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A Fundamental Mechanism of Solar Eruption Initiation

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ABSTRACT

Solar eruptions are spectacular magnetic explosions in the Sun's corona and how they are initiated remains unclear. Prevailing theories often rely on special magnetic topologies which, however, may not generally exist in the pre-eruption source region of corona. Here using fully three-dimensional magnetohydrodynamic simulations with high accuracy, we show that solar eruption can be initiated in a single bipolar configuration with no additional special topology. Through photospheric shearing motion alone, an electric current sheet forms in the highly sheared core field of the magnetic arcade during its quasi-static evolution. Once magnetic reconnection sets in, the whole arcade is expelled impulsively, forming a fast-expanding twisted flux rope with a highly turbulent reconnecting region underneath. The simplicity and efficacy of this scenario argue strongly for its fundamental importance in the initiation of solar eruptions.

1. INTRODUCTION

From time to time, the Sun produces eruptive activities, such as solar flares and coronal mass ejections (CMEs). It is now confirmed that such eruptions are explosive releases of magnetic energy in the Sun's corona (1). Research on solar eruptions has a long history of more than a century, from which a basic physical picture has been established (2; 3). Prior to eruptions, the coronal magnetic field is line-tied at the solar surface (i.e., the photo-

sphere), and is continuously but rather slowly stressed by motions at the photosphere (such as surface shear and rotational flows) that could last for a few hours or even days, during which magnetic free energy accumulates. Since plasma is strongly-magnetized in the corona, the Lorentz force dominates and is mostly self-balanced, that is, the outward magnetic pressure of the low-lying, strongly stressed flux is cancelled by the inward magnetic tension of the overlying, mostly un-sheared flux. At a critical point, there is a catastrophic disruption of this force balance, and the free magnetic energy is rapidly converted into impulsive heating and fast acceleration of the plasma. If the overlying flux is not too strong, the eruptive magnetic field can successfully eject into the heliosphere, forming a CME. Otherwise, it fails to escape, resulting in a confined flare or failed eruption.

A fundamental question that still lies in this picture, also a central point of controversy, is how the pre-eruption force balance is abruptly destroyed. Due to the lack of regular measurements of magnetic field in the corona, the mechanism governing the initiation of solar eruptions has remained a subject of intense investigation for decades (3; 4; 5; 6; 7; 8). The existing theories fall into two categories; one is based on ideal magnetohydrodynamic (MHD) instability and the other on a resistive process, i.e., magnetic reconnection. The first category requires the preexistence of a magnetic flux rope (MFR), a group of twisted magnetic field lines winding tightly enough about a common axis, in the corona before eruption, for the triggering of eruption to be a loss of equilibrium (9) or ideal instabilities of the MFR, such as torus instability (10; 11; 12; 13; 14). On the other hand, the most prevailing model based on magnetic reconnection, namely, the breakout model (15; 16; 17; 18), relies on a multipolar magnetic configuration in which there must be a magnetic null point above the sheared magnetic flux, such that reconnection at the null can remove the overlying restraining flux to trigger an eruption.

However, the key prerequisite of magnetic topology for these models, either an MFR or a null point, may not generally exist in the source region of eruptions, in particular, in solar active regions (ARs). For the MFR-based models, although there is little doubt that MFR constitutes the core structure of CMEs, the existence of MFR before CME initiation is still in intense debates (19). Almost all the observed features that have been invoked to support the preexistence of MFRs, such as coronal sigmoids and filaments, can also fit in simply sheared arcades with only weak twist (20; 5). Furthermore, significant magnetic twist is rarely seen before but only observed during filament eruptions (21; 22). For the breakout model, the coronal null point, which exists primarily in multipolar magnetic configuration, is not universally present in ARs, considering that the commonly-seen ARs are a bipolar configuration consisting of a pair of sunspots with opposite polarities. Furthermore, in this large, multipolar magnetic field, the null point must be situated right above the sheared arcade concentrated around the polarity inversion line (PIL) such that the breakout reconnection can be effective enough, which is difficult to fulfill in reality (23).

Here, with an ultra high-resolution, fully three-dimensional (3D) MHD simulation, we show that solar eruptions can be initiated from a more universal bipolar magnetic configuration without the aforementioned special topology. The simulation covers the whole

process from the energy accumulation in the source region to the triggering of eruption and its subsequent evolution. It shows that with surface shear along the PIL of a bipolar field, a vertical current sheet (CS) can spontaneously form above the PIL, essentially between the strongly-sheared legs of the core of the magnetic arcade. Once the CS is sufficiently thin such that ideal MHD is broken down, reconnection sets in and triggers the eruption. The magnetic topology does not change before the eruption, but transforms to a complex one having a highly twisted erupting MFR after the eruption onset. This simulation effectuates an early proposed idea, namely the runaway tether-cutting reconnection model (24; 25; 26), which was originally surmised from observation (and continued to be a popular “cartoon” model) but has never been accomplished in 3D simulations. Thus, our simulation establishes the runaway tether-cutting reconnection as a fundamental process in the initiation of solar eruptions.

2. RESULTS

Our simulation solves the full MHD equations with both coronal plasma pressure and solar gravity included. It is started with a potential, bipolar magnetic field that mimics a typical solar AR consisting of a pair of sunspots with opposite magnetic polarities (Fig. 1). In particular, the flux distribution has a relatively strong-gradient and elongated PIL, which is a characteristic magnetic field pattern for eruption-productive ARs (27; 28). The initial background atmosphere is set in hydrostatic state and configured to simulate typical coronal environment with low plasma β (i.e., ratio of gas pressure to magnetic pressure) and high Alfvén speed (Fig. A1). Then we energize the MHD system by applying anti-clockwise rotational flow to both polarities at the bottom surface. Such a flow follows the contours of the magnetic flux and concentrates near the PIL, thus it preserves the magnetic flux distribution and produces strong shear along the PIL. The flow speed, a few kilometers per second, is smaller than the sound speed by two orders and the Alfvén speed by three orders of magnitude, respectively, thus representing a quasi-static stress of the coronal magnetic field.

Figure 1 and Movie 1 show evolution of magnetic field lines and electric current structure driven by the rotational flow. Since the surface velocity has the largest gradient across the PIL, it creates strongly-sheared, low-lying magnetic field lines there, and the overall structure resembles an inverse S shape. In details, these highly sheared field lines consist of two groups of J shape having an oppositely curved elbow on their ends, and their arms are sheared past each other above the middle of the PIL, where the electric current is the strongest. Initially the current is volumetric but later it is squeezed into a vertical, narrow layer extending above the PIL as an inverse S shape (Fig. 1C and D), which is reminiscent of hot sigmoid structures often observed prior to flare in the corona. On the other hand, field lines connecting the central parts of the magnetic polarities (analogous to sunspot’s umbra) are only weakly sheared, which play the role of the strapping field overlying the inner strongly-sheared core. Clearly, the whole magnetic configuration inflates during the energizing phase as magnetic pressure of the sheared arcade increases continuously, which

then stretches outward its overlying field, making the bipolar arcade tend to approach an open field configuration. But the magnetic field is still close to force-free, i.e., the outward magnetic pressure gradient is balanced by the inward magnetic tension force, and furthermore, the strapping field is close to current-free, although it has been greatly strengthened compared with the initial potential field (Fig. A2).

The surface flow continuously injects magnetic energy into the simulation volume (Fig. 2A). In the early phase, the magnetic energy increases almost linearly, while the kinetic energy is negligible. Thus almost all the energy brought by the surface flow through Poynting flux is stored in the magnetic field. From around $t = 150$ min to 220 min, the kinetic energy shows a slow rise (Fig. 2A and B), indicating that a small amount of magnetic energy is converted into kinetic energy and gravitational potential energy of the plasma as it expands with the magnetic field. But the system is still quasi static as the kinetic energy remains to be three orders of magnitude less than the magnetic energy, and the velocity in the core of the AR is less than the local Alfvén speed by two orders of magnitude (Fig. 2C).

A sharp transition of the evolution pattern, namely an eruption, occurs at $t = 221$ min as the kinetic energy increases impulsively by nearly two orders of magnitude in about 10 min, amounting to $\sim 5\%$ of the original magnetic energy. Meanwhile, the magnetic energy drops immediately, despite the continual injection of Poynting flux through the bottom surface, indicating that the magnetic energy releases quickly during the eruption. The transition time, i.e., the onset time of eruption, is more distinctly shown by time profiles of the magnetic energy releasing rate (which is the subtraction of the magnetic energy changing rate from the total Poynting flux) and the kinetic energy increasing rate. Both of them increase sharply at the eruption onset, and reach their peaks simultaneously at around $t = 227$ min. The kinetic energy gained by plasma (mainly the CME) accounts for approximately one third of the amount of released magnetic energy, indicating that the flare energy should consume the other two thirds. This is consistent with the energy partition between flare and CME in typical eruptive flares (29). Also such a synchronization of the evolutions of flare energy releasing rate and CME acceleration agrees well with observations (30). The impulsiveness of the eruption is further seen from the evolution of velocity at a fixed point in the AR core (Fig. 2C), which increases by more than 10 times in 2 min, reaching an Alfvénic speed of $\sim 1000 \text{ km s}^{-1}$. We further traced the rising apex of a single field line (corresponding to a coronal loop in observation) initially in the AR core (Fig. 2D). Prior to the eruption, the loop rises slowly with velocity of $\sim 10 \text{ km s}^{-1}$, and once the eruption is triggered, it ascends exponentially, gaining a speed of $\sim 700 \text{ km s}^{-1}$ in about 5 min before its reconnection with others during the eruption. Such a transition from slow-rise to fast-acceleration phases is frequently observed for ejecting hot coronal loops and filaments in eruptions (31; 32).

