_L(R) = b_{\theta,L}\frac{pR_0}{R}\hat{\mathbf{e}}_x + b_{\theta,L}\frac{X}{R}\hat{\mathbf{e}}_y + b_{z,L}\hat{\mathbf{e}}_z\,, \qquad (7)$$
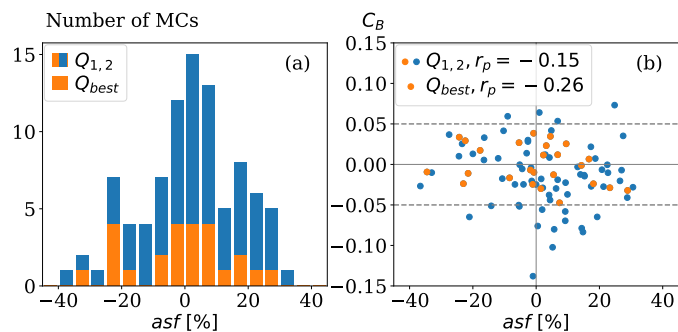
Fig. 2. (a) Histogram of the signed asymmetry factor asf (related to the time of the closest approach to the FR axis with Eq. (2)). (b) Scatter plot of asf vs C_B (related to the magnetic field profile symmetry). The group $Q_{1,2}$ of analysed MCs and its subset Q_{best} are shown. The dashed line in (b) corresponds to the most symmetric MCs with $|C_B| \leq 0.05$.

where X is given by Eq. (4), pR_0 is the distance of the spacecraft from the flux rope axis at closest approach point, and $b_{\theta,L}$ and $b_{z,L}$ are the normalised azimuthal and axial magnetic field components from Lundquist solution (Eq. 6).

Next, we compute the two possible models for each MC as the example shown in Fig. 1 with blue and red lines corresponding to $t_{0,minus}$ and $t_{0,plus}$, respectively. The quality of the fit between the normalized Lundquist magnetic field components and the normalized observations is characterised by the reduced chi-square defined as

$$\chi_R = \sqrt{\frac{\left(b_x - b_{x,L}\right)^2 + \left(b_y - b_{y,L}\right)^2 + \left(b_z - b_{z,L}\right)^2}{3N_d - n}}, \qquad (8)$$

where $n = 5$ is the number of parameters of the fit and N_d is the number of data points as defined by Lepping et al. (2006). Then, we computed χ_R for both fits (with $t_{0,minus}$ and $t_{0,plus}$).

Finally, we designate a sign to asf according to the fit that presents the lowest χ_R. This implies that asf > 0 when the best fit is obtained with $t_{0,plus}$, and asf < 0 when the best fit is obtained with $t_{0,minus}$. As a summary, we present in Fig. 2a the distribution of the signed asymmetry factor for $Q_{1,2}$ and the subset Q_{best} defined with $|C_B| \leq 0.05$, and with $|p| \leq 0.3$ (Lanabere et al. 2020, we remind that all C_B values reported in this paper are larger by a factor 2). In particular, we found 53 cases (58 % of cases, see Table A) having asf > 0, which corresponds to have more erosion in the MC back, assuming the observed asymmetry is mainly due to erosion. The other 38 cases (42 % of cases) with asf < 0 correspond to more erosion in the front.

The distribution of $Q_{1,2}$ presents a maximum near zero, with a low bias to positive values (58% positive). Furthermore, there were no cases with |asf| > 40%. Meanwhile, the distribution for Q_{best} is more evenly distributed (52% positive).

The shift of time for the closest axis approach, t_0, from the central MC time could be due to the FR erosion during the travel from the Sun. For example, if reconnection at the FR front had removed magnetic flux, t_0 is earlier than $\Delta t/2$, or asf < 0, and also $C_B < 0$ as $B(t)$ is stronger in front. At the opposite, erosion at the FR rear implies t_0 later than $\Delta t/2$, asf > 0, and $C_B > 0$. Another possibility is the asymmetric compression of the FR. For example, if the inbound is more compressed (by a strong sheath), $B(t)$ is stronger there, $C_B < 0$, and the inbound is less extended implying asf < 0. Then, if erosion or asymmetric compression of the FR is the main origin of a finite |asf| we expect a positive correlation between asf and C_B. In fact, only a weak
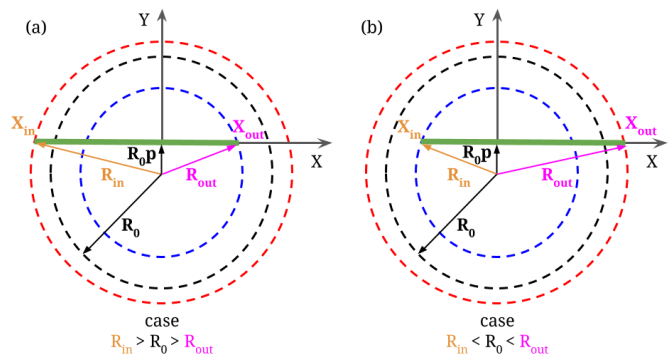
Fig. 3. Schema of a MC cross-section used to define the MC parameters defined by Démoulin et al. (2019). The MC interval, deduced from *in situ* observations, is schematised with a thick green line. The dashed circles represent the boundary for three characteristics FR: in blue for the *in situ* FR, in black for the fitted Lundquist FR limited within $B_z(R_0) = 0$, and in red for the expected fully formed FR without erosion at its boundary. Two cases are shown: (a) $R_{in} > R_0 > R_{out}$ and (b) $R_{in} < R_0 < R_{out}$ corresponding to the MC examples shown in Fig. 4.

anti-correlation is present with Pearson and rank correlation coefficients only slightly negative (-0.15 for $Q_{1,2}$ and -0.26 for Q_{best}). Then, the asymmetry in the magnetic field profile $B(t)$, either by erosion or compression, is not dominantly at the origin of the shift in time of the position of the closest axis approach.

