COMPARISON OF MAGNETIC PROPERTIES IN A MAGNETIC CLOUD AND ITS SOLAR SOURCE ON 2013 APRIL 11–14

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ABSTRACT

In the context of the Sun–Earth connection of coronal mass ejections and magnetic flux ropes (MFRs), we studied the solar active region (AR) and the magnetic properties of magnetic cloud (MC) event during 2013 April 14–15. We use in situ observations from the Advanced Composition Explorer and source AR measurements from the Solar Dynamics Observatory. The MCs magnetic structure is reconstructed from the Grad–Shafranov method, which reveals a northern component of the axial field with left handed helicity. The MC invariant axis is highly inclined to the ecliptic plane pointing northward and is rotated by 117° with respect to the source region PIL. The net axial flux and current in the MC are comparatively higher than from the source region. Linear force-free alpha distribution (10^-7–10^-6 m^-1) at the sigmoid leg matches the range of twist number in the MC of 1–2 au MFR. The MFR is nonlinear force-free with decreasing twist from the axis (9 turns/au) toward the edge. Therefore, a Gold–Hoyle (GH) configuration, assuming a constant twist, is more consistent with the MC structure than the Lundquist configuration of increasing twist from the axis to boundary. As an indication of that, the GH configuration yields a better fitting to the global trend of in situ magnetic field components, in terms of rms, than the Lundquist model. These cylindrical configurations improved the MC fitting results when the effect of self-similar expansion of MFR was considered. For such twisting behavior, this study suggests an alternative fitting procedure to better characterize the MC magnetic structure and its source region links.

Key words: solar–terrestrial relations – Sun: coronal mass ejections (CMEs) – Sun: filaments, prominences – Sun: flares – Sun: heliosphere – Sun: magnetic fields

1. INTRODUCTION

Magnetic clouds (MCs) are large-scale, organized magnetic structures in interplanetary space (Burlaga et al. 1981), characterized by a smoothly rotating field of enhanced field strength, low proton temperature, and low proton beta. They are usually observed in situ as interplanetary coronal mass ejections (ICMEs) that are generally preceded by the occurrence of major coronal mass ejections (CMEs) at the Sun. Many ICMEs are likely to be associated with an MC depending on the trajectory of spacecraft (Xie et al. 2013). It is now believed and shown from a variety of independent studies that ICMEs are magnetic flux ropes (MFRs) of locally straight cylindrical geometry (Burlaga 1988; Farrugia et al. 1995; Shodhan et al. 2000; Liu et al. 2008; Gopalswamy et al. 2013; Hu et al. 2014). In this picture, the MC is thought to be part of a large-scale bent flux rope extending from the Sun into interplanetary space with its feet possibly still connected to the Sun (Burlaga 1991; Farrugia et al. 1993; Bothmer & Schwenn 1998; Webb et al. 2000). From this point of Sun–Earth connection, a major interesting, important question is how the solar source regions are connected to the in situ MCs, which should lead to important clues on how to forecast the internal magnetic field of CMEs around Earth and other planets.

Toward this scientific aspect, MCs are mostly studied from in situ one-dimensional observations. Various fitting models have been developed to reconstruct the global picture of MCs in two or three dimensions (e.g., Lepping et al. 1990; Hu & Sonnerup 2002; Al-Haddad et al. 2013; Janvier et al. 2015). On the other hand, the solar source regions are studied for the onset of the CME (Moore et al. 2001; Forbes et al. 2006; Kliem & Török 2006; Chen 2011; Cheng et al. 2012; Vemareddy et al. 2012b; Vemareddy & Zhang 2014) and its propagation is tracked from Sun to near Earth using various space based observations to confirm the connection of solar source regions with MCs (Gopalswamy et al. 2001a; Manoharan 2006; Davies et al. 2009; Liu et al. 2010a, 2010b, 2013; Harrison et al. 2012; Möstl et al. 2012, 2014; Temmer et al. 2012; Webb et al. 2013; Vemareddy & Mishra 2015). Although, at the two ends, we enhanced our understanding of connecting MCs at 1 au to the Sun in many cases (Gopalswamy et al. 2013; Xie et al. 2013), relating the source region signatures to magnetic properties in MCs is still lacking.