The key to understanding how the eruption is triggered lies in the evolution of the central current layer. From Figure 1D to 3A, the current layer is seen to become progressively thinner, essentially in its core where the current density is the largest. The thinning of the current layer occurs in a quasi-static way as driven by the slow shearing motion applied

at the bottom surface (Appendix A.5). Eventually, the current layer turns into a CS as it thins down to the grid resolution, and fast magnetic reconnection kicks in (Fig. 3 shows result for resolution of 90 km in the main run; see also results of other runs with higher resolutions in Appendix A.4 and Movie 2). This occurs at 221 min, exactly the onset time of eruption shown in the energy evolution. The profile of magnetic field component B_z crossing the CS shows that it thins down to a tangential discontinuity in numerical sense (Fig. 3C), since its thickness is only $2 \sim 3$ grid spacings (e.g., 0.20 Mm) which approaches the limit resolvable by the numerical code. Meanwhile, the current density increases fast in the CS but decreases elsewhere to nearly zero, rendering its profile crossing the CS to a Dirac Delta function. This happens when the field, if with ever increasing magnetic shear in the absence of resistivity, asymptotically reaches a fully open state (33; 34), in which the magnetic energy attains its upper limit (i.e., the Aly-Sturrock limit, which is approximately 1.7×10^{30} erg in our case, see Fig. 2A) and all the field is current-free except in the CS where the current density is infinite (Fig. A3). However, such open field can never be reached with finite resistivity, and reconnection is unavoidable once the CS is sufficiently thin. The reconnection starts with the Petschek type (35) as its onset is clearly indicated by bidirectional, collimated Alfvénic outflows from the reconnection site (Fig. 3D). At the onset of the reconnection (or eruption), the vertical length of the CS is about 10 Mm, while horizontally it extends up to over 40 Mm (Fig. 3E), and thus its aspect ratios in the vertical and horizontal directions are estimated to be ~ 40 and 150, respectively.

Once the reconnection begins, the fast rise of the kinetic energy, i.e., the eruption, ensues, and the subsequent development of the CS is extremely dynamical. At large scale, it exhibits a picture of the standard flare model: a plasmoid originates from the tip of the CS and rises quickly, leaving behind a cusp structure separating post-flare loops from un-reconnected fields (Fig. 4A and Movie 3). The plasmoid, when initially formed, is very small with size of a few megameters (Fig. 3B, $t = 221$ min 54 s), and expands substantially to hundreds of megameters at the end of the simulation. In 3D, it corresponds to a fast growing MFR (Fig. 5 and Movie 4), which has a weakly twisted core but wrapped by highly twisted envelope, in line with formation of MFR in the tether-cutting model (26). Meanwhile, an arc-shaped fast magnetosonic shock forms ahead of the plasmoid and later encloses the whole erupting structure. All these evolving structures demonstrate a typical coronal magnetic eruption leading to a CME, as seen in observations (Movie 5) as well as previous numerical simulations with different scenarios (36; 37; 38). With the magnetic reconnection proceeds continuously, the cusp structure expands in both vertical and horizontal directions (Fig. A4). The apex of the cusp ascends with speed of about 22 km s^{-1} . The transverse expansion of the bottom of cusp, which corresponds to the separation of flare ribbons in observation, goes with a speed of 11 km s^{-1} , while the leading edge of the CME reaches a speed of $\sim 600 \text{ km s}^{-1}$. All these apparent motions are quantitatively comparable to observed values in typical eruptive flares (39; 40; 41).

At the onset time of the eruption, the Lundquist number of the CS is on the order of $10^{4\sim 5}$ (Appendix A.6), and thus tearing mode instability immediately occurs with the erup-

tion, which fragments the CS and results in strongly turbulent fluctuations in the reconnection (Fig. 4). Such small-scale dynamics emerge only in sufficiently high-resolution computation, and the complexity of the turbulent reconnecting CS increases in even higher resolutions (Appendix A.4). In the later phase of the eruption, the CS becomes highly fragmented, and many filamentary currents, which are small plasmoids in two-dimensional (2D) slice and mini flux ropes in 3D (Fig. A5), are seen in the lower part of the CS (Fig. 5 and Movie 6). The turbulent reconnection is manifested as intermittency in the temporal profile of kinetic energy increasing rate (Fig. 2B) and the distribution and evolution of velocity (Fig. 4B).

The eruption is powered by magnetic energy and particularly, here the driver of the eruption comes mainly from the magnetic tension force of the newly reconnected field through its slingshot effect. As can be seen in Figure 4C, which shows the vertical component of the Lorentz force divided by density (i.e., the vertical acceleration of the plasma), the strongest upward acceleration is always located in the outflow of the reconnection site, whereas near the central part of the MFR is mostly downward acceleration. Consequently, as the reconnected field lines are incorporated in the MFR, they first experience an impulsive acceleration driven by the strong tension force, and then slow down quickly in the MFR (Movie 7). The vertical velocity is the strongest in the outflow of the reconnection site (Fig. 4B), and through this high-speed jet flow, the newly reconnected magnetic field lines continually join and pile up in the MFR. Thus our analysis suggests that the on-the-fly formed MFR does not drive the eruption, but is passively pushed by the reconnection outflow, at least before the CME acceleration reaches its peak (i.e., $t = 227$ min). Furthermore, at the onset of eruption, the apex of newly formed MFR is located much lower than the critical height of torus instability (Fig. A2), i.e., the height at which the decay index of the strapping field reaches the canonical threshold of 1.5 (10). Thus, the role of torus instability is minor at the onset of the eruption.

3. DISCUSSION

We have presented a fully 3D MHD simulation of solar eruption produced in a single bipolar magnetic field, encompassing the entire process from the gradual accumulation of magnetic free energy to its sudden release. The simulated initiation process of eruption bears the major characteristic features of eruptive flares that are associated with CMEs, such as the formation of coronal sigmoid, the transition from slow rise to fast acceleration of coronal loop, the elongation and separation motions of double flare ribbons (Appendix A.8), the growth of a flaring cusp structure, as well as the escape and expansion of a plasmoid, which evolves into a coherent MFR driving a shock ahead.

Early simulations in 2D or translationally-invariant geometries (42; 43) show that by continuous shearing of its footpoints a magnetic arcade asymptotically approaches an open state containing a CS, which is consistent with the Aly-Sturrock conjecture. However, when one takes into account finite resistivity, the system experiences a global disruption with reconnection setting in at the CS, which, in particular, begins at the point with the largest

current density in the CS. For the first time, our simulation demonstrated this scenario in fully 3D, which is the essence of the tether-cutting model. That is, prior to eruption, the CS forms internally within the strongly-sheared arcade core in a quasi-static evolution as driven by photospheric shearing motion. It seamlessly transforms to a flare CS once reconnection kicks in and the eruption ensues. As the pre-flare short field lines reconnect to long ones with a double-arc shape, they are concave upward, thus having strong upward tension forces which propel upward the newly reconnected flux from the top of the CS. As a result, more fluxes are allowed to collapse into the CS and then reconnect, which establishes a positive feedback between the escape of the newly reconnected flux and the reconnection. As the reconnection proceeds from the strongly sheared core flux to the weakly sheared (and nearly current-free) enveloping field, a large-scale MFR is generated as the core of CME with weakly twisted axis wrapped by highly winding field lines. Further mediated by the tearing mode instability, the reconnection runs into a turbulent way, which strongly fragments the CS.

Compared with other fully 3D simulations (36; 44; 13) which also start from a bipolar region that is energized by photospheric flows, ours is unique in twofold. First, we have shown that the eruption can be initiated by shearing solely without flux cancellation. Second, it is unnecessary for an MFR to form before and subsequently trigger the eruption. More importantly, the fact that the central CS forms in a quasi-static way distinguishes ours from other 3D simulations of eruption, in which the CS accounting for flare reconnection forms in a dynamic evolution. For instance, in the MFR-based models, the CS forms after the rise of the unstable MFR, which forces the oppositely-directed field lines below the MFR to approach quickly. Similarly in the breakout model, the central flare CS forms only after a feedback is triggered between the expansion of the inner sheared arcade and the breakout reconnection at the null, in which the central CS is thinned by the fast converging flow induced by the dynamic expansion of the sheared arcade (45). In contrast, the thinning of CS in our simulation is directly driven by the slow quasi-static shearing, which requires a sufficiently low numerical diffusion in the computation and a high accuracy in the line-tied bottom boundary condition, therefore more challenging than thinning the CS through dynamic inflows (Appendix A.5).

In summary, our simulation with sufficiently high fidelity demonstrated a fundamental mechanism for the initiation of solar eruptions, which includes no more ingredient than necessary, consistent with the principle of Occam's razor, and can potentially be applied universally.

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281
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283 ysis and wrote the draft. X.S.F contributed to the design of numerical MHD schemes. All
284 authors participated in discussions and revisions on the manuscript.

285
286 **Competing financial interests.** The authors declare no competing financial interests.

287
288 **Code and data availability.** We have opted not to make our numerical code publicly avail-
289 able owing to its complexity, which demands expert assistance to set up, run and analyze
290 simulations, and because it is continually being improved and extended, which requires
291 frequent software updates. Besides, the data generated by the simulations and analyzed for
292 this paper occupy a large amount of approximately 10 TB. All the code and data that sup-
293 port the findings of this study are available from the corresponding authors upon reasonable
294 request.

Figure 1. Evolution of magnetic field lines and electric currents prior to eruption. (A) Top view of magnetic field lines. The colored thick lines represent magnetic field lines and the colors denote the value of nonlinear force-free factor defined as $\alpha = \mathbf{J} \cdot \mathbf{B} / B^2$, which indicates how much the field lines are non-potential. In particular, for a perfectly force-free field, this parameter is constant along any given field line. As can be seen, the magnetic field is close to force-free since the color is nearly the same along any single field line. Note that at all different times, the field lines are traced from the same set of seeds at the bottom surface convected with the surface flow. The background shows the magnetic flux distribution on the bottom boundary (i.e., plane of $z = 0$), and contours of $B_z = (-30, -20, -10, 0, 10, 20, 30) \text{ G}$ are shown. (B) 3D perspective view of the same field lines shown in panel (A). (C) Vertical integration of current density, i.e., $I_J = \int J dz$. (D) Vertical cross section (i.e., the $x = 0$ slice) of current density.

