SIMULATION OF HOMOLOGOUS AND CANNIBALISTIC CORONAL MASS EJECTIONS PRODUCED BY THE EMERGENCE OF A TWISTED FLUX ROPE INTO THE SOLAR CORONA

PIYALI CHATTERJEE AND YUHONG FAN
High Altitude Observatory, National Center for Atmospheric Research, 3080 Center Green Drive, Boulder, CO 80301, USA; mppiyali@ucar.edu

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ABSTRACT

We report the first results of a magnetohydrodynamic simulation of the development of a homologous sequence of three coronal mass ejections (CMEs) and demonstrate their so-called cannibalistic behavior. These CMEs originate from the repeated formations and partial eruptions of kink unstable flux ropes as a result of continued emergence of a twisted flux rope across the lower boundary into a pre-existing coronal potential arcade field. The simulation shows that a CME erupting into the open magnetic field created by a preceding CME has a higher speed. The second of the three successive CMEs is cannibalistic, catching up and merging with the first into a single fast CME before exiting the domain. All the CMEs including the leading merged CME, attained speeds of about 1000 km s$^{-1}$ as they exit the domain. The reformation of a twisted flux rope after each CME eruption during the sustained flux emergence can naturally explain the X-ray observations of repeated reformations of sigmoids and “sigmoid-under-cusp” configurations at a low-coronal source of homologous CMEs.

Key words: Sun: coronal mass ejections (CMEs) – Sun: magnetic fields

Online-only material: color figures, animations

1. INTRODUCTION

Emerging solar active regions with strong photospheric magnetic twist are known to repeatedly flare and produce homologous coronal mass ejections (CMEs; e.g., Gibson et al. 2002; Schrijver 2009). Some of these regions exhibit continued coronal mass ejections (CMEs; e.g., Gibson et al. 2002; Brown et al. 2003; Zhang et al. 2008; Vemareddy et al. 2012), which may indicate continued emergence of highly twisted flux ropes from the interior into the corona (e.g., Schrijver 2009; Fan 2009; Fang et al. 2012). Gibson et al. (2002) studied AR 8668 throughout its passage on the solar disk and found repeated reformation of the soft X-ray sigmoid morphology after every filament eruption and temporarily parts of the sigmoid transform into cusp shape. Homologous CMEs have been observed to give rise to “cannibalism” or CME–CME interactions which are one of the most energetic and geo-effective space weather phenomena (Gopalswamy et al. 2001). Such cannibalism events taking place in the solar wind in the heliosphere have been modeled by Lugaz et al. (2005), by launching identical CMEs with the introduction of non equilibrium flux ropes in the lower corona at appropriate times. Magnetohydrodynamic (MHD) simulations of homologous eruptions have been achieved by DeVore & Antiochos (2008) using a breakout magnetic configuration in the corona driven by twisting footpoint motions, although the resulting eruptions are confined. In this Letter we present a three-dimensional MHD simulation of the initiation of homologous CMEs in the corona driven at the lower boundary by the quasi-static emergence of a highly twisted magnetic torus. We observe cannibalism of the erupting CMEs as well as repeated reformation of the helical flux rope after every eruption.

2. THE NUMERICAL MODEL

In this simulation, we solve the MHD equations in spherical geometry as given in Fan (2012, hereafter F12), except that here we exclude the field aligned thermal conduction term from the energy equation. We have assumed an ideal gas with a low adiabatic index of $\gamma = 1.1$, which allows the coronal plasma to maintain its high temperature without an explicit coronal heating. The MHD equations are solved numerically with the MFE code described in F12. The setup of the simulation is the same as that of F12 except for the changes described below. The spherical simulation domain is given by $r \in [R_0, 6 R_0]$ with $R_0$ being the solar radius, $\theta \in [11\pi/24, 13\pi/24], \phi \in [-\pi/12.8, \pi/12.8]$. The domain is resolved by a grid of $480 \times 192 \times 360$, which is uniform in $\theta$ and $\phi$, and non-uniform in $r$ with the highest resolution being $dr = 0.95$ Mm in region from $r = R_0$ to $r = 1.41 R_0$, and then with $dr$ increasing gradually for $r > 1.41 R_0$, reaching about $dr = 0.11 R_0$ at the outer boundary. Compared to F12, here we have reduced the horizontal extent of the simulation domain by about a factor of two and increased the resolution in the lower coronal region by about the same factor, with the aim to model a more compact CME source region with a stronger coronal magnetic field, representative of a highly twisted, strong emerging active region that is capable of producing fast CMEs. As in F12, the domain is set to be initially in hydrostatic equilibrium with a uniform temperature of $T_0 = 1$ MK, and contains a pre-existing potential arcade field, whose normal field distribution at the lower boundary is as given in F12 (see Equations (12) and (13)) in that paper), except that the parameter for the width of the arcade normal field is reduced to $\theta_a = 0.025$ and the peak field strength is increased to $B_0 = 70$ G.

