A Sun-to-Earth Analysis of Magnetic Helicity of the 2013 March 17–18 Interplanetary Coronal Mass Ejection

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Abstract

We compare the magnetic helicity in the 2013 March 17–18 interplanetary coronal mass ejection (ICME) flux rope at 1 au and in its solar counterpart. The progenitor coronal mass ejection (CME) erupted on 2013 March 15 from NOAA active region 11692 and is associated with an M1.1 flare. We derive the source region reconnection flux using the post-eruption arcade (PEA) method that uses the photospheric magnetogram and the area under the PEA. The geometrical properties of the near-Sun flux rope is obtained by forward-modeling of white-light CME observations. Combining the geometrical properties and the reconnection flux, we extract the magnetic properties of the CME flux rope. We derive the magnetic helicity of the flux rope using its magnetic and geometric properties obtained near the Sun and at 1 au. We use a constant-α force-free cylindrical flux rope model fit to the in situ observations in order to derive the magnetic and geometric information of the 1 au ICME. We find a good correspondence in both amplitude and sign of the helicity between the ICME and the CME, assuming a semi-circular (half torus) ICME flux rope with a length of π au. We find that about 83% of the total flux rope helicity at 1 au is injected by the magnetic reconnection in the low corona. We discuss the effect of assuming flux rope length in the derived value of the magnetic helicity. This study connecting the helicity of magnetic flux ropes through the Sun–Earth system has important implications for the origin of helicity in the interplanetary medium and the topology of ICME flux ropes at 1 au and hence their space weather consequences.

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

1. Introduction

Magnetic clouds (MCs) are a special kind of interplanetary manifestation of coronal mass ejections (CMEs) characterized by (1) a low proton temperature and a low proton beta compared to the typical solar wind, (2) an enhanced magnetic field strength, and (3) a smoothly rotated magnetic field (Burlaga et al. 1981). The flux rope magnetic structure of MCs makes them a distinct subset of interplanetary coronal mass ejections (ICMEs). The characteristics of MCs are of great interest because about 90% of the observed MCs are responsible for driving geomagnetic storms with Dst\textsubscript{min} (minimum Dst index observed in geomagnetic storm interval) ≤ −30 nT (e.g., Wu & Lepping 2007, 2008).

CMEs are generated due to the destabilization of coronal magnetic field structure, usually triggered by magnetic field evolution due to flux emergence, twisting, shearing, and converging motions in the photosphere. Magnetic reconnection in the solar corona allows transferring the photospheric shear to the twisted magnetic flux rope (Low 1996; Démoulin et al. 2006). The coronal flux rope thus formed becomes an MC after propagating through the interplanetary medium. Several studies have shown that all ICMEs have plausibly flux rope structure (Gopalswamy et al. 2013; Marubashi et al. 2015), which is an important fact that can be used for space weather predictions. However, only in situ observations of CMEs are not sufficient to conclude that flux rope configuration is present in all CMEs (Al-Haddad et al. 2011; Vourlidas et al. 2013).

One of the most important characteristics of CMEs is the magnetic helicity, which describes how the magnetic flux tubes are twisted, linked, and wound around each other in a closed volume. In the solar atmosphere and heliosphere the magnetic helicity is almost conserved (Berger & Field 1984). Theoretical considerations based on the conservation of magnetic helicity generate important constraints on flux tube dynamics in the solar convection zone and the tilt and twist of solar active regions (ARs; Nandy 2006). Beyond the solar atmosphere, throughout the propagation of MCs in the interplanetary medium, the magnetic helicity also remains invariant in a closed volume unless they significantly reconnect with the surrounding interplanetary magnetic field (IMF). This approximation has been the basis of several studies that connect interplanetary flux ropes with their solar sources (Daso et al. 2005; Qiu et al. 2007; Cho et al. 2013; Hu et al. 2014).

The computation of magnetic helicity of a flux rope requires the estimation of its geometry and axial magnetic field intensity (DeVore 2000; Démoulin et al. 2002). Based on the observed data at 1 au, it is possible to analyze the MC geometry by fitting a cylindrical or a torus-shaped flux rope model. Thus the axial magnetic field strength can be estimated. Considering the geometry of the causative CME and its poloidal flux, the helicity of the progenitor coronal flux rope can be measured. Several studies have shown that the low coronal reconnection flux is almost equivalent to the azimuthal flux of the flux rope formed due to reconnection (Longcope & Beveridge 2007; Qiu et al. 2007; Gopalswamy et al. 2017a). Gopalswamy et al. (2017a) devised a convenient method to compute the reconnection flux using the area under the post-eruption arcade (PEA) and the photospheric flux threading through this area.