Figure 2. Temporal evolution of different parameters in the simulations. (A) Evolution of magnetic energy E_M and kinetic energy E_K . The dashed curve shows the energy injected into the volume (i.e., time integration of total Poynting flux) from the bottom boundary through the surface flow. The horizontal dashed line denotes the value of the total magnetic energy for an open force-free field with the same magnetic flux distribution on the bottom surface. (B) Releasing rate of magnetic energy and increasing rate of kinetic energy. (C) Magnitude of velocity and Alfvénic Mach number at a fixed point with location of $(x, y, z) = (0, 0, 28.75)$ Mm. (D) Height and rising speed of the apex of a magnetic field line in the AR's core initially overlying the current sheet. In all panels, the red lines are shown for denoting the transition time (at $t = 221$ min) from pre-eruption to eruption.

Figure 3. Formation of CS and trigger of reconnection. (A) Distribution of current density on the central vertical slice, i.e., the $x = 0$ slice. (B) Projection of magnetic field lines on the same cross section shown in A. Note that before $t = 221 \text{ min } 12 \text{ s}$, the magnetic field exhibits still an arcade configuration, and a plasmoid at the tip of the CS is seen at $t = 221 \text{ min } 54 \text{ s}$ as a result of reconnection, indicating the formation of MFR. (C) 1D profile of the magnetic field component B_z and current density J along a horizontal line crossing perpendicular to the CS center (i.e., the point with largest J). The diamonds denote values on the grid nodes. (D) Distribution of vertical velocity on the same cross section shown in (A). The magnitudes of maximal Alfvénic Mach number are also denoted. (E) Horizontal slice of the current density crossing the center of the CS.

Figure 4. Evolution of different parameters during the eruption shown in the central vertical slice. (A) Current density J normalized by magnetic field strength B . (B) Magnitudes of velocity. The largest velocity and Alfvénic Mach number are also denoted. (C) The vertical component of Lorentz force F_z normalized by density ρ . Also see Movie 1 for a high-cadence evolution of the eruption process.

Figure 5. Evolution of magnetic field lines (left) and CS (right) in 3D during the eruption. In the left panels, the thick colored lines are shown for magnetic field lines. Note that the MFR is weakly twisted in its core but highly twisted in its envelope. The bottom surface is shown with distribution of magnetic flux. The vertical, transparent slice is shown with distribution of current density normalized by magnetic field strength, i.e., J/B . In the right panels, the CS in 3D is shown by iso-surface of $J/B = 0.5 \text{ Mm}^{-1}$.

APPENDIX

A. METHODS AND SUPPLEMENTARY TEXT

A.1. *Model equations*

We numerically solve the full MHD equations in 3D Cartesian geometry by the advanced conservation element and solution element (CESE) method (46; 47; 48). The MHD equations are given as

$$\begin{aligned}
 \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
 \rho \frac{D\mathbf{v}}{Dt} &= -\nabla p + \mathbf{J} \times \mathbf{B} + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v}), \\
 \frac{\partial \mathbf{B}}{\partial t} &= \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \mu_0 \mathbf{J}), \\
 \frac{\partial T}{\partial t} + \nabla \cdot (T \mathbf{v}) &= (2 - \gamma) T \nabla \cdot \mathbf{v},
 \end{aligned} \tag{A1}$$

where $\mathbf{J} = \nabla \times \mathbf{B} / \mu_0$ and μ_0 is the magnetic permeability in a vacuum. In the momentum equation, a small kinetic viscosity ν is used for the purpose of keeping numerical stability during the very dynamic phase of the simulated eruptions. Specifically, the coefficient is given depending on the local spatial resolution Δ and time step Δt as $\nu = 0.05 \Delta^2 / \Delta t$, which corresponds to grid Reynolds number of 10. In the magnetic induction equation, the trigger of magnetic reconnection depends on the specific choice of magnetic diffusivity η . Here we avoid such a sensitivity by relying it solely on the numerical diffusion, that is, we set $\eta = 0$ in the magnetic induction equation. As such, we can minimize the resistivity and thus maximize the Lundquist number (with given spatial resolutions), since any finite value of η will result in larger resistivity than solely the numerical one. In this sense, magnetic reconnection occurs when a current layer is sufficiently narrow such that its width is close to the grid resolution, on which scale the numerical diffusivity takes effect. We have carefully estimated the value of numerical diffusivity η_n (see Appendix A.6). In the energy (or temperature) equation, γ is the adiabatic index, and here for simplicity as we focus on the dynamics of the magnetic field, it is set as $\gamma = 1$ such that the energy equation describes an isothermal process.

A.2. *Initial conditions*

We start from a potential magnetic field with vertical component on the photosphere given by

$$B_z(x, y, 0) = B_0 e^{-x^2/\sigma_x^2} (e^{-(y-y_c)^2/\sigma_y^2} - e^{-(y+y_c)^2/\sigma_y^2}), \tag{A2}$$

where $B_0 = 37.2$ G, $\sigma_x = 28.8$ Mm, $\sigma_y = \sigma_x/2$, and $y_c = 11.5$ Mm. Such magnetic configuration is similar to that used in reference (44). As shown in Fig. A1A, it mimics a bipolar solar AR of typical size, but the magnetic field strength is weaker than that of real sunspots by a least one order of magnitude to avoid a too heavy burden on computation.

The background atmosphere is stratified by solar gravity with density $\rho = 2.3 \times 10^{-15} \text{ g cm}^{-3}$ at the bottom and an uniform temperature of $T = 10^6 \text{ K}$ (corresponding to sound speed of 110 km s^{-1}). Here we find that if using the real number of the solar gravity ($g_{\odot} = 274 \text{ m s}^{-2}$), it results in a pressure scale height of $H_p = 43.8 \text{ Mm}$, by which the plasma pressure and density decay with height much slower than the magnetic field. With the weak magnetic field strength we used, the plasma β will increase with height very fast to above 1, which is not realistic in the low corona. To make the pressure (and density) decrease faster in the lower corona, we modified the gravity by defining it as

$$g = \frac{k}{(1 + z/L)^2} g_{\odot}. \quad (\text{A3})$$

where $k = 5.7$ and $L = 76.8 \text{ Mm}$. By this, we get a plasma $\beta < 1$ mainly within $z < 120 \text{ Mm}$ and the smallest value is 4×10^{-3} (Fig. A1C). Note that with the energizing of the magnetic field by the shearing flow, the magnetic field inflates and its strength increases significantly in the upper volume, and the plasma β will decrease further. As can be seen in Fig. A1, just prior to the eruption, the plasma β is much smaller than unity in the height up to 200 Mm , and the Alfvén speed higher than 1000 km s^{-1} within $z < 100 \text{ Mm}$.

A.3. Boundary conditions

On the bottom boundary ($z = 0$), we apply the surface rotation flow (with $v_z = 0$) to add free magnetic energy to the initial potential field. To ensure that such flow will not modify the magnetic flux distribution B_z at the photosphere, the flow is incompressible and the streamlines coincide with the contour lines of B_z . Specifically, the surface velocity is set as

$$v_x = \frac{\partial \psi(B_z)}{\partial y}; v_y = -\frac{\partial \psi(B_z)}{\partial x}; \quad (\text{A4})$$

with ψ given by

$$\psi = v_0 B_z^2 e^{-(B_z^2 - B_{z,\max}^2)/B_{z,\max}^2} \quad (\text{A5})$$

where $B_{z,\max}$ is the largest value of the photosphere B_z , and v_0 is a constant for scale such that the maximum of the surface velocity is 4.4 km s^{-1} , close to the magnitude of typical flow speed in the photosphere ($\sim 1 \text{ km s}^{-1}$). The flow pattern is shown in Fig. A1A and B. As the flow speed is smaller than the sound speed by two orders of magnitude and the local Alfvén speed by three orders, it stresses the corona magnetic field very slowly. Such flow mimics the frequently-observed sunspot rotation during evolution of ARs (49; 50; 51), and similar rotational flows have been employed in numerous numerical simulations for the same purpose of energizing pre-eruption fields but the magnitude is often larger than ours by an order (52; 53; 54; 55). The energizing phase is linearly ramped on by a time of $t = 10.5 \text{ s}$.

We fix plasma density on the bottom surface as being their initial, uniform value, because the surface flow is incompressible. Furthermore, as the velocity is prescribed there and B_z does not change, we only need to specify how the horizontal magnetic field evolves. To deal with this, many codes use simple linear extrapolation from the inner grid points, which,

however, could falsely increase the magnetic energy (as shown in Fig. A6). To minimize numerical errors introduced by any inappropriate treatment of the boundary conditions, we directly solve the ideal induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \quad (\text{A6})$$

on the bottom surface. By this we can self-consistently update the magnetic field and simulate the line-tied effect at the photosphere, which is essential for the success of the simulations in this type. Solving this equation is realized by second-order difference in space and forward difference in time. Specifically, on the bottom boundary (we do not use any ghost or guard cell), we first compute $\mathbf{v} \times \mathbf{B}$, and then use central difference in horizontal direction and one-sided difference (also 2nd order) in the vertical direction to compute the convection term $\nabla \times (\mathbf{v} \times \mathbf{B})$. We have further checked the accuracy with which the line-tied condition is implemented. To illustrate this, we traced the successive movements of footpoints of a single field line that is sheared through the area with the largest surface flow, which is shown in Fig. A7. Since both footpoints of the field line convect with surface flow, we assume that the footpoint in the positive polarity (i.e., the $y > 0$ part) moves with flow exactly and trace the field line to its conjugated footpoint. If the line-tied condition is accurately implemented, the positions of the conjugated footpoint should be exactly the positions expected due to the applied flow. As shown in Fig. A7, we traced the movement of the footpoints with a time cadence of 35 min until the onset of the eruption. As can be seen, the exact footpoints are almost excellently matched by the computed ones, except that the last one (i.e., $t = 6 \times 35$ min) has a finite, but still small, offset of about 0.5 Mm. Such a finite offset is more likely resulted by numerical errors in magnetic field line tracing rather than an actual slippage. In particular, as the field immediately prior to the eruption is strongly sheared, it forms a quasi-separatrix layer (QSL) in which the gradient of field-line mapping is extremely large, and small errors in field-line tracing can result in large offset. We note that a sufficient resolution of the driving surface is also important to avoid unwanted slipping of the field lines (see Appendix A.7).