The plasma structures commonly recognized as flux ropes in magnetically active regions (ARs) on the Sun include filaments, sigmoids, and erupting loops. Because direct magnetic observations of the coronal flux ropes are not possible, the amount and distribution of twist in the flux ropes are inferred generally, as a proxy, from photospheric magnetic field observations (Pevtsov et al. 1995; Hagino & Sakurai 2004; Vemareddy et al. 2012a). Furthermore, there is great difficulty in identifying an unambiguous one-to-one association between the MC and its solar progenitor due to CME–CME interactions (Gopalswamy et al. 2001b; Burlaga et al. 2002; Lugaz et al. 2005; Harrison et al. 2012; Liu et al. 2012, 2014a, 2014b; Möstl et al. 2012; Temmer et al. 2012; Mishra et al. 2015), CME-deflection (Wang et al. 2004, 2014; Liewer et al. 2015; Möstl et al. 2015), or multiple Earth facing ARs. Therefore, before associating the magnetic signatures from the
solar source region to the in situ MC, it has to be assured that the MC is uniquely identified from its source region.

Given the model of flux rope configuration to the in situ MCs (Lepping et al. 1990), the total field line lengths at the MC boundary must be larger than at the center. This is a fundamental physical point to help assess the flux rope model of Sun–Earth connecting MCs. Based on this point, following the approach of Larson et al. (1997), Kahler et al. (2011a, 2011b) compared the total field line lengths derived from the energetic electron beam spectrum, with that derived from Lundquist and flux conservation models. Their comparison, in a set of WIND MC events, implied a poor correlation between measured and modeled field line lengths, indicating doubt on the Lundquist flux rope concept to the MCs. Recently, this issue has been further clarified by the study of Hu et al. (2015), where they employed the Grad–Shafranov (GS; Hu & Sonnerup 2002) reconstruction technique for the MC’s magnetic structure. It had been shown that the MC’s magnetic structure is more aligned with the constant twist Gold–Hoyle (GH) model (Gold & Hoyle 1960) but not with the Lundquist model, which features increasing twist from the axis of the flux rope to its boundary. In addition, there were difficulties in finding comparable magnetic parameters in the MC magnetic structure and its source regions. In a study of 12 interplanetary MCs, Leamon et al. (2004) found the MC magnetic flux to be comparable to that of the associated AR. They used a cylindrically symmetric constant α Lundquist model to derive the field line twist, total current, total magnetic flux from in situ observations of the MC. However, the total field twists of the MCs were about an order of magnitude larger than those of the ARs. These findings led them to believe that MCs associated with AR eruptions are formed by magnetic reconnection between these regions and their larger-scale surroundings, rather than the simple eruption of preexisting structures in the corona or chromosphere.

In the present paper, we study the source region magnetic properties of an MC event observed on 2013 April 14 using in situ observations from the Advanced Composition Explorer (ACE) and solar source AR measurements from the Solar Dynamics Observatory (SDO). Studies of the solar origins of its initiation and eruption mechanisms unambiguously revealed build-up and onset of a sigmoidal flux rope to a large-scale CME eruption facing Earth from AR 11719 (Vemareddy & Zhang 2014). Further connections of this CME eruption to our MC of interest are uncovered by another detailed study by tracking the CME to a near Earth environment (Vemareddy & Mishra 2015).

Motivated by many previous studies (e.g., Larson et al. 1997; Leamon et al. 2004; Möstl et al. 2009; Kahler et al. 2011a, 2011b; Hu et al. 2014, 2015), in an attempt to provide further details about the in situ magnetic structure of flux ropes and their Sun–Earth connections of major solar eruptions, we employ the GS reconstruction technique and then compare the MC’s orientation and magnetic signatures to its solar source region (Liu et al. 2010b, 2016; Nieves-Chinchilla et al. 2012). Moreover, the GS reconstruction results are compared with the cylindrically symmetric linear force-free Lundquist model and the nonlinear force-free GH model fitting results in order to assess the differences in the estimated fitting parameters. In Section 2, we present the observations of the solar source region of the MFR. The results of GS reconstruction from in situ MC observations are described in Section 3, and its magnetic signatures are compared to that from the source region in Section 5. In Section 4, the MC fitting based models are discussed in conjunction with GS reconstruction. Conclusions are highlighted in the discussion in Section 6.

2. SOURCE AR OF CME ERUPTION

The MC’s source region on the Sun is AR 11719. From this AR, a halo CME eruption occurred on 2013 April 11 at 06:50UT. At this moment, the AR is located at N9E13. The AR consists of a filament channel that is overlaid by an inverse-S sigmoid (see Figure 1). Regarding this sigmoid as an MFR system, an exceedingly critical twist in the MFR (kink instability) is interpreted as an initiation mechanism of the eruption at 06:50UT preceded by a GOES class M6.6 flare (see more details in Vemareddy & Zhang 2014). Moreover, a torus instability (Török & Kliem 2005) is evidenced as a later mechanism to further drive the CME eruption.