3. Method

The main aim of the present section is to improve the SEA of MCs as outlined in Sect. 1. In order that the magnetic field components of the different MCs add up constructively, they need to represent the same quantity (*e.g.* the axial component) and with the same polarity (Sect. 3.2). More over, since a spacecraft provides data only on an eroded, or partially formed, FR we also need to infer a coherent FR for each MC so that the SEA adds up coherently the same FR portion of the data. This FR definition could be realised with the fitted FR model, or with the FR remaining when the MC is observed, or even with the expected fully formed FR (counting on the statistical approach to fill the data gap of individual MCs for the eroded part). This procedure of defining a FR associated to the data is the object of Sect. 3.1. The steps needed to perform a SEA of the vector magnetic field are described in Sect. 3.2. Since we identified biases in this SEA, we define MC subsets to decrease them, at the expense of lower statistics (Sect. 3.3). Finally, we analyse the various SEA results (Sect. 3.4).

3.1. Definition of FR radius

In order to define a FR from MC data, we apply the procedure described by Démoulin et al. (2019). We first define the inferior and superior values of the FR radius (R) at the MC boundaries, for each MC of the set $Q_{1,2}$. This procedure is shown applied to two examples of MCs in Figs. 3 and 4. The MC observed on 22 August 1995 is represented by the schema shown in Fig. 3a with the time of the closest approach $t_0 = t_{0,plus}$ (see Fig. 1 and Sect. 2.2). The MC observed on 24 July 2004 with $t_0 = t_{0,minus}$ is represented by Fig. 3b.

The observed MCs are typically not compatible with a full FR since the time of the FR axis closest distance, t_0, is typically not at the centre of the observed MC time interval. This is linked
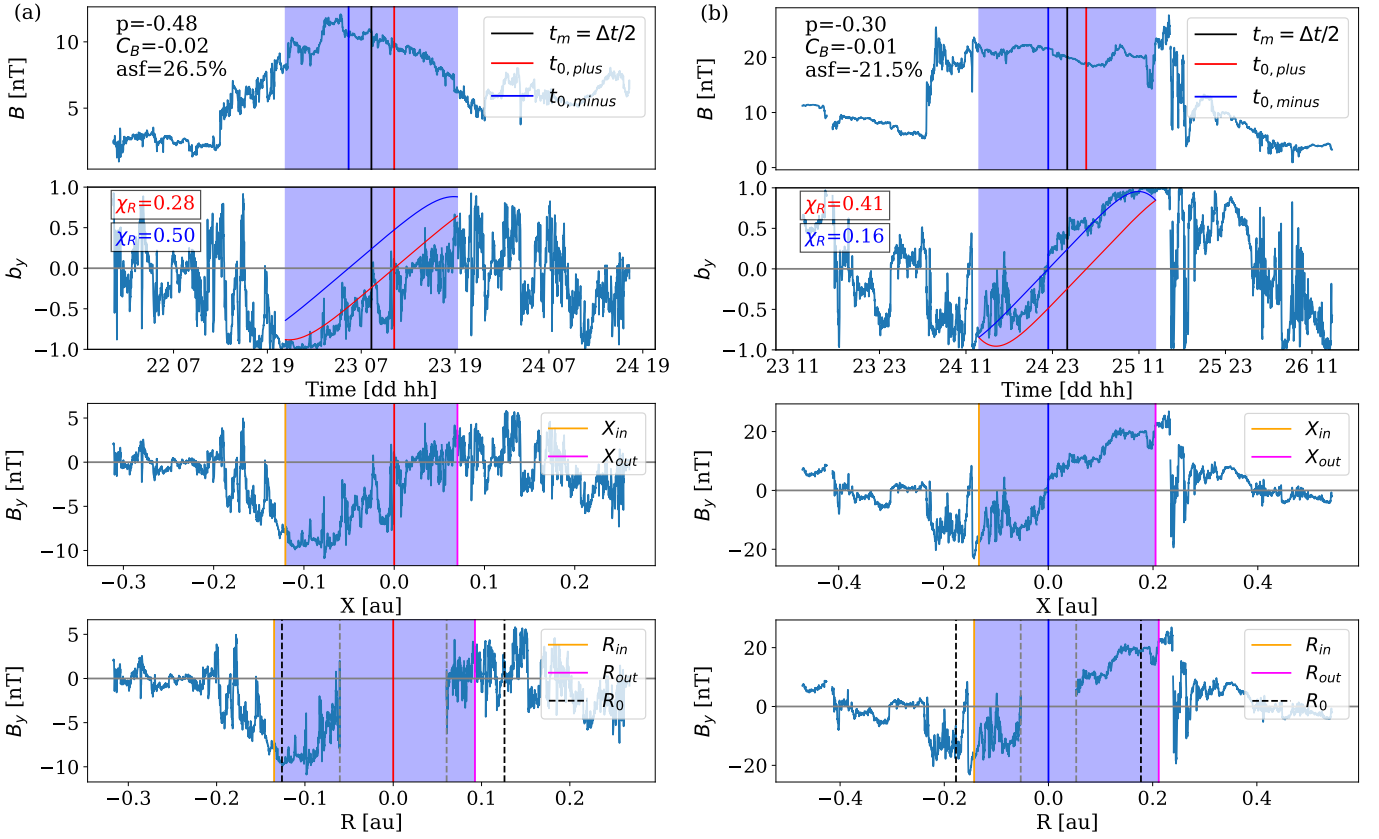
Fig. 4. Definition of the asf sign and the in- and outbound of the MC in X and R spacial coordinates. From top to bottom, the first two rows show the magnetic field magnitude B and the B_y component in function of time. B_y profile is dominating in χ_R (Eq. 8) to determine the sign of asf. The third and fourth rows show the in- and outbound of the MC in X and R spacial coordinates, respectively. The column (a) corresponds to a MC observed on 22 August 1995 as an example of asf > 0 with $R_{in} > R_0 > R_{out}$ as the schema shown in Fig. 3a. Furthermore, in this case $R_{inf} = R_{out}$ and $R_{sup} = R_{in}$. The column (b) corresponds to a MC observed on 24 July 2004 as an example of asf < 0 with $R_{in} < R_0 < R_{out}$ as the schema shown in Fig. 3b. In this case, $R_{inf} = R_{in}$ and $R_{sup} = R_{out}$.

to the asymmetry of the magnetic field profile due to asymmetric compression and erosion (Dasso et al. 2007; Ruffenach et al. 2015). More precisely, the amount of azimuthal magnetic flux is not balanced between the in- and out-bound. To precisely correct this the FR boundary could be computed by imposing this flux balance from the data transformed to the FR frame. An alternative is to use the fitted FR model to define this flux balance. It has the advantage to filter out magnetic fluctuations such as the ones created by Alfvén waves. In any case, the two procedures are expected to provide very close results since we select the set of MCs which are best fitted by the model. The remaining small differences are further minimised by the SEA procedure.

