Eruption of Solar Magnetic Flux Ropes Caused by Flux Feeding

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Abstract

Large-scale solar eruptions are believed to have a magnetic flux rope as the core structure. However, it remains elusive as to how the flux rope builds up and what triggers its eruption. Recent observations found that a prominence erupted following multiple episodes of “flux feeding.” During each episode, a chromospheric fibril rose and merged with the prominence lying above. In this Letter, we carried out 2.5-dimensional magnetohydrodynamic (MHD) numerical simulations to investigate whether the flux-feeding mechanism can explain such an eruption. The simulations demonstrate that the discrete emergence of small flux ropes can initiate eruptions by feeding axial flux into the preexistent flux rope until its total axial flux reaches a critical value. The onset of the eruption is dominated by an ideal MHD process. Our simulation results corroborate that the flux feeding is a viable mechanism to cause the eruption of solar magnetic flux ropes.

Unified Astronomy Thesaurus concepts: Solar prominences (1519); Solar filaments (1495); Solar flares (1496); Solar magnetic flux emergence (2000); Solar coronal mass ejections (310); Solar filament eruptions (1981)

1. Introduction

Large-scale solar eruptions are manifested as the observed phenomena of flares, prominence/filament eruptions, and coronal mass ejections (CMEs). It is widely accepted that these kinds of events are intimately associated with a coronal magnetic flux rope system and are essentially different manifestations of the same physical process, i.e., the eruption of the rope system (Zhang et al. 2001; van Driel-Gesztelyi & Green 2015; Green et al. 2018; Jiang et al. 2018; Yan et al. 2018). A typical scenario is that, during a flux rope eruption, the prominence/filament contained in the rope also erupts with the rope, and the magnetic reconnection in the current sheet formed beneath the rope dramatically converts free magnetic energy in the coronal magnetic system into thermal energy and nonthermal particle acceleration, so that a flare occurs; this flux rope further propagates outwards and expands, so as to be observed as a CME in the corona and the interplanetary space (e.g., Lin & Forbes 2000). These large-scale eruptive activities are generally considered to be the major disturbance affecting the solar-terrestrial system (e.g., Shen et al. 2014). Therefore, it has great significance to study the formation process of an erupting magnetic flux rope and its trigger mechanism.

Various theoretical models have been proposed to investigate the eruptive mechanism of flux ropes, either based on magnetic reconnection (Antiochos et al. 1999; Chen & Shibata 2000; Moore et al. 2001; Sterling & Moore 2004; Archontis & Hood 2008; Inoue et al. 2015) or ideal MHD instabilities (Romano et al. 2003; Török & Kliem 2003; Kliem & Török 2006; Fan & Gibson 2007; Aulanier et al. 2010; Guo et al. 2010; Savcheva et al. 2012). It was also suggested by many authors that catastrophes could be responsible for solar eruptions: the onset of the eruption corresponds to a catastrophic loss of equilibrium (Forbes & Isenberg 1991; Isenberg et al. 1993; Lin et al. 2001; Chen et al. 2007; Démoulin & Aulanier 2010; Kliem et al. 2014a; Longcope & Forbes 2014). Flux rope catastrophes could be triggered by various physical processes. For example, it was found that there exists a critical value of the total axial (also called toroidal in a tokamak configuration) magnetic flux of a flux rope (e.g., Bobra et al. 2008; Su et al. 2009, 2011; Zhang et al. 2016, 2017a, 2017b; Zhuang et al. 2018). If the axial flux of the rope is smaller than this critical value, the rope system stays in equilibrium states; when this critical value is exceeded, loss of equilibrium occurs in the rope system: the flux rope jumps upward, with magnetic reconnection occurring below it, so that the rope erupts outward. This critical axial flux is of the order $10^{19} \sim 10^{20}$ Mx, and is influenced by various conditions, such as photospheric magnetic flux distributions (e.g., Zhang et al. 2017b).