As described in F12, we impose (kinematically) at the lower boundary (at $r = R_0$) the emergence of a twisted magnetic tube $B_{tube}$, by specifying a time dependent transverse electric field $E_x |_{r=R_0} = \hat{r} \times \left[ - (1/c) v_0 \times B_{tube} \right] \times \hat{r}$ that corresponds to the upward advection of the torus at a velocity $v_0$. The form of the torus $B_{tube}$ is given in F12 except that here it is more compact, tightly wound, and has a stronger field, with the minor and the major radii $a = 0.0212 R_0$ and $R' = 0.11 R_0$, the twist rate $q/a = 0.142$ rad Mm$^{-1}$, and the field strength at the torus axis $B_{a/R'} = 93$ G. This field strength chosen is such that the emerging rope can be confined by the arcade field during the quasi-static build up phase yet strong enough to produce an ejective eruption (instead of a confined one).
produce large flares (Caspi & Lin 2010). Note that the outer coronal field strength in strong active regions that during the loss of equilibrium phase and is also consistent with Figure 1.

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The three-dimensional magnetic field evolution of the twisted flux rope emerging into the corona at times indicated in hours. The red colored field lines have footpoints in the ambient arcade where as the blue, green and cyan field lines originate from the emerging flux region.

(An animation and a color version of this figure are available in the online journal.)

during the loss of equilibrium phase and is also consistent with the typical coronal field strength in strong active regions that produce large flares (Caspi & Lin 2010). Note that the outer poloidal field of the emerging flux rope has nearly the same orientation as the arcade field in order to minimize magnetic reconnection during the quasi-static build up phase. The field of the torus \( B_{\text{torus}} \) is truncated to zero outside of the flux surface whose distance to the torus axis is \( 2a \). For specifying the lower boundary electric field \( E_{\perp} \left|_{r=R_c} \right. \), it is assumed that at \( t = 0 \) the torus’ center is located at a distance of \( R' + 2a \) below the lower boundary (with the torus outer edge just approaching the lower boundary), and it moves upward at a constant emergence speed of \( v_0 = 4.9 \text{ km s}^{-1} \). This speed is much smaller than the peak Alfvén speed \( v_{\text{Alf}} = 6.8 \text{ Mm s}^{-1} \) at the footpoints of the arcade field, and also significantly smaller than the (initial) sound speed \( c_{\phi} = 135 \text{ km s}^{-1} \) of the corona. The emergence is thus sufficiently slow such that the fast coronal Alfvén speed can quickly establish equilibria and allow the coronal magnetic field to evolve quasi-statically in response to the driving flux emergence at the lower boundary, until instabilities and catastrophic loss of equilibrium take place. Conversely, we may not reduce the emergence speed too much so as to avoid a significant numerical dissipation of the flux rope current during the quasi-static phase. The other boundary conditions are the same as those used in F12, where we assume perfectly conducting walls for the side boundaries, and use a simple outward extrapolating boundary condition for the top boundary that allows plasma and magnetic field to flow through.