The typical MC asymmetry implies that the fitted FR extends to a radius R_{in} and R_{out} which are generally different at the in- and out-bound MC boundaries. Then, the model is not a FR ending at a given radius R. This could occur when either the MC is formed of a smaller FR, of radius $R_{inf} = \min(R_{in}, R_{out})$, with extra B flux on one side, either the initial FR was eroded on one side during its travel, so that the total FR would have been $R_{sup} = \max(R_{in}, R_{out})$ without erosion. These two interpretations are shown in Fig. 3 for the two cases $R_{in} > R_{out}$ and $R_{in} < R_{out}$. We precise the derivation of these radius below, with the computation steps summarised in Fig. 4 for two MCs with similar asymmetry factor, impact parameter and a nearly symmetric B profile.

After the definition of asf sign, we computed the spatial coordinate X using Eq. (4) with its origin set at $t_{0,plus}$ or $t_{0,minus}$ (third

row of Fig. 4). In this spatial coordinate the in- and outbound boundaries of the MC are located at X_{in} and X_{out} as defined by Démoulin et al. (2019). For the MC of Fig. 4a the maximum χ_R selects $t_{0,plus}$, then the inbound is more extended than the outbound, meanwhile in Fig. 4b $t_0 = t_{0,minus}$ and the outbound is larger than the inbound. The MC boundaries are associated with the FR radius R defined as (Eq. 5).

$$R_{in} = \sqrt{X_{in}^2 + (pR_0)^2} \quad \text{and} \quad R_{out} = \sqrt{X_{out}^2 + (pR_0)^2} . \qquad (9)$$

The in- and outbound MC radius boundaries are shown in the bottom row of Fig. 4 with $B_y(R)$. The blank space around the magnetic cloud axis ($R = 0$) is associated with the distance to the spacecraft at the closest approach. The last step is to define the inferior and superior values of R at the MC boundaries

$$R_{inf} = \min(R_{in}, R_{out}) \quad \text{and} \quad R_{sup} = \max(R_{in}, R_{out}) . \qquad (10)$$

The examples shown in Fig. 4 have R_0 in between R_{inf} and R_{sup}. This is not observed for all the cases (see Fig. 2f of Démoulin et al. 2019). In particular, 42% of MCs in the set $Q_{1,2}$ have $R_{inf} < R_{sup} < R_0$, so where $B_z = 0$ is located beyond the MC boundaries. At the opposite, 20% have $R_{inf} > R_{sup} > R_0$, so where the FR core ($B_z > 0$) is surrounded by $B_z < 0$ so they are named annulus cases (see, e.g., Vandas & Geranios 2001). Finally, in Table A.1 we present the results of sgn(asf), R_{inf}, R_{sup}, and the values of χ_R for the Lundquist fit with both possible signs of asf for the set $Q_{1,2}$.
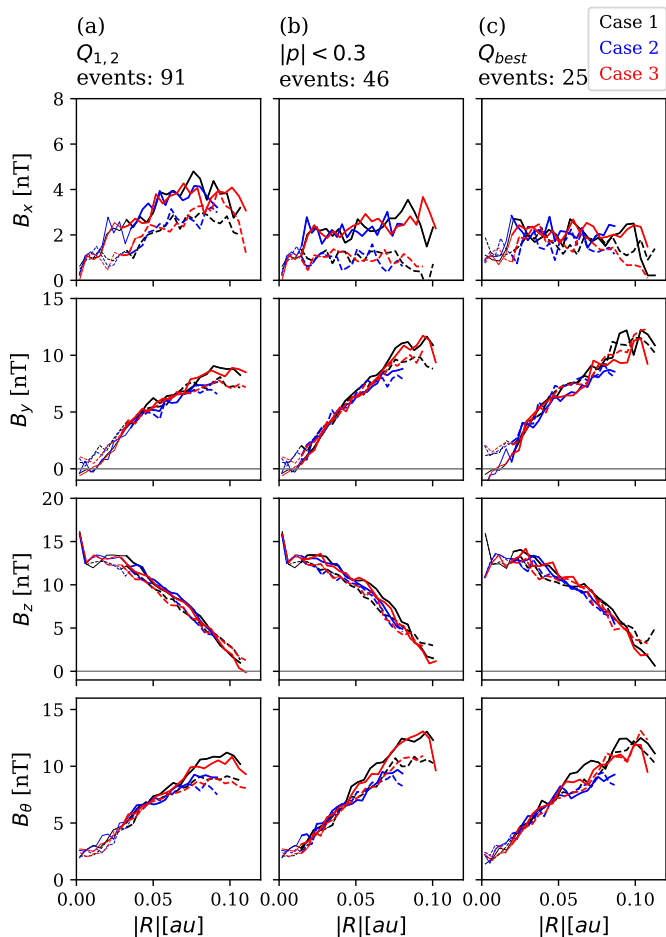
Fig. 5. Median profile of the magnetic field components derived with a SEA using first the MCs data in $[-R_0, R_0]$ with $B_z(R_0) = 0$ (black), second in the *in situ* FR $[-R_{inf}, R_{inf}]$ (blue), and third in the non-eroded FR $[-R_{sup}, R_{sup}]$. The in- and outbound profiles are drawn with continuous and dashed lines, respectively. The columns show three different samples: (a) the set $Q_{1,2}$ (b) a subset of $Q_{1,2}$ with low impact parameter ($|p| \leq 0.3$), and (c) a subset of $Q_{1,2}$, Q_{best}, with symmetric magnetic field profile ($|C_B| \leq 0.05$) and low impact parameter ($|p| \leq 0.3$).