Recently, it was observed by Zhang et al. (2014; hereafter Paper I) that a sequence of flux feeding episodes occurred within the two-day period prior to the eruption of a prominence. As shown in the right panel of Figure 1, a chromospheric fibril appeared as a dark structure at about 20 Mm along the slit before about 08:50 UT, after which it rose and merged with the prominence within about 40 ~ 60 Mm along the slit. During a flux feeding process, magnetic flux and mass are injected into the target prominence from the chromosphere underneath. This is reminiscent of bubbles rising and expanding into quiescent prominences (e.g., Berger et al. 2010), as well as the transfer of magnetic flux and current between the different branches in a double-decker configuration (e.g., Liu et al. 2012; Cheng et al. 2014; Kliem et al. 2014b). As observed in Paper I, flux feeding events successively occurred three times, which increased the slow-
rising velocity of the prominence. Eventually, the prominence erupted. Therefore it was suggested that the eruption could be initiated by flux feeding processes. This also indicates that flux feeding could be regarded as one of the precursors of solar eruptions (e.g., Wang et al. 2017a). The physical nature of the flux rope eruptions initiated by flux feeding, however, remains unclear; there are still many issues about this scenario. The emergence ends at \( t = t_E = 30\tau_A \) s; \( \tau_A = L_0^2 \sqrt{\mu_0 \rho_0 / \psi_0} = 17.4 \) s is the characteristic Alfvén transit time, where \( \rho_0 = 3.34 \times 10^3 \) kg m\(^{-3}\) and \( \psi_0 = 3.73 \times 10^7 \) Wb m\(^{-1}\). With a constant emerging speed, the emerged part of the small rope at time \( t \) is located within \(-x_E \leq x \leq x_E\), where
\[
x_E = (a^2 - h_E^2)^{1/2}, \quad h_E = a(2t/t_E - 1).
\]
Based on this, the emergence of the small flux rope is achieved by adjusting \( \psi, B_z \), velocities \( v_{x,y,z} \), temperature \( T \), and density \( \rho \) at the base of the emerged part of the small rope \((y = 0, -x_E \leq x \leq x_E)\):
\[
\psi(t, x, y = 0) = \psi_i(x, y = 0) + \psi_E(t, x),
\]
\[
\psi_E(t, x) = \frac{C_E}{2} \ln \left( \frac{2a^2}{a^2 + x^2 + h_E^2} \right),
\]
\[
B_z(t, x, y = 0) = C_E a (a^2 + x^2 + h_E^2)^{-1},
\]
\[
v_y(t, x, y = 0) = v_E = 2a/\tau_A,
\]
\[
v_z(t, x, y = 0) = v_z(t, x, y = 0) = 0,
\]
\[
T(t, x, y = 0) = 2 \times 10^5 \text{ K}, \quad \rho(t, x, y = 0) = 1.67 \times 10^{-12} \text{ kg m}^{-3}.
\]
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3. Simulation Results

The simulation result of a typical flux feeding process with \( C_E = 1.90 \) is shown in Figure 2. At the early stage of the flux feeding process, the emerging small flux rope appears below the major rope, as shown in Figure 2(c). A horizontal current sheet forms at the interface between the small and major ropes, as marked by the blue curves in Figure 2, which are the contours of the current density \( j = 5.63 \times 10^{-4} \text{ A m}^{-2} \). The emerged small rope could be clearly recognized in Figure 2(g) and the corresponding distribution of \( B \) in Figure 3(e). As a result of the magnetic reconnection within the current sheet, the magnetic field lines of the small rope gradually reconnect with those of the major rope (see Figures 2(e)–(h)). The height of the current sheet gradually increases with time, triggering flows within the major rope, as illustrated by the red arrows in Figures 2(e)–(h). Eventually, the two flux ropes merge together. Note that since the major rope sticks to the photosphere, the reconnection occurs immediately after the small rope begins to emerge. The topology of the resultant flux rope system after flux-feeding is shown in Figure 4(a).