On the side and top boundaries, we fixed the plasma density, temperature and velocity. The tangential components of magnetic field are linearly extrapolated from the inner points, while the normal component is modified according to the divergence-free condition to avoid accumulation of numerical magnetic divergence near the boundaries. Furthermore, the simulation runs are stopped before the disturbance by the eruption reaches any of these boundaries to minimize the influence of these numerical boundaries on the computation.

It is worth noting that the time scale of the quasi-static, pre-eruption evolution is determined by the speed of the surface motion. Since the surface velocity we used is still a few times (say, 5) larger in magnitude than typical photosphere flow, our simulated pre-flare evolution time, if compared with the realistic time scale, should be multiplied by a factor of 5, thus corresponding to roughly one day. On the other hand, the time scale of the eruption is controlled by the evolution in the coronal volume, and thus is not changed.

A.4. *Grid setting and influence of eruption onset by different resolutions*

The computational volume spans a sufficiently large box of approximately $(-370, -370, 0) \text{ Mm} < (x, y, z) < (-370, 370, 740) \text{ Mm}$ (where $z = 0$ represents the solar surface) such that during eruption the saturation of kinetic energy (i.e., the completion of CME acceleration) occurs prior to the moment when any disturbance reaching the side and top boundaries. The full volume is resolved by a block-structured grid with adaptive mesh refinement (AMR). The AMR is designed to automatically resolve with highest resolutions the narrow layers with strong currents (mainly in the low β region) as well as the regions where the magnetic field has a strong gradient (see Movie 8). Specifically, the base resolution is $\Delta x = \Delta y = \Delta z = \Delta = 2.88 \text{ Mm}$, and we carried out four different runs with different highest resolutions, including $\Delta = 180 \text{ km}$, 90 km , 45 km and 22.5 km (will be referred to RES0, RES1, RES2, and RES3 respectively, where RES1 is the main run). During the calculation any location with $J\Delta/B > 0.1$ will be refined to the highest resolution, and any location with strong magnetic field gradient or strong current, with criteria given by $|\nabla(B^2/2)|\Delta/\rho > 10$ and $|(\mathbf{B} \cdot \nabla)\mathbf{B}|\Delta/\rho > 10$ respectively, will also be refined. Furthermore, at the bottom boundary where the surface flow is applied, the resolution is forced to be no less than 180 km . If using uniform grids, to reach these resolutions requires grid numbers of 4096^3 , 8192^3 , 16384^3 , and 32768^3 , respectively, which is formidable.

The energy evolution curves from the different runs are compared in Fig. A8. In all the runs, the energies evolve similarly, with pre-eruption to eruption clearly denoted by sharp transitions of energy curves and their changing rates. Note that the different resolutions do not change the evolution in the pre-eruption phase, i.e., the ideal MHD process, indicating that our simulation converges in the ideal MHD regime. However, the onset time of eruption in the runs is clearly different; it is postponed by about 100 s incrementally from run of RES0 to RES3. This is because, as we have mentioned before, the reconnection results from numerical diffusion when the pre-eruption CS is thin enough as close to the grid resolution. In this sense, the onset time of reconnection depends on the grid spacing, since with a smaller grid size a thinner CS can develop, and can sustain stronger current density (and thus more free energy), which needs more time to accumulate, and thus the onset of reconnection in the CS is postponed relative to runs with lower resolutions. This effect is exactly shown in Fig. A8 and Movie 2. With the resolution increased from RES0 to RES3, the thickness of the CS at the eruption onset decreases from approximately 500 km to 50 km , and correspondingly, the peak current density in the CS increases proportionally from approximately $2 \times 10^{-3} \text{ A m}^{-2}$ to $14 \times 10^{-3} \text{ A m}^{-2}$. The fast reconnection always starts when the CS thins down to about $2 \sim 3$ grid spacings, independent of how small the grid spacing is, and once the reconnection kicks in, the eruption starts. These tests with different resolutions confirm again that reconnection plays the key role in triggering the eruption. It is expected that by using further higher resolutions the CS will be thinner and the current density can increase accordingly. If needed (though formidable in computation), it could be even thinned down to the kinetic scale, i.e., the ion gyro-radius or inertial length, where the

MHD approximation fails, as the current density may exceed the threshold of a microscopic instability and anomalous resistivity arises to trigger reconnection (56).

Once the eruption is triggered, it evolves rather differently on small scales in the different runs, since with the higher resolution, the earlier the tearing instability can be triggered, and the more complex the turbulent reconnecting CS will be (Movie 9), and thus there are more fluctuations seen in the curves of energy evolutions (Fig. A8B and C).

A.5. *Quasi-static formation of CS*

A key aspect of our 3D simulation is that the CS forms in a quasi-static way. Prior to the eruption onset, the horizontal flow on two sides of the current layer converges to it and plays the role of thinning the current layer to CS (Movie 2C and F). As the converging motion is directly driven by the surface shearing motion, the converging speed, i.e., the thinning speed of the current layer, is on the same order of the surface flow speed, which is several km s^{-1} (for instance, see Fig. A9 for the runs of RES2 and RES3). This is distinguished from other 3D simulations of eruption where the central CS accounting for the flare reconnection is formed in a dynamic way. For example, in the MFR-based models, the CS forms after the rise of the erupting MFR, which forces the oppositely directed field lines below the MFR to approach each other quickly. Similarly, in the breakout model, firstly the reconnection begins at the null and triggers a feedback between the expansion of the inner sheared arcades and the breakout reconnection, making the system run into a dynamic phase, and then the main flare CS forms.

In numerical simulations, it is much more challenging to form a CS in a quasi-static way than in a dynamic way (especially in the absence of magnetic topological separatrices such as the magnetic null point). This is because, a current layer will diffuse and broaden by the numerical diffusion η_n . Say, for a thin current layer with thickness of l , it will diffuse (or broaden) with a speed of $v_d = \eta_n/l$ in the absence of inflow (57). The current layer can only be thinned by a inflow v_i larger than the diffusing speed, i.e., $v_i > v_d$. This means to form a CS with thickness l , one must have $\eta_n < v_i l$. In the dynamic formation of CS, this can be easily fulfilled since the inflow speed v_i is sufficiently large to exceed the diffusion speed v_d . In our simulation, the inflow v_i is as slow as several km s^{-1} . For instance, in our RES3 run, $l \approx 60 \text{ km}$, $v_i \approx 3 \text{ km s}^{-1}$, which requires the numerical diffusivity $\eta_n < v_i l \approx 180 \text{ km}^2 \text{ s}^{-1}$. Thus only with a sufficiently small numerical diffusivity can the CS form in a quasi-static way. Note that the quasi-static formation of CS is directly related to degree of the magnetic shear and free energy storage. If the numerical diffusivity is too large, the CS cannot form since magnetic free energy diffuses faster than the injection rate from the bottom surface. Such a numerical effect is also seen in a previous 2D simulation (58), and this might be the key reason why early simulations fail to reproduce the tether-cutting model in fully 3D since they have too large numerical diffusion to form a thin CS in the pre-eruption quasi-static evolution. As a result, the numerical resistivity takes effect much earlier before the CS forms, and the resulted reconnection, which is slow, will readily build up MFR in the pre-eruption phase. Such an MFR formation process, aided with surface

converging motion (or flux cancellation), has been commonly seen in earlier 3D simulations (44; 13). This also explains why many 3D numerical simulations tend to support the MFR-based eruption scenarios. However, we note that the quasi-static formation of CS is a key process in the pre-eruption evolution, and besides, it is also essential for explaining confined flares, in which only flare emission is observed but without noticeable movement of coronal loops (59), indicating that CS thinning and the subsequent reconnection are not driven by dynamic evolution.

A.6. Estimation of effective magnetic diffusivity and Lundquist number

In the solar corona, the magnetic diffusivity as derived from the Spitzer resistivity (60) is $\eta \approx 1 \text{ m}^2 \text{ s}^{-1}$, and at a typical length scale, e.g., $L = 10 \text{ Mm}$, and Alfvén speed of $v_A = 10^3 \text{ km s}^{-1}$, the coronal environment has extremely large Lundquist number of $S = Lv_A/\eta \approx 10^{13}$. Thus fast reconnection only occurs when a CS is sufficiently thin, e.g., with thickness of a few to tens of meters. Although it is prohibitive to reach such a high Lundquist number in numerical simulations of large-scale eruptions, we attempted to mimic the coronal conditions as much as we can. Here we estimate the values of the numerical diffusivity η_n and the corresponding Lundquist number in the runs with different resolutions. Since the eruption is triggered by reconnection, the different values of actual diffusivity will naturally result in different onset times of reconnection and thus eruption. That is, the larger the diffusivity is, the earlier the eruption is triggered. As our MHD code has a second-order accuracy, the numerical diffusivity decreases with resolution by a power of two, i.e., $\eta_n \propto \Delta^2$. For example, in RES0 the numerical diffusivity is four times of that in RES1. If the onset time of eruption in RES1 using a particular value of η coincides with the eruption onset time in RES0 without explicit diffusivity, then we can estimate that $\eta = 3\eta_n$ in RES1, as such the total diffusivity in RES1 is $4\eta_n$, which equals to the numerical diffusivity in RES0.