3. RESULTS

Our simulation shows repeated formation and eruption of a coronal flux rope (at least three times) during the course of about 5 hr of evolution, as a result of the continued emergence of the magnetic torus imposed at the lower boundary. Figure 1 shows snapshots of the three-dimensional magnetic field evolution illustrating this pattern of evolution in the corona. Panel (a) shows the emerged coronal flux rope just before the onset of the first eruption. The first eruption is found to initiate when the twist of the emerged flux rope field lines in the vicinity of the axis has reached about 2.1 winds between the anchored footpoints. The helical kink instability is expected to develop for a line-tied coronal flux rope if the total winds of the field line twist about the axis exceed a critical value between the line-tied ends (e.g., Hood & Priest 1981; Török & Kliem 2003; Török et al. 2004). This critical value is 1.25 based on the analytical calculation of a one-dimensional uniformly twisted cylindrical flux tube (Hood & Priest 1981). Figure 1(b) clearly shows the development of substantial writhing motion at the onset of the eruption, indicative of the onset of the helical kink instability. Further, we check if the flux rope at this time is also unstable to the torus instability (Bateman 1978; Kliem & Török 2006; Isenberg & Forbes 2007), an expansion instability of a flux rope that occurs when the external strapping field confining the flux rope decreases with height, \( h \), above the surface at a sufficiently steep rate. The external strapping field is taken to be the potential field \( B_{\phi} \) with the same normal field distribution at the lower boundary. The rate of decline with \( h \) is measured by the decay index \( n = -d \ln B_{\phi}/d \ln h \). We calculate this decay index at the apex of the axial field line of the coronal flux rope at the start of the acceleration phase, which we estimate to be at \( r = 1.035 R_\odot \). The apex of the flux rope axis is determined using the technique outlined in Section 3.1 of Fan (2010). The critical rate of decline for the onset of the torus instability is determined to be \( n_{\text{cr}} = 1.5 \) (Bateman 1978) for a freely expanding two-dimensional axisymmetric toroidal current. The \( n_{\text{cr}} \) value for a three-dimensional line-tied arched flux rope has been calculated by Isenberg & Forbes (2007) and is found to be close to 1.5. In general, \( n_{\text{cr}} \) and the critical height are expected to depend on the detailed normal flux distribution at the lower boundary as well as the profile of the flux rope. Aulanier et al. (2010) found that their flux rope becomes unstable after reaching a critical height at which \( n = 1.74 \) for \( n_{\text{cr}} \). In our case the rope is probably stable against the torus instability at the onset of the kink instability since
we find a decay index of \( n \sim 1.0 \) at the apex of the rope axis when it has started to kink and accelerate rapidly. Subsequently in Figure 1(c), we see the top of the erupting rope pinching off via magnetic reconnections and a new second flux rope has formed due to further flux emergence. The new flux rope constitutes not only sigmoid-shaped dipped field lines left over from the first eruption but also additional twist due to continued flux emergence. The second flux rope appears to again become kink unstable and erupt (see Figure 1(d)) about 0.4 hr after the onset of the first, and as it erupts upward and pinches off it leaves behind a third newly formed flux rope that grows quasi-statically (see Figure 1(e)). The process repeats again for the third eruption (see Figures 1(f) and (g)). All the three eruptions are triggered by the helical kink instability (see panels (b), (d) and (f) of Figure 1), with the values of the decay index \( n \) at the apex of the flux rope axis at the onset of rapid acceleration being 1.0, 1.05, and 1.1 for the first, second, and third eruptions respectively. These values suggest that all the three flux ropes are still stable against the torus instability as they become kink unstable. Furthermore the configurations shown in panels (c), (e), and (g) of Figure 1 indicate that all three eruptions are partial eruptions of the flux rope, with internal reconnections between the two legs of the flux rope that break the rope in two (e.g., Tripathi et al. 2009; Gibson & Fan 2006). After the third eruption, a fourth flux rope forms. But in the course of time this flux rope is found to undergo a sideways herniation (see Figure 1(h)) rather than erupting radially. Note that each newly formed flux rope remains in a quasi-static state if the flux emergence is stopped before sufficient twist is transported in to trigger another kink instability, emphasizing the importance of sustained flux emergence.

Figure 2 shows the temporal evolution of the free magnetic energy, \( E_{\text{free}}^M \), defined as the difference between the magnetic energy and the energy \( E_P \) of the corresponding potential field having the same radial magnetic field distribution on the lower boundary. \( E_{\text{free}}^M \) measures the maximum available energy for driving the eruptions. Also shown in Figure 2 is the evolution of the total kinetic energy \( E_K \). The three vertical red dashed lines mark the times for the onset of the three eruptions characterized by the onset of a sharp increase in \( E_K \) and a drop in \( E_{\text{free}}^M \). Also note for the plot of \( E_K \) that the second CME occurs while the first CME blob is still in the domain. Similarly the third CME occurs when the second and the first are still in the domain. Thus the total \( E_K \) reflects the accumulated kinetic energy for all three eruptions until about \( t = 3.9 \) hr, when the front of the leading ejecta begins to exit the domain and \( E_K \) starts to decrease. We find that both the drop in \( E_{\text{free}}^M \) as well as the sharp increase in \( E_K \) become progressively greater with each successive eruption, indicating that each CME is more energetic than its predecessor. A natural consequence of such progressively more energetic eruptions is the cannibalism in homologous CMEs.