Further evolution of the resultant flux rope system indicates that this flux feeding process with \( C_E = 1.90 \) eventually triggers the major rope to erupt. As shown in Figure 4(g), the eruption of the rope occurs after the flux feeding process. After the onset of the eruption, the lower boundary of the rope is not detached from the photosphere instantly, but keeps sticking to the photosphere for a certain period (Figures 4(b) and (c)). As the height of the rope increases, the lower part of the rope, along with the adjacent background field lines, are stretched, during which the flux rope is gradually accelerated. Eventually, a vertical current sheet forms beneath the flux rope, as shown in Figures 4(d)–(f). The magnetic reconnection that occurs in this current sheet should drive the further acceleration of the flux rope. The obvious delay of the appearance of this current sheet relative to the onset of the eruption indicates that the eruption should be triggered by an ideal process. This is consistent with the observations in Paper I, in which there was no intense heating around the source region of the prominence during the early period of its eruption, indicating that fast magnetic reconnection plays no crucial role in triggering the eruption. It is noteworthy that the initial state is a stable equilibrium: if there is no flux feeding process, the major rope will keep sticking to the photosphere forever.

4. Analysis

As shown in the simulations demonstrated in Section 3, flux feeding is able to eventually cause a flux rope system to erupt, consistent with the conclusion in Paper I. To further understand the physical nature of this scenario, detailed investigation about the influence of different settings of the flux feeding is needed. It has already been mentioned in Section 2 that \( C_E \) determines the magnetic field strength in the emerging small flux rope, so...
that cases with different $C_E$ correspond to different intensities of flux feeding.

The properties of the major rope is characterized by the axial magnetic flux, $\Phi_z$, and the poloidal magnetic flux per unit length along the $z$-direction, $\Phi_p$. In the initial state shown in Figure 2(b), the axial flux $\Phi_{z0} = 9.31 \times 10^{19}$ Mx, the poloidal flux $\Phi_{p0} = 1.49 \times 10^{10}$ Mx cm$^{-1}$. Assuming the length of the rope is 100 Mm, the total poloidal flux of the flux rope is of the order $1.5 \times 10^{20}$ Mx. For the case with $C_E = 1.90$ shown in Section 3, the axial flux $\Phi_z$ of the resultant rope at $t = 30 \tau_A$ increases to $11.73 \times 10^{19}$ Mx, whereas the poloidal flux $\Phi_p$ is still $1.49 \times 10^{10}$ Mx cm$^{-1}$, almost the same as the initial state. This indicates that the twist angle within the rope should decrease after flux feeding. Simulation results with other different $C_E$ also comes to a similar conclusion, indicating that flux feeding processes only inject axial flux into the major rope. This is because the poloidal flux of the small rope is entirely canceled out by the magnetic reconnection during its merging process with the major rope. The injected axial flux is mainly distributed near the boundary of the flux rope, which results in the current in this region after flux feeding (see Figure 4(a)).

The flux feeding process, however, is not always able to trigger the major flux rope to erupt; it requires a certain threshold. For the cases with different $C_E$, $\Phi_z$ of the resultant rope at $t = 30 \tau_A$ is plotted in Figure 5(a); the noneruptive cases (i.e., the major rope keeps sticking to the photosphere after flux feeding) with different $C_E$ are plotted in circles with different colors, while the eruptive ones are plotted in black solid dots. For the case with larger $C_E$, the magnetic field in the small emerging rope is stronger, so that more axial flux is injected. It is obvious in Figure 5(a) that $\Phi_z$ of the resultant rope in the eruptive cases is larger than that in the noneruptive ones. For each noneruptive case in Figure 5(a), through using the noneruptive state as the new pre-feeding state, we let a new
small rope emerge from below the major rope, and these cases are called the second round of flux feeding; the corresponding \( \Phi_c \) at \( t = 30 \tau_{\lambda} \) is plotted in Figure 5(b), and their colors are the same as their corresponding pre-feeding states. Similarly, the noneruptive cases are plotted in circles, and eruptive cases in dots. For clarification, the cases starting from the initial state in Figure 5(a) are called the first round. It is demonstrated in Figure 5 that the eruptive and noneruptive cases are separated. There should exist a critical value \( \Phi_{zc} \) of the order \( 1.2 \times 10^{20} \) Mx. If \( \Phi_c < \Phi_{zc} \) (circles), the eventual height of the major rope is finite, whereas if \( \Phi_c > \Phi_{zc} \) (dots), the eventual height should be infinite.