The main aim of this study is to compare the magnetic properties of an MC with its associated coronal flux rope. In
particular, the magnetic helicity in the two domains is compared. For this study, we choose an identified MC event observed on 2013 March 17 at 1 au with a distinct solar source having a clear coronal signature and available LOS and vector magnetograms. Next, we extract the geometrical and magnetic information of the MC and its solar counterpart. Finally, we comment on the conservation of magnetic helicity in the Sun–Earth system based on our study and reflect upon the major source of magnetic helicity of CME flux ropes.

2. Observations

2.1. In situ Observation of ICME at 1 au

Figure 1 shows the in situ solar wind plasma and magnetic properties measured by the Advanced Composition Explorer (ACE) spacecraft (Stone et al. 1998; http://www.srl.caltech.edu/ACE/ASC/level2/1v12DATA_MAG-SWEPAM.html) at the L1 Lagrangian point along with the geomagnetic activity index (Dst) (http://wdc.kugi.kyoto-u.ac.jp/dst_final/index.html) during 2013 March 17–18. Starting from the top, we plot the total IMF intensity ($B$ in nT), the $y$ component of IMF ($B_y$ in nT), the $z$ component of IMF ($B_z$ in nT), the solar wind plasma flow speed ($V_{sw}$ in km s$^{-1}$), the proton density ($N_p$ in cm$^{-3}$), the proton temperature ($T_p$ in K), the proton beta (beta), and the Dst index in nT. The dashed curve overplotted on $T_p$ represents $T_{ex}$ and the horizontal dashed line on beta points the value, beta = 1. The black (dotted), red, and blue vertical lines indicate the shock arrival, start, and the end boundary of MC, respectively.
arrives with an interplanetary (IP) shock at 05:30 UT on 2013 March 17 (marked by a dotted vertical line in Figure 1). The observed shock velocity is 751 km s$^{-1}$. A sheath region with a high fluctuation of IMF vectors is present after the IP shock. The peak value of the IMF intensity and the minimum value of its $z$ component ($B_z$) in this region are, respectively, 22.1 and $-18.5$ nT. After the sheath region, a decrease in $T_e$ compared to $T_{ex}$, beta with a value less than 1, constant westward (negative) $B_z$, and south to north (negative to positive) smooth rotation of $B_z$ with strong magnetic field strength confirms that a small inclination bipolar (south–north) MC (Gonzalez et al. 1990; Li & Luhmann 2004) passes through L1. Moreover, the decrease in $T_e$ compared to $T_{ex}$ is only present close to the beginning and at the end of the MC. Within the identified boundaries, $T_e$ is not below $T_{ex}$ during some interval, although beta is $<1$. However, the speed has the declining profile indicative of MC expansion; the By component shows that the MC axis points to the west, while the Bz component shows rotation from south to north. Consistent with the Burlaga et al. (1981) definition the MC starts at 14:39 UT (marked by the red vertical line) and ends at 00:44 UT on March 18 (marked by the blue vertical line). We note that the rear boundary is well defined in this case, indicated by the discontinuities in the total magnetic field and solar wind speed. However, it must be noted that frequently the MC boundaries are not well defined. The duration of the MC is about 10 hr, which is $\sim48\%$ smaller than the average duration of solar cycle 24 MC at 1 au, $\Delta_{mc} = 19.19$ hr (Gopalswamy et al. 2015). The plasma speed at the MC’s leading edge and its trailing edge are, respectively, 671 and 567 km s$^{-1}$ (Gopalswamy et al. 2015). From these values, we derive the cloud’s central speed as 619 km s$^{-1}$ and the expansion speed as 104 km s$^{-1}$. The peak field strength and the minimum value of $B_z$ during MC interval are recorded as 13.4 nT and $-10.6$ nT, respectively. The ICME resulted in a classic double-dip, major geomagnetic storm (Kamide et al. 1998) due to southward IMF in the sheath, and MC. The minimum value of Dst is $-100$ nT during the sheath and $-134$ nT during the MC.

