THE ROLE OF A FLUX ROPE EJECTION IN A THREE-DIMENSIONAL MAGNETOHYDRODYNAMIC SIMULATION OF A SOLAR FLARE

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ABSTRACT

We investigated the dynamic evolution of a three-dimensional (3D) flux rope eruption and magnetic reconnection process in a solar flare by simply extending the two-dimensional (2D) resistive magnetohydrodynamic simulation model of solar flares with low \(\beta\) plasma to a 3D model. We succeeded in reproducing a current sheet and bidirectional reconnection outflows just below the flux rope during the eruption in our 3D simulations. We calculated four cases of a strongly twisted flux rope and a weakly twisted flux rope in 2D and 3D simulations. The time evolution of a weakly twisted flux rope in the 3D simulation shows behaviors similar to those of the 2D simulation, while a strongly twisted flux rope in the 3D simulation clearly shows a different time evolution from the 2D simulation except for the initial phase evolution. The ejection speeds of both strongly and weakly twisted flux ropes in 3D simulations are larger than in the 2D simulations, and the reconnection rates in 3D cases are also larger than in the 2D cases. This indicates positive feedback between the ejection speed of a flux rope and the reconnection rate even in the 3D simulation, and we conclude that the plasmoid-induced reconnection model can be applied to 3D. We also found that small-scale plasmoids are formed inside a current sheet and make it turbulent. These small-scale plasmoid ejections have a role in locally increasing the reconnection rate intermittently as observed in solar flares, coupled with a global eruption of a flux rope.

Key words: magnetic reconnection – magnetohydrodynamics (MHD) – Sun: coronal mass ejections (CMEs) – Sun: filaments, prominences – Sun: flares – turbulence

Online-only material: color figures

1. INTRODUCTION

The mechanisms of energy storage and release in solar flares remain puzzles (see the review by Shibata & Magara 2011). Magnetic reconnection converts stored magnetic energy to thermal and kinetic energy by reconnecting two anti-parallel magnetic field lines. Coronal currents store the energy required for power eruptions. Indeed, it has been shown that active regions exhibiting a sigmoidal morphology are more likely to erupt than non-sigmoidal ones (Canfield et al. 1999). It has long been suspected that solar filaments are helical in structure (Rust & Kumar 1994), and much progress has been made in modeling filament eruptions with two- and three-dimensional (2D and 3D) magnetohydrodynamic (MHD) simulations (Chen & Shibata 2000; Amari et al. 2003; Török & Kliem 2005; Karlický & Kliem 2010; Kliem et al. 2010; Karpen et al. 2012; Kusano et al. 2012).

Magnetic shear due to slow footpoint motions in the vicinity of the polarity inversion line, especially the case of reversed shear, causes a large-scale eruption of the magnetic arcade in association with the formation of a sigmoidal structure (Kliem et al. 2010; Kusano et al. 2012). The eruption depends on the initial helicity, and a strongly twisted flux rope rises faster with a large amount of energy release (Amari et al. 2003). The initial force-free configuration with a flux rope may be linear kink unstable when it loses the equilibrium state (Forbes & Priest 1994; Inoue & Kusano 2006). Helical kink instability may be one candidate for the trigger mechanism of a solar flare (Török & Kliem 2005; Karlický & Kliem 2010; Kliem et al. 2010) and small-scale reconnection by emerging fluxes or magnetic flux cancellation by moving magnetic features is another (Chen & Shibata 2000; Moore et al. 2001; Sterling et al. 2010).

It is numerically shown by 2D MHD simulations that a flux rope eruption induces reconnection inflow to the current sheet and enhances both the current density and electric field, finally leading to fast reconnection (Cheng et al. 2003; Nishida et al. 2009). This process is called plasmoid-induced reconnection by Shibata & Tanuma (2001). Interestingly, these features have been verified in solar observations (Zhang et al. 2001; Qiu et al. 2004; Shimizu et al. 2008; Nishizuka et al. 2010) and laboratory experiments (Ono et al. 2011). To answer the question of whether this is valid even for 3D configuration, we performed a 3D resistive MHD simulation of a solar flare by simply extending the 2D MHD model. In Section 2, we explain our numerical model and show our results in Section 3. Finally, we discuss and summarize our results in Section 4.

2. NUMERICAL MODEL

We numerically solved the resistive MHD equations (Equations (4)–(7) and (12) in Shiota et al. 2005) in a 3D Cartesian geometry. We simply uniformly extended the previous 2D MHD model to 3D direction (see 2D models; Chen & Shibata 2000; Shiota et al. 2005) and assumed anomalous resistivity depending on the current density and neglected gravity, thermal conduction, and radiation cooling and heating terms. Hence, this simulation is valid only in the period when the effects of gravity, thermal conduction, and radiation cooling/heating are small enough.
Initially we assumed an isolated horizontal flux rope sustained in the corona in a near-equilibrium but unstable state. The background magnetic field is a potential quadrupole field which is produced by four virtual line currents and one image current inside. To satisfy the force balance within the flux rope, a force working only in 3D simulation (see Section 4). We slightly raised the center of the flux rope in the initial state, which triggers a loss of equilibrium the flux rope, then ejection starts via Lorentz force after an initial slight movement, while both edges of the flux rope are forced down and collide with the bottom boundary (solar surface). As the flux rope is ejected upward, it expands because the surrounding magnetic field decreases with height. In the case of a weakly twisted flux rope, it moves upward, keeping the 2D-model-like configuration shown in Figure 2(c).

