MHD Simulations of the Slow-rise Phase of Solar Eruptions Initiated from a Sheared Magnetic Arcade (Postprint)

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Abstract

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Full Text

Preamble

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Abstract

Before solar eruptions, a short-term slow-rise phase is often observed, during which the pre-eruption structure ascends at speeds much greater than photospheric motions but much less than those of the eruption phase. Numerical magnetohydrodynamic (MHD) simulations of coronal evolution driven by photospheric motions up to eruptions have been used to explain the slow-rise phase, but their bottom driving speeds are much larger than realistic photospheric values. Therefore, it remains an open question how excessively fast bottom driving impacts the slow-rise phase. Here we modeled the slow-rise phase before eruption initiated from a continuously sheared magnetic arcade. In particular, we performed a series of experiments with bottom driving speeds unprecedentedly approaching the photospheric value of around 1 km s^{-1}. The simulations confirmed that the slow-rise phase is an ideal MHD process, i.e., a manifestation of the growing expansion of the sheared arcade in the process of approaching a fully open field state. The overlying field line above the core flux has a slow-rise speed modulated by the driving speed's magnitude but is always over an order of magnitude larger than the driving speed. The core field also expands with speed much higher than the driving speed but much lower than that of the overlying field. By incrementally reducing the bottom-driving speed to realistic photospheric values, we anticipate better matches between the simulated slow-rise speeds and some observed ones.

Key words: Sun: coronal mass ejections (CMEs) – Sun: flares – magnetohydrodynamics (MHD) – methods: numerical

1. Introduction

Solar eruptions, encompassing phenomena such as solar flares and coronal mass ejections (CMEs), are among the most dynamic and powerful events in the solar system (Lin et al. 2003; Zhou et al. 2003, 2006; Chen 2011; Jiang 2024). These events are characterized by the sudden release of vast amounts of magnetic free energy stored in the coronal magnetic field, resulting in dramatic changes to solar and interplanetary environments. Understanding the initiation mechanisms behind these eruptions is not only fundamental to solar physics (Cheng et al. 2017; Guo et al. 2017; Yuan et al. 2019; Zhong et al. 2021; Yan et al. 2022) but also critical for predicting space weather events that can have profound impacts on Earth's technological infrastructures (Teng et al. 2024).

The initiation of CMEs is often associated with a slow-rise phase (Kahler et al. 1988; Joshi et al. 2017; Cheng et al. 2020), which occurs after the quasi-static evolving state of CME progenitors but right before the impulsively eruptive state. This phase is closely linked to the eruption mechanism, although its physical nature remains unclear. The slow-rise phase is characterized by coronal magnetic field expansion, indicated by motion of filaments (e.g., Mackay et al. 2010; Guo et al. 2019), hot channels (e.g., Cheng et al. 2013; Yao et al. 2024), and overlying loops (e.g., Xing et al. 2024b), with typical speeds of a few tens km s^{-1}—much larger than photospheric motion (~1 km s^{-1}) but much smaller than eruption speed (hundreds to a few thousand km s^{-1}). Therefore, it represents a unique intermediate state that is neither fully quasi-static nor eruptive.

Currently, two distinct explanations exist for the slow-rise phase, which may fit different circumstances depending on specific magnetic configurations. Based on some observations (Cheng et al. 2023) and a magnetohydrodynamic (MHD) simulation (Aulanier et al. 2010) of the formation and eruption of a magnetic flux rope (MFR), Xing et al. (2024a) suggested the slow-rise phase results from slow tether-cutting magnetic reconnection below the MFR shortly before eruption. This reconnection not only weakens the overlying field but also drives the slow ascent of the newly formed MFR due to upward magnetic tension from the reconnected field lines. Since the reconnection is slow, the energy release is gradual, leading to slow-rise of the MFR compared to the eruption phase.