Figure 3(a) shows two snapshots of the radial velocity in the central cross-section. The earlier snapshot shows the second CME erupting while the front of the first ejecta has already reached 2.4 \( R_\odot \). The latter snapshot shows the time just after the second CME blob has “gobbled up” the first blob, forming a single fast ejecta moving outward at a speed of \( \sim 1 \) Mm s\(^{-1}\). A movie showing this evolution of \( v_r \) in the cross-section is available in the online version. More quantitatively, Figures 3(b) and (c) show respectively the height versus time and \( v_r \) versus time for three Lagrangian points (ER1, ER2 and ER3), each tracked starting from the apex of each of the three flux ropes’ axes at the onset of its eruption. Figure 3(b) shows that point ER2 catches up with ER1 at \( t = 3.35 \) hr. The point ER3 is fastest of the three but does not catch up with ER1 and ER2 inside the domain. If the radial extent of our domain had been much longer, we might have witnessed another event.

(A color version of this figure is available in the online journal.)
of cannibalism. It is clear from Figure 3(c) that ER1, ER2 and ER3 exhibit increasingly stronger acceleration, reaching peak velocities of 650 km s\(^{-1}\), 1400 km s\(^{-1}\) and 1800 km s\(^{-1}\) respectively. All three CMEs in our simulation can be classified as fast CMEs. The greater acceleration of the following CME compared to its precursor is because the following flux rope is erupting into the field that has been opened up by the leading eruption and therefore has less downward magnetic tension to overcome. However at the instant of collision between the first and the second CME the merged ejecta attains a speed that is greater than the first CME but slower than the second in order to conserve momentum. The merged CME exits the domain traveling at a speed of 950 km s\(^{-1}\).

The repeated reformation of the coronal flux rope after each eruption may be identified with the repeated reformation of the X-ray sigmoid in the active region. Figure 4 shows snapshots of the morphology of the most heated field lines between the first and the second eruptions to illustrate this point. These most heated field lines are selected by tracing field lines from the points in the thin current layers with \(J/B\) above a selected high value, which is \(\sim 1/8\delta x\) for sigmoid fieldlines in panels (a), (c) and (d), and \(\sim 1/3.5\delta x\) for cusped fieldlines of panels (b) and (c) in Figure 4, where \(J, B\), and \(\delta x\) denote the current density, the field strength, and the minimum grid spacing respectively. Panel (a) shows the most heated field lines (the red field lines) at the onset of the kink instability of the first flux rope, and they show an inverse S morphology as expected for a left-hand-twisted flux rope (e.g., Low & Berger 2003; Fan & Gibson 2004). As the eruption of the first flux rope progresses, the current sheet intensifies and rapid reconnections take place. The heated field lines traced from the most intense part (with \(J/B > 1/3.5\delta x\)) of the current sheet form the cusped post flare loops as shown in Figure 4(b). As the current sheet stretches outward, the footpoints of the post flare loop widens (red field lines in Figure 4(c)). A new sigmoid traced by a family of yellow colored field lines has appeared below the cusped post flare loop as shown in Figure 4(c). The formation of the second flux rope is aided by the magnetic reconnections in the partial eruption of the first flux rope, as flux emergence continues during the course of a sustained emergence of highly twisted magnetic fields in an active region. The first of a sequence of homologous CMEs must perform work to open up a confining field that is closed ahead of it. The subsequent CMEs tend to be cannibalistic because each is erupting into the already opened field stretched out by its preceding CME, the former thus being able to accelerate to a higher speed to catch up and merge into the latter. The speeds of the CMEs in our simulation are \(\sim 1000\) km s\(^{-1}\). A merged CME produced by such a cannibalistic process is naturally fast and massive, and, therefore, geoeffective. The essential point is about the MHD conversion of total free magnetic energy available in the highly twisted, complex magnetic fields that continually emerge and create multiple CMEs sufficiently close in time for a few of them to eventually merge cannibalistically. A significant part of that free energy is converted into the terminal kinetic energy by this process. If these CMEs were to be individually created in separate events, each involving opening up and reclosing of an initially closed field, a significant amount of the free magnetic energy must go into opening up the confining field. This non-trivial amount of energy (Aly 1987) does not become a part of the terminal CME kinetic energy because it is to be liberated in a post-CME flare associated with the re-closing of the open field. We will study the detailed magnetic field structure and topology of the merged CMEs in a subsequent paper. Our current simulation has only considered highly twisted emerging flux ropes that develop the kink instability. There may also exist other mechanisms for triggering multiple eruptions (e.g., MacTaggart & Hood 2009). A detailed parametric study with varying twist of the emerging flux rope is needed to study how the development of homologous CMEs depends on the onset of the kink instability.