Figure 1 (left panel) shows the vector magnetic field measurements of the AR by Helioseismic Magnetic Imager (HMI; Schou et al. 2012; Centeno et al. 2014; Hoeksema et al. 2014) on board SDO. The AR consists of a main sunspot (inset) from which the sigmoid (right panel) originates and lies along the polarity inversion line between negative flux in the north and positive flux in the south. Magnetic fields are evolving with decreasing flux content in both polarities for three days preceding the eruption. Magnetic fields in the sunspot from which the sigmoid originates clearly show left handed orientations. Using these vector magnetic field observations, we calculate the average value of the force-free parameter (αav) given by

$$\alpha_{av} = \frac{\sum_j J_j (x, y) \text{sign} [B_z (x, y)]}{\sum |B_z|}$$

(1)

where $J_j (x, y) = \frac{1}{\mu_0} (\nabla \times B (x, y))_z$ is the vertical current distribution. As the local distribution of $\alpha (x, y)$ ($J_j (x, y) / B_z (x, y)$) measures the extent of twist of the field lines due to field-aligned currents, its average $\alpha_{av}$ is a proxy to quantify the overall twist of the entire AR magnetic structure (Hagino & Sakurai 2004). Its value at the start (00:00UT) of April 11, is calculated as $-0.3 \times 10^{-8} m^{-1}$ and found to increase predominantly to around $-2 \times 10^{-8} m^{-1}$ by 12:00UT on April 11. The negative value of $\alpha_{av}$ indicates a left handed magnetic field twist in the AR and hence a dominant negative helicity. This is well consistent with the observed geometry of the inverse-S shaped coronal sigmoid.

As further studied in Vemareddy & Mishra (2015), the disappearing net flux was suggested to help in sustaining and developing the sigmoid with increasing twist. Localized twist measurements from vector magnetograms also support the availability of critical twist (more than one turn within the arc length of the sigmoid, see Figure 7 in Vemareddy & Zhang 2014) in the sigmoid before the onset of the eruption. This critical twist is crucial for the onset of the initial rise motion as a mechanism of the kink instability (Török & Kliem 2005).

The tilt of the sigmoid (referred to as MFR) is 45° to the central meridian, i.e., the flux rope axis makes an angle of
roughly 225° to the solar north in the counterclockwise direction (See schematic in Figure 3). This value of the tilt angle, in combination with other source region parameters, visually fits the observed CME morphology captured in the STEREO and LASCO field of view to a good extent (Vemareddy & Mishra 2015). Because this CME is a halo and Earth directed, its arrival at the L1 point is identified with a shock (on 13 April, 22:50UT), a leading edge (on 14 April 14:35UT), and a trailing edge (on 15 April 17:50UT) with the characteristics of an MC from the in situ velocity and magnetic field measurements. As studied in Vemareddy & Mishra (2015), the in situ parameters interpret a tilt angle of 360° with respect to solar north in the anti-clock direction. This mismatch in the orientation of the MFR (difference of roughly 135° tilt angle) in the source region and in the in situ MC could well be due to the rotation of the MFR apex during its initiation and/or propagation (Liu et al. 2010b; Vourlidas et al. 2011). As predicted by numerical and observational studies (Fan & Gibson 2003; Green et al. 2007; Lynch et al. 2009), the apices of MFRs would rotate due to inherent twist in them, left handed helical ones in the counterclockwise direction and right handed in the clockwise direction. In our case of the left handed MFR, a counterclockwise rotation is expected.

As seen in Figure 1, the MFR axial field is pointing in the lower right (southwest), because the MFR poloidal field is coming out of the photosphere in the south and going into the photosphere in the north of the magnetic neutral line. For such a poloidal field, a left handed MFR has an axis to the southwest. Therefore, the presumed MFR rotation would be counterclockwise roughly on the order of 135° to match the in situ flux rope orientation (see Figure 3). Resolving the source region signatures of MFRs is essential for their Sun–Earth connections because observationally tracking the magnetic structure of the CME has not yet been made possible.

3. GS RECONSTRUCTION OF THE MC MAGNETIC STRUCTURE

We employed the GS reconstruction technique (Hu & Sonnerup 2002) to construct the magnetic field structure in the MC cross-section. This technique involves the assumption of translational symmetry of the magnetic field along the flux rope and thus enables us to construct the field in a 2D cross-section with an invariant z-axis. The required in situ magnetic and velocity field observations (in GSE coordinate system) of the MC are obtained from ACE. In Figure 2, we show various observed parameters with time, during the MC passage through the spacecraft. An MC passage is generally identified by a strong magnetic field strength, low plasma $\beta = 2\rho B^2 / T$, rotation of any magnetic field component (reversal of sign during passage). As an outcome of the application of the GS method, we set the time interval between 15:56UT on April 14 [day of year as 104] and 17:56UT April 15 [day of year as 105], indicating its large size. Note that the $B_z$ component changes sign from positive to negative, while $B_x$ and $B_y$ components remain positive during this MC passage. This means that this MC belongs to the east–north–west category according to the classification schemes introduced by Bothmer & Schwenn (1998) and Mulligan et al. (1998).