3.2. Superposed epoch analysis (SEA) procedure

The SEA is a statistical tool useful to reinforce the common features between several individual MC profiles and minimise the peculiarities of each event. After defining the boundaries of the data to be superposed, a SEA of scalar quantities can be done. For vectors quantities, the data need first to be rotated in a common meaningful frame and defined with the same global sign so that the SEA of the components are meaningful.

In order to make a coherent superposition of the events, we rotated the magnetic field components into the FR frame defined so that $B_z > 0$ in the FR core. The sign of B_x and B_y in the FR frame depends on the sign of the FR helicity (H) so we first need to change all the MCs to positive helicity. Next, B_x sign depends on the sign of the closest approach distance (CA). In summary, we change B_x to sgn($CA\,H$) B_x and B_y to sgn(H) B_y to have a set of FRs with positive helicity and positive closest approach distance.

Next, we need to define which is the relevant portion of the data to include for each MC. We investigate three possibilities that we call below the model, the *in situ* and the initial FR.
Case 1: The first one use the Lundquist fitted model to define

the FR boundaries where $B_z(R_0) = 0$. This can be partly justified by the presence in the corona of a potential field arcade above the erupting flux rope which provides $B_z = 0$ after reconnection behind the FR (this argument has its own limitations, see Démoulin et al. 2013). This is the way Lepping build his MC tables and related papers.
Case 2: The second choice, or *in situ* FR extension, is to consider only the FR crossed by the spacecraft, so to analyse the data within $[-R_{inf}, R_{inf}]$. Two extreme interpretations of this choice are that this FR corresponds either to the remaining of the solar FR due to erosion or either the restrictive region where a FR could be formed in the corona. In this last case the extra flux present on one side would be flux which could not be incorporated, via reconnection, in the FR (*e.g.* an overlying coronal magnetic arcade).
Case 3: Finally, a third choice, or non-eroded FR extension, is to consider all the MC data, so a FR defined within $[-R_{sup}, R_{sup}]$, considering that the flux missing on one side was lost by erosion during the travel. This missing flux is treated as data gap. Since the missing flux is present about in half MCs, either on the in-bound either on the out-bound (Ruffenach et al. 2015), the corresponding SEA has approximately half the MCs near the interval boundaries.

We also remind that the central part of a MC, $[-pR_0, pR_0]$, has no data since the spacecraft is not exploring the FR core. It implies that for all above boundary selection, the central part of the SEA is only realised with few MCs (those observed with low impact parameter p).

In order to superpose the FRs data in a SEA, the extension of the FRs should be the same. This is achieved for each MC data by normalising R with R_0, R_{inf} or R_{sup}, respectively for the three above selected FR extensions. The result is an abscissa inside $[-1, 1]$ which allows to superpose the various MC data.

The computation of the SEA requires that each individual profile has the same number of data points. The number of data points increases with the duration of the observed MC. In order to obtain the same number of data points in every MC profile, we defined a grid of equally spaced bins, so that there are 25 bins within the inbound and 25 bins within the outbound of MCs. All data points that are present in each bin are averaged to a single value. Next, the average (mean or the median values) of the MC set is performed in each bin. This defines the SEA profile for each magnetic field component. Here we use the median as it is more robust to outlier values (see Regnault et al. 2020; Lanabere et al. 2020, for a comparison between mean and median results).

The results of the above three SEAs can not be directly compared since a different normalisation of R was needed. We correct this by multiplying the normalised radius by $\langle R_0 \rangle$, $\langle R_{inf} \rangle$ and $\langle R_{sup} \rangle$, where $\langle \rangle$ is an average over the MCs considered. For $Q_{1,2}$ set $\langle R_0 \rangle = 0.109$ au, $\langle R_{inf} \rangle = 0.094$ au and $\langle R_{sup} \rangle = 0.113$ au, for $p < 0.3$ set $\langle R_0 \rangle = 0.102$ au, $\langle R_{inf} \rangle = 0.082$ au and $\langle R_{sup} \rangle = 0.104$ au, while for Q_{best} $\langle R_0 \rangle = 0.115$ au, $\langle R_{inf} \rangle = 0.088$ au and $\langle R_{sup} \rangle = 0.110$ au. Then, the renormalisation of the SEA results to comparable sizes is a modest factor. First, the above normalisations of R by R_0, R_{inf} or R_{sup}, and second the normalized radius is multiplied by $\langle R_0 \rangle$, $\langle R_{inf} \rangle$ or $\langle R_{sup} \rangle$ to set the SEAs comparable and to provide a radius R in au used in Fig. 5.

3.3. Definition of MC subsets

The full set of MCs corresponds to 91 MCs from Lepping's catalogue with quality $Q_0 = 1$ and $Q_0 = 2$ defined as $Q_{1,2}$ in Sect. 2.1. Next, we defined new subsets according to the impact parameter p and the asymmetry C_B.

The impact parameter p expresses how far from the MC axis the spacecraft scans the MC. This implies that the azimuthal magnetic field components (B_x, B_y) are significantly dependant on the impact parameter p. In order to superpose the magnetic field components, with low B_x values and a better FR orientation, we select MCs with $|p| \leq 0.3$. This keeps almost half of $Q_{1,2}$ events. Finally, the set defined by Q_{best} (Sect. 2.2) keeps 25 events. It corresponds approximately to symmetric events with low impact parameter, $|C_B| \leq 0.05$ and $|p| \leq 0.3$.