In the case of an eruption initiated from a sheared arcade (rather than a gradually formed pre-eruption MFR), Xing et al. (2024b) suggested that the slow-rise phase is a purely ideal MHD process (i.e., not associated with reconnection) based on the simulation by Jiang et al. (2021) in which reconnection within a sheared magnetic arcade leads to eruption. They suggested that the slow-rise phase is a manifestation of the growing expansion of the arcade in the process of approaching a fully open field state, which is inherent to the formation of a current sheet before eruption. In this scenario, reconnection begins only at the onset of eruption, and in particular, the slow-rise is more prominently demonstrated by the overlying field, which has a rising speed significantly larger than that of the core field. Xing et al. (2024b) further investigated some flare events with slow-rise phase and found they are consistent with the simulation: the overlying coronal loops present an expansion much faster than the slow-rise of the filament that represents the core field.

Nevertheless, in the aforementioned MHD simulations (and essentially all currently available MHD simulations designed to mimic coronal magnetic field energization driven by photospheric motions until eruptions, e.g., Amari et al. 2003; DeVore & Antiochos 2008; Aulanier et al. 2010), the driving speed applied at the bottom boundary—e.g., the often-used shearing and converging motions—is much larger than realistic values observed at the photosphere. For example, Xing et al. (2024a) used a driving speed with maximum value around 20 km s^{-1}, larger than observations by over an order of magnitude. This large boundary velocity weakly affects the quasi-static phase (where equilibrium is nearly achieved) and the eruption phase (where coronal velocities far exceed those at the lower boundary). However, since the driving speed is comparable to the typical slow-rise speed of a few tens km s^{-1}, the fast-driving speed may have a drastic effect during the slow-rise phase. Although Jiang et al. (2021) used a much smaller value of approximately 5 km s^{-1} (which is smaller than typical slow-rise speed), it is still larger than actual photospheric values by a few times. As such, it remains to be seen how the magnitude of the driving speed affects the slow-rise phase.

To conduct MHD simulations using actual photospheric driving speed, however, is computationally challenging. Since the quasi-static energizing phase often takes hours to days (Zuccarello et al. 2014), which is much longer than the eruption phase, the entire evolution time t_c (and the required computing time) is dominated by the pre-eruption evolution. The energy injection rate P_s from the bottom surface is roughly proportional to the driving speed v_d, say P_s = kv_d (where k is a coefficient depending on specific magnetic configuration). Therefore, with reduced driving speed, the time required for accumulation of the same amount of magnetic energy E will increase proportionally, i.e., t_c = E/P_s = E/(kv_d). Note that we have not yet considered numerical diffusion (resistivity), which inevitably affects the accumulation of magnetic energy in the corona. The numerical diffusion depends on the nature of the numerical scheme (in both the implementation of boundary conditions and when solving the MHD equation in the corona) and the grid resolution. For a given scheme and grid resolution, the energy loss rate P_n by numerical diffusion depends mainly on the magnetic field configuration (i.e., distribution of current density). For simplicity, let us further assume that energy flows across all other boundaries as well as magnetic energy conversion into other forms (e.g., thermal or kinetic energy) are negligible. Consequently, the accumulation of coronal magnetic energy is determined by the competition between energy injection from the bottom boundary and energy dissipation within the volume, i.e., the net increase rate of magnetic energy is P = P_s - P_n, and thus the simulation time should be t_c = E/(P_s - P_n). As can be seen, the time also depends on the ratio P_n/P_s. A too small driving speed v_d may result in a surface energy injection rate P_s comparable to the numerical diffusion rate P_n, and the time will significantly increase according to the equation. Even worse, the simulation will fail when P_s < P_n, i.e., the energy injection rate is overtaken by numerical diffusion, and no free magnetic energy can be accumulated in the corona. This is why many previous simulations chose to use an amplified driving speed to shorten computing time and, more importantly, to ensure that P_s P_n to avoid failure by numerical diffusion. Clearly, using a realistic driving speed requires the computation to have sufficiently small numerical diffusion.