Recovering the magnetic field in the MC cross-section essentially involves determining the deHoffmannTeller (HT) frame and orientation of the MC axis (Hu & Sonnerup 2002). Minimization of the mean square convective electric field in a moving frame gives the velocity of the HT frame ($V_{HT}$) as 414 km s$^{-1}$. Minimum variance analysis of magnetic field vectors and construction of residue maps determined the exact MC axis orientation pointing at 72° latitude ($\theta$) and 101° longitude($\phi$). $\phi$ is the longitude, being 0° toward GSE X, +90° toward GSE Y, and so on. $\theta$ is the latitude, which can also be called inclination, that is 0° in the ecliptic, +90° toward ecliptic.
north (along GSE +Z), and −90° to ecliptic south (GSE − Z). We note that the latitude of 72° refers to an alignment of MC axis with respect to the ecliptic. In other words, it is away from the ecliptic north (vertical plane to ecliptic) by 18°. This is consistent with the interpreting arguments by Vemareddy & Mishra (2015), who speculate a possible rotation of the MFR apex up to 135° due to the inherent nature of handedness of the magnetic field in the MFR. In this case, the left handed helicity of the magnetic field in the MFR might lead to a rotation in the counterclockwise direction (as seen in the line of sight) during its outward propagation, tending to align the MFR axis plane roughly perpendicular to the ecliptic plane. Particularly from the source region observations, the apex is likely rotated by about 117° (45° + 72°) to match the GS result of the MC axis orientation. The schematic in Figure 3 depicts the above described orientation of the in situ and source region MFR with respect to the ecliptic plane. We believe that the MC axis orientation is a crucial physical parameter and provides constraining clues on the Sun–Earth connection of MFRs.

Next, the measurements of transverse pressure $P_t(A)$, which is a sum of plasma pressure $p$ and axial magnetic pressure $B_z^2/2\mu_0$, are re-sampled onto a grid of 17 points using an anti-aliasing re-sample function, and are then fitted with a second order polynomial as shown in Figure 4 (right). A residue value $R_f = 0.08$ quantitatively describes the goodness of fit to the most data points. The resulting reconstructed map of MC’s cross-section is plotted as contours of the flux function (A) and filled contour plot of $B_z$ in color with a scale (left panel in Figure 4). The white thick contour refers to the MC boundary used for calculating the magnetic fluxes, which is based on the point of divergence of the inbound and outbound $P_t(A)$ functions at the value of $A_b$ in the right panel. This contains a slightly smaller interval than the MC interval as given by the boundaries in Figure 2. Closed contours of A represent helical field lines winding the axis in projection. The MC is larger than earlier studied cases (Hu & Sonnerup 2002; Möstl et al. 2009) having a size of 0.26 au. The closest distance of the spacecraft from the MC axis is 0.034 au on the positive y-side. This cross-sectional map could be influenced by a possible MC expansion.
Leading and trailing edges of MC are moving at a velocity of 461.4 and 376.7 km s\(^{-1}\) respectively. The ratio of MC expansion velocity \(V_{\text{exp}}\) (leading-trailing) to edge velocity \(V_{\text{IT}}\) is 0.102, which is feeble to a significant expansion effect.

The \(B_z\) distribution is positive with a maximum field strength of 13 nT. The transverse \((B_x, B_y)\) components magnetic components show a left hand winding of field lines in the MC and therefore the helicity is negative, which is consistent with the source region (Figure 1). The GS results of various parameters of the MC are summarized in Table 1.

Having three components of magnetic field in the MC cross-section, we can quantify the twist of the flux rope. As a measure of goodness of the fit, we compute the root-mean-square deviation \(\text{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (B_i(t_i) - B_{\text{fit}}(t_i))^2} \) between the observed magnetic field \(B_i(t_i)\) and the modeled field \(B_{\text{fit}}(t_i)\) (Marubashi & Lepping 2007). As can be noticed, both models reproduce the global trend of the field components, especially along the full length of the rope. In Figure 5, we have plotted field lines in different radial positions from the center of the MC. By the nature of the twist, the field lines wind about the axis in every flux shell. These field lines give an impression of a locally straight section of a large-scale bent flux rope, which is constituted by flux shells. Note that the central field line (axis) is almost straight. We then measure the axial length of each field line that completes one full turn about the axis. The twist number in three different radial directions from the axis (i.e., \(A_0\)) is plotted as a function of the shifted flux function \(|A - A_0|\) in Figure 6. In the three different radial directions, starting from 9 turns/au, \(\tau\) declines rapidly from the center to 1.2 turns/au in within a few units of flux function (radius). From there, the twist number shows slight increase to 1.75 turns/au and continues further till the MC boundary.