2.2. Identification and Observation of ICME Solar Source

To identify the solar source of the ICME, we use observations from different instruments on the Solar and Heliospheric Observatory (SOHO) and Solar Dynamic Observatory (SDO) missions. The Large Angle and Spectrometric Coronagraph (LASCO) telescope’s C2 and C3 on board SOHO observe the CME near the Sun. The fields of view of C2 and C3 (Brueckner et al. 1995) are respectively 2–6 and 4–30 $R_{\odot}$ measured in units of solar radius from the disk center of the Sun. We use the LASCO CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/) (Yashiro et al. 2004; Gopalswamy et al. 2009) to identify the MC-associated CME. To analyze the structure of the identified source CME, we use the observations from the Sun–Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al. 2008) COR2 A and B on board the Solar Terrestrial Relations Observatory (STEREO) mission along with the LASCO images. We study the solar source of MC-associated CME by using SDO’s Atmospheric Imaging Assembly (AIA) (Lemen et al. 2012) images at 193 Å, Helioseismic Magnetic Imagers (HMI; Scherrer et al. 2012) line-of-sight (LOS) magnetogram, and the Space-Weather HMI AR Patch (SHARP; Bobra et al. 2014) vector magnetogram to study the source AR of the ICME.

We identify the CME associated with the ICME in question by following the procedure described in Zhang et al. (2007). We consider the solar wind speed at shock arrival (757 km s$^{-1}$) as the transit speed of the CME-driven shock travels from the Sun to the Earth and estimate the transit time as $\sim54$ hr, suggesting that the associated CME should start only after 00:00 UT of 2013 March 15. By searching the LASCO CME catalog for frontside wide CMEs during the transit time interval, we find only one CME originating close to the disk center in the LASCO/C2 FOV at 07:12 UT on 2013 March 15. It has a high projected speed of 1063 km s$^{-1}$ consistent with the fast ICME. The CME is associated with an M1.1 GOES soft X-ray flare that initiated at 05:46 UT on March 15. The CME leaves behind a PEA as an apparent coronal feature observed by SDO/AIA at 193 Å during the decay phase of the long duration flare. Thus we identify the source location of the CME as N11E12, which corresponds to the NOAA AR 11692. In Figure 2, we show the running difference image of the associated CME observed by LASCO/C2 along with the PEA in solar corona observed by SDO/AIA at 193 Å.

3. Analysis and Results

3.1. Analysis of ICME Data

To understand the structure and magnetic nature of the cloud, we use a constant-$\alpha$ (linear) force-free cylindrical flux rope model with self-similar expansion, which was proposed by Farrugia et al. (1992, 1993) with a modification based on Shimazu & Vandas (2002). Following Marubashi & Lepping (2007), we perform the fitting of the model during the interval, when the magnetic field rotates smoothly in the Y–Z plane, proton temperature and proton beta decrease from their average values, $He^{++}/H^+$ value increases, proton number density decreases, and the fluctuation in the ratio of standard deviation to the mean magnetic field intensity ($S_B/B$) is relatively small. Figure 3 shows the solar wind data during 2013 March 17–18 with the cylindrical model fitting results. From top to bottom, we plot $B_r$, $B_p$, $S_B$, $V_{sw}$, $N_p$, $He^{++}/H^+$, $T_p$, beta, and vector plots of the magnetic field projected on $X-Y$, $X-Z$, and $Y-Z$ plane in 30 minute average. The vertical solid lines in the figure denote the start and end times of the cloud. The red curves overplotted on $B_r$, $B_p$, $S_B$, and $V_{sw}$ represent the fit. $T_p$ is overplotted on $T_{ex}$ in a dashed curve. Table 1 lists the best-fit parameters such as, latitude ($\theta_{mc}$) and longitude angles ($\psi_{mc}$) of the axial magnetic field, axial field strength ($B_{max}$), radius ($R_{max}$) of the fitted cylinder, handedness of the twisted field ($D$) of the cloud, and impact parameter ($p$) in columns 1–6. The impact parameter is the distance between the spacecraft trajectory and the MC axis normalized to the MC radius. Column 7 shows the relative error of the fitting ($\epsilon_{rms}$). $F_{rms}$ is the ratio of $\Delta$ and the maximum observed magnetic field intensity, $B_{max}$. Here $\Delta$ is the rms deviation between the observed magnetic field, $B(t_i)$, and the model magnetic field, $B^M(t_i)$ ($i = 1, \ldots, N$).