Figure 2(d) shows the simulation result for a vertical velocity field $v_z$ on the $y$–$z$ plane ($x = 0$). Blue and red colors indicate upward and downward flows, respectively. Figure 2(d) shows intermittent bi-directional outflows at several different heights just below the flux rope. This indicates magnetic reconnection intermittently occurring along the polarity inversion line during the eruption. The maximum velocity of the reconnection outflow is 1500 km s$^{-1}$, which is comparable to Alfvén velocity ($V_A$). These features are consistent with observations of multiple downflows (Asai et al. 2004; Sheeley et al. 2004; McKenzie & Savage 2009; Savage et al. 2010). A larger number of reconnection outflows are solved with 800$^3$ grids compared with 400$^3$ grids.

For comparison, snapshot images of a strongly twisted flux rope ejection are shown in Figures 2(e)–(g). A strongly twisted flux rope initially shows greater upward acceleration than a weakly twisted flux rope and shows a rotation about the $z$-axis, the so-called writhe (Kliem et al. 2010), during the nonlinear evolution. At that time, the footpoints of the flux rope move closer (similar to Török & Kliem 2005; Karlícký & Kliem 2010; Kliem et al. 2010) and a current sheet becomes shorter in depth below the flux rope, while the reconnection outflows become smaller because of lower reconnection magnetic field strength (Figure 2(h)). This is not reproduced in the 2D simulation, thus this is an original 3D dynamic and is quite different from 2D.

The time evolutions of height and ejection speed of the two flux ropes and the electric field $\eta J$ (the reconnection rate) in 2D and 3D simulations are compared in Figure 3. The onset of each ejection is at $\tau = 0$. Both strongly and weakly twisted flux ropes in 3D simulations are accelerated more strongly than in 2D simulations (Figures 3(b) and (e)). This is because a flux rope in 3D can be more easily ejected upward without removing or reconnecting with the whole ambient magnetic field in 3D, although it must remove or reconnect with the entire ambient field for this in 2D. The other reason is that a flux rope is additionally accelerated by the 3D effect, i.e., a force working only in 3D simulation (see Section 4). We also stress here that the flux rope is actually not ejected in the strongly twisted 3D case (confined or “failed” eruption; see Figures 3(d) and (e)) because magnetic tension force or the restoring force becomes stronger compared with a weakly twisted flux rope in the later phase in our configuration (see also Török & Kliem 2005). Furthermore, the reconnection...
Figure 2. (a)–(c) Time evolution of a weakly twisted flux rope ejection in the 3D configuration. Color indicates the magnetic field strength. (d) Vertical velocity map in the y–z plane (x = 0) of a weakly twisted flux rope. White (black) color indicates the upward (downward) flow (colored blue and red, respectively, in the online journal). The dotted line shows a position of the flux rope. (e)–(g) Time evolution of a strongly twisted flux rope. (h) Vertical velocity map in the y–z plane (x = 0) of a strongly twisted flux rope.

Figure 4 shows the iso-surface of resistivity and magnetic field lines colored by magnetic field strength in the case of a weakly twisted flux rope in 3D with 8003 grids. Initially a Sweet–Parker-type steady current sheet is formed below the flux rope and continues thinning until it becomes unstable for the tearing instability or the anomalous resistivity sets in. At that time, the current sheet is fragmented to several small-scale current sheets with multiple X-lines and O-lines where current density is locally enhanced. They are located at the origins of bi-directional reconnection outflows, that is, reconnection points at several different heights in Figures 2(d) and (h). Multiple X-lines or small-scale current sheets generate multiple plasmoids among themselves and eject these plasmoids upward or downward intermittently, which is resolved with an 8003 grids simulation. This makes the current sheet turbulent and more dynamic. Simultaneously, inflows are induced to small-scale current sheets, enhancing the local electric field and finally driving faster reconnection (Figure 5). The bursty short time scale variations of the electric field η J and the reconnection rate correspond to these small-scale plasmoid ejections or the merging of multiple plasmoids into a single plasmoid. The enhancements of the electric field may also be observed in hard X-ray emission and radio bursts (or type III bursts) as a result of particle acceleration in association with harder energy release.

4. SUMMARY AND DISCUSSION

We performed a 3D resistive MHD simulation of a solar flare and reproduced a flux rope eruption by simply uniformly extending the 2D flare model to a 3D model. After the initial slight movement of the center of the flux rope, the flux rope is ejected upward developing into nonlinear evolution. The ejection of a weakly twisted flux rope occurs upward keeping its time evolution in the 2D x–z plane quite similar to the standard 2D model. By contrast, a strongly twisted flux rope nonlinearly evolves more rapidly, with a horizontal rotation of 90°.
Figure 3. (a) Time evolution of the height of a flux rope, (b) the ejection velocity, and (c) the electric field $\eta J$ in the reconnection region for a weakly twisted flux rope in the 2D (dotted black line) and 3D (solid red line) simulations. We choose peak values of the electric field in each $x-z$ plane, and average them along the $y$-direction. (d)-(f) Time evolutions of the same parameters for a strongly twisted flux rope in the 2D and 3D simulations. (A color version of this figure is available in the online journal.)

