The triple-layered leading-edge of Coronal Mass Ejections

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ABSTRACT

In a high-resolution, 3D resistive magnetohydrodynamic (MHD) simulation of an eruptive magnetic flux rope (MFR), we revisit the detailed 3D magnetic structure of a coronal mass ejection (CME). Our results highlight that there exists a helical current sheet (HCS) that wraps around the CME bubble. This HCS results from the interaction between the CME bubble and the ambient magnetic field, where it represents a tangential discontinuity in the magnetic topology. Its helical shape is ultimately caused by the kinking of the MFR that resides within the CME bubble. In synthetic SDO/AIA images, processed to logarithmic scale to enhance otherwise unobservable features, we show a clear triple-layered leading edge: a bright fast shock front, followed by a bright HCS, and within it a bright MFR. These are arranged in sequence and expand outward continuously. We suggest that the HCS is a possible explanation for the bright leading edges seen near CME bubbles and also for the non-wave component of global EUV disturbances.

Keywords: Sun: coronal mass ejections (CMEs) — Sun: activity — magnetohydrodynamics (MHD)

1. INTRODUCTION

Coronal mass ejections (CMEs) usually result from rapidly erupting magnetic flux ropes (MFRs). These MFRs may exist prior to the eruption, containing filaments/prominences (Lin & Forbes 2000; Gopalswamy et al. 2003; Yan et al. 2012) or hot channels (Cheng et al. 2014; Cheng & Ding 2016), or form during the CME eruption (Mikic & Linker 1994; Antiochos et al. 1999). In the past two solar cycles, observations using white-light coronagraphs demonstrated that 30% of CMEs have three components, a bright leading front enclosing a dark cavity, which contains a bright core (Webb & Howard 2012). Recently, such three-part components have also been observed in the early stages of eruptions (in the low corona) in extreme-ultraviolet (EUV) passbands (Song et al. 2018).

It still remains an open question as to how these erupting MFRs evolve into the typical CMEs with three components (Manchester et al. 2017). The CME cores used to be interpreted as eruptive filaments (Gilbert et al. 2000). However, Song et al. (2017) performed a statistical work based on looking into 42 CMEs with three-part structures and illustrated that 70% of the events are not associated with filaments. Theories for the CME front/leading edges are fairly involved and reviewed in Chen (2011) and Warmuth (2015). Early theory regarded the CME front as a fast-mode MHD wave (Nakagawa et al. 1975), but this was discarded since the legs of the CME front do not expand laterally at several solar radii in observations (Howard et al. 1982). Later, the CME front was interpreted as coronal plasma pileup in front of the eruptive MFR (Thernisien et al. 2009; Forbes et al. 2006). However, the physical mechanism of this plasma pileup needs further investigations. A third interpretation involves a bimodal (wave and non-wave) aspect of coronal EUV waves, in which the non-wave components of EUV disturbances relate to the expanding CME leading edges (Chen et al. 2002).

Numerical experiments have been performed extensively to study the eruption process of CMEs, including their triggering mechanism (Forbes 1990), the reconnecting current sheet (Reeves et al. 2019), the large-scale evolution (Roussev et al. 2012; Jiang et al. 2018) and the associated coronal EUV disturbances (Downs et al. 2012). In earlier numerical studies preceding modern CME simulations, evolutions of cylindrical straight MFRs have been simulated as well (Baty 2001; Bareford et al. 2010). These all demonstrate that usually, a current concentration wraps around the straight MFR

and takes the form of a helical current ribbon/sheet (HCS) during the non-linear development of the kink instability. Its formation is due to the interaction between the MFR and the ambient magnetic field. Török et al. (2004) and Mei et al. (2018) studied the kink instability in torus-shaped MFRs, and also confirmed the formation of this HCS surrounding the MFR, where the eruptive magnetic structure collides with the overlying background.

Here, we perform a high-resolution 3D resistive MHD simulation on the basis Titov & Démoulin (1999) model (TD99, also in Lin et al. 2002), and we employ forward modelling (Van Doorselaere et al. 2016) to obtain synthetic SDO/AIA images, which allows a direct comparison with observations. Our goal is to highlight the magnetic and overall structure of the CME and its interaction with the background field as it departs from the lower corona. In section 2, the setup of this numerical experiment is given. In section 3, the results are presented and the last section summarizes our work.