Figure 4 depicts the geometry of the MC at the time of encounter with the spacecraft. In this figure, arrow A indicates the axis of the MC flux rope, arrow S shows the direction of the poloidal magnetic field, and the arrow denoted by S/C demonstrates the path of the spacecraft. It is observed from the figure that the spacecraft comes across the MC near its flank and far below from its axis.

3.1.1. Calculation of the Cloud’s Magnetic Parameters

In this section, we compute MC unsigned magnetic flux and magnetic helicity ($H_{mc}$) of the MC using Lundquist’s constant-
\( \alpha \)-force-free field solution in cylindrical coordinates (Lepping et al. 1990). The solution provides the axial magnetic field component, \( B_z = B_0 J_0(\alpha r) \), the poloidal (azimuthal) magnetic field components, \( B_\theta = D B_0 J_1(\alpha r) \), and the radial field component, \( B_r = 0 \). Where \( B_0 \) is the axial magnetic field strength, \( D = \pm 1 \) is the flux rope handedness (plus for right-handed and minus for left-handed), \( J_n \) is the \( n \)th order Bessel function, and \( \alpha = x_{01}/R_{\text{mc}} \) is the twist per unit length, where \( x_{01} = 2.4048 \) is the location of the first zero of \( J_0 \).

The magnetic flux is defined as

\[
\phi = \int \mathbf{B} \, dA
\]  

(1)

using cylindrical symmetry, \( dA = 2\pi r \, dr \).

The axial and poloidal components of magnetic flux (\( \phi_c \) and \( \phi_p \)) in a cylindrical flux rope is given by (e.g., Leamon et al. 2004; Qiu et al. 2007)

\[
\phi_c = 2\pi \int_0^{R_0} B_z \, r \, dr = \frac{2\pi J_1(x_{01})}{x_{01}} B_0 R_0^2 \]  

(2)

and

\[
\phi_p = 2\pi \int_0^{R_0} B_\theta \, r \, dr = \frac{L}{x_{01}} B_0 R_0, \]  

(3)

where \( R_0 \), \( B_0 \), and \( L \) are, respectively, the radius, axial magnetic field strength, and length of the cylindrical flux rope.

Within a volume \( V \) the magnetic helicity \( H \) of a field \( \mathbf{B} \) is defined by

\[
H = \int_V \mathbf{A} \cdot \mathbf{B} \, dV,
\]  

(4)

where \( \mathbf{A} \) is the vector potential. This definition of helicity is meaningful only if the normal component of \( \mathbf{B} \) (\( B_n \)) at any surface \( S \) surrounding the volume \( V \) is zero, i.e., \( B_n = 0 \). In the case of \( B_n = 0 \), relative magnetic helicity (\( H_r \)) is derived by subtracting the reference magnetic field (\( \mathbf{B}_{\text{ref}} \)) helicity from \( H \) (Berger & Field 1984). Thus, \( H_r \) is defined by

\[
H_r = \int_V \mathbf{A} \cdot \mathbf{B} \, dV - \int_V \mathbf{A}_{\text{ref}} \cdot \mathbf{B}_{\text{ref}} \, dV.
\]  

(5)

Here \( H_r \) is gauge-invariant if \( A \times \vec{n} = A_{\text{ref}} \times \vec{n} \) on \( S \) of \( V \). For a cylindrical flux tube, \( \mathbf{B}_{\text{ref}} \) can be chosen as \( B_{\text{ref}} = B_{\text{ref}} \hat{\mathbf{z}} \) and \( \mathbf{B} = B_\theta \hat{\mathbf{\theta}} + B_z \hat{\mathbf{z}} \). Considering \( \mathbf{A} = \mathbf{B}/\alpha \), we compute the magnetic helicity of cylindrical flux rope (DeVore 2000; Démoulin et al. 2002; Berger 2003; Dasso et al. 2003) as

\[
H = \frac{4\pi L}{\alpha} \int_0^{R_0} A_\theta B_\theta \, r \, dr
\]  

\[
= \frac{4\pi B_0^2 L}{\alpha} \int_0^{R_0} J_1^2(\alpha r) \, r \, dr \approx 0.7 B_0^2 R_0^3 L.
\]  