3.4. Comparing SEA profiles

A comparison of the SEA profiles for the three sets of MCs ($Q_{1,2}$, $Q_{1,2}$ with $|p| \leq 0.3$, and Q_{best}) is shown for three different FR boundaries: the model FR in $[-R_0, R_0]$, the *in situ* FR in $[-R_{inf}, R_{inf}]$, and the non-eroded FR $[-R_{sup}, R_{sup}]$. In order to compare the asymmetry between the in- and out-boundaries of the FR, we set the abscissa to $|R|$ and we flip B_y sign in the inbound (to better compare it to the outbound values).

The SEA of B_x is shown in the top row of Fig. 5. With $Q_{1,2}$ set, B_x is increasing with R up to $R \approx 0.07$. This contrasts with the flat profile of B_x obtained with $|p| \leq 0.3$ and Q_{best}. In fact, the increasing profile with $Q_{1,2}$ set is due to a bias: only MCs observed with a low p contribute near the origin, and a small $|p|$ implies small B_x values (Eq. 7). Progressively, for larger $|R|$, more MCs contribute with larger $|p|$, implying a larger B_x contribution. Selecting MCs with $|p| \leq 0.3$ limits this bias to $|R|$ values closer to the origin (middle and right columns). Moreover, the slight decrease of B_x near the boundaries for FRs defined with R_0 and R_{sup} could be due to perturbations by the surrounding medium present at the FR periphery or the inclusion of non MC data. We conclude that the results show a flat B_x profile when the biases are minimised.

The profile of B_y is also affected by the p bias while differently than B_x. Going more to the periphery (larger $|R|$), more MCs with larger $|p|$ contribute, so B_y is weaker for $Q_{1,2}$ compared with $|p| \leq 0.3$ and Q_{best} results. For all sets $B_y(0) \approx 0$ as expected in the FR model. The azimuthal component B_θ is computed from B_x and B_y assuming a circular FR cross section. Then, it includes the biases of B_x and B_y. For $|p| \leq 0.3$ and Q_{best}, B_θ is almost a linear function of R.

B_x is significantly stronger in the in-bound (continuous lines in Fig. 5) compare to the out-bound for the $Q_{1,2}$ and $|p| \leq 0.3$ sets. This is also present for B_y to a lower level for large R values. This is due to the frequently stronger B measured in the in-bound compared to the out-bound (C_B is strongly negative for a fraction of MCs, Fig. 2b). This effect disappears if we limit the B asymmetry of the included MCs as in the Q_{best} set.

The profile of B_z is expected to be much less affected by the $|p|$ value since it is maximum around the origin with a weak dependence in the core on R, then on p. Indeed, B_z profiles in the third row of Fig. 5 are closer than for the other components. Still, near $R = 0$, there is too few MCs for SEA to be reliable. Then, the local B_z peak near the origin is due to a larger B for the few MCs with low $|p|$ cases. At the FR boundary, B_z is almost zero, especially for the $Q_{1,2}$ set.

Setting the FR boundary at R_0, R_{inf} or R_{sup} before making the SEA has finally a low effect on the results since the curves of these cases nearly superpose in Fig. 5. Indeed, in the common core region the same *in situ* data are included and they are phased the same way (using the closest approach distance to separate in- and outbound). Then, the difference between the three SEAs is related to how the binning is done (same number of SEA bins while the radial extension taken is different). Then, the closeness
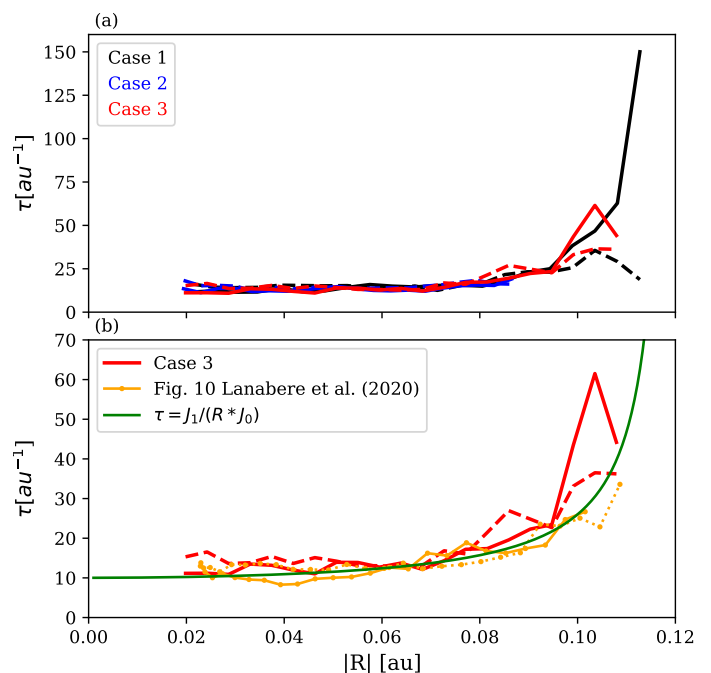
Fig. 6. Twist profiles for Q_{best} set. (a) Comparison of the in- and outbound profiles for the three cases: the Lepping FR extension $[-R_0, R_0]$ (black, case 1), the *in situ* FR extension $[-R_{inf}, R_{inf}]$ representing the eroded FR observed at 1 au (blue, case 2), and the non-eroded FR extension $[-R_{sup}, R_{sup}]$ representing the possible initial FR (case 3). The in- and outbound are represented with solid and dashed lines, respectively. (b) Comparison of case 3 (R_{sup} boundary) with the results of Fig. 10 in Lanabere et al. (2020). Their SEA results for in- and outbound (in orange) and the Lundquist model with $R_0 = 0.12$ au (in green) are included.

of the curves in Fig. 5 is a logical consequence of the weak effect of the data rebinning. The main difference between the results obtained with different selected FR boundary is for the large $|R|$ values, as expected.

The bias introduced by p, is partly solved by selecting MCs with low $|p|$ values with the limit of having enough MCs, at least few tens, to perform a SEA which is not too affected by fluctuations (due to individual MC peculiarities). With these limitations, B_x profile is almost flat and both B_y and B_θ profiles are close to be linear with the radius. This implies an axial current density which is uniform such as in the model of Hidalgo et al. (2002).