2. SETUP OF NUMERICAL SIMULATION

The initial magnetic configuration comes from the TD99 model, which consists of three parts, as shown in the upper-left panel of Fig 1. The first part is the MFR with major radius R , minor radius a , and total current I , uniformly distributed over its circular cross-section. The second is a background field due to a pair of magnetic sources $\pm q$ separated by a distance L , lying on the symmetry axis of the MFR, buried at $z = d$ below the photospheric surface $z = z_p$. In order to control the twist of the MFR, a third part is introduced by a dipole located at $z = d_d$ on the z -axis with strength q_d and direction along the y -axis (Mei et al. 2020).

A two-layer, gravitationally stratified atmosphere is employed. Gravity $\rho \mathbf{g}$ is along the z -axis and $\mathbf{g} = g_\odot \hat{z}/(1 + z/R_\odot)^2$ with $g_\odot = -2.742 \times 10^{-4} \text{ cm s}^{-1}$ being the gravity acceleration at $z = z_p$. The atmosphere with $z \leq z_p$ and $z > z_p$ represents the photosphere and the extended corona. The initial temperature is T_p under the photosphere and T_c above the photosphere such that we obtain a layer with high density and a sharp increase in pressure near the bottom of the simulation box. For all other five boundaries, we use open boundary: all physical variables in the ghost cells are deduced via extrapolation of internal grid points.

The resistive MHD equations in our simulation are solved by the MPI-parallelized Adaptive Mesh Refinement code MPI-AMRVAC¹ (Keppens et al. 2012; Porth et al. 2014; Xia et al. 2018). We employ a third-order accurate shock-capturing finite volume spatial discretization, using a Harten-Lax-van Leer approximate Riemann Solver (Harten 1983), a third-order limited reconstruction (Čada & Torrilhon 2009) and a three-step Runge-Kutta time marching method. The heat conduction is purely field aligned and temperature dependent, hence the heat conduction $\kappa = \kappa_{\parallel} T^{2.5} \hat{e}_B \hat{e}_B$. The unit vector $\hat{e}_B = \vec{B}/|B|$ and $\kappa_{\parallel} = 10^{-6} \text{ erg s}^{-1} \text{ cm}^{-1} \text{ K}^{-3.5}$.

For convenience, all physical quantities are normalized to $5 \times 10^9 \text{ cm}$, $1.165 \times 10^7 \text{ cm s}^{-1}$, $4.293 \times 10^2 \text{ s}$, $2.342 \times 10^{-14} \text{ g cm}^{-3}$, 10^6 K , 3.175 Pa , 6.317 G and $7.54 \times 10^{20} \text{ A}$ for length, velocity, time, density, temperature, pressure, magnetic field and electric current intensity respectively. The computation domain is a 3D box of sizes $-6 \leq x \leq 6$, $-6 \leq y \leq 6$ and $0 \leq z \leq 12$ in a Cartesian coordinate system, and 360^3 grid points are employed. The relevant parameters R , a , d , d_d , L , q , I , z_p , T_p and T_c are set to 1.2, 0.2, -0.1 , -1.2 , 0.3, 22.8, 83.2, 0.4, 0.006 and 1, respectively. The resistivity $\eta = 0.03$ and so the resulting Reynolds number is about 2×10^3 . In addition, the uniform temperature inside the MFR is set to $T_{in} = 0.04$, and the total mass inside the MFR equals about 95 (in our units), i.e. $4.66 \times 10^{16} \text{ g}$.

3. NUMERICAL RESULTS

Due to an intentional departure from a perfect force-balanced equilibrium state and the high twist, the MFR erupts immediately after the launch of the simulation, and experiences kink instability simultaneously. Evolution snapshots of the magnetic structure are shown in Fig 1. The colored curves are magnetic field lines inside or outside the MFR. The red curve represents the outmost magnetic field line of the CME bubble, which is referred as the “boundary” of the CME bubble (see also discussion of Lin et al. 2004; Lin & Soon 2004). Pink current iso-surfaces show the 3D geometrical shape of current structures. During the eruption, the MFR moves upward and expands its volume significantly. Around the MFR, a helical current shell/sheet (HCS, marked in Fig 1) appears and also

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Figure 1. Evolution snapshots of magnetic structure during the eruption. The dimensionless units of time and length are 4.293×10^2 s and 5×10^9 cm respectively. Colorful curves are magnetic field lines of the background field (blue) and the field inside the MFR (golden). Red curve is the CME bubble boundary. The pink surfaces are current iso-surfaces with different values 10, 1.5 and 0.4 respectively. Texts marked on figure are the CME bubble boundary, the HCS (helical current sheet) and the MFR (magnetic flux rope).