(6)

To derive the axial and poloidal components of MC flux (\( \phi_{\text{mc}} \) and \( \phi_{\text{pmc}} \)) and the magnetic helicity (\( H_{\text{mc}} \)) of the MC, we apply \( B_0 = B_{\text{mc}}, R_0 = R_{\text{mc}}, \) and \( L = L_{\text{mc}} \) in Equations (2), (3), and (6). Here \( L_{\text{mc}} \) is the estimated length of the MC.

The largest uncertainty in calculating the flux and helicity of an MC arises from the MC flux rope length approximation. Larson et al. (1997) estimated the length of MC as 2.5 au by measuring the travel time of suprathermal electrons moving along with the twisted magnetic field lines. The presence of bidirectional electrons in MCs observed at 1 au suggests the possibility of MCs rooted on the Sun when they reach at 1 au (Shodhan et al. 2000). We consider the MC a half torus that has a circular cross section as an approximation to the expanded flux rope, extending from Sun to Earth. Then the length of MC at 1 au is \( \pi \) au if the major axis length of the torus is 1 au. We note that the length is only 21% higher than the statistical value (2.6 \pm 0.3 au) reported in Démoulin et al. (2016). In our study, we measure the cloud’s flux and helicity using each of the approximated MC flux rope lengths. In column 8–11 of Table 1, we show the twist density (\( \phi_{\text{mc}} \)) of the magnetic field in MC flux rope, \( \phi_{\text{mc}}, \phi_{\text{pmc}}, \) and \( H_{\text{mc}} \) corresponding to different \( L_{\text{mc}} \)s.
3.2. Analysis of the Solar Source

In this subsection, we obtain the geometrical and magnetic properties of the flux rope near the Sun to compute the helicity. The geometrical properties are obtained by forward-modeling white-light CMEs using the GCS model. The magnetic properties are obtained by equating the reconnected flux in the eruption region to the poloidal flux of the erupted flux rope.

3.2.1. The Associated CME

The CME is a halo CME observed from the LASCO/C2 coronograph at 05:12 UT on 2013 March 15. It appears as a...
Table 1

| $\phi_{mc}$ | $\psi_{mc}$ | $B_{mc}$ | $R_{mc}$ | $D$ | $p$ | $E_{mc}$ | $\alpha_{mc}$ | $\phi_{mc}$ | $\phi_{mc}$ | $H_{mc}$ |
|-------------|-------------|-----------|----------|-----|-----|----------|--------------|-------------|-------------|---------|
| ($^\circ$)  | ($^\circ$)  | (nT)      | (au)     | (au) | (Gm$^{-1}$) | (10$^{11}$ Mx) | (10$^{11}$ Mx) | (10$^{12}$ Mx$^2$) |
| (1)         | (2)         | (3)       | (4)      | (5) | (6) | (7)      | (8)          | (9)         | (10)       |
| -24.4       | 247.8       | 20.30     | 0.1152   | $R$ | 0.87 | 0.23     | 0.14         | 0.82        | 4.37        |

Notes.

* $R$ stands for right-handed rotation of the magnetic field.

* $\phi_{mc}$ derived using $L_{mc} = 2$ au.

* $\phi_{mc}$ derived using $L_{mc} = 2.5$ au.

* $\phi_{mc}$ derived using $L_{mc} = \pi$ au.

* $H_{mc}$ derived using $L_{mc} = 2$ au.

* $H_{mc}$ derived using $L_{mc} = 2.5$ au.

* $H_{mc}$ derived using $L_{mc} = \pi$ au.

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Thernisien et al. (2006) and 3D speed from the time evolution of CME leading edge. In Figure 5, we show the GCS model in the green wire frame overplotted on the white-light CME, observed by LASCO/C3, and SECCHI/COR2 A and B around the same time.

