Simulations of Prominence Eruption Preceded by Large-amplitude Longitudinal Oscillations and Draining

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Abstract

We present magnetohydrodynamic (MHD) simulations of the evolution from quasi-equilibrium to eruption of a prominence-forming twisted coronal flux rope under a coronal streamer. We have compared the cases with and without the formation of prominence condensations, as well as the case where prominence condensations form but we artificially initiate the draining of the prominence. We find that the prominence weight has a significant effect on the stability of the flux rope and can significantly increase the loss-of-equilibrium height. The flux rope can be made to erump earlier by initiating draining of the prominence mass. We have also performed a simulation where large-amplitude longitudinal oscillations of the prominence are excited during the quasi-static phase. We find that the gravity force along the magnetic field lines is the major restoring force for the oscillations, in accordance with the “pendulum model,” although the oscillation periods are higher (by about 10%–40%) than estimated from the model because of the dynamic deformation of the field line dips during the oscillations. The oscillation period is also found to be slightly smaller for the lower part of the prominence in the deeper dips compared to the upper part in the shallower dips. The oscillations are quickly damped out after about two to three periods and are followed by prominence draining and the eventual eruption of the prominence. However, we do not find a significant enhancement of the prominence draining and earlier onset of eruption with the excitation of the prominence oscillations compared to the case without.

Unified Astronomy Thesaurus concepts: Magnetohydrodynamics (1964); Magnetohydrodynamical simulations (1966); Solar coronal mass ejections (310); Solar prominences (1519); Solar filament eruptions (1981)

Supporting material: animations

1. Introduction

Both observations and theoretical analysis have suggested that the weight of the prominence/filament mass can have a significant role in the stability and eruption of the hosting magnetic structure that supports it (e.g., Low 1996; Seaton et al. 2011; Jenkins et al. 2018, 2019). Using 3D reconstruction of an eruption on 2010 April 3 based on observations from multiple viewpoints, Seaton et al. (2011) showed that mass offload in an underlying filament triggers the slow rise of a coronal flux rope, which then reaches a critical height for a catastrophic loss of equilibrium and produces a coronal mass ejection (CME). Jenkins et al. (2019) studied the effect of prominence mass and mass draining using an analytical model of a flux rope as a line current suspended within a background potential field. They showed that the inclusion of the prominence mass can increase the height at which the line current experiences an ideal-MHD instability or loss of equilibrium. With mass draining, which allows the flux rope to rise, the critical height for the loss of equilibrium can occur at a range of heights depending explicitly on the amount and evolution of the mass.

Besides potentially playing an important role in the development of eruption, prominence plasma exhibits various dynamic phenomena that can provide information about the conditions of the hosting coronal magnetic structure, which is difficult to observe directly. One interesting dynamic phenomenon is the large-amplitude longitudinal (LAL) oscillations first reported by Jing et al. (2003). These are coherent oscillations of the prominence material (nearly) along the filament axis with amplitudes of 30–100 km s$^{-1}$ and periods of 0.83–2.66 hr, triggered by an energetic event close to the filament footpoints (e.g., Luna & Karpen 2012; Tripathi et al. 2009). Luna & Karpen (2012) developed the “pendulum model” to explain the LAL oscillations, where the projected gravity force along the magnetic field lines is the restoring force for the prominence condensations to oscillate in the magnetic concavity of the field-line dips, and the period of the oscillations is determined by the curvature radius of the dips, analogous to the length of the pendulum. These oscillations therefore provide a useful means of diagnosing the conditions of the magnetic support of the prominence and can put a constraint on the magnetic field strength (Luna & Karpen 2012). The LAL oscillations are not necessarily associated with a subsequent eruption (e.g., Jing et al. 2003, 2006; Vršnak et al. 2007). However, Bi et al. (2014) reported the observation of a filament eruption where both LAL oscillations followed by filament material draining are found to precede the eruption. This raises the question of the role LAL oscillations may play for the initiation of the draining and the eruption.

Increasingly, 3D MHD simulations of CMEs and CME source regions are conducted with more realistic treatment of the thermodynamics to allow for the formation of the prominence condensations to study their dynamic effects and observable signatures (e.g., Xia et al. 2014; Xia & Keppens 2016; Fan 2017, 2018; Zhou et al. 2018). Xia et al. (2014) and Xia & Keppens (2016) have carried out the first 3D MHD simulations of the formation of a prominence in a stable equilibrium coronal flux rope, with the inclusion of the nonadiabatic effects of an empirical coronal heating, optically thin radiative losses, and field-aligned thermal conduction. They have used an adaptive grid to resolve the fine-scale internal dynamics of the prominence and reproduced many
observed features seen in SDO/AIA observations of the prominence-cavity systems. Zhou et al. (2018) have performed 3D MHD simulations of prominence oscillations (both longitudinal and transverse oscillations) in a stable magnetic flux rope and compared the results with idealized analytical models. They excite the oscillations by imparting initial velocity perturbations to the prominence. They found that the resulting LAL oscillations are in agreement with the pendulum model where the field-aligned component of the gravity serves as the restoring force. The period of the LAL oscillations is higher than that predicted by the pendulum model by up to 20%. Fan (2017, 2018) have carried out 3D MHD simulations of a prominence-forming coronal flux rope that transitions from quasi-equilibrium to eruption. The thermodynamics treatment incorporates the nonadiabatic effects of a simple empirical coronal heating, optically thin radiative losses, and field-aligned thermal conduction. In these simulations a significantly twisted, long coronal flux rope builds up under a preexisting coronal streamer by an imposed flux emergence at the lower boundary. Cool prominence condensations form in the dips of the long emerged twisted field lines owing to the radiative instability driven by the optically thin radiative cooling. The prominence-carrying flux rope undergoes a long quasi-static rise phase and develops prominence draining during the later stage as the dips become shallower with the rise (Fan 2018).