Thus, to quantify the η_n in RES1, we run a series of tests with RES1 using different values of explicit diffusivity η . Since this needs many runs, we speedup the bottom boundary flow by 5 times such that the largest speed is 22 km s^{-1} to save the computing time. By this speed, it is still a slow quasi-static driving of the coronal field, though the pre-eruption evolution is faster than that in our main run. Fig. A10A shows the energy curves for the run with $\eta = 0$, which is very similar to those of the main run shown in Fig. 2, except that the timing is different and the pre-eruption kinetic energy is somewhat larger. Then in Fig. A10B, we compare the RES1 using a sequence of η with the RES0 using $\eta = 0$ by plotting the changing rate of kinetic energy from the pre-eruption to eruption phases. Clearly, the larger the diffusivity is, the earlier the eruption is triggered. From these tests, we can estimate the numerical diffusivity with RES1 to be $\eta_n \approx 1.3 \times 10^{-3} \text{ Mm}^2 \text{ s}^{-1}$ or $1300 \text{ km}^2 \text{ s}^{-1}$, and thus the Lundquist number $S = Lv_A/\eta_n \approx 1 \times 10^4$, where $L = 10 \text{ Mm}$ is the vertical length scale of the CS immediately prior to eruptions and $v_A = 10^3 \text{ km s}^{-1}$ is the typical Alfvén speed around the CS. Accordingly, the numerical diffusivity in runs of RES2 and RES3 are approximately $300 \text{ km}^2 \text{ s}^{-1}$ and $80 \text{ km}^2 \text{ s}^{-1}$ (the latter is consistent

with aforementioned requirement for CS formation in Appendix A.5, i.e., $\eta_n < v_i l = 180 \text{ km}^2 \text{ s}^{-1}$), and the Lundquist numbers are 4×10^4 and 1.6×10^5 , respectively. The Lundquist numbers further increase with the length of the CS, which grows as the eruption goes on. We note that the Lundquist numbers in our fully 3D simulations are comparable to and even larger than values used in 2D simulations of the similar type (42; 43; 58). If considering to extrapolate our values to the real coronal conditions, we would need a grid resolution of $\Delta \approx \Delta_{\text{RES3}}/10^4$, on which the effective diffusivity can then be $\eta = \eta_{\text{RES3}}/10^8 \approx 1 \text{ m}^2 \text{ s}^{-1}$, the Lundquist number $S = S_{\text{RES3}} \times 10^8 \approx 10^{13}$ and the CS thickness $l \sim 3\Delta \approx 7 \text{ m}$, which are all consistent with the classical values derived from the Spitzer resistivity.

A.7. A “failed” simulation with inaccurate boundary conditions

As aforementioned, a sufficiently high resolution at the bottom boundary is also required to accurately implement the line-tied boundary condition, and further to form sufficiently thin CS. To show this, we run an experiment with the highest resolution of 90 km (same as RES1) to resolve the current layer but using a four times lower resolution (i.e., 720 km with respect to 180 km in the main run) at the bottom boundary. As can be seen in Fig. A11A, this run failed to produce an eruption, as no impulsive release of magnetic energy accompanied with fast rise of kinetic energy is seen. In contrast to the high-resolution run, there is a considerable amount of magnetic energy loss in the surface driving process. This is because the line-tying condition is not accurately achieved (see Fig. A11B) in the lower resolution due to numerical errors. Consequently, the field lines slip backward and are unable to obtain the amount of shear as needed for the CS formation. If putting the two negative factors together, i.e., the MHD code has a large numerical diffusion and the line-tied boundary condition is not accurately implemented, it is very likely that the magnetic energy eventually saturates once the net energy injection rate from the bottom surface is totally cancelled by the diffusion rate. Therefore eruption can not happen even if the surface shearing is continuously applied.

A.8. Evolution of magnetic topology and formation of MFR

The magnetic topology is a simple arcade until the eruption onset and, once reconnection begins, it transforms to complex one having a highly twisted MFR formed during the eruption. To reveal the variation of magnetic topology, we inspected the distribution and evolution of two parameters, the magnetic squashing degree and magnetic twist number, which are commonly used for study of 3D magnetic fields and their dynamics (61; 62; 63; 64; 65; 66). The magnetic squashing degree Q quantifies the gradient of magnetic field-line mapping with respect to their footpoints, and it is helpful for searching QSLs of magnetic fields (67), which can have extremely large values of Q (e.g., $\geq 10^5$) and are preferential sites of magnetic reconnection. Specifically, for a field line starting at one footpoint (x, y) and ending at the other footpoint (X, Y) where X and Y are both functions

of x and y , the squashing degree Q associated with this field line is given by (67)

$$Q = \frac{a^2 + b^2 + c^2 + d^2}{|ad - bc|} \quad (\text{A7})$$

where

$$a = \frac{\partial X}{\partial x}, \quad b = \frac{\partial X}{\partial y}, \quad c = \frac{\partial Y}{\partial x}, \quad d = \frac{\partial Y}{\partial y}. \quad (\text{A8})$$

The magnetic twist number T_w (68) is defined for a given (closed) field line by taking integration of $T_w = \int_L \mathbf{J} \cdot \mathbf{B} / B^2 dl / (4\pi)$ along the length L of the field line between two conjugated footpoints on the photosphere. Note that T_w is not identical to the classic winding number of field lines about a common axis, but an approximation of the number of turns that two infinitesimally close field lines wind about each other (65).

Fig. A12 and Movie 10 show evolution of magnetic squashing degree Q on the central vertical slice, as well as both the Q , T_w and current density J on the bottom surface, respectively. As can be seen, the formation of CS is accompanied by the formation of corresponding QSLs. Initially the distribution of Q is rather smooth, and with narrowing of the current layer, there is an evident increasing of Q (reaching $\sim 10^5$) in two thin strips of J shape, i.e., QSLs, on either side of the PIL on the bottom surface. These QSLs correspond to the intersection of the CS with the photosphere, and thus two thin ribbons of enhanced current density are also seen, co-spatial with the QSLs. With onset of the reconnection, the two J-shaped QSLs and the current ribbons on the bottom surface evolve rapidly, which corresponds to the apparent motion of footpoints of the field lines that were undergoing reconnection, or simply the motion of observed flare ribbons (69; 64; 70).

In the early phase, the reconnection is fully a 3D manner with a strong guide field component (i.e., B_x) because joining in the reconnection is mainly the strongly-sheared, low-lying flux. While in the later phase, it transfers into a quasi-2D manner, which consumes mainly the large-scale, overlying flux that is weakly sheared. Such transition is clearly manifested by the fast elongation of the arms of the J-shaped QSLs along the direction of the PIL on the bottom surface, which agrees with observed elongation of flare ribbons (71). Specifically, the arm of the QSL in the north (south) of the PIL spreads to the left (right), and as a result, the observed two ribbons naturally exhibit an evolution pattern of strong-to-weak shear (72). As the eruption proceeds, more and more magnetic fluxes reconnect, and consequently, the two J-shaped QSLs continuously separate with each other, in agreement with the well-know separation motion of two flare ribbons. At the end of the simulation, they have swept to near the center of each magnetic polarity (or the umbra of the sunspots). On the central vertical slice, the QSLs intersect with each other, developing into an X shape, which is referred to a hyperbolic flux tube (HFT) (67), and the intersection X point is essentially the main reconnection site (in analogy to the null point in a 2D X-shaped reconnection configuration). As the reconnection proceeds, the X point of the HFT rises upward progressively with the cusp region below expanding.

Starting from the hooks of the J-shaped QSLs, twisted magnetic flux (as indicated with $T_w < -2$) begins to form owing to the tether-cutting reconnection, which creates long

field lines connecting the far ends of the two pre-reconnection sheared field lines. With the twisted flux accumulated through the continuation of reconnection, the areas occupied by the footpoints of the highly twisted field lines at the hooks expand. Consequently, the hook of each J-shaped QSL continuously extends inward until it reaches the arm, forming a closed curve encircling the highly twisted flux (see the panels of $t = 226 \text{ min } 06 \text{ s}$). Such a transition of QSLs ought to be observed as flare ribbons that gradually forms close rings (22). Accordingly, as can be seen in the vertical cross section, the QSLs form a closed tear-drop shape connecting the HFT. Thus, in magnetic topology, at this moment the MFR is fully separated with its surrounding magnetic field by the QSLs (73; 74; 75). Interestingly, this moment is close to the peak time of the magnetic energy release rate and the kinetic energy increasing rate. We note that the distribution of magnetic twist degree is rather inhomogeneous, and the most strongly twisted flux is seen around the boundary of the MFR, meaning that the newly-formed MFR has weaker twisted axis wrapped by stronger winding field lines. It is also worthy noting that the details of the QSLs associated with the MFR become extremely complex in the later phase with many fast evolving small structures (see Movie 10) because of the turbulence excited in the reconnection. The current ribbons also show small evolving kernels, which might correspond to the observed bright kernels or knots within flare ribbons (76).

Figure A1. (A) Magnetic flux distribution and surface rotation flow at the bottom surface (i.e., $z = 0$). The background is color-coded by the vertical magnetic component B_z , and the vectors show the rotation flow. (B) Profile of velocity and its ratio to local Alfvén speed along $(x, z) = 0$ line. (C) Plasma β (i.e., ratio of gas pressure to the magnetic pressure) profile along the central vertical line, i.e., $(x, y) = 0$. (D) Profile of Alfvén speed along the central vertical line. In (C) and (D), the black lines are shown for the initial values, while the red lines represent the values at time immediately prior to the eruption onset.