In summary, when the effect of the various bias are well decreased, a typical profile of B is obtained independently of the precise method used to derive it (right column of Fig. 5). The selection of FR extension at R_0, R_{inf} or R_{sup} does not change significantly the SEA profiles of the magnetic field components in the common region of the radius R. Using the FR extension up to R_{sup} extend the profiles to larger radius, with more fluctuations since only about half of the MCs contribute to the largest R values. It is much more significant to select low impact parameter $|p|$ and asymmetry $|C_B|$ to limit the corresponding biases.

4. Generic twist profile

A main characteristic of a FR is its amount of magnetic twist which is defined as the amount of rotation magnetic field lines make around the FR axis per unit length along the axis. The twist distribution can be computed considering a cylindrical symmetry

as $\tau = B_\theta/(RB_z)$ in radian/au (or simply au^{-1}), with R the radial distance from the FR axis.

The twist as a function of R for the three subsets of Sect. 3.3 are computed following the procedure described in Lanabere et al. (2020). In order to show a representative twist profile for each subset, the twist is shown where more than the 50% of events contribute to the SEA (so that there is a limited variation of the statistical weight across the twist profile).

The twist profiles derived with the SEA extension set to the model (case 1), *in situ* (case 2) and non-eroded FR (case 3) are compared in Fig. 6a for Q_{best} set (to avoid biases as much as possible). The twist profile is almost constant in the FR core ($|R| < 0.06$ au) and comparable within the in- and outbound. Indeed, the average of in- and outbound are $\tau = 13.85, 13.82$ and 13.4 au^{-1} for case 1 to 3, respectively. This slight difference is the result of the sensitivity of the twist profile to the SEA binning, to magnetic fluctuations in MCs and to the low number of MCs included, at most 25 events, to avoid biases (Sect. 3.4).

The twist profile near the origin could not be reliably determined as there are too few MCs observed with small impact parameter. Even more, the twist determination implies the ratio of two small quantities (B_θ and R) in the vicinity of the FR axis. Since R is vanishing by definition of the FR axis, while B_θ incorporates the fluctuations of B_x and B_y, B_θ is typically not vanishing in the data of individual MC, not even in SEAs (last row of Fig. 5). This implies that the computed twist profile typically diverges near the FR axis. In fact, the twist profile cannot be reliably derived there with a SEA and even less for an individual MC.

For $|R| > 0.06$ au, the twist has a small increase with $|R|$ which is coherent between the cases up to $|R| \approx 0.09$ au. For larger $|R|$ values, in cases 1 and 3 there is a large dispersion of the results. This dispersion is enhanced by the low B_z value reached in the inbound of case 1 (Fig. 5, left column). At the opposite, B_z has a local increase for case 1 at the FR boundary which implies a decrease of the twist there. The results of case 3 is in between these two extremes (Fig. 6a). Selecting the set $Q_{1,2}$ or $|p| \leq 0.3$ would lead to different values of B_z near the FR boundary. This implies important variations of the deduced twist. We conclude that the twist significantly increases at the FR periphery, but its value has a large uncertainty.

We next compare the present results to the ones of Lanabere et al. (2020) in Fig. 6b. The global twist trend is comparable. This justifies a posteriori the results of Lanabere et al. (2020) where the SEA was simply performed using the central time, and not the time of minimum distance approach to the FR axis as in this study, so finally using R_{in} and R_{out} even if they differ. The similarity of the results is at first surprising because SEA could accumulate the bias of a dominant erosion from one side. In that case, there would be a systematic shift of the MC and the FR boundaries, so different SEA profiles. In fact, MCs are statistically eroded about symmetrically at the front and rear (Ruffenach et al. 2015), as present also approximately in our various samples, so that a systematic bias of one side erosion has a weak signature in the SEA using MC boundaries. This is the strength of the SEA to erase the peculiarities (here erosion side and amount) of individual cases. Finally, the above uniform twist values are larger than previous studies, with $\tau \sim 9.4$ au^{-1} (Möstl et al. 2009, performed with a Grad-Shafranov model applied to a MC crossed by two-spacecraft), and with $\tau \sim 11.5$ au^{-1} (Lanabere et al. 2020, derived with a SEA analysis) .

Finally, we compare the results to the Lundquist model (green curve in Fig. 6b). The SEA twist is even flatter than the Lundquist's twist in the FR core especially for cases 1-3. Within

the SEA twist dispersion discussed above, the SEAs show a comparable increase of the twist at the FR periphery. Then, we confirm that the Lundquist's model represent well the median twist of MCs.

5. Summary and Conclusions

Previous studies have shown contrasted results about the magnetic twist profile present in MCs even in the framework of a supposed locally cylindrical symmetric magnetic field (Sect. 1). The twist profile is especially delicate to derive both because the data needs to be precisely rotated in the FR frame and because the twist is derived from the ratio of two quantities which vanish at the FR axis. A way to improve the derived twist profile is to use the powerful SEA method which weakens the individual MC peculiarities and decreases fluctuations. This was done in a simple way by Lanabere et al. (2020) choosing the central time of the time series to split the in/out bound branches, and also using the MC boundaries to superpose the magnetic field in the FR frame. However, since MCs are differently eroded during their travel from the Sun, one may wonder how justified it is to superpose data where the FR magnetic flux was partly removed on either sides. Then, one of the main aims of this paper was to correct this possible bias.