5. Discussion and Conclusion

In this Letter, we have carried out MHD numerical simulations to investigate the effect of flux feeding on coronal flux rope systems. In our simulations, it is found that the flux feeding processes only inject axial magnetic flux into the major rope, whereas the poloidal magnetic flux of the rope remains almost unchanged. The physical scenario of the eruption caused by flux feeding is by injecting axial flux into a flux rope in an incremental and intermittent fashion, flux feeding effectively drives the rope to evolve toward a critical condition and eventually can trigger its eruption. Therefore, our simulation results corroborate that flux feeding is a viable mechanism to cause the eruption of solar magnetic flux ropes. For the major flux rope, there exists a threshold \( \Phi_{zc} \): if the major rope’s axial flux \( \Phi_c \) is below \( \Phi_{zc} \), it will keep sticking to the photosphere, no matter how many flux feeding episodes have occurred; on the other hand, if \( \Phi_c \) exceeds \( \Phi_{zc} \), the rope system will erupt.

The existence of the threshold \( \Phi_{zc} \) indicates that the number of flux-feeding episodes is not important; only when the amount of its axial flux exceeds the critical value will the major rope erupt. Based on this result, the evolution of the observational event analyzed in Paper I can be interpreted as follows. The injected axial magnetic flux via the first and second observed flux feeding episodes might not be sufficient for the flux rope embedding the prominence to reach its critical state, thus the prominence remained in a quasi-equilibrium (slow-rising) state. But the third episode of flux feeding became the “last straw,” so that the flux rope erupted. The early flux feeding processes might not trigger the eruption, but with each episode of flux feeding the rope system was one step closer to the eruption.

As introduced in Section 1, previous studies suggested the presence of a critical axial flux for flux ropes; a catastrophe occurs if this critical value is reached. Our simulation results also support this theoretical conclusion. In the eruptions caused by flux feeding, the flux feeding processes continually inject axial flux, acting as a build-up toward the onset of the eruption. When the critical axial flux is reached, an upward catastrophe is triggered, and the further evolution of the upward catastrophe, along with the magnetic reconnection within the current sheet below the rope, drives the eruption of the flux rope (see Green et al. 2018 for the classification of “trigger” and “driver” for solar eruptions). The critical value in our simulation is of the order \( 1.2 \times 10^{20} \) Mx, which is comparable with both the derived values in theoretical analyses (e.g., Su et al. 2011; Zhang et al. 2017b) and the observed magnetic fluxes of CMEs (e.g., Qiu et al. 2007; Hu et al. 2015; Wang et al. 2015, 2017b; Gopalswamy et al. 2017). The increase of \( \Phi_c \) in the theoretical studies mentioned above is artificial, i.e., the discovered upward catastrophe is only a phenomenon in the parameter space of \( \Phi_c \), not reflecting the dynamic evolution of the system. The flux rope eruption in the corona, however, is a dynamic phenomenon in the physical space. Our simulations demonstrate flux feeding as a viable mechanism to prepare a flux rope for the upward catastrophe in the physical space, not just in the parameter space. It is noteworthy that, because of the different initial states and simulating procedures, the critical axial fluxes in, e.g., Zhang et al. (2017b), are not exactly the same as ours, and the rope systems eventually reach equilibria in that study.