4. MC FITTING

In this section, we present MC fitting results from two different cylindrical configurations in order to compare with GS results.

4.1. GH versus Lundquist Models

We fitted the in situ magnetic field observations with the cylindrically symmetric linear force-free flux rope model (Lundquist 1950) with radial functions of axial and poloidal field components

\[
B_z(r) = B_0 \text{Bessel}J(0, \alpha r) \\
B_x(r) = H B_0 \text{Bessel}J(1, \alpha r)
\]

where \(\alpha\) is the force-free parameter, \(H\) is the sign of helicity, and \(B_0\) is the field strength. In this model, the magnetic field profile along the spacecraft’s observational path is determined by the orientation of the flux rope axis, i.e., the \(z\)-axis, which is given by the elevation and azimuth angle \((\theta\) and \(\phi)\), the closest approach of the observational path \(p\), the flux rope diameter \(D\), the helicity sign \(H\), and the field strength \(B_0\) in the center of the flux rope (Lepping et al. 1990; Leitner et al. 2007). As a second flux rope fitting model, we used the nonlinear force-free GH model (Gold & Hoyle 1960) assuming a uniform field line twist (e.g., Farrugia et al. 1999; Dasso et al. 2006; Hu et al. 2015). In this model, the radial functions of axial and poloidal field components are

\[
B_z(r) = \frac{B_0}{1 + T_0^2 r^2} \\
B_x(r) = \frac{H B_0 r}{1 + T_0^2 r^2}
\]

where \(T_0\) is twist number at the center. The fitting converges when \(T_0 = 1.2\) turns/au rather the GS result of \(T_0 = 9\) turns/au because the rest of GH is totally consistent with GS.

Figure 7 shows the results of the Lundquist model fitting (solid red) and the GH model fitting (dashed blue) to the in situ magnetic field observations (black). The vertical lines mark the edges of the MFR. As a measure of goodness of the fit, we compute the root-mean-square deviation \(\text{rms} = \frac{1}{N} \sum_{i=1}^{N} (B_i(t_i) - B_{\text{fit}}(t_i))^2 \) between the observed magnetic field \(B_i(t_i)\) and the modeled field \(B_{\text{fit}}(t_i)\) (Marubashi & Lepping 2007). As can be noticed, both models reproduce the global trend of the field components, especially...
the rotating component, quite well. However, the GH configuration performs slightly better in terms of the Erms parameter \((\text{E rms} = \text{rms}/\text{max}(|\mathbf{B}|))\). It is 0.266 for the Lundquist and 0.175 for the GH fit. The resulting orientation of the flux rope for both models is almost the same. The helicity sign \(H\) and the field strength \(B_0\), inclination angles are in agreement with the GS reconstruction results; however, other parameters differ considerably. The derived parameters are listed against the GS values in Table 1.

The radial profile of GS inferred \(\tau\) is compared with that by the GH and Lundquist models (Figure 6). For this purpose, the GS derived field strength \((B_0 = 13\text{ nT})\), twist \((T_0 = 9 \text{ turns/au} = 56.5 \text{ radians/au})\), and radius \((R_0 = 0.26 \text{ au})\) are supplied to Equations (3) and (4). The Lundquist flux rope model implies increasingly varying \(\tau\) from the axis, whereas the GH model gives a constant twist from center to the boundary of the flux rope. This kind of \(\tau\) variation was also found in some case studies of Hu et al. (2014). GH configuration is thus inferred to be more consistent with the general behavior of field line turns in the GS result of the MCs magnetic structure.

Since the Lundquist fit infers the radius of MC as 0.135 au, the twist number is \((T_0 = \frac{\alpha}{\rho} = \frac{2.405}{0.135 \times 2} \text{ turns/au})\) estimated to be 2.83 turns/au. In the GH fitting, the twist serves as an additional fitting parameter, so the fitting directly results in 1.2 turns/au. Therefore, the result of about one turn from the GH result is quite consistent for most of the GS twist (flat value of 1.75) results in Figure 6. This inference is based on one event; however, a better fit in most of the cases, especially the rotating component, is generally expected from the GH model fitting than the Lundquist model fitting due to the internal field configuration.