We estimate the axial magnetic field strength ($B_{ocme}$) of the CME from its poloidal flux component ($\phi_{pcme}$) by taking

$$B_{ocme} = \phi_{pcme} \frac{V_{01}}{L_{cme} R_{0cme}}.$$  

Here $L_{cme}$ is estimated from the GCS model and can be computed as

$$L_{cme} = 2h_{\ell_{eg}} + y(h - h_{\ell_{eg}}/\cos \gamma)/2 - 2R_{c},$$

where $h_{\ell_{eg}}$ is the height of the legs of the CME flux rope computed using Equation (3) in Thernisien et al. (2006), $(h - h_{\ell_{eg}}/\cos \gamma)/2$ is the radius of the arc of the flux rope, $y = 2(\pi/2 + \gamma)$ is the arc angle in radians, and $R_{c}$ represents the solar radius. Longcope et al. (2007) demonstrated that $\phi_{pcme}$ is approximately equal to the magnetic reconnection flux ($\phi_{RC}$) in the low corona. Gopalaswamy et al. (2017a) proposed a process to estimate the reconnection flux considering the half of the unsigned photospheric flux underlying the area occupied by the PEA (as discussed in the next section).

In Equation (6), we use $B_0 = B_{ocme}$, $R_0 = R_{0cme}$ and $L = L_{cme}$ to obtain the magnetic helicity ($H_{cme}$) of the CME flux rope. In Table 2, we present the GCS fitting results along with $R_{0cme}$ at 10 $R_{c}$ ($R_{0cme}^{10R_{c}}$), $L_{cme}$, and 3D speed ($V_{cme}^{3D}$) of the CME estimated from the fitting.

3.2.2. The Photospheric Source AR

To analyze the source active region (AR 11692) of the ICME, we consider the $SDO$/HMI LOS photospheric magnetogram together with the $SDO$/AIA 193 Å image and the solar X-ray imager on board the Geostationary Operational Environmental Satellite (GOES) system (Hill et al. 2005), which spatially maps soft X-ray emission of solar corona. We calculate the reconnection flux at the decay phase of the flare (when the post-eruption arcade is almost matured) by using $SDO$/HMI LOS, AIA 193 Å data and GOES SXI data. We identify the post-eruption arcade (PEA) region in both AIA 193 Å and GOES SXI images, find the pixels associated with

Figure 4. Geometry of the 2013 March 17–18 MC obtained from fitting data. The three directions indicated in the figure are axial field direction (A), direction of the poloidal magnetic field (S), and spacecraft trajectory (S/C).
the arcade area, and overlay it on HMI LOS data. Considering $B_{\text{LOS}}$ and the area of each of those pixels from HMI LOS data, we derive the total reconnection flux ($\phi_{\text{RC}}$) using the Equation (Gopalswamy et al. 2017a),

$$\phi_{\text{RC}} = \frac{1}{2} \int |B_{\text{LOS}}| dA. \quad (8)$$

To estimate the uncertainty in the arcade area measurement, we consider a range of arcade area ($A_{\text{PEA}}$). We derive the upper and lower limits of the range by selecting the arcade foot points in GOES SXI and AIA 193 Å images. The X-ray imager has a broader temperature response than the EUV image at a particular wavelength. In Figures 6(a) and (b), we show the estimated arcade foot points in red and blue lines superposed on AIA 193 Å and GOES SXI images, respectively, around 15:00 UT. In Figure 6(d), we overlay the foot points derived from AIA 193 Å and GOES SXI images on the differential-rotation corrected HMI LOS magnetogram in their respective colors at 6:11 UT (time of available HMI data just at the beginning of the flare). In Figure 6(c), we show the ribbon structures by arrows in the AIA 1600 Å image around 7:35 UT. Figure 6(e) shows the temporal evolution of GOES X-ray flare intensity. The solid vertical lines a, b, and d on the plot indicate the epochs of measuring arcade in AIA 193 Å, SXI, and HMI LOS magnetogram. The vertical line c indicates the time when a faded ribbon structure is shown in the AIA 1600 Å image. The shaded interval between the dotted vertical line and line c shows an SDO data gap. Due to the absence of SDO/AIA observations during the impulsive phase of the co-produced flare, it is not possible to analyze $\phi_{\text{RC}}$ using the flare ribbon method as in Kazachenko et al. (2017). In principle, one expects an overestimate of the area of the PEA (and hence $\phi_{\text{RC}}$) if the ribbons start at a finite distance from the polarity inversion line (PIL). However, Gopalswamy et al. (2017a) considered this issue using events that had both ribbon and PEA data and found no evidence of an overestimate. Another possible uncertainty in $\phi_{\text{RC}}$ is in identifying the boundaries of PEAs: the PEA is identified in the corona, but superposed on the photosphere. This was also considered by Gopalswamy et al. (2017a) and found that the difference is not significant because ribbon and arcade methods give the same value. However, there may be other uncertainties when the arcade appears differently in EUV and X-ray images. This is explicitly shown in Figure 6: the AIA arcade has a smaller area than the SXI area, giving a 37% lower $\phi_{\text{RC}}$.