Figure A2. **Left:** current density and projection of magnetic field lines on the slice of $x = 0$ at the time when the MFR first forms during the eruption (i.e., $t = 221$ min 33 s). The MFR forms at the tip of the CS by reconnection of the sheared arcades, and its axis is denoted by the lower arrow. Above the MFR, the field is close to current-free and plays the role of strapping field of the MFR, and the critical height of torus instability (TI) is denoted by the upper arrow. **Right:** current density, magnetic field component B_y , and decay index of B_y along z axis (i.e., the line with both $x, y = 0$). Since it is only the component B_y that actually straps the MFR, the decay index is calculated for this component, which is defined as $n = -\ln(-B_y)/\ln(z)$. The threshold of decay index 1.5 for TI and the corresponding height are denoted by the dashed lines. The thick vertical line colored in gray denotes the height at which the MFR is initially formed. For comparison, results for the initial potential field are also shown. Clearly at the onset of the eruption, the strapping field is significantly strengthened comparing with the initial potential field, and the MFR forms well below the critical height of TI.

Figure A3. The fully opened magnetic field discretized on grid with resolution of 90 km. **(A)** Current distribution and magnetic field lines on the central cross section. Note that the current only distributes in the central CS, and all other regions are current-free with magnetic field lines extending from the bottom surface to infinity. **(B)** Profile of current density along z axis. Note that here with a finite grid resolution, the CS has a finite thickness of 90 km. Thus the current density is not infinite. It rather changes with height and at approximately $z = 10 \text{ Mm}$ it reaches the maximum of $14 \times 10^{-3} \text{ A m}^{-2}$. This value is close to triple of the maximal current density in the CS in RES1 run, which is consistent with the fact that the CS thickness in RES1 run is approximately triple of 90 km.

Figure A4. Parameters that are comparable with observations. **(A)** Current distribution on the central cross section. **(B)** A time stack map of the current distribution around $x, y = 0$, which can reveal the evolution speed of the CME. **(C)** Temporal evolution of the edge of the post-flare loops. **(D)** Rising of the post-flare loop top. **(E)** Horizontal motion of the post-flare loop footpoints, which corresponds to the separation of flare ribbons. The dashed lines in **D** and **E** denote the average speeds of the motions.

Figure A5. Mini flux ropes formed in the reconnecting CS. The field lines are colored differently and the bottom surface is shown with the magnetic flux distribution.

Figure A6. Comparison of energy evolution in the runs with two different boundary conditions on photosphere. The blue lines are shown for the main run in which the line-tied boundary condition is self-consistently applied. The red lines denoted the run with linear extrapolation of the horizontal field to specify the bottom boundary condition. The dashed line, which almost coincides with the blue line, show the magnetic energy injected into the volume from the bottom boundary through the surface flow, i.e., the time integration of the total Poynting flux at the bottom surface. Note that the simple linear extrapolation falsely increased the magnetic energy of the volume by a significant amount.

Figure A7. Check of line-tied boundary conditions. The background is shown by magnitude of the rotational velocity v at the bottom boundary. The plus signs are the exact locations of two footpoints of a single field line as convected with surface flow at each moments, which are denoted by the numbers, and the black lines are contour lines of B_z , also the trajectories in which the footpoints should move. Note that the field line as chosen is rooted in the area with the largest surface velocity. At $t = 0$, the positions of two footpoints (the two plus signs in pink) are exactly symmetrical with the PIL. The X signs are computed ones, which are traced along the field line from the positive-polarity footpoints to the negative polarity at each moments. Note that the computed locations match the exact ones excellently except the last moment (numbered by 6) which is close the eruption onset.

Figure A8. Evolution of different parameters in runs with different resolutions. (A) Magnetic energy E_M and kinetic energy E_K . (B) Releasing rates of magnetic energy. (C) Increasing rates of kinetic energy. (D) The maximum values of current density in the current layer that eventually forms CS. (E) Thickness of the current layer. The vertical dashed lines in all the panels are used to denote the eruption onset times in the different runs, and their values are also labeled in panel B.

Figure A9. Thinning of CS in two high-resolution runs RES2 and RES3. **(A)** Increasing rate of kinetic energy. **(B)** Thickness of CS. **(C)** The horizontal velocity of the flow converging into the CS. **(D)** Alfvénic Mach number of the the horizontal converging flow. The vertical dashed lines are used to denote the eruption onset times in the different runs.

Figure A10. Comparison of runs with different values of explicit diffusivity in two different resolutions, for the purpose of estimating the value of numerical diffusivity. **(A)** Energy evolutions for run using grid resolution RES1 with explicit diffusivity $\eta = 0$ and with the bottom boundary flow increased by 5 times. **(B)** Increasing rates of kinetic energy in a series of runs on RES1 with different values of explicit diffusivity η , and compared with run on RES0.

Figure A11. Comparison of runs using insufficiently resolved bottom boundary and the well-resolved one. **(A)** Evolution of energies. The yellow lines are shown for the low-resolution run, which failed to produce an eruption. **(B)** Check of the line-tied boundary conditions. The format is the same as Fig. S7. Note the for the failed run, evident slippage of the field line footpoint is seen.

Figure A12. Magnetic topology evolution and formation of MFR during the eruption. (A) Magnetic squashing degree Q on the bottom surface. The colored lines are contours of $B_z = -30 \text{ G}$ (blue) and 30 G (red). (B) Magnetic twist number T_w on the bottom surface. (C) Current density on the bottom surface. (D) Q on the central vertical slice.

B. CAPTIONS FOR MOVIES

- **Movie 1.** Supplementary movie for Fig. 1.
- **Movie 2.** Formation of CS and onset of reconnection and eruption: comparison of runs with increasing resolutions. **(A)** Central vertical slice of current density J . **(B)** same as **(A)** and overlaid with 2D field lines on the plane. **(C)** Velocity on the plane. The arrows show the flow directions and the background shows the vertical component of the flow. The largest Alfvénic Mach number is denoted. **(D)** Evolution of changing rates of magnetic and kinetic energies. The vertical blue line denotes the time for which all other panels are shown. **(E)** 1D profile of the vertical magnetic field component B_z and current density J along a horizontal line crossing perpendicular to the core of the CS (i.e., the point with the largest J). Location of the line is denoted by the short lines in **(A)** and **(C)**. The diamonds denote values on the grid nodes. The thickness of CS is denoted, which is defined by the FWHM of a Gauss function fitting (the thin black curve) of the profile of current density. **(F)** Horizontal velocity and Alfvénic Mach number along the same line shown in **(E)**. Before the onset of reconnection, the horizontal flow plays a role of thinning the current layer to CS; once the reconnection starts, the inflow Mach number measures the reconnection rate.
- **Movie 3.** Supplementary movie for Fig. 4.
- **Movie 4.** Evolution of magnetic field lines during the eruption shown in two different view angles. Supplementary movie for left panels of Fig. 5.
- **Movie 5.** Comparison of the eruptive structure with that of an observed flare eruption. Left: A GOES X8.2 eruptive flare that occurred on 2017 September 10 as observed by SDO/AIA in three EUV emission lines including 131, 211 and 171 Å. Right: The simulated eruption process. The background is shown with the distribution of J/B on the central cross section, and some sampled magnetic field lines are plotted in comparison with the structure of the coronal loops in observation.
- **Movie 6.** Evolution of 3D structure and different slices of the CS.
- **Movie 7.** Evolution of three sampled magnetic field lines and their rising speeds in the process of reconnection and join in the MFR. In the left two panels, the three magnetic field lines are plotted in three different colors. The bottom surface is shown with the contour of B_z , and the central cross section, i.e., the $x = 0$ slice, is shown with the J/B and velocity v . In the right panel, the colored curves show the evolution of rising speed at middle of these field lines, i.e., the point where the field lines cross the central cross section. The gray curve shows the increasing rate of kinetic energy.
- **Movie 8.** Structure of the block-based AMR grid. Two cross sections of the grid and current density are shown. The black lines denote the blocks, each of which further

consists of 8^3 cells. Note the strong current regions are always resolved by meshes with the finest grids.

- **Movie 9.** Comparison of CS evolution in runs with different highest resolutions.
- **Movie 10.** The left panel shows magnetic squashing degree Q on central vertical slice (i.e., $x = 0$ plane). The right panels show Q , the magnetic twist number T_w , and current density on the bottom surface.