expands continuously. This HCS has been reported by many studies on kink processes of straight cylindrical MFRs (Hood et al. 2009; Gordovskyy et al. 2014; Pinto et al. 2015) and of torus-shaped MFRs (Török et al. 2004; Mei et al. 2018). For the straight case, the kinking MFR interacts with the ambient magnetic field, so that a helical current sheet/ribbon forms and wraps around the MFR. For torus-shapes, the MFR is embedded entirely into the CME bubble, as shown by the red curves in Fig 1. Instead of the MFR field, it is the entire CME bubble which serves as an agent for the kinking MFR within it, to interact with the ambient background magnetic field.

The resultant HCS is exterior to the bubble boundary but wraps around the bubble tightly, as shown in Fig 2. Because the HCS is along the magnetic field (seen in the upper-left panel of Fig 2), this HCS is a tangential discontinuity between two different magnetic systems (Priest 2014). Lower panels of

Figure 2. Upper: Distributions of the current on the cuts $y = 0$ (left) and $x = 0$ (right) at $t = 2$. The colorful curves are the magnetic field lines outside the MFR (blue) and the boundary of the CME bubble (red). Marked on this figure are the MFR and the fast-mode shock (FS). Lower: Distribution of different physical quantities along the z -axis.

Fig 2 give the distributions of different physical quantities along the z -axis. On the distribution of the current intensity j , we can see the MFR, the HCS and the FS clearly. The helical geometry of this HCS results from the kink process of the MFR within the bubble, which rotates the MFR during its upward eruption. In addition, it is worth mentioning that the HCS and the bubble boundary have completely different physical properties although they are fairly close in space. The bubble boundary has been defined as the outmost magnetic field line of the CME bubble, which separates the magnetic system inside the bubble from the outside.

In Fig 3, a spatio-temporal map from the cut $y = 0$ nearby the z -axis shows the evolution of the current distribution during the eruption. In this figure, the fast shock (FS), the HCS, the MFR, the highly nonlinear turbulence region (TR) and the reconnecting CS have been marked. Here, the TR identifies the intensive interaction between the CME bubble and the reconnection outflow from the

Figure 3. Spatio-temporal map for the cut $y = 0$ nearby the z -axis. The golden shading gives the distribution of current. Marked on figure are the FS, the HCS, the MFR, the turbulence region (TR) and reconnecting current sheet (CS).

underlying CS (Nishida et al. 2013; Takahashi et al. 2017; Ye et al. 2019). Thus, the TR indicates the lowest point of the bubble boundary and the upper tip of the CS. For the MFR, it shows a clear acceleration of 1.7 km s^{-2} in the early stage of the simulation. Later, it moves upward with uniform speed of about 367 km s^{-1} and its cross-section radius displays an obvious expansion. In front of the MFR, the FS propagates upward with constant speed of about 520 km s^{-1} , and the HCS expands with a speed about 470 km s^{-1} . Due to this speed difference, a gradual slow separation develops between the FS and the HCS.

To obtain the corresponding observational consequences, we performed forward modelling of SDO/AIA observables by the forward modelling code (FoMo, Van Doorselaere et al. 2016), which calculates the EUV emission from the optically thin coronal plasma. Two angles $\mathcal{L}$ and $-\mathcal{B}$ connect the coordinate system x - y - z in our experiment with x' - y' - z' in the rotated frame of reference of the observation. Here, $\mathcal{L}$ is between the line of sight (LOS) and the z -axis, $-\mathcal{B}$ is between the LOS and

Figure 4. Bronze-left: synthetic AIA193Å snapshots in the image plane (i.e. the plane-of-the-sky) with viewing angles $\mathcal{L} = -30^\circ$ and $\mathcal{B} = 86^\circ$ at different times. Bronze-right: same as the left column, but in a log-scale. Pink and Green: synthetic AIA211Å (pink) and 131Å (green) images in a log-scale with same viewing angles.

the y -axis, and $x'-y'$ is the synthetic image plane (i.e. the plane-of-the-sky). Panels of Fig 4 with bronze color show synthetic images of SDO/AIA193Å snapshots at different times, with view angles $\mathcal{L} = 30^\circ$ and $-\mathcal{B} = 86^\circ$. The synthetic AIA 193Å images in the bronze-left panels of Fig 4 are the same as the images at bronze-right panels, but the latter use a log-scale to highlight otherwise hidden features.