In this letter, based on the high-accuracy simulation of Jiang et al. (2021), we managed to perform a series of experiments with bottom-driving speeds unprecedentedly approaching photospheric values, which provides a unique opportunity to study how the slow-rise phase is influenced by the magnitude of the driving speed.

2. Simulations

Jiang et al. (2021) examined the initiation of solar eruptions through MHD simulations, demonstrating that slow shearing motion at the photosphere of a bipolar magnetic field can quasi-statically form an internal current sheet. The advantage of this simulation is that the code, combined with sufficiently high resolution, has small enough numerical diffusion to make magnetic energy loss negligible during the quasi-static energizing phase. When the current sheet becomes sufficiently thin, rapid magnetic reconnection occurs, triggering eruption (Bian et al. 2022; Jiang et al. 2024). Initially, the magnetic field is modeled as a potential arcade.

Rotational flows were continuously applied to both polarities at the base, primarily at their edges, to inject free energy into the coronal field. This surface driving motion generates a magnetic configuration with substantial shear above the polarity inversion line. Such shearing methods are widely used in numerous three-dimensional (3D) simulations to energize the coronal field before eruption (e.g., Amari et al. 2003; DeVore & Antiochos 2008; Aulanier et al. 2010). This technique preserves the vertical component of the photospheric magnetic field distribution while enabling self-consistent evolution of the horizontal components under the influence of applied shearing flows, as described by the induction equation. It ensures that the potential field energy remains constant while facilitating an increase in free energy as the magnetic field evolves. The MHD simulation solves the full set of 3D, time-dependent ideal MHD equations except that a small kinetic viscosity ($= 0.05\Delta x^2/\Delta t$ where Δx and Δt are the spatial resolution and time step, respectively) is included in the momentum equation. The details of the MHD equations can be found in Jiang et al. (2021). The initial temperature is uniform, with a typical coronal value of $T = 10^6$ K. The initial plasma density is uniform in the horizontal direction and vertically stratified by solar gravity. The magnetic flux distribution at the bottom boundary is characterized by a bipolar field composed of two Gaussian functions, $B_z(x, y, 0) = B_0[\exp(-(x^2 + (y-y_c)^2)/\sigma_x^2) + \exp(-(x^2 + (y+y_c)^2)/\sigma_x^2)]$, where $B_0 = 30$ G, $\sigma_x = 28.8$ Mm, $\sigma_y = \sigma_x/4$, and $y_c = 11.5$ Mm. Here σ_x and σ_y determine the spread of magnetic flux in the x and y directions, respectively, while y_c dictates the separation between the two magnetic polarities along the y-axis.

Our computational domain extends from -360 to 360 Mm in the transverse directions and from 0 to 720 Mm in the vertical direction, and is resolved with an adaptive mesh refinement (AMR) grid with the highest resolution of 180 km. At the bottom boundary ($z = 0$ plane), we impose slow-driving rotational flows at the field's footpoints. The velocity profile is defined by v = v_0(B_z/B_z,max)ê, where B_z,max represents the maximum value of B_z(x, y, 0) and v_0 is a coefficient that controls the magnitude of the flow. At the bottom boundary, the magnetic induction equation is directly solved to update the magnetic field self-consistently, driven by the surface flow. At the side and top surfaces, the tangential components of the magnetic field are linearly extrapolated from internal points, while the normal component is adjusted to satisfy the divergence-free condition, thereby minimizing numerical magnetic divergence near the boundaries.

We first apply the driving flow with a maximum speed of 5.5 km s^{-1} until t = 100 minutes, which is well before the start of a slow-rise phase. Then, starting from t = 100 minutes, we carried out three simulations with the same settings except that the driving speed is reduced (by adjusting v_0 in the velocity equation). The three simulations, referred to as Run1, Run2, and Run3, have maximum driving speeds of 3.3 km s^{-1}, 2.2 km s^{-1}, and 1.65 km s^{-1}, respectively. By reducing the driving speed to approach realistic photospheric values, we can examine how the magnitude of the bottom-driving flow affects the evolution of the system, and more importantly, whether the appearance of the slow-rise phase before eruption onset is related to the driving speed. We do not stop the driving flow throughout the simulation, since in observations the photospheric motion is ceaseless regardless of whether there is an eruption.