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4. DISCUSSION

We have demonstrated with an MHD simulation that cannibalistic, homologous CMEs may result from repeated formations and partial eruptions of kink unstable flux ropes during the course of a sustained emergence of highly twisted magnetic fields in an active region. The first of a sequence of homologous CMEs must perform work to open up a confining field that is closed ahead of it. The subsequent CMEs tend to be cannibalistic because each is erupting into the already opened field stretched out by its preceding CME, the former thus being able to accelerate to a higher speed to catch up and merge into the latter. The speeds of the CMEs in our simulation are \(\sim 1000\) km s\(^{-1}\). A merged CME produced by such a cannibalistic process is naturally fast and massive, and, therefore, geoeffective. The essential point is about the MHD conversion of total free magnetic energy available in the highly twisted, complex magnetic fields that continually emerge and create multiple CMEs sufficiently close in time for a few of them to eventually merge cannibalistically. A significant part of that free energy is converted into the terminal kinetic energy by this process. If these CMEs were to be individually created in separate events, each involving opening up and reclosing of an initially closed field, a significant amount of the free magnetic energy must go into opening up the confining field. This non-trivial amount of energy (Aly 1987) does not become a part of the terminal CME kinetic energy because it is to be liberated in a post-CME flare associated with the re-closing of the open field. We will study the detailed magnetic field structure and topology of the merged CMEs in a subsequent paper. Our current simulation has only considered highly twisted emerging flux ropes that develop the kink instability. There may also exist other mechanisms for triggering multiple eruptions (e.g., MacTaggart & Hood 2009). A detailed parametric study with varying twist of the emerging flux rope is needed to study how the development of homologous CMEs depends on the onset of the kink instability.

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Figure 4. Transition in the morphology of the heated field lines from a sigmoid shape to cusped post flare loops and back to sigmoid. The red fieldlines belong to the current layer isosurface with a value of \(J/B > \delta x\) whereas the cusped fieldlines in panels (b) and (c) (in red), are traced from the current layer isosurface with a value \(J/B = 1/3.5\delta x\). Time is indicated in hours. (A color version of this figure is available in the online journal.)
REFERENCES

Aly, J. J. 1987, SoPh, 111, 287
Aulanier, G., Török, T., Démoulin, P., & DeLuca, E. E. 2010, ApJ, 708, 314
Bateman, G. 1978, MHD Instabilities (Cambridge, MA: MIT Press), 84
Brown, D. S., Nightingale, R. W., Alexander, D., et al. 2003, SoPh, 216, 79
Caspi, A., & Lin, R. P. 2010, ApJL, 725, 161L
DeVore, C. R., & Antiochos, S. K. 2008, ApJ, 680, 740
Fan, Y. 2009, ApJ, 697, 1529
Fan, Y. 2010, ApJ, 719, 728
Fan, Y. 2012, ApJ, 758, 60
Fan, Y., & Gibson, S. E. 2004, ApJ, 609, 1123
Fang, F., Manchester, W., Abbott, W. P., & van der Holst, B. 2012, ApJ, 745, 37
Gibson, S. E., & Fan, Y. 2006, ApJL, 637, 65L

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ERRATUM: “SIMULATION OF HOMOLOGOUS AND CANNIBALISTIC CORONAL MASS EJECTIONS PRODUCED BY THE EMERGENCE OF A TWISTED FLUX ROPE INTO THE SOLAR CORONA”

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PIYALI CHATTERJEE AND YUHONG FAN
High Altitude Observatory, National Center for Atmospheric Research, 3080 Center Green Drive, Boulder, CO 80301, USA; piyali@astro.uio.no

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We have found that the magnetic and kinetic energies were erroneously over-estimated by a factor of $4\pi$ in making the plot in Figure 2 of the published paper. A corrected version of Figure 2 is included below, giving the corrected magnetic free energy, $E_{\text{free}}^M$, the magnetic potential energy, $E_P$, and the kinetic energy, $E_K$, as a function of time. All the other results and conclusions from the original paper remain unchanged.

Figure 2. Magnetic free energy, $E_{\text{free}}^M$, $E_P$ and kinetic energy, $E_K$ as a function of time. The red dashed lines indicate the times for the three CME events. (A color version of this figure is available in the online journal.)