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Appendix

Basic Equations and Initial Preparations

Through using Equation (1), the 2.5-dimensional MHD equations can be rewritten in dimensionless form as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (A1)$$

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + \nabla T + \frac{T}{\rho} \nabla \rho + \frac{2}{\rho \beta_0} (\Delta \psi \nabla \psi + B_z \nabla B_z + \nabla \psi \times \nabla B_z) + g \psi = 0, \quad (A2)$$

$$\frac{\partial \psi}{\partial t} + \mathbf{v} \cdot \nabla \psi = \frac{2 \eta}{\beta_0} \Delta \psi = 0, \quad (A3)$$

$$\frac{\partial B_z}{\partial t} + \nabla \cdot (B_z \mathbf{v}) + (\nabla \psi \times \nabla v_z) \cdot \mathbf{\hat{z}} - \frac{2 \eta}{\beta_0} \Delta B_z = 0, \quad (A4)$$

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + T \nabla \cdot \mathbf{v} - \frac{4 \eta (\gamma - 1)}{\rho R \beta_0^2} [(\Delta \psi)^2 + |\nabla \times (B_z \mathbf{\hat{z}})|^2] = 0, \quad (A5)$$

where

$$\Delta \psi = \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2}, \quad \Delta B_z = \frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial y^2}, \quad (A6)$$

and $\rho$ and $T$ denote the density and the temperature; $v_x$, $v_y$, and $v_z$ represent the $x$-component, $y$-component, and $z$-component of the velocity, respectively; $\gamma$ is the polytropic index, which is selected to be $5/3$ in our simulation; $g$ is the normalized gravity; and $\eta$ is the resistivity. Here $\beta_0 = 2 \mu_0 \rho_0 R T_0 L_0^2 / \psi_0^2 = 0.1$ is the characteristic ratio of the gas pressure to the magnetic pressure, where $\rho_0 = 3.34 \times 10^{-13}$ kg m$^{-3}$, $T_0 = 10^6$ K, $L_0 = 10^7$ m, and $\psi_0 = 3.73 \times 10^3$ Wb m$^{-1}$ are the characteristic values of density, temperature, length, and magnetic flux function, respectively, which are also the calculating units in the simulation. The characteristic values of other quantities are $v_0=128.57$ km s$^{-1}$, $t_0 = 77.8$ s, $B_0 = 3.37 \times 10^{-4}$ T, and $g_0 = 1.65 \times 10^3$ m s$^{-2}$. The numerical domain is $0 < x < 200$ Mm, $0 < y < 300$ Mm, and discretized into $400 \times 600$ uniform meshes with grid spacing $\Delta x = \Delta y = 0.5$ Mm. Symmetric boundary condition is used for the left side ($x=0$). The radiation and the heat conduction in the energy equation are neglected.

In order to investigate the influence of flux feeding on flux rope systems, we must first construct a typical coronal flux rope system, and then realize the flux feeding process in simulations. Here we select a partially open bipolar field, with negative and positive surface magnetic charges located at the photosphere within $-b < x < -a$ and $a < x < b$, respectively, as the background field, which can be obtained by the complex variable method (e.g., Hu et al. 1995; Zhang et al. 2017b). The background magnetic field can be cast in the complex variable form

$$f(\omega) \equiv B_x - i B_y = \frac{\left(\omega + i \eta_N \right)^2 / 2}{\left(\omega - i \eta_N \right)^2 / 2} \ln \left(\frac{\omega^2 - a^2}{\omega^2 - b^2} \right) \quad (A7)$$
where \(\omega = x + iy\), and
\[
F(a, b, y_N) = \frac{1}{b - a} \int_a^b (x^2 + y_N^2)^{1/2} dx
\]
\[
= \frac{1}{2(b - a)} \times \left[ b(b^2 + y_N^2)^{1/2} - a(a^2 + y_N^2)^{1/2} + y_N^2 \ln \left( \frac{b + (b^2 + y_N^2)^{1/2}}{a + (a^2 + y_N^2)^{1/2}} \right) \right].
\]
(A8)