Another aim of the present study is to search, then to correct other possible biases present within the SEA. For that we limit our study to the MCs of best quality present in Lepping's list. The fitted Lundquist model provides the FR frame where the data are rotated in order to superpose, in a consistent way, the magnetic field components (azimuthal and axial components). We remind that comparable results have been obtained with FR orientation defined with the minimum variance method (Lanabere et al. 2020). The magnetic components also need to add up. This requires that all cases have the same sign of magnetic helicity and impact parameter. Furthermore, the magnetic signals need to be phased in time so that the closest approach distance of all the FRs syncronized to a common reference time. This is typically not the case when the MC boundaries are used for the SEA (Lanabere et al. 2020) since MCs are typically eroded on one or both sides when observed at 1 au. The Lepping's list does not provide the time of the axis closest approach because it provides only the absolute value of a related parameter, called asf (see, Démoulin et al. 2019). We then performed a least square fit, as originally done, to recover the sign of asf. This is a useful byproduct obtained in the present study, and presented in Table A.1. This fully complete the parameter set of the best Lundquist model associated to each MC.

In order to have a more coherent superposition of the magnetic field components in the SEA we use the fitted model to align the various parameter data. We select three possible FR boundaries (see Fig. 3). The first one is set at R_0, where $B_z(R_0) = 0$ for the Lundquist model (original Lepping's choice). The second one, R_{inf}, is set to include only the inner spatially symmetric part of the FR extension, crossed by the spacecraft, so it corresponds to the FR remaining when crossed by the spacecraft. Extra magnetic flux present before or after is interpreted as the remaining magnetic flux on the side opposite to erosion (rather than extra flux not belonging to the FR close to the Sun). The third radius, R_{sup} is designed to incorporate also this extra magnetic field at the outer part. This implies a data gap on the outer part of the other side. Since erosion occurred almost as frequently at the front and the rear (Ruffenach et al. 2015), the periphery part of the profiles are based on about half MC data.

Even selecting the best observed MCs, of quality $Q_{1,2}$, within Lepping's list, biases are present in the corresponding SEA. A first bias is tied to the magnitude of the impact parameter p. The largest effect is an increasing profile of B_x with distance to the FR axis. This bias is strongly weakened when the impact parameter is limited to $|p| \leq 0.3$ (Fig. 5). A second bias is linked to the field strength asymmetry between in- and outbound. This bias can affect the quality of the obtained FR orientation, with consequences on possible mixing of B components in the local FR frame. This asymmetric effect is also again mostly present in B_x component, and could be reduced by limiting the B asymmetry of the MCs included within the SEA. Finally, a third possible bias is linked to flux erosion during the travel from the Sun. This bias is found to be weak as the profile of the B components are similar with the data limited to the MC or by a given radius of the fitted FR. All these results justify and set on a more firm ground the results of Lanabere et al. (2020) obtained with directly including the MC data in a simple way, neglecting the in-out bound asymmetries present in each of the analysed events.

The twist profile within a MC is typically difficult to derive because the spacecraft crosses typically only a part of the FR, missing in general the core, and because the computations need to be done in the FR frame with an axisymmetric hypothesis. Magnetic fluctuations and peculiarities of individual MCs worsen the derivation of the twist profile. The expected singularity of the twist profile at the FR radius (with finite B fluctuations) and at its periphery (where the axial field component vanishes) worsen the derivation of the twist profile. These difficulties are soften with a superposed epoch analysis (SEA). The various derived profiles, with different selected outer FR radius and different set of MCs (to analyze bias effects) point to a flat twist profile in the FR core (about two third of the FR radius). In the vicinity of the FR axis, there is presently not enough MCs observed with low impact parameter to get a reliable twist profile. At the FR periphery the twist is sharply increasing, while the uncertainty is large mostly due to a weak axial B component easily affected by external perturbations. This implies that the original FR present close to the Sun is expected to have a more strongly twisted periphery, in agreement with the solar FR further building up during eruptions (see Démoulin et al. 2019).

Summarizing, we verify that SEA in MCs is weakly sensible to the precise definition of the boundaries considered to do the superposition. Still, SEA includes the biases present in the original data set. The selection of the included MCs can significantly reduce these biases, but with the cost of decreasing the number of events and consequently having weaker statistics, thus including more fluctuations in the SEA profiles. Further improvements would require a larger data base of observed MCs especially to better constrain the twist profile near the centre and the periphery of the FR).

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Appendix A: Table of analyzed MCs, including the obtained sgn(asf).

Table A.1. Results for Lepping MCs events of quality $Q_{1,2}$. The event Lepping's code, |asf|, R_0 and Q_{best} are from Lepping's table. The sign of asf is obtained by selecting the case with minimum χ_R. R_{inf} and R_{sup} are defined in Eq. (10).