In the original bronze-left panels, we can see a 3D FS hemispherical front and a bright MFR. The 3D FS front is seen clearly in the AIA193Å images, because the plasma temperature and density following the FS front increase significantly. Because the untwisting process creates lots of sub-structures, and so speeds up the ohmic heating and the magnetic reconnection, plasma inside the MFR is heated to $T = 6$ MK in the early stages of our resistive MHD experiment, so that the dark MFR in the beginning of the simulation lights up later in the synthetic AIA images. When this heated MFR experiences continuous expansion, the increase of total MFR volume results in a dramatic decrease in its internal temperature in the subsequent evolution, so the MFR gradually darkens and disappears in the image.

In the logarithmically stretched bronze-right panels of Fig 4, more features can be discovered in the synthetic images. First, the HCS can be seen clearly, situated in between the FS front and the MFR during eruption. Second, the MFR can also be identified from the ambient background at later stages of the eruption, although it becomes invisible in the unprocessed corresponding images at left panels. Fig 4 also displays AIA synthetic images with the log-scale in 211Å and 131Å. The HCS and the MFR can be identified easily in these bands during the whole simulation as well. The FS can be seen in AIA 211Å, but is absent in 131Å, because of its contribution function (Lemen et al. 2012).

In the enhanced synthetic images, the HCS, the bright MFR, and the dimming regions between them together form the typical three-components of the CME. This is to say, our results here suggest that the leading-edge of the CME is the HCS, which is close to, but different from the boundary of the CME bubble. According to the bimodal interpretation of global EUV disturbances, the FS front is followed by a non-wave diffusive front, which has been related to the leading edge of the CME

Figure 5. Synthetic AIA193Å images at $t = 2$ with log-scale from different view angles: $\mathcal{L} = 0^\circ$ and $\mathcal{B} = 0^\circ$ for upper-left panel, $\mathcal{L} = -90^\circ$ and $\mathcal{B} = 0^\circ$ for upper-right, $\mathcal{L} = 0^\circ$ and $\mathcal{B} = -90^\circ$ for lower-left panel, and $\mathcal{L} = -90^\circ$ and $\mathcal{B} = -90^\circ$ for lower-right panel.

(Chen 2011; Warmuth 2015). We here further suggest that the non-wave component corresponds to the HCS in our synthetic images.

Because the EUV emission measure depends in an important way on the orientation of the LOS, synthetic AIA193Å images with different viewing angles are given in Fig 5. The upper panels show the EUV disturbance observed near the centre of the solar disc, and the lower panels show the EUV disturbance observed at the limb. In the lower panels, the FS, the HCS and the MFR can be identified clearly at $t = 2$. In the upper panels, on the other hand, only a diffusive front can be identified and the FS, the HCS and the MFR cannot be identified although all of these structures have a contribution to the EUV emission of disturbances on the solar disc. In the upper panels, the

outer edge of the EUV disturbance is determined by the outmost part of the FS hemispherical front,
 instead of the FS front nearby the photosphere, as indicated by blue lines in Fig 5.

4. CONCLUSION

When the MFR erupts upward, the reconnecting CS below it grows continuously, in which magnetic field lines disconnect and reconnect to form new closed magnetic field lines, which outline the boundary of the expanding CME bubble. Wrapping around this bubble, a 3D helical current sheet (namely HCS) develops. This HCS results from the interaction of the CME bubble with the background magnetic field. Its helical topology is indirectly caused by the kink instability of the MFR that happens in the center of the CME bubble.

We created synthetic images of SDO/AIA in different bands by employing forward modelling for EUV observations. Because of the untwisting process, the internal plasma of the MFR gets heated significantly so that it can be observed in synthetic images in the early stage of the simulation. Above the MFR, the FS dome as a 3D hemispherical front can be seen to propagate outwards continuously. In the log scaling, also the HCS can be identified clearly as a bright front between the FS and the MFR in enhanced synthetic images. The HCS, the MFR and the dimming region between them together form the typical three-component structure of a CME, which can be observed in the enhanced synthetic images during the whole eruption. The HCS in our simulation corresponds to the outmost component of the CME, i.e. the CME leading edge in observations. According to the bimodal interpretation of EUV disturbances, a non-wave component relates to the expanding of the leading edge of the CME. Here, we rather suggest that the previously underresolved HCS component may form the non-wave component of large-scale EUV disturbances.

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