Evolution of the Toroidal Flux of CME Flux Ropes during Eruption

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GRAPHICAL ABSTRACT

PUBLIC SUMMARY

- A new method is proposed to identify the footpoint region of the CME flux rope
- The toroidal flux of the CME flux rope first rapidly increases and then decreases
- The evolution of the toroidal flux is basically synchronous with that of the SXR flux
- The peak time of the toroidal flux is \(\sim 10\)–20 min later than that of the SXR flux
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INTRODUCTION

Coronal mass ejections (CMEs) are large-scale eruptions of the coronal magnetic field. It is believed that magnetic reconnection significantly builds up the core structure of CMEs, a magnetic flux rope, during the eruption. However, the quantitative evolution of the flux rope, particularly its toroidal flux, is still unclear. In this paper, we study the evolution of the toroidal flux of the CME flux rope for four events. The toroidal flux is estimated as the magnetic flux in the footpoint region of the flux rope, which is identified by a method that simultaneously takes the coronal dimming and the hook of the flare ribbon into account. We find that the toroidal flux of the CME flux rope for all four events shows a two-phase evolution: a rapid increasing phase followed by a decreasing phase. We further compare the evolution of the toroidal flux with that of the Geostationary Operational Environmental Satellites soft X-ray flux and find that they are basically synchronous in time, except that the peak of the former is somewhat delayed. The results suggest that the toroidal flux of the CME flux rope may be first quickly built up by the reconnection mainly taking place in the sheared overlying field and then reduced by the reconnection among the twisted field lines within the flux rope, as enlightened by a recent 3D magnetohydrodynamic simulation of CMEs.

KEYWORDS: SUN: CORONA; SUN: CORONAL MASS EJECTIONS (CME); SUN: FLARES

RESULTS

For each event, we measure the toroidal flux of the CME flux rope mainly at a time cadence of 3 min. The evolutions of the identified footpoint regions are demonstrated in Figure 1, which present obvious drifting of the flux rope footpoints as mentioned in previous papers.16,39–41 The reason is that the footpoint regions are believed to be enclosed by the footprints of quasi-separatrix layers,16–23 which are highly consistent with the J-shaped flare ribbons.14–20 This finding was further confirmed by Cheng and Ding,27 who found that the two footpoints of the CME flux rope that appears as an EUV hot channel are even co-spatial with the regions mostly surrounded by the two hooks of flare ribbons. For the latter, the eruption of CMEs leads to plasma rarefaction in the low corona that manifests as dimmings inside and/or around the source regions, as shown in the EUV passbands.24–30 There are two types of coronal dimmings: twin (or core) dimmings, which are located at opposite magnetic polarities in the source region of the eruptions;31,32 and remote (or secondary) dimmings, which are far away from the source region and are shallower than the former.33–35 Twin dimmings are often believed to map the footpoints of the erupting flux rope.21,22,26,30 In this paper, to identify the footpoint regions of the CME flux rope with a higher accuracy, we propose a new method that combines the previous two methods (see Material and Method for details). We show the results about the evolution of the toroidal flux during the eruption and give a discussion in the following.
The evolution during the eruption: a quick increasing phase followed by a decreasing phase, although the reduction in the toroidal flux for cases 1 and 2 seems to be less obvious than that in cases 3 and 4 considering that the absolute decrease is comparable with the errors. Quantitatively, for events 1, 2, 3, and 4, the toroidal flux increases by 84%, 40%, 78%, and 121%, respectively, relative to the first data point during the first phase; after the peak, it decreases by 15%, 11%, 23%, and 15%, respectively, relative to the peak flux during the second phase. Note that the period that we analyze covers only part of the CME evolution when the footpoint region can be clearly identified, and that the actual increase and decrease in the toroidal flux during the whole CME evolution could be larger than the deduced values.

Interestingly, for case 4, the toroidal flux at 14:16 universal time (UT) (the last moment in Figure 2D) is close to the toroidal flux of the associated magnetic cloud estimated by Wang et al.19.

Figure 1. HMI Radial Magnetograms Overlaid by the Boundaries of the Identified Footpoint Regions of the CME Flux Ropes The evolution of the footpoint regions is denoted by different colors. (A)–(D) are for cases 1–4, respectively.