Event	Code	|asf|	sgn(asf)	R_{inf}/R_0	R_{sup}/R_0	R_0	$\chi_{R,minus}$	$\chi_{R,plus}$	Q_{best}
1	1	17.4	+	0.860	1.118	0.108	0.43	0.27	0
2	2.2	6.8	+	0.929	0.987	0.152	0.31	0.27	0
3	3	1.0	+	1.208	1.222	0.042	0.15	0.15	0
4	5	26.5	+	0.734	1.070	0.126	0.50	0.28	0
5	6	2.3	+	1.050	1.099	0.129	0.16	0.15	1
6	8	27.5	+	0.679	1.184	0.175	0.52	0.27	0
7	9	6.8	+	0.806	0.920	0.086	0.28	0.28	1
8	10	10.3	-	0.898	1.053	0.107	0.27	0.30	0
9	11	4.2	+	1.036	1.108	0.143	0.19	0.17	0
10	12	14.3	+	0.921	1.225	0.095	0.31	0.13	1
11	14.1	6.3	+	0.636	0.689	0.131	0.36	0.34	0
12	15	19.3	+	0.754	1.084	0.093	0.37	0.20	0
13	17	5.2	-	0.814	0.866	0.093	0.25	0.28	0
14	22	7.4	+	0.601	0.697	0.117	0.11	0.08	1
15	23	12.0	-	0.728	0.859	0.198	0.30	0.38	0
16	24	4.1	+	1.152	1.227	0.114	0.15	0.14	0
17	25	1.8	-	0.577	0.597	0.110	0.11	0.11	1
18	26	1.6	-	0.899	0.920	0.058	0.24	0.25	0
19	28	1.5	+	0.928	0.957	0.119	0.15	0.14	1
20	30	5.5	-	1.361	1.454	0.147	0.12	0.18	0
21	31	5.5	+	0.880	0.982	0.164	0.18	0.16	1
22	33	22.7	+	0.589	0.902	0.035	0.35	0.19	0
23	34	24.3	-	0.716	1.136	0.104	0.13	0.39	1
24	35	4.4	+	1.081	1.179	0.107	0.31	0.28	0
25	36	14.8	+	0.965	1.194	0.204	0.27	0.14	0
26	38	5.3	-	1.097	1.217	0.124	0.18	0.21	0
27	41	9.5	+	0.873	1.041	0.136	0.28	0.21	1
28	44.3	20.8	+	0.719	0.954	0.132	0.34	0.19	0
29	47	33.0	-	0.683	1.005	0.115	0.28	0.29	0
30	49	14.2	-	0.945	1.257	0.142	0.21	0.36	0
31	51	1.1	-	1.021	1.043	0.092	0.16	0.16	1
32	52	16.7	+	0.572	0.794	0.119	0.24	0.15	1
33	54	22.4	-	0.658	1.011	0.138	0.13	0.34	1
34	55.1	0.8	-	0.851	0.864	0.083	0.14	0.15	1
35	56	21.1	-	0.956	1.072	0.191	0.17	0.19	0
36	57	9.2	+	0.774	0.813	0.125	0.14	0.10	0
37	58	28.9	+	0.625	1.130	0.133	0.43	0.12	1
38	59	15.3	+	0.685	0.859	0.116	0.21	0.11	0
39	60	22.5	+	0.713	1.031	0.126	0.29	0.18	0
40	61	16.4	-	1.182	1.570	0.127	0.29	0.45	0
41	64	17.7	-	0.472	0.650	0.104	0.09	0.17	1
42	65	3.2	+	0.993	1.058	0.216	0.23	0.22	1
43	66	1.4	-	0.795	0.807	0.159	0.19	0.20	0
44	68	5.2	+	1.058	1.082	0.212	0.09	0.09	0
45	71	8.4	-	0.544	0.640	0.127	0.09	0.12	1
46	72.1	24.8	+	0.696	1.052	0.073	0.34	0.27	0
47	73	1.6	+	1.015	1.034	0.105	0.17	0.17	0
48	76	27.0	+	0.497	0.847	0.144	0.37	0.24	0
49	77	14.4	+	1.049	1.401	0.090	0.43	0.23	0
50	78	2.6	-	1.045	1.089	0.197	0.26	0.28	0
51	80	21.5	-	0.804	1.192	0.178	0.16	0.41	1
52	81	5.4	-	0.793	0.884	0.120	0.15	0.19	1
53	82	1.0	-	0.939	0.956	0.087	0.12	0.12	0
54	83	6.7	-	0.862	0.964	0.072	0.21	0.24	0
55	84	1.9	+	0.859	0.885	0.075	0.12	0.11	0
56	85	0.5	+	1.140	1.147	0.195	0.13	0.13	0
57	86	13.1	+	1.134	1.449	0.090	0.38	0.30	0

Table A.1. Continued.

Event	Code	|asf|	sgn(asf)	R_{inf}/R_0	R_{sup}/R_0	R_0	$\chi_{R,minus}$	$\chi_{R,plus}$	Q_{best}
58	87	28.8	+	0.520	0.840	0.131	0.27	0.12	0
59	89	9.9	+	0.892	1.043	0.074	0.23	0.19	0
60	92	18.7	+	0.883	1.289	0.068	0.42	0.22	0
61	94	18.1	+	0.640	0.891	0.113	0.21	0.14	1
62	95	2.6	-	1.004	1.044	0.067	0.17	0.17	0
63	99	4.5	+	0.928	1.011	0.046	0.20	0.20	1
64	100	3.0	-	1.131	1.200	0.066	0.30	0.32	0
65	102	23.0	-	0.552	0.826	0.066	0.10	0.27	1
66	104	14.0	+	0.659	0.872	0.060	0.28	0.26	0
67	105	9.0	-	1.124	1.335	0.085	0.23	0.32	0
68	107	2.9	+	0.845	0.863	0.091	0.32	0.30	0
69	108	34.5	-	0.414	0.850	0.034	0.15	0.42	1
70	109	23.4	-	0.616	0.855	0.061	0.13	0.27	0
71	110	16.5	-	0.521	0.719	0.033	0.17	0.27	0
72	113	6.8	+	0.862	0.900	0.168	0.36	0.34	0
73	119	15.2	+	0.937	1.266	0.092	0.34	0.19	0
74	120	0.0	+	1.102	1.102	0.144	0.54	0.54	0
75	123	2.1	+	0.878	0.893	0.055	0.22	0.22	0
76	131	23.3	+	0.664	1.053	0.174	0.33	0.14	1
77	132	10.7	-	0.992	1.229	0.057	0.20	0.29	0
78	133	30.6	+	0.555	1.033	0.046	0.42	0.23	0
79	136	24.4	-	0.641	1.014	0.106	0.30	0.48	0
80	137	17.3	+	1.218	1.680	0.017	0.53	0.22	0
81	142	0.7	-	0.988	1.001	0.080	0.21	0.22	1
82	144	4.8	+	1.001	1.099	0.111	0.24	0.21	0
83	145	4.0	-	0.831	0.877	0.078	0.46	0.49	0
84	146	20.0	-	0.993	1.056	0.101	0.18	0.26	0
85	148	5.7	+	0.898	1.005	0.069	0.20	0.17	0
86	150	4.4	-	0.886	0.951	0.070	0.17	0.18	0
87	151	21.3	+	1.000	1.066	0.100	0.58	0.50	0
88	153	36.6	-	0.566	0.883	0.057	0.33	0.53	0
89	158	9.3	+	0.895	1.054	0.125	0.31	0.25	0
90	159	27.5	-	0.795	1.244	0.094	0.16	0.47	0
91	160	9.2	+	1.142	1.370	0.093	0.30	0.22	0