Figure 4. Snapshot image of small plasmoids in a current sheet for an 800$^3$ grid case. Color indicates the magnetic field strength. The white lines show plasmoids. The dark gray (pink in the online journal) surfaces show a region where the anomalous resistivity works. (A color version of this figure is available in the online journal.)
global helical shape of the erupting flux rope makes a current sheet shorter in depth below the flux rope and localizes the outflow region.

Each flux rope in our 3D simulations reaches a higher upward velocity than a rope in the corresponding 2D simulation with the same initial configuration. This is because a flux rope in the 3D configuration can relatively easily escape from the closed coronal loops compared with that in a 2D configuration. This is also because the additional force by the 3D effect works on a flux rope for acceleration. A flux rope with stronger twist shows a higher ejection speed and larger reconnection rate in the initial phase \( t < 350 \text{ s} \) (Figure 3(f)). This means that a stronger twist enables the rapid acceleration of a flux rope and consequently a rapid increase of the reconnection rate in the earlier phase. In the latter phase after \( t > 350 \text{ s} \), a flux rope with a stronger twist is decelerated by the magnetic tension force and reconnection is suppressed, while a flux rope with a weaker twist continues to be ejected upward and finally reaches the upper boundary.

Next we consider the 3D additional force for flux rope acceleration. It is higher with a larger amount of twist in the initial phase. It is known that a twisted flux tube with free ends is subject to helical kink instability. The amount by which a given line is twisted in going from one end of the tube (of length \( l \)) to the other is given by \( \Phi(R) = l B_y(R) / R B_z(R) \). The flux rope is not affected by kink instability under conditions where \( \Phi \leq 2\pi \) (Kruskal–Shafranov limit; Bateman & Peng 1977). The effect of line-tying at the edges of a flux rope is stabilizing, and a uniform-twist force-free flux rope requires a twist \( (\Phi) \) larger than \( 2.5\pi \) before it becomes kink unstable (Einaudi & van Hoven 1983). A weakly twisted flux rope is stabilized with an amount of twist \( \Phi(0) = 3.0 \pi \), and a strongly twisted flux rope is \( \Phi(0) = 4.5 \pi \). Therefore, the two cases in our simulation are kink unstable.

The larger ejection velocity of the flux rope induces faster inflow to the current sheet, satisfying mass conservation. When this occurs, magnetic flux is piled up and the current density is increased as well. Once current density surpasses the threshold value, anomalous resistivity sets in and drives fast reconnection with a large amount of released thermal energy. Inversely, fast reconnection also accelerates the ejection and evolves into nonlinear instability. This was originally proposed as plasmoid-induced reconnection in a 2D model (Shibata & Tanuma 2001), and our simulation results show that this model can be applicable to a 3D model as well. Here we stress that the instabilities (such as kink instability, torus instability, or loss of equilibrium; e.g., Aulanier et al. 2010) are necessary for the eruption and formation of a current sheet. However, they are not always enough to determine the reconnection rate (or equivalently, the energy release rate). We propose that when the feedback from magnetic reconnection to the eruption or the instabilities working on the flux rope works effectively, greater energy release is enabled. Therefore, in our opinion, not only the instabilities but also the feedback from magnetic reconnection to the instabilities is important to understand the process of energy release in a solar flare.

We also reproduced small structures of a turbulent/fragmented current sheet, in which patchy reconnection (Aschwanden 2002; Linton & Longcope 2006; Guidoni & Longcope 2011), turbulent reconnection (Kowal et al. 2011; Lazarian et al. 2012), or fractal reconnection (Shibata & Tanuma 2001; Ji & Daughton 2011; Nishizuka & Shibata 2013; Drake et al. 2013) occurs at several heights. They produce small-scale multiple plasmoids inside and eject them intermittently, as observed in solar flares (Nishizuka et al. 2010; Takasao et al. 2012). This makes the current sheet turbulent and more dynamic not only in the 2D \( x-z \) plane (see also Samtaney et al. 2009; Huang &
Bhattacharjee 2010; Bárta et al. 2011; Janvier et al. 2011; Kowal et al. 2011; Shen et al. 2011; Loureiro et al. 2012; Mei et al. 2012) but also in the 3D direction (Edmondson et al. 2010; Bárta et al. 2012; Daughton & Roytershteyn 2012). The tendency toward fragmentation and turbulence found in the present simulation may be quantitatively different if a stronger guide field (shear field) is included. The correlation between the flux rope/plasmoid acceleration and the reconnection rate is valid even for small-scale plasmoids inside a current sheet. This is why the coupling of global- and small-scale dynamics of plasmoid ejections explains the intermittent energy release, enhanced reconnection rate, and particle acceleration in a solar flare.

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