Figure 2. Temporal Evolutions of the Toroidal Flux of the Four CME Flux Ropes (Blue) and the GOES SXR 1–8 Å Flux of the Associated Flares (Red) The error of the toroidal flux is from the SD of multiple measurements. The orange and blue vertical dashed lines mark the peak times of the toroidal flux and the flare, respectively. (A)–(D) are for cases 1–4, respectively.
Table 1. Parameters of the Four CME/Flare Events

| Number | Magnitude | NOAA Date | Start Time | Peak Time |
|--------|-----------|-----------|------------|-----------|
| Flare 1 | X1.1 | 11429 | 2012/3/5 | 02:30 | 04:09 |
| Flare 2 | C5.3 | 11444 | 2012/3/27 | 02:50 | 03:08 |
| Flare 3 | M1.4 | 12403 | 2015/8/21 | 09:34 | 09:48 |
| Flare 4 | M3.7 | 12443 | 2015/11/4 | 13:31 | 13:52 |

An interesting finding is that the temporal evolution of the toroidal flux of the CME flux rope is roughly synchronous with that of the Geostationary Operational Environmental Satellites (GOES) soft X-ray (SXR) flux of the associated flare. Qualitatively, both of them show a quick increase followed by a decrease. Quantitatively, the increase in the toroidal flux mainly takes place during the flare rise phase, which amounts to 85%, 84%, and 57% of the total increase for cases 1, 2, and 4, respectively. Considering that the CME flux rope may have evolved for a while before the first point of measurement, this ratio could be even larger. This finding indicates that the build-up of the CME toroidal flux is highly related to the rise phase of the associated flare when the energy is mostly released. Nevertheless, we also find a time delay in the peak of the toroidal flux relative to the peak of the GOES SXR flux. After the flare peak, the SXR flux starts to decline, but the toroidal flux continues to increase for ~10–20 min. It should be pointed out that, in our measurement, the toroidal flux of case 3 mainly increases after the flare peak. A possible reason is that our measurement for this case covers a shorter period of the rise phase. It is likely that the toroidal flux already has significantly increased before the first measurement point, and, thus, the main increase in the toroidal flux still takes place during the rise phase, which is similar to the other three cases.

DISCUSSION

In this paper, we quantify the toroidal flux of a CME flux rope with a practical method of identifying the footpoint region of the flux rope. It is revealed that the toroidal flux first quickly increases and then decreases during the eruption for all four of the events we studied. The more important finding is that the evolution of the toroidal flux is generally synchronized with the evolution of the SXR flux, but the peak time of the former is ~10–20 min later than that of the latter. The recent 3D MHD simulation of the CME performed by Aulanier and Dudík18 presents one of the models that may explain these results. In the context of the paper by Aulanier and Dudík,18 the increase and decrease in the toroidal flux may be related to the reconnection in the sheared overlying field (aa-rf reconnection) and that in the flux rope field (m-rf reconnection), respectively. As mentioned earlier, the aa-rf reconnection can definitely increase the toroidal flux of the flux rope by converting the flux of the sheared overlying field into that of the flux rope. The m-rf reconnection, as shown by Aulanier and Dudík,18 takes place between two field lines of the flux rope that are anchored close to the boundary of the footpoint region, producing a multi-turn flux rope field line and a post-flare loop. In this process, part of the flux of the flux rope can be transferred to the post-flare loop, thus resulting in a decrease in the toroidal flux. This process may account for the observational phenomenon that the flare ribbon sweeps and erodes the footpoint of the flux rope, which could lead to a contraction of the footpoint region and thus a reduction in the corresponding magnetic flux, as revealed in our study. By further combining the evolution of the associated flare, we speculate that these CME/flare events may experience the following three processes during the eruption. First, in the flare rise phase, the reconnection mainly takes place underneath the erupting flux rope, which quickly converts the sheared overlying flux into the flux rope and increases its toroidal flux. At the same time, the reconnection effectively heats the plasma and enhances the flare emission. After the flare peak, a similar but less energetic reconnection process continuously occurs in the early stage of the gradual phase, further increasing the toroidal flux of the flux rope but failing to sustain the increase in the SXR flux. Many studies13,43 have revealed that a less energetic reconnection could occur after the flare peak (in the EUV late phase of flares) but does not give rise to a significant enhancement of the SXR flux. The above two processes may correspond to the increasing phase of the toroidal flux. Finally, in the later gradual phase, the eruption process may be dominated by an even weaker reconnection in the flux rope field, which leads to a gradual decrease in the toroidal flux of the flux rope. Note that the eruption of the CME flux rope may also involve the reconnection between the flux rope and the ambient sheared arcades that are anchored close to the footpoint, which, however, is believed to lead to only some drifting of the footpoint without a change in the toroidal flux of the flux rope.19 It should be mentioned that, in some cases, a small part of the CME flux rope footpoint may jump from one place to another rather than drift gradually when the flux rope reconnects with the ambient field that is rooted far away from the footpoint.64 This phenomenon might also lead to a reduction in the toroidal flux as derived here.