### 4.2. GH versus Lundquist Models with Expansion Effect

While the spacecraft traverses the MC, it undergoes expansion significantly in a timescale of a day. To account for this expansion in the fitting, Farrugia et al. (1992) proposed a self-similar expansion model to the MC. This model was later applied to cylinder and torus geometry by Marubashi & Lepping (2007). In this model, the radius of the MC (cylinder, Equations (3) and (4)) varies with time \((t)\) as \(r(t) = r_0(1 + Et)\), where \(E\) is the expansion rate by which means force-free parameter \(\alpha\) is time varying while being spatially constant. Furthermore, the magnetic field components are also inversely proportional to \((1 + Et)^2\). The model relies on the observed data of solar wind in addition to magnetic field components, and the MC fitting determines \(E\), the average solar wind velocity \(U_0\), along with other parameters as in the models without expansion. Following this fitting procedure described in Marubashi & Lepping (2007, Appendix A), the results for GH and Lundquist configurations are plotted in Figure 8, and the fitted parameters are listed in Table 1.

During the fitting procedure, we set \(U_0\) to the \(V_{\text{fitt}}\) frame velocity \((414 \text{ km s}^{-1})\) for both the configurations. In the Lundquist configuration, the MC radius \((r_0 = 0.12 \text{ au})\) yields \(T_0 = 3.19 \text{ turns/au}\). Whereas, for the GH configuration, the fitting converges (especially the rotating component) when \(T_0 = 1.1 \text{ turns/au}\). This is a consequence of reducing the twist number from the center toward the MC boundary to a uniform level of 1.75 turns/au and the expansion effect mimics it to reproduce the observations. The expansion coefficient \((0.22 \text{ per day})\) is significant that the initial MC radius increases by 25% at the time the spacecraft passes the MC rear boundary. The orientation differs significantly in \(\phi (132^\circ)\) with a similar \(\theta\) as in the GS method. The rms deviation between the observed and model magnetic fields for the Lundquist and GH fits are 26.1 and 19.1, respectively, which delineates the goodness of GH fit over the earlier.

### 5. COMPARISON OF MAGNETIC PROPERTIES IN THE MC AND THE SOURCE AR

To compare the AR twist with that of the MC, the total field line length is required because a direct comparison of the twist parameter is not suitable because field lines stretch while the
flux rope structure expands. Kahler et al. (2011b) derived total field line lengths by using solar energetic particles, like electrons, of known speeds. The procedure requires the observations of solar release times as bursts and their 1 au onset times in the form of type III radio emission. Recently, Hu et al. (2015) utilized these procedures and showed that the in situ measurements of field line lengths are consistent with a flux rope structure with spiral field lines of constant and low twist. Based on their analysis of a limited number of MC events, they argued that under most circumstances, the effective axial length of a cylindrical flux rope is $L_{1,2}^{eff}$. They suggested to adopt this range of field line axial length for the relevant studies of deriving and relating various physical quantities to their solar sources.

Considering the field lines of total length $L = 1$–2 au, the GS-based MC twist distribution $(\alpha L)_{MC}$ comes out to be 1.75–18.00 turns, reflecting the full variation from the center to the edge in Figure 6. Note that $(\alpha L)_{MC}$ can also be referred to as $(\tau L)_{MC}$. Now in the source region, given the distance of 66 Mm (see Figure 1, and also, Vemareddy & Zhang 2014) between the legs of the sigmoidal flux rope, assuming a half torus shape, the average length of the field lines in the sigmoidal flux rope would be 103 Mm. The average twist from

| Method       | $V_{HT}$ | $B_0$ | $\theta$ | $\phi$ | $T_0$ | $D$   | $p$ | $\Phi_A$ | $\Phi_P$ | I    | $U_0$ | E    | Erms |
|--------------|----------|-------|----------|--------|-------|-------|-----|----------|----------|------|------|------|------|
| GS           | 414      | 13.0  | 72       | 101    | $-9.0$| 0.26  | 0.03| 0.46     | 0.73     | 0.477| ...  | ...  | ...  |
| Lundquist    | 414      | 13.0  | 73.8     | 73.7   | $-2.83$| 0.27  | 0.04| 0.71     | 1.63     | 0.675| ...  | ...  | 0.266|
| GH           | 414      | 12.2  | 74.6     | 74.4   | $-1.2$ | 0.28  | 0.05| 1.12     | 1.34     | 0.637| ...  | ...  | 0.176|
| Lundquist+Exp| 414      | 17.3  | 69.8     | 132    | $-3.19$| 0.24  | 0.06| 0.76     | 1.94     | 0.807| 414  | 0.28 | 2.016|
| GH+Expansion | 414      | 14.1  | 72.6     | 62.5   | $-1.1$ | 0.24  | 0.04| 1.1      | 1.19     | 0.621| 414  | 0.22 | 0.147|