Using the reconnection flux limits, we derive a range of $B_{0\text{cme}}$ at $10 \, R_S (B_{0\text{cme}}^{10R})$ and $H_{\text{cme}}$. In Table 3, we show the upper and

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**Figure 5.** GCS model fitting on 2013 March 15 CME in LASCO/C3, SECCHI A and B data. (a)–(c) are observed images of the CME by STEREO and LASCO. (d)–(f) show the CME with the GCS wire frame overlaid on it.

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**Table 2**

| CME Properties | Values |
|----------------|--------|
| $\psi_{\text{cme}}$ (Carrington coordinate) | 68°82 |
| $\theta_{\text{cme}}$ (Carrington coordinate) | $-6^\circ15$ |
| $\gamma$ | $25^\circ16$ |
| $\lambda$ | $-74^\circ35$ |
| $\kappa$ | 0.27 |
| $R_{\text{cme}}$ | 2.13 $R_S$ |
| $L_{\text{cme}}$ | 17.07 $R_S$ |
| $V_{\text{cme}}$ | 1321 km s$^{-1}$ |

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lower limits of $A_{\text{PEA}}$ ($A_{\text{PEA}}^u$ and $A_{\text{PEA}}^l$), $\phi_{\text{RC}}$ ($\phi_{\text{RC}}^u$ and $\phi_{\text{RC}}^l$), $B^{10}\text{mcme}$ ($B^{10}\text{mcme}_u$ and $B^{10}\text{mcme}_l$), and $H_{\text{cme}}$ ($H_{\text{cme}}^u$ and $H_{\text{cme}}^l$).

In Table 4, we show the helicity difference between the near-Sun and 1 au flux rope for $L_{\text{mc}} = 2$, 2.5, and $\pi$ au. For each approximated MC length, $H_{\text{mc}}$ is less than $H_{\text{cme}}$ which suggests that the helicity of the flux rope at 1 au is primarily invoked by magnetic reconnection at low corona during the eruption. We find a minimum helicity difference in the case of $L_{\text{mc}} = \pi$ au with $H_{\text{mc}} = H_{\text{cme}}^l$. So, the lower boundary of source region
Figure 7. Linear regression models derived in Gopalswamy et al. (2017b) for the statistical relationship between $\phi_{RC}$ and (a) CME FR-fit speed, (b) Flare fluence, and (c) $\phi_{mc}$. The red and blue dotted lines are, respectively, upper(+10%) and lower (−10%) uncertainty levels of the model equations. The circular and triangular symbols correspond to $\phi_{RC}$ and $\phi_{mc}$.

4. Discussion

Along with the study of magnetic helicity, we measure other nonpotential parameters, such as total unsigned vertical current ($I$), mean of global twist density ($\alpha_{AR}$; Leka & Skumanich 1999), length of the strong-field neutral line ($L_s$; Falconer et al. 2011), and mean photospheric excess energy density ($Q$; Bao et al. 1999) of the source AR using the HMI SHARP vector magnetogram just before the eruption. To calculate those parameters, we consider pixels with vertical magnetic field intensity greater than 100 G ($|B_s| > 100$ G) and the horizontal magnetic field strength greater than 200 G ($B_l > 200$ G; e.g., Tiwari et al. 2015). Thus, we remove the noisy pixels and those which do not belong to the AR. In Table 5, we give the measured values of the parameters. Using $\alpha_{AR}$, we calculate the overall global twist of the AR as $\alpha_{AR} L_{AR}$, where $L_{AR}$ is approximated as the length of the semi-circular field line with a radius of half of the distance between positive and negative flux weighted centers of the AR. We calculate $L_{AR} = 7.8 \times 10^7$ m thus $\alpha_{AR} L_{AR} = 0.73$. The overall twist of the MC ($\alpha_{mc} L_{mc}$) is calculated as 40 when $L_{mc} = 2$ au, 50 when $L_{mc} = 2.5$ au, and 63 when $L_{mc} = \pi$ au. For each of the $L_{mc}$s, the MC twists are an order of two greater than that of the AR. This result is consistent with what Leamon et al. (2004) found in their study of AR and MC overall twist with $L_{mc} = 2.5$ au. It means the global twist of AR fails to estimate the twist invoked due to reconnection. The positive value of $\alpha_{AR}$ suggests that the rotation of magnetic field line in the flux rope at the source is right-handed, which is consistent with the rotation of the magnetic field in 1 au flux rope. It indicates that, in this case, the direction of magnetic field rotation in flux rope does not change after reconnection.