We note that the evolution of the toroidal flux of the CME flux rope during the eruption revealed here has been suggested by previous papers. Aiming at the shifting of the footpoints of the CME flux rope, Chen et al.19 used a trial-and-error method to detect the core-dimmining region and found that the magnetic flux there (i.e., the toroidal flux) shows a decreasing trend, if the core-dimmining region is considered the footpoint region of the CME flux rope. In addition, Wang et al.18 studied the evolution of the twist of a CME flux rope and estimated its toroidal flux during the eruption. Their result also shows that the toroidal flux first increases and then decreases (see Figure 6 in Wang et al.18). In fact, case 4 in the current study is the same as the event studied by Wang et al.18 We notice some quantitative differences between the toroidal flux obtained in our study and that in Wang et al.18 especially in the decreasing phase. This finding can mainly be ascribed to the different methods of identifying footpoints used in the two studies. In the later stage of the event, Wang et al.19 assumed that only the brightening segment of the boundary of the flux rope footprint evolves with time, but the dimmed segment remains unchanged. By comparison, the whole boundary evolves over time in the framework of our method. In addition, these two studies detect coronal dimmings at different passbands, which may also lead to a slight difference in the derived toroidal flux.

The method of identifying the footpoint region of the CME flux rope, which is the cornerstone of our study, is different from the previous methods. First, our method is also applicable to events that include partially closed ribbon hooks, which is a significant improvement to the methods that can be applied only to events with closed hooks.19 Second, our method has more geometrical restrictions on the dimming region, which is often determined with empirical thresholds for the absolute intensity or the difference intensity.14,35,45,46 However, it can more accurately identify the footpoint regions of the flux rope, which are co-spatial with the twin dimming regions rather than the remote ones. If the remote dimming regions cannot be clearly separated from the twin dimming regions, their mixture15 can lead to an inaccurate estimation of the toroidal flux of the CME flux rope and its evolution. Our method can thus avoid such cases and give relatively accurate results.

MATERIAL AND METHOD

To quantify the toroidal flux of a CME flux rope, we measure the magnetic flux in its footpoint region. The footpoint region is defined as an isolated region that manifests as coronal dimming in EUV passbands and is surrounded by the flare ribbon hook. Here, we assume that the flux rope is not bifurcated. The events suitable for measurements should meet the following requirements. There is at least one J-shaped dimming region in the EUV passbands and not be obscured by the foreground, such as coronal loops and post-flare loops. In this study, the dimming region is detected at the 211 Å passband, as widely used in previous studies.56,47 In addition, the event should be located far away from the solar limb to ensure an accurate measurement of the magnetic field. Finally, we select four CME/flare events that meet the above requirements for this study. For cases 1 and 4 (2 and 3), we focus on only their western (eastern) footpoints. We do not consider their conjugate footpoints for the following reasons. The eastern footpoint for case 1 and the western footpoint for case 2 are obscured by post-flare loops. The dimming associated with the western footpoint...
for case 3 cannot be clearly identified, while the dimming within the eastern footpoint for case 4 seems to be mixed with the remote dimmings. The basic information of the four events is shown in Table 1. The 211 Å images provided by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO), displaying the source regions of the four CMEs, are shown in Figure 3. The dark pink boxes mark the regions where the flux rope footpoints are located.

In the following, we first introduce the method for identifying the footpoint region of the CME flux rope, taking case 3 that occurred on August 21, 2015 in National Oceanic and Atmospheric Administration (NOAA) Active Region 12403 as an example. Its footpoint region at 09:55 UT is shown in Figure 4 with the same field of view as that of the square in Figure 3C. To more clearly reveal the coronal dimming, we introduce the percentage difference (D) to show its relative change in intensity, which is defined by:

\[ D = \frac{I_t - I_{t_0}}{I_{t_0}} \]  

(Equation 1)

where \( I_t \) and \( I_{t_0} \) are the intensities at 211 Å at times during (\( t \)) and prior to (\( t_0 \)) the eruption, respectively. At time \( t_0 \), no obvious brightening appears in the dimming region. Figure 4A shows the percentage difference image with contours of \( D = 0 \) (light pink), which delineate the boundary of the dimming region. In addition, as the intensity...
at the flare ribbon hook increases but the intensity at the dimming region decreases during the eruption, the leading edge of the flare ribbon hook also refers to the boundary of the dimming region that the hook surrounds, as clearly shown in Figure 4C.