Note. The columns refer to the following parameters. $V_{HT}$: deHoffmannTeller frame velocity (km s$^{-1}$), $B_0$: field strength at the center of the cylinder (nT), $\theta$: latitude angle of MC axis (degree), $\phi$: longitude angle of MC axis (degree), $T_0$: twist number at the center (turns/au), $D$: MC diameter (au), $p$: impact parameter (au), $\Phi_A$: axial flux ($10^{21}$ Mx), $\Phi_P$: poloidal flux ($10^{21}$ Mx), $I$: axial current (GA), $U_0$: velocity of solar wind (km s$^{-1}$), $E$: expansion rate (/day), Erms: error in root mean square between observed and modeled field.
Figure 7. Cylindrically symmetric constant $\alpha$ linear force-free Lundquist model fitting (solid red) and nonlinear force-free GH (dashed blue) model fitting are plotted against the in situ observations (black) in each panel. $T_0 = 1.2$ turns/au is used for the GH configuration. The orange vertical lines mark the MC start and end times. Notice the better fitted rotating component with GH model.

the sunspot, where one of the legs of the sigmoidal flux rope lies, at the time of eruption is estimated as $-4.16 \pm 0.32 \times 10^{-5} m^{-1}$. This results in an AR twist distribution ($\alpha L_{AR}$) of 0.7 turns, which is less by a factor of three with the range of $(\alpha L_{MC})$. Note a $2\pi$ factor when referring to $(\alpha L_{MC})$ in units of turns. We note that $\alpha$ values in the sunspot region are distributed in the range of $(10^{-7} - 10^{-6}) m^{-1}$. Since the twist distribution in the GS-based MC is derived from the local magnetic field distribution, we argue that one should use the local range of $\alpha$ in the source AR too. By doing so, we arrive at $(\alpha L_{AR})$ as 1.6–16 turns, which is well within the range of $(\alpha L_{MC})$. Note that we followed the same procedures as Leamon et al. (2004), who found differing MC’s twist distribution of an order compared to their source regions. They assumed $L = 2.5$ au for the computation. Their result could likely be due to the use of average $\alpha$ over the entire AR and also less resolution magnetic field observations. Indeed, this is the case here (0.16 turns) for the entire AR value ($\alpha_{av} = 1.0 \times 10^{-8} m^{-1}$, see Table 2). Note that high resolution, highly sensitive, magnetic field observations will always improve the AR twist estimation with higher magnitude. It is thus obvious that even the moderate values $0.5 \times 10^{-7} m^{-1}$ of AR twist distribution would be comparable to most of the twist distribution in MC cross-section.

The ratio of axial flux ($0.46 \times 10^{14}$ Mx) from the MC and from the source sunspot region ($3 \times 10^{19}$ Mx) is 0.15. Similarly, the net current ratio is $0.34 \times 10^{-3}$. These values are typical and consistent with the cases presented in Leamon et al. (2004). From both the fittings with and without expansion, due to the increasing twist from center to the boundary, the Lundquist fit converges at a higher value of twist number for the MC than that from the GH fitting. Due to this fact, the poloidal flux in Lundquist fitting is significantly higher (by a factor of 2.5) than axial flux.

6. SUMMARY AND DISCUSSION

We have analyzed in situ observed MC and its solar source region in an effort to emphasize the flux rope connections of the Sun and the Earth. MFRs play a prime role in the Sun–Earth connections during major solar eruptive events like CMEs. The MC structures are accepted to be part of large-scale bent flux ropes with legs still having connections to the solar source AR. The solar AR 11719 is found to be the source region of the observed MC during 2013 April 14–15. The pre-eruptive AR has a well-developed inverse-S sigmoidal flux rope under the evolving conditions of canceling and approaching flux regions. This sigmoidal flux rope erupted on 6:50UT on 2013 April 11 and launched a halo CME directed at an average speed of 861 km s$^{-1}$ toward Earth.

Utilizing the in situ magnetic field observations, we examined the magnetic structure of the flux rope by the GS reconstruction method. The MC axis points at 72° latitude ($\theta$) and 101° longitude ($\phi$) in the GSE system, where the latitude determines the deviation of the MC axis from the zenith. Since the source region sigmoid is aligned at 225° from the ecliptic north, a possible rotation of the apex of the flux rope (up to 117°, Green et al. 2007; Lynch et al. 2009) in its expansion during CME eruption, could result in such a predicted axis orientation of 72° latitude. The axial field ($B_z$) in the MC structure is positive (northward) with a left handed twist consistent with the source region sigmoid morphology and magnetic field distribution.