REFERENCES

- [1] Gregory D. Fleishman, Dale E. Gary, Bin Chen, Natsuha Kuroda, Sijie Yu, and Gelu M. Nita. Decay of the coronal magnetic field can release sufficient energy to power a solar flare. *Science*, 367(6475):278–280, January 2020.
- [2] E. R. Priest and T. G. Forbes. The magnetic nature of solar flares. *A&A Rv*, 10:313–377, 2002.
- [3] T. G. Forbes, J. A. Linker, J. Chen, C. Cid, J. Kóta, M. A. Lee, G. Mann, Z. Mikić, M. S. Potgieter, J. M. Schmidt, G. L. Siscoe, R. Vainio, S. K. Antiochos, and P. Riley. CME Theory and Models. *SSRv*, 123:251–302, March 2006.
- [4] K. Shibata and T. Magara. Solar Flares: Magnetohydrodynamic Processes. *Living Reviews in Solar Physics*, 8:6, December 2011.
- [5] P. F. Chen. Coronal Mass Ejections: Models and Their Observational Basis. *Living Reviews in Solar Physics*, 8(1):1, Apr 2011.
- [6] B. Schmieder, P. Démoulin, and G. Aulanier. Solar filament eruptions and their physical role in triggering coronal mass ejections. *Advances in Space Research*, 51(11):1967–1980, June 2013.
- [7] G. Aulanier. The physical mechanisms that initiate and drive solar eruptions. In B. Schmieder, J.-M. Malherbe, and S. T. Wu, editors, *IAU Symposium*, volume 300 of *IAU Symposium*, pages 184–196, January 2014.
- [8] M. Janvier, G. Aulanier, and P. Démoulin. From Coronal Observations to MHD Simulations, the Building Blocks for 3D Models of Solar Flares (Invited Review). *SoPh*, 290:3425–3456, December 2015.
- [9] Jun Lin, N A Murphy, Chengcai Shen, John C Raymond, K K Reeves, J Zhong, Ning Wu, and Yan Li. Review on current sheets in cme development: Theories and observations. *Space Science Reviews*, 194:237–302, 2015.
- [10] B. Kliem and T. Török. Torus Instability. *Physical Review Letters*, 96(25):255002, June 2006.
- [11] T. Török and B. Kliem. Confined and Ejective Eruptions of Kink-unstable Flux Ropes. *ApJL*, 630:L97–L100, September 2005.
- [12] Y. Fan and S. E. Gibson. Onset of Coronal Mass Ejections Due to Loss of Confinement of Coronal Flux Ropes. *ApJ*, 668:1232–1245, October 2007.
- [13] G. Aulanier, T. Török, P. Démoulin, and E. E. DeLuca. Formation of Torus-Unstable Flux Ropes and Electric Currents in Erupting Sigmoids. *ApJ*, 708:314–333, January 2010.
- [14] T. Amari, A. Canou, J.-J. Aly, F. Delyon, and F. Alauzet. Magnetic cage and rope as the key for solar eruptions. *Nature*, 554:211–215, February 2018.
- [15] S. K. Antiochos, C. R. DeVore, and J. A. Klimchuk. A Model for Solar Coronal Mass Ejections. *ApJ*, 510:485–493, January 1999.
- [16] G. Aulanier, E. E. DeLuca, S. K. Antiochos, R. A. McMullen, and L. Golub. The Topology and Evolution of the Bastille Day Flare. *ApJ*, 540:1126–1142, September 2000.
- [17] B. J. Lynch, S. K. Antiochos, C. R. DeVore, J. G. Luhmann, and T. H. Zurbuchen. Topological Evolution of a Fast Magnetic Breakout CME in Three Dimensions. *The Astrophysical Journal*, 683(2):1192–1206, August 2008.
- [18] P. F. Wyper, S. K. Antiochos, and C. R. DeVore. A universal model for solar eruptions. *Nature*, 544:452–455, April 2017.
- [19] S. Patsourakos, A. Vourlidas, T. Trk, B. Kliem, S. K. Antiochos, V. Archontis, G. Aulanier, X. Cheng, G. Chintzoglou, M. K. Georgoulis, L. M. Green, J. E. Leake, R. Moore, A. Nindos, P. Syntelis, S. L. Yardley, V. Yurchyshyn, and J. Zhang. Decoding the Pre-Eruptive Magnetic Field Configurations of Coronal Mass Ejections. *arXiv:2010.10186 [astro-ph]*, October 2020. arXiv: 2010.10186.
- [20] C. Richard DeVore and Spiro K. Antiochos. Dynamical Formation and Stability of Helical Prominence Magnetic Fields. *ApJ*, 539(2):954–963, Aug 2000.

- [21]Haimin Wang, Wenda Cao, Chang Liu, Yan Xu, Rui Liu, Zhicheng Zeng, Jongchul Chae, and Haisheng Ji. Witnessing magnetic twist with high-resolution observation from the 1.6-m New Solar Telescope. *Nature Communications*, 6(1):7008, November 2015.
- [22]W. Wang, R. Liu, Y. Wang, Q. Hu, C. Shen, C. Jiang, and C. Zhu. Buildup of a highly twisted magnetic flux rope during a solar eruption. *Nature Communications*, 8:1330, November 2017.
- [23]Ignacio Ugarte-Urra, Harry P. Warren, and Amy R. Winebarger. The Magnetic Topology of Coronal Mass Ejection Sources. *The Astrophysical Journal*, 662(2):1293–1301, June 2007.
- [24]R. L. Moore and B. J. Labonte. The filament eruption in the 3B flare of July 29, 1973 - Onset and magnetic field configuration. In M. Dryer and E. Tandberg-Hanssen, editors, *Solar and Interplanetary Dynamics*, volume 91 of *IAU Symposium*, pages 207–210, Jan 1980.
- [25]R. L. Moore and G. Roumeliotis. Triggering of Eruptive Flares - Destabilization of the Preflare Magnetic Field Configuration. In Z. Svestka, B. V. Jackson, and M. E. Machado, editors, *IAU Colloq. 133: Eruptive Solar Flares*, volume 399 of *Lecture Notes in Physics*, Berlin Springer Verlag, page 69, 1992.
- [26]R. L. Moore, A. C. Sterling, H. S. Hudson, and J. R. Lemen. Onset of the Magnetic Explosion in Solar Flares and Coronal Mass Ejections. *ApJ*, 552:833–848, May 2001.
- [27]Carolus J. Schrijver. A Characteristic Magnetic Field Pattern Associated with All Major Solar Flares and Its Use in Flare Forecasting. *The Astrophysical Journal*, 655(2):L117–L120, February 2007.
- [28]Shin Toriumi and Haimin Wang. Flare-productive active regions. *Living Reviews in Solar Physics*, 16(1):3, December 2019.
- [29]A. G. Emslie, B. R. Dennis, A. Y. Shih, P. C. Chamberlin, R. A. Mewaldt, C. S. Moore, G. H. Share, A. Vourlidas, and B. T. Welsch. GLOBAL ENERGETICS OF THIRTY-EIGHT LARGE SOLAR ERUPTIVE EVENTS. *The Astrophysical Journal*, 759(1):71, oct 2012.
- [30]J. Zhang, K. P. Dere, R. A. Howard, M. R. Kundu, and S. M. White. On the Temporal Relationship between Coronal Mass Ejections and Flares. *ApJ*, 559(1):452–462, Sep 2001.
- [31]J. Zhang and K. P. Dere. A Statistical Study of Main and Residual Accelerations of Coronal Mass Ejections. *The Astrophysical Journal*, 649(2):1100–1109, October 2006.
- [32]X. Cheng, J. Zhang, B. Kliem, T. Török, C. Xing, Z. J. Zhou, B. Inhester, and M. D. Ding. Initiation and Early Kinematic Evolution of Solar Eruptions. *ApJ*, 894(2):85, May 2020.
- [33]J. J. Aly. How much energy can be stored in a three-dimensional force-free magnetic field? *The Astrophysical Journal*, 375:L61, July 1991.
- [34]P. A. Sturrock. Maximum energy of semi-infinite magnetic field configurations. *The Astrophysical Journal*, 380:655, October 1991.
- [35]H. E. Petschek. *Magnetic Field Annihilation*, volume 50, page 425. 1964.
- [36]J. A. Linker, Z. Mikić, R. Lionello, P. Riley, T. Amari, and D. Odstreil. Flux cancellation and coronal mass ejections. *Physics of Plasmas*, 10:1971–1978, May 2003.
- [37]T. Amari, J. F. Luciani, J. J. Aly, Z. Mikic, and J. Linker. Coronal Mass Ejection: Initiation, Magnetic Helicity, and Flux Ropes. I. Boundary Motion-driven Evolution. *ApJ*, 585:1073–1086, March 2003.
- [38]T. Török, C. Downs, J. A. Linker, R. Lionello, V. S. Titov, Z. Mikić, P. Riley, R. M. Caplan, and J. Wijaya. Sun-to-Earth MHD Simulation of the 2000 July 14 Bastille Day Eruption. *ApJ*, 856:75, March 2018.
- [39]Haimin Wang, Jiong Qiu, Ju Jing, and Hongqi Zhang. Study of Ribbon Separation of a Flare Associated with a Quiescent Filament Eruption. *ApJ*, 593(1):564–570, Aug 2003.
- [40]J. Hinterreiter, A. M. Veronig, J. K. Thalmann, J. Tschernitz, and W. Pötzi. Statistical Properties of Ribbon Evolution and Reconnection Electric Fields in Eruptive and Confined Flares. *SoPh*, 293(3):38, Mar 2018.