3. Results

Figure 1 presents the magnetic and kinetic energy evolution profiles for the three simulations with different driving speeds (note that from t = 0 to 100 minutes, they have the same driving speed). The different simulations show the same behavior of free magnetic energy accumulation before eruption and release during eruption. The magnetic field evolves in accordance with what has been shown in Jiang et al. (2021): before eruption, the core field slowly expands outward with a current sheet gradually forming within; then, magnetic reconnection occurs at the current sheet, triggering the eruption and leading to rapid release of magnetic energy. In each simulation, the eruption onset time, as indicated by the dashed lines in Figure 1, is identified by the beginning of a sudden increase in kinetic energy (which corresponds to the start of magnetic energy decrease). Note that in the different simulations, the onset times of eruption differ because, right before eruption onset, the accumulated magnetic energy should be approximately the same amount while the energy injection rates (which depend on driving speed) are different. As explained in Jiang et al. (2021), to form a current sheet, the magnetic energy should be not far from the open field energy. Indeed, in all simulations, the magnetic energies right before eruption onset are very close to each other (around 1.9E_{P0}).

From the kinetic energy evolution, three phases can be identified. The first is the quasi-static phase (from the beginning to around t = 100 minutes), in which there is negligible change in kinetic energy. After that and before eruption onset time, the kinetic energy starts to increase noticeably but still gradually. This mild increase of kinetic energy is likely associated with the slow-rise phase in observations. The eruptive phase is marked by a sharp increase in kinetic energy. Since we focus on the slow-rise phase before eruption (and to save computing time), all simulations are stopped shortly after eruption onset. Therefore, at the end of the simulations, the erupting field is still undergoing rapid acceleration and has not reached very high in the computational volume. Comparing the three simulations reveals that kinetic energy during the slow-rise phase has different magnitudes, decreasing incrementally with smaller driving speeds, indicating that driving speed affects the slow-rise phase.

Figure 2 illustrates the evolution of magnetic field lines at different times in the Run3 simulation (with maximum bottom-driving speed of 1.65 km s^{-1}). These field lines are integrated accurately with their footpoints moving with the surface driving flow, thus tracking the evolution of the same set of field lines over time. Before the slow-rise phase, the entire field expands slowly with roughly the same rate, but during the slow-rise phase, the field expands with rather different rates. Especially when approaching the time when the current sheet is formed (Figure 2(G)), the expansion of the overlying field is significantly faster than that of the core field. Therefore, to comprehensively analyze the slow-rise phase, we need to inspect the behavior of different field lines, in particular differentiating the overlying field and the core field.

To quantify how field expansion is influenced by driving speed, in Figure 3 we plot the height-time curves of the overlying and core fields in the three simulations by tracking two representative field lines. For the overlying field, a field line is traced from the center of the magnetic polarity (i.e., the point with the largest B_z) on the bottom surface. Since the driving velocity is zero at the polarity center, the footpoint of this field line can be traced from this fixed footpoint at different times. The evolution of this field line is shown by the lowest case (colored solely in red, and marked by the red arrow) in each panel of Figure 2. Since this field line undergoes significant shearing in the pre-eruption phase, we only traced it back to t = 100 minutes. For the core field, we first locate a footpoint of the MFR axis at the early phase of the eruption (note that here the MFR forms during the eruption), and then track the motion of this footpoint as driven by the surface driving flow at the bottom surface. Consequently, a field line can be traced from this moving footpoint at different times. The evolution of this field line is shown by the highest case (pseudo-colored by height and marked by the green arrow) in each panel of Figure 2. The field line can be easily traced from the beginning of the simulation (t = 0). Since this field line is not sheared, it can represent well the overlying field.