Here \(a = 30\) Mm, \(b = 40\) Mm, and \((y = y_N = 60.6\) Mm, \(x = 0\)) is the position of the neutral point of the partially open bipolar field. The neutral current sheet of the background field is located at \((x = 0, y \geq y_N)\). The width of the surface magnetic charges is \(w = b - a = 10\) Mm, and the distance between them is \(d = 2a = 60\) Mm. The magnetic flux function could then be calculated by:
\[
\psi(x, y) = \text{Im} \left\{ \int f(\omega) d\omega \right\},
\]
and the flux function at the lower base is
\[
\psi_1(x, 0) = \begin{cases} 
\psi_e, & |x| < a \\
\psi_e F(|x|, b, y_N)/F(a, b, y_N), & a \leq |x| \leq b \\
0, & |x| > b 
\end{cases}
\]
(A10)

where \(\psi_e = \pi \psi_{0e}\); the flux function at the neutral point \(y = y_N\) is
\[
\psi_N = \frac{\pi(b^2 - a^2)}{2F(a, b, y_N)}.
\]
(A11)

The background field is potential everywhere except along the neutral current sheet and at the lower base. For potential magnetic fields, \(f(\omega) = B_x - iB_y\) satisfies the Cauchy–Riemann condition, so that the integral in Equation (A9) is independent of the integration path in as far as the integration path does not touch the neutral current sheet and the lower base. The flux function along the neutral current sheet of the background partially open bipolar field is a constant, which is given by Equation (A11); the flux function at the lower base is given by Equation (A10). With the flux function calculated above, and let \(B_z\) equals 0 in the background field, the configuration of the background field is obtained, as shown in Figure 2(a). The reconnection in the current sheet of the background field is prohibited by the method introduced in Hu et al. (2003). The initial corona is isothermal and static with
\[
T_c \equiv T(0, x, y) = 1 \times 10^6 \text{K}, \quad \rho_c \equiv \rho(0, x, y) = \rho_0 e^{-\gamma y}.
\]
(A12)

As mentioned above, symmetric condition is used at the left boundary. Except during the emergence of the small rope, the lower boundary is fixed: the flux function \(\psi\) is fixed at \(\psi_N\) given by Equation (A10); \(B_z\) is fixed at 0; the velocity at the lower boundary is zero; the density and the temperature are fixed at their initial values, which are given by Equation (A12). The quantities at the right and top boundaries are evaluated by increment equivalent extrapolations (e.g., Hu & Liu 2000):
\[
U^{n+1}_b = U^{n+1}_b - U^n_b - U^{n-1}_b.
\]

Here \(U\) represents the quantities (e.g., \(\rho, v, \psi\)); the superscript \(n\) and \(n + 1\) indicates the quantities at the current and the next time steps, respectively; \(U_b\) represents the quantities at the boundary, and \(U_{b-1}\) the quantities at the location next to the boundary. The boundary quantities at the next time step, \(U^{n+1}_b\), are then prescribed.

With the initial and background conditions, Equations (A1)–(A5) are simulated by the multistep implicit scheme (Hu 1989). Starting from the background field, first by letting a flux rope emerge from the lower base, we obtain a flux rope system with the rope sticking to the photosphere; then adjust the axial and poloidal fluxes of the rope to \(\Phi_{0a} = 9.31 \times 10^{19} \text{Mx} \) and \(\Phi_{0p} = 1.49 \times 10^{19} \text{Mx cm}^{-1}\), respectively, and let the rope system relax to a stable equilibrium state. The relaxation is achieved by letting the rope system evolve for a long enough time, during which the fluxes of the rope are fixed at \(\Phi_{0a}\) and \(\Phi_{0p}\); as a result of the numerical diffusion in the simulation, the rope system eventually reaches an equilibrium state. The final equilibrium state is just the initial state of our simulation (as shown in Figure 2(b)), and the rope with \(\Phi_e = \Phi_{0a}\) and \(\Phi_p = \Phi_{0p}\) in this state is the so-called major flux rope. This flux rope system is in a bald patch separatrix configuration. Note that the radius of the flux rope is finite here, i.e., there is no constraint on the ratio of the radius to, e.g., the characteristic photospheric length, so that the initial state could not be derived by analytical methods but could only be obtained by numerical procedures.

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