If the flare ribbon hook is closed, the dimming region surrounded by the hook naturally corresponds to the footpoint region of the flux rope.

However, in most cases, the hook is only partially closed, as is shown in the example event. This phenomenon means that only part of the boundary of the footpoint region can be determined by the flare ribbon hook. For the remaining part of the boundary, we apply a region-grow method (performed by REGION_GROW in IDL (Interactive Data Language)) to the percentage difference images. The method generates an isolated region (called the grown region) that starts from a seed and evolves until its boundary value reaches a pre-set threshold. With a given seed and a critical threshold, the method can generate a reference region that is as large as possible but still meets the following requirements: (1) the region is completely located at the concave side of the ribbon hook, (2) most (at least 50%) of the boundary of the region matches the leading edge of the ribbon hook, and (3) the region does not contain subregions that are far away from the ribbon hook and connected to the main part by narrow corridors. Then, the reference region can help us replenish the remaining part of the boundary of the footpoint region.

To perform the above procedure, we need to determine the seed and the critical threshold. The first step is to approximately select a region that includes the footpoint region. The seed is then set to a subregion of 2 × 2 pixels that contains the minimum value of $D$ (denoted by $D_s$) in the presupposed region and is obviously located at the concave side of the ribbon hook. To determine the critical threshold, we try 101 test thresholds ($T_j = \frac{j}{100} \times D_s$) (Equation 2).

Then, we search for the critical threshold $T_c$ and the corresponding reference region. The critical threshold is determined such that the grown region with $T_c$ meets the requirements for the reference region, while the grown region with $T_{c-1}$ extends dramatically and no longer meets these requirements. This method is practical since the relative change in the area of the grown region from $T_c$ to $T_{c-1}$ is larger than 10% for a majority of the footpoint regions that we study.

The results derived by the region-grow method for case 3 are displayed in Figures 4A–4D. In Figures 4A and 4B, we show the boundaries of the grown regions (green contours) generated with $T_{0}$ and $T_{40}$, respectively. They are also overlaid on the 211 Å image, as shown in Figures 4C and 4D, respectively. Apparently, the grown region with $T_{0}$ meets the requirements for the reference region, while the grown region with $T_{40}$ has an obvious superfluous part that is not located at the concave side of the ribbon hook. Therefore, we consider $T_{0}$ as the critical threshold, which gives rise to a reasonable grown region, as shown in Figure 4C.

We can now determine the boundary of the footpoint region. On the side adjacent to the ribbon hook, the boundary of the footpoint region is mainly determined by the contour of $D = 0$. For the remaining part of the boundary, it is determined by jointly considering the contour of $D = 0$ and the boundary of the grown region. The boundary of the footpoint region for the example event is overlaid on the 211 Å image (Figure 4E) and the image of the 1600 Å to 1700 Å intensity ratio (Figure 4F) that enhances the visibility of the flare ribbon.

It is worth mentioning that the contours of $D$ and the leading edge of the flare ribbon in the 211 Å images detected by an edge-detection method (performed by MORPH_GRADIENT in IDL) provide a double-check on the identification of the footpoint region. For each case in our study, we show the identified footpoint regions at three moments during the eruption (Figure 5). It is obvious that the footpoint regions map the main coronal dimming regions, and the majority of boundaries match well with the associated ribbon hooks.

Finally, the toroidal flux of the CME flux rope is estimated by integrating the radial component of the vector magnetic field ($B_t$) in the footpoint region. The vector magnetic field is obtained by the method in Guo et al. using the 720 s cadence data, which are observed by the Helioseismic and Magnetic Imager (HMI) on board the SDO just before the flare start. To reduce the influence of noise in the magnetic field data, we integrate only the regions with $|B_t| > 20$ G, following the threshold used by Wang et al. We multiply the projected area of each pixel by a factor of $1/\cos\theta$.
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SLIP-RUNNING RECONNECTION PROCESSES

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