- [41]X. L. Yan, J. C. Wang, G. M. Pan, D. F. Kong, Z. K. Xue, L. H. Yang, Q. L. Li, and X. S. Feng. Successive X-class Flares and Coronal Mass Ejections Driven by Shearing Motion and Sunspot Rotation in Active Region NOAA 12673. *ApJ*, 856:79, March 2018.
- [42]Z. Mikic and J. A. Linker. Disruption of coronal magnetic field arcades. *ApJ*, 430:898–912, August 1994.
- [43]G. S. Choe and L. C. Lee. Evolution of Solar Magnetic Arcades. I. Ideal MHD Evolution under Footpoint Shearing. *ApJ*, 472:360–+, November 1996.
- [44]T. Amari, J. F. Luciani, J. J. Aly, Z. Mikic, and J. Linker. Coronal Mass Ejection: Initiation, Magnetic Helicity, and Flux Ropes. I. Boundary Motion-driven Evolution. *ApJ*, 585:1073–1086, March 2003.
- [45]J. T. Karpen, S. K. Antiochos, and C. R. DeVore. THE MECHANISMS FOR THE ONSET AND EXPLOSIVE ERUPTION OF CORONAL MASS EJECTIONS AND ERUPTIVE FLARES. *The Astrophysical Journal*, 760(1):81, November 2012.
- [46]C. W. Jiang, X. S. Feng, J. Zhang, and D. K. Zhong. AMR Simulations of Magnetohydrodynamic Problems by the CESE Method in Curvilinear Coordinates. *SoPh*, 267:463–491, 2010.
- [47]X. S. Feng, L. P. Yang, C. Q. Xiang, S. T. Wu, Y. F. Zhou, and D. K. Zhong. THREE-DIMENSIONAL SOLAR WIND MODELING FROM THE SUN TO EARTH BY A SIP-CESE MHD MODEL WITH A SIX-COMPONENT GRID. *ApJ*, 723:300–319, 2010.
- [48]C. W. Jiang, S. T. Wu, X. S. Feng, and Q. Hu. Data-driven mhd simulation of a flux-emerging active region leading to solar eruption. *Nature Comm.*, 7:11522, 2016.
- [49]D. S. Brown, R. W. Nightingale, D. Alexander, C. J. Schrijver, T. R. Metcalf, R. A. Shine, A. M. Title, and C. J. Wolfson. Observations of Rotating Sunspots from TRACE. *SoPh*, 216(1):79–108, Sep 2003.
- [50]X. L. Yan and Z. Q. Qu. Rapid rotation of a sunspot associated with flares. *A&A*, 468(3):1083–1088, Jun 2007.
- [51]X. L. Yan, Z. Q. Qu, D. F. Kong, and C. L. Xu. Sunspot Rotation, Sigmoidal Filament, Flare, and Coronal Mass Ejection: The Event on 2000 February 10. *ApJ*, 754(1):16, Jul 2012.
- [52]T. Amari, J. F. Luciani, J. J. Aly, and M. Tagger. Very Fast Opening of a Three-dimensional Twisted Magnetic Flux Tube. *ApJL*, 466:L39+, July 1996.
- [53]M. Tokman and P. M. Bellan. Three-dimensional Model of the Structure and Evolution of Coronal Mass Ejections. *ApJ*, 567(2):1202–1210, Mar 2002.
- [54]T. Török and B. Kliem. The evolution of twisting coronal magnetic flux tubes. *A&A*, 406:1043–1059, Aug 2003.
- [55]C. Richard DeVore and Spiro K. Antiochos. Homologous Confined Filament Eruptions via Magnetic Breakout. *ApJ*, 680(1):740–756, Jun 2008.
- [56]Kazunari Shibata and Syuniti Tanuma. Plasmoid-induced-reconnection and fractal reconnection. *Earth, Planets and Space*, 53(6):473–482, June 2001.
- [57]E. R. Priest. *Solar magneto-hydrodynamics*. Springer Netherlands, 1987.
- [58]D. Shiota, K. Kusano, T. Miyoshi, N. Nishikawa, and K. Shibata. A quantitative MHD study of the relation among arcade shearing, flux rope formation, and eruption due to the tearing instability: MHD STUDY OF ARCADE SHEARING. *Journal of Geophysical Research: Space Physics*, 113(A3):n/a–n/a, March 2008.
- [59]Chaowei Jiang, Shi Tsan Wu, Vasyl B Yurchyshyn, Haimin Wang, Xueshang Feng, and Qiang Hu. How did a major confined flare occur in super solar active region 12192. *ApJ*, 828(1):62, 2016.
- [60]L. Spitzer. *Physics of fully ionized gas (2nd edition)*. Interscience, New York, 1962.
- [61]G. Aulanier, M. Janvier, and B. Schmieder. The standard flare model in three dimensions. I. Strong-to-weak shear transition in post-flare loops. *A&A*, 543:A110, July 2012.
- [62]M. Janvier, G. Aulanier, E. Pariat, and P. Dmoulin. The standard flare model in three dimensions: III. Slip-running reconnection properties. *Astronomy & Astrophysics*, 555:A77, July 2013.

- [63] S. Inoue, K. Hayashi, D. Shiota, T. Magara, and G. S. Choe. Magnetic Structure Producing X- and M-class Solar Flares in Solar Active Region 11158. *ApJ*, 770:79, June 2013.
- [64] A. Savcheva, E. Pariat, S. McKillop, P. McCauley, E. Hanson, Y. Su, and E. E. DeLuca. The Relation between Solar Eruption Topologies and Observed Flare Features. II. Dynamical Evolution. *ApJ*, 817:43, January 2016.
- [65] Rui Liu, Bernhard Kliem, Viacheslav S. Titov, Jun Chen, Yuming Wang, Haimin Wang, Chang Liu, Yan Xu, and Thomas Wiegmann. Structure, stability, and evolution of magnetic flux ropes from the perspective of magnetic twist. *The Astrophysical Journal*, 818(2):148, 2016.
- [66] Aiying Duan, Chaowei Jiang, Wen He, Xueshang Feng, Peng Zou, and Jun Cui. A study of pre-flare solar coronal magnetic fields: Magnetic flux ropes. *The Astrophysical Journal*, 884(1):73, oct 2019.
- [67] V. S. Titov, G. Hornig, and P. Démoulin. Theory of magnetic connectivity in the solar corona. *J. Geophys. Res.*, 107:1164, August 2002.
- [68] M. A. Berger and C. Prior. The writhe of open and closed curves. *Journal of Physics A Mathematical General*, 39:8321–8348, June 2006.
- [69] Jiong Qiu, Jeongwoo Lee, Dale E. Gary, and Haimin Wang. Motion of Flare Footpoint Emission and Inferred Electric Field in Reconnecting Current Sheets. *ApJ*, 565(2):1335–1347, Feb 2002.
- [70] Chaowei Jiang, Peng Zou, Xueshang Feng, Qiang Hu, Rui Liu, P. Vemareddy, Aiying Duan, Pingbing Zuo, Yi Wang, and Fengsi Wei. Magnetohydrodynamic simulation of the x9.3 flare on 2017 september 6: Evolving magnetic topology. *The Astrophysical Journal*, 869(1):13, dec 2018.
- [71] Jiong Qiu, Dana W. Longcope, Paul A. Cassak, and Eric R. Priest. Elongation of Flare Ribbons. *The Astrophysical Journal*, 838(1):17, March 2017.
- [72] Yingna Su, Leon Golub, and Adriaan A Van Ballegooijen. A statistical study of shear motion of the footpoints in two-ribbon flares. *The Astrophysical Journal*, 655(1):606, 2007.
- [73] P. Démoulin, E. R. Priest, and D. P. Lonie. Three-dimensional magnetic reconnection without null points 2. Application to twisted flux tubes. *J. Geophys. Res.*, 101(A4):7631–7646, Apr 1996.
- [74] A. Savcheva, E. Pariat, A. van Ballegooijen, G. Aulanier, and E. DeLuca. Sigmoidal Active Region on the Sun: Comparison of a Magnetohydrodynamical Simulation and a Nonlinear Force-free Field Model. *ApJ*, 750:15, May 2012.
- [75] M. Janvier, G. Aulanier, V. Bommier, B. Schmieder, P. Démoulin, and E. Pariat. Electric currents in flare ribbons: Observations and three-dimensional standard model. *The Astrophysical Journal*, 788(1):60, 2014.
- [76] Ju Jing, Yan Xu, Wenda Cao, Chang Liu, Dale Gary, and Haimin Wang. Unprecedented Fine Structure of a Solar Flare Revealed by the 1.6 m New Solar Telescope. *Scientific Reports*, 6(1):24319, July 2016.

Figures

Figure 1

Evolution of magnetic field lines and electric currents prior to eruption. (A) Top view of magnetic field lines. The colored thick lines represent magnetic field lines and the colors denote the value of nonlinear force-free factor defined as $a = J \cdot B/B^2$, which indicates how much the field lines are non-potential. In

particular, for a perfectly force-free field, this parameter is constant along any given field line. As can be seen, the magnetic field is close to force-free since the color is nearly the same along any single field line. Note that at all different times, the field lines are traced from the same set of seeds at the bottom surface convected with the surface flow. The background shows the magnetic flux distribution on the bottom boundary (i.e., plane of $z = 0$), and contours of $B_z = (-30; -20; -10; 0; 10; 20; 30)$ G are shown. (B) 3D prospective view of the same field lines shown in panel (A). (C) Vertical integration of current density, i.e., $IJ = \int J dz$. (D) Vertical cross section (i.e., the $x = 0$ slice) of current density.

Figure 2

Temporal evolution of different parameters in the simulations. (A) Evolution of magnetic energy EM and kinetic energy EK. The dashed curve shows the energy injected into the volume (i.e., time integration of total Poynting flux) from the bottom boundary through the surface flow. The horizontal dashed line denotes the value of the total magnetic energy for a open force-free field with the same magnetic flux distribution on the bottom surface. (B) Releasing rate of magnetic energy and increasing rate of kinetic energy. (C) Magnitude of velocity and Alfvénic Mach number at a fixed point with location of $(x; y; z) = (0; 0; 28.75)$ Mm. (D) Height and rising speed of the apex of a magnetic field line in the AR's core initially overlying the current sheet. In all panels, the red lines are shown for denoting the transition time (at $t = 221$ min) from pre-eruption to eruption.

Figure 3

Formation of CS and trigger of reconnection. (A) Distribution of current density on the central vertical slice, i.e., the $x = 0$ slice. (B) Projection of magnetic field lines on the same cross section shown in A. Note that before $t = 221$ min 12 s, the magnetic field exhibit still arcade configuration, and a plasmoid at the tip of the CS is seen at $t = 221$ min 54 s as a result of reconnection, indicating the formation of MFR. (C) 1D profile of the magnetic field component B_z and current density J along a horizontal line crossing

perpendicular to the CS center (i.e., the point with largest J). The diamonds denote values on the grid nodes. (D) Distribution of vertical velocity on the same cross section shown in (A). The magnitudes of maximal Alfvénic Mach number are also denoted. (E) Horizontal slice of the current density crossing the center of the CS.

Figure 4

Evolution of different parameters during the eruption shown in the central vertical slice. (A) Current density J normalized by magnetic field strength B . (B) Magnitudes of velocity. The largest velocity and Aflv'enic Mach number are also denoted. (C) The vertical component of Lorentz force F_z normalized by density ρ . Also see Movie 1 for a high-cadence evolution of the eruption process.

Figure 5

Evolution of magnetic field lines (left) and CS (right) in 3D during the eruption. In the left panels, the thick colored lines are shown for magnetic field lines. Note that the MFR is weakly twisted in its core but highly

twisted in its envelope. The bottom surface is shown with distribution of magnetic flux. The vertical, transparent slice is shown with distribution of current density normalized by magnetic field strength, i.e., $J=B$. In the right panels, the CS in 3D is shown by iso-surface of $J=B = 0.5 \text{ Mm}$

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