As shown in Figure 3, the three phases can be clearly seen in the expansion of the two field lines. From the overlying field line, one can see the quasi-static and slow-rise phases. Before t 100 minutes, the field line expands quasi-statically with speed of around 6–16 km s^{-1}, which is on the same order of magnitude as the maximum driving speed of 5.5 km s^{-1}. Then after t = 100 min, the field expansion is accelerated significantly, with speeds of approximately 80 km s^{-1}, 50 km s^{-1}, and 30 km s^{-1}, respectively, in the three simulations. These speeds are higher than the corresponding maximum driving speeds by an order of magnitude, and thus this phase can be taken as the slow-rise phase. This suggests the slow-rise phase is a generic phenomenon in the simulation, although it is modulated by the driving speed.[1] From the core field line, one can see three phases with distinct speeds. In the quasi-static phase, this core field line expands with speed around 1 km s^{-1}, somewhat slower than the driving speed. In the slow-rise phase it expands with speeds of 13 km s^{-1}, 11 km s^{-1}, and 7 km s^{-1}, a few times (around 5) the corresponding driving speeds. So in both pre-eruption phases, the core field line expands much more slowly than the overlying one. These speeds are then rapidly accelerated to over 200 km s^{-1}, marking the onset of eruption. Since the eruption flow (and the core field) has not reached the heights of the overlying field line at the end of our simulations, the overlying field line is still at slow-rising speed, even passing the onset time of eruption. After a few minutes when the core field catches up to the overlying one from behind, the overlying field will also be accelerated rapidly as driven by the core field.

We further compare the slow-rise speeds of our simulation with an event: the slow-rise phase of an X1.0 flare eruption that occurred on 2021 October 28 in AR 12887. This event has been carefully analyzed by Duan et al. (2023) and Xing et al. (2024b). They measured the slow-rise speeds of the overlying loops and filament (corresponding to the core field) and eliminated the projection effect using a triangulation approach based on SDO and STEREO observations as well as coronal field extrapolation analysis. It is found that the actual slow-rise speeds of the overlying loops and the filament are around 5 km s^{-1} and 20 km s^{-1}, respectively. As affirmed in Figure 3(C), a simple extrapolation of the results of the three simulations suggests that if having a driving speed of 1 km s^{-1} (which is typically the realistic value in the photosphere), the slow-rise speeds of the overlying field and the core field would also be around 20 km s^{-1} and 5 km s^{-1}, respectively, closely matching the observed values.

[1] It should be noted that when the driving speed becomes smaller, the slow-rise motion is also influenced more by the viscosity in the simulation, which reduces the slow-rise speed.

4. Conclusion

In the context of Jiang et al. (2021)'s simulations, which have established a fundamental mechanism for solar eruptions, we have lifted the model to a higher level of reality by reducing the speed of the bottom-driving flow to closely approach actual photospheric values. Our simulations show that the mechanism of eruption initiation is not sensitive to the driving speed (that is, all the different simulations produce eruption in the same way), while the slow-rise phase is indeed influenced by the magnitude of the driving speed. By incrementally reducing the bottom-driving speed, we observed a correspondingly slower increase in the kinetic energy growth curve during the slow-rise phase. We further traced the expansion of magnetic field lines which clearly exhibit slow-rising before eruption onset. The overlying field line above the core flux has a slow-rise speed always larger than the driving speed by over an order of magnitude, and it is modulated by the driving speed. The core field also expands with speed much higher than the driving speed but much lower than that of the overlying field. By incrementally reducing the bottom-driving speed to realistic photospheric values, we anticipate better matches between simulated slow-rise speeds and some observed ones. Finally, it is worth noting that our findings are only applicable to cases where the pre-eruptive structure is a sheared arcade and reconnection does not occur before eruption. It remains to be investigated in future study whether the findings are also correct for cases where the pre-eruptive structure is a flux rope, or where there is pre-eruptive magnetic reconnection.

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Note: Figure translations are in progress. See original paper for figures.