We compare our results with those of Gopalswamy et al. (2017b), who studied 23 MCs among 54 ICMEs of solar cycle 23, computed their near-Sun and 1 au parameters, and obtained the relationship between them. In each of the panels of Figure 7, we plot the linear fit curve (with a black firm line) with 10% uncertainty in coefficients (p and q; with red and blue dashed lines) derived from the statistical relationship between $\phi_{RC}$ and CME flux rope fit (FR-fit) speed, flare fluence, and poloidal flux of MC. The circular and triangular points plotted on the figure, corresponds to $\phi_{RC}$ and $\phi_{mc}$. Figures 7(a) and (c) show that the measured values of CME speed and $\phi_{mc}$ corresponding to the $\phi_{RC}$ and $\phi_{mc}$ almost match the values estimated using the Equations of linear fit curves, whereas Figure 7(b) shows that according to the linear fit curve equation, the estimated flare fluence corresponding to the measured $\phi_{RC}$ range should be around half of the observed value in our case. From the distribution of $\phi_{RC}$, $R_{FR}^{10Mx}$ and $R_{FR}^{10Mc}$ of 20 MC events (see Figure 5 of Gopalswamy et al., 2017b) of solar cycle 23, we notice that the range of $\phi_{RC}$ and $R_{FR}^{10Mc}$ is smaller than the average values (respectively, 8.8 $\times$ 10^{21} Mx and 4.12 $R_s$)
derived from the distribution, whereas the $B_{\text{ICME}}^{10\%}$ is greater than the average value of the distribution, i.e., 51.9 mG. Furthermore, at 1 au, the values of $\phi_{\text{DC}}$, $B_{\text{DC}}$ and $R_{\text{DC}}$ is smaller than the average values found from the distribution of 17 MC events (see Figure 6 of Gopalswamy et al. 2017b).

5. Summary and Conclusions

The main purpose of our study is to compare the relative magnetic helicity of ICME flux ropes at 1 au and their solar source with the aim of understanding the origin and evolution of helicity of interplanetary flux ropes. For this study, we select the 17–18 March 2013 ICME as it has a clear solar source and 1 au information. We compute the helicity of the flux rope using its axial magnetic field strength and physical parameters such as the radius of its cross section and the total length. We find a correspondence within 83% between the measured quantity of helicity at solar source and 1 au when the ICME flux rope is estimated as a half torus with a total length of $\pi$ au.

The main conclusions are as follows:

1. The helicity of MC at the source and 1 au is broadly similar when MC length is $\pi$ au or the statistical value is $2.6 \pm 0.3$ au considering the flux rope is still attached to the Sun.
2. The amplitude of $H_{\text{ICME}}$ is greater than that of $H_{\text{MC}}$, which suggests that 1 au ICME flux rope helicity is primarily invoked by low coronal reconnection at the time of the eruption.

Extracting the helicity information of CME at the source and 1 au is challenging because (1) flux rope fitting results of MC and CME are not always perfect for each event, (2) the solar wind data are only available at the localized position of the satellite, and (3) a major uncertainty exists in estimating MC length as well as CME flux rope length. However, this study indicates that it is crucially important to perform a more comprehensive analysis of large data bases of MC events together with their source information. This may eventually lead to better estimates and predictions of the magnetic properties of ICME flux ropes at 1 au and help us ascertaining their geo-effectiveness in advance.

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