The flux rope eventually erupts and develops an associated prominence eruption when the center portion of the flux rope rises to a certain height. It is found that once the prominence is formed, the magnetic field supporting the prominence becomes significantly non-force-free, despite the fact that the entire flux rope has low plasma $\beta$. Through a comparison of the simulations with and without the formation of the prominence condensations (the “PROM” and “non-PROM” simulations in Fan 2018), it is found that the prominence weight can suppress the development of the kink instability of the highly twisted emerged flux rope and delay its rise to the critical height for the loss of equilibrium and dynamic eruption of the flux rope (Fan 2018).

In this paper we expand on the study of Fan (2018) and carry out further simulations to investigate the dynamic effects of prominence draining and prominence LAL oscillations. Further comparison of the simulations with and without prominence formation shows that the presence of the prominence weight also causes a significant increase of the loss-of-equilibrium height of the flux rope, consistent with the result from the analytical model by Jenkins et al. (2019). A new simulation where we artificially initiate prominence draining by reducing the pressure at one footpoint of the flux rope during the quasi-static rise phase shows that a significant reduction of the total prominence mass allows the flux rope to rise more quickly to the loss-of-equilibrium height and develop a dynamic eruption significantly earlier. We also perform a new simulation where we excite LAL oscillations by adding an initial velocity (parallel to the magnetic field) to the prominence plasma during the quasi-static rise phase. We find that prominence LAL oscillations with a period of roughly 2 hr develop in the magnetic dips. It is found that the main restoring force of the oscillations is the field-aligned gravity force consistent with the pendulum model, although the oscillation period is found to be larger than predicted by the model. The oscillations are strongly damped and die out after about two to three periods. They are followed by episodes of prominence draining toward the two ends of the flux rope and an eventual dynamic eruption of the prominence. However, the excitation of the LAL oscillations is not found to significantly enhance the draining and cause an earlier eruption compared to the case without the LAL oscillations.

2. Model Description

The MHD numerical simulations we use in this work are specifically the “PROM” and “non-PROM” simulations described in Fan (2018, hereafter F18) and two additional simulations: “PROM-drain” with induced prominence draining and “PROM-LALO” with induced LAL oscillations, by modifications to the previous “PROM” simulation as described below. The readers are referred to Section 2 in F18, as well as Sections 2 and 3.1 in Fan (2017, hereafter F17), for a detailed description of the setup of the previous “PROM” and “non-PROM” simulations and the numerical model. As a summary, we use the “Magnetic Flux Eruption” (MFE) code to solve the set of semirelativistic MHD equations in spherical geometry (F17). The energy equation explicitly incorporates the nonadiabatic effects of a simple empirical coronal heating (which depends on height only), optically thin radiative cooling, and the field-aligned heat conduction. The simulation domain is in the corona, excluding the photosphere and chromosphere layers, with the lower boundary temperature and density set at the transition region. With the inclusion of the above nonadiabatic effects, the simulations allow in situ formation of prominence condensations in the corona as a result of the development of the radiative instability. The simulations are carried out in a spherical wedge domain with a radial range $r \in [R_s, 11.47R_s]$, a colatitude range $\theta \in [75^\circ, 105^\circ]$, and an azimuthal range $\phi \in [-75^\circ, 75^\circ]$, where $R_s$ is the solar radius. The domain is first initialized with a 2D quasi-steady solution of a coronal streamer with an ambient solar wind (Section 3.1 in F18). At the lower boundary, the emergence of a portion of a twisted magnetic torus is imposed as described in F17 (Equations (19)–(22) in the paper) such that a long twisted flux rope is built up quasi-statically under the streamer dome. The same flux emergence is imposed in the “PROM” and “non-PROM” simulations in F18. An extended prominence condensation develops in the dips of the emerged flux rope field lines in the “PROM” case, whereas in the “non-PROM” case the prominence formation is suppressed by modifying the radiative cooling and thermal conduction (F18). The resulting subsequent evolution of the flux rope is drastically different between the two cases as described in F18.