This MC magnetic structure has a field line twist number of 9 turns/au at the center, which is decreasing to a flat value of 1.75 turns/au up to the boundary. As also found in a handful of cases by Hu et al. (2014, 2015), this inferred field line turns from the GS method is more consistent with the constant twist GH configuration rather the Lundquist configuration of increasing twist from the axis of the flux rope to its boundary. Because of this, the GS magnetic structure is nonlinear force-free and hence it would be more appropriate to use GH magnetic configuration to fit the in situ magnetic fields for estimating parameters of cylindrically symmetric MC structures.

For more clues on the connections of the source region, we compared source region magnetic properties with the GS-based MC magnetic structure. The net absolute axial flux and vertical current from the source sunspot region are comparatively small to that from the MC. These values are typical and consistent with the cases presented in Leamon et al. (2004). In contrast with their findings, the magnetic twist of the pre-eruptive AR is comparably in the range of the MC’s twist number. Identifying the anchoring region of the flux rope foot point, high resolution and high sensitive magnetic field observations in the source region better quantify the twist that manifests the flux rope. On the other hand, the length of field lines in the MCs is better constrained [1–2 au] now by previous studies (i.e., from Hu et al. 2015) and we now have a better grasp of the MC structure. We suggest the consideration of the distribution of $\alpha$ from the source region for its comparison with the in situ MC.
The cylindrically symmetric Lundquist and GH configurations reproduce the global trend of in situ magnetic field observations especially the rotating component. The resulting orientation of the flux rope for both the models is almost the same. The helicity sign $H$ and the field strength $B_0$, inclination angles are in agreement with the GS reconstruction results. Due to the flat value of twist, for the most part the MC, GH configuration with 1.1 turn/au resembles the GS twist value and fits the observations better over the Lundquist configuration. In fact, these fitting results improved (in terms of $\text{Erms}$) when considering the self-similar expansion into account (Marubashi & Lepping 2007). All the results including GS method yield the higher poloidal flux than the axial flux, indicating the twisted nature of field lines in the MC. Due to an increasing twist profile from center to boundary, the Lundquist fit estimates higher twist and poloidal flux than the GH fit. The GS reconstruction provides clues on the MC twist structure, which is, for the first time, fitted with the GH configuration as an alternative to general practice of the Lundquist configuration. Although the fitting improved to a great extent, it is not yet possible to see, in a large sample of data sets, the goodness of GH fitting (including the expansion effect) in characterizing the properties of in situ MC structures and their source region links.

In conclusion, the connection of the AR to the MC is unambiguous. The length of the field lines, both in the MC and in the source region sigmoid, is better constrained for a quantitative comparison of source region magnetic signatures in the in situ MC. The fitting procedures determine the lower twist values away from the MFR center. These are the important points that have been hindered in previous studies on definite conclusions of how the twist behaves in MFRs on the Sun and at 1 au. For such twisting behavior, this study suggests an alternative fitting procedure to better characterize

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**Table 2**

Comparison of Magnetic Twist in the MC and the Source AR

| AR Twist at 06:50UT on 2013 April 11 | $(\alpha L)_{AR}$ | $(\alpha L)_{MC}$ |
|-------------------------------------|------------------|------------------|
| $\alpha_{av} = 1.0 \times 10^{-5}\text{m}^{-1a}$ | 0.16 turns | 1.75–18.0 turns |
| $\alpha_{av} = 4.16 \times 10^{-8}\text{m}^{-1b}$ | 0.7 turns | 1.75–18.0 turns |
| $\alpha = 10^{-7}–10^{-6}\text{m}^{-1c}$ | 1.6–16 turns | 1.75–18.0 turns |

Notes.

- $a$ Average over entire AR, i.e., field of view of Figure 1(a).
- $b$ Average over sunspot region, i.e., inset in Figure 1(a).
- $c$ Local distribution in the sunspot region.

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**Figure 8.** Same as Figure 7, but accounting for the effect of self-similar expansion (Marubashi & Lepping 2007) in the MC fitting. $T_0 = 1.1$ turn/au is used for the GH configuration.
the MC magnetic structure. These two points open up the possibility to predict the MC twist configuration from the solar imaging information, which is of very high relevance to understanding the origin of the CME magnetic field (and its $B_z$) and thus space weather prediction in general.

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