Here we further carry out two simulations labeled as the “PROM-drain” and “PROM-LALO” cases. For the “PROM-drain” simulation we artificially initiate draining of the prominence at a time instance during the “PROM” simulation after the prominence has formed in the emerged flux rope but while it is still in the quasi-static phase of the evolution. We do this by modifying the pressure at the lower boundary at one footpoint of the flux rope. As described in F17, we adjust the base pressure at the lower boundary (as given by Equations (17) and (18) in F17) such that it is driven toward a value that is proportional to the downward heat conductive flux to crudely represent the effect of chromospheric evaporation. To facilitate the draining, we reduce the constant of proportionality $C$ for the base pressure in Equation (18) in F17 by about 50 times for a period of about 9.9 hr (from about $t = 17.2$ hr to $t = 27.1$ hr) during the quasi-static evolution phase, over a region that encloses the right footpoint of the emerged flux rope, in the
original "PROM" simulation. For the "PROM-LALO" simulation, we initiate LAL oscillations by imparting an initial parallel momentum (parallel to the direction of the magnetic field lines) to the cool prominence mass at a time instance during the quasi-static phase in the original "PROM" simulation. At about \( t = 17.15 \) hr, we add a velocity parallel to the magnetic field of about 100 km s\(^{-1}\) to the cool plasma where temperature \( T < 10^5 \) K. We examine the subsequent evolutions of the "PROM-drain" and "PROM-LALO" simulations after their respective initiation of the perturbations and compare them with the evolution of the original "PROM" simulation.

3. Simulation Results

3.1. The Effect of Prominence Weight and Initiation of Eruption by Prominence Draining

First, as an overview of the result from F18 on the "PROM" and "non-PROM" simulations, Figure 1 (and the associated animation in the online version) shows a side-by-side comparison of the evolutions produced by the "PROM" simulation with the formation of the prominence condensations (first and second columns) and the "non-PROM" simulation without prominence formation (third and fourth columns). The second and fourth columns show the synthetic SDO/AIA 304 Å images corresponding to the 3D field-line images to their left (with the same perspective view). The synthetic SDO/AIA 304 Å channel emission images are computed by line-of-sight (LOS) integrations through the simulation domain using Equation (23) in F17, and they show concentrations of cool plasma with a peak temperature response at about \( 8 \times 10^4 \) K. In carrying out the LOS integrations here, we have also assumed that the prominence condensations are opaque such that when the LOS reaches a plasma where both the temperature goes below \( 7.5 \times 10^4 \) K and the number density is above \( 10^7 \) cm\(^{-3}\), we stop the integration for that LOS assuming that the emission from behind the plasma is blocked and does not contribute to the integrated emission for the LOS.

As described in F18, for both the "PROM" and "non-PROM" simulations, Figure 1 shows a side-by-side comparison of the evolution from the "PROM" and "non-PROM" simulations. The first and second columns show snapshots of the 3D magnetic field lines and the corresponding synthetic SDO/AIA 304 Å emission images from the "PROM" simulation, and the third and fourth columns show those at the concurrent times for the "non-PROM" simulation. An animation of the evolution for the two cases in comparison is also available in the online version of the paper. The animation shows the evolution of both models from \( t = 5.95 \) to 22.30 hr and continues the PROM simulation from 22.30 to 39.64 hr.

(An animation of this figure is available.)

Figure 1. Side-by-side comparison of the evolution from the "PROM" and "non-PROM" simulations. The first and second columns show snapshots of the 3D magnetic field lines and the corresponding synthetic SDO/AIA 304 Å emission images from the "PROM" simulation, and the third and fourth columns show those at the concurrent times for the "non-PROM" simulation. An animation of the evolution for the two cases in comparison is also available in the online version of the paper. The animation shows the evolution of both models from \( t = 5.95 \) to 22.30 hr and continues the PROM simulation from 22.30 to 39.64 hr.
cases, the emergence of an identical twisted flux rope is imposed at the lower boundary and the emergence is stopped (at \( t = 8.82 \) hr, panels (a)–(d)), when the total field-line twist about the axis of the emerged flux rope reaches 1.83 winds, which is above the critical twist (1.25 winds) for the onset of the kink instability for a line-tied, uniformly twisted cylindrical force-free flux tube (Hood & Priest 1981). In the “PROM” case, a long prominence has formed in the field-line dips of the emerged flux rope (panels (a), (b)), whereas no prominence forms in the “non-PROM” case (panels (c), (d)), and the subsequent evolution is found to be very different for the two cases. In the “non-PROM” case, the flux rope quickly develops the kink motion with the central portion protruding upward and then erupts dynamically when it reaches a certain height (panels (g) and (k) and the online movie). In contrast, during this same period, the prominence-carrying flux rope in the “PROM” case remains confined, showing very little motion (panels (e) and (f) and the online movie). It is found that the flux rope undergoes a long quasi-static rise phase (of about 30 hr) with episodes of prominence draining before eventually its center portion rises to a certain height where it erupts dynamically, with an associated prominence eruption and draining along the two legs of the erupting flux rope (see the online movie and also F18). F18 found that the prominence-carrying magnetic field in the flux rope is significantly non-force-free despite the low plasma \( \beta \). The weight of the prominence suppresses the development of the kink instability and delays the flux rope’s rise to the critical height for the loss of equilibrium.

In this paper, we further show that the loss-of-equilibrium height of the flux rope is significantly increased for the “PROM” case compared to the “non-PROM” case. Figure 2 shows the acceleration as a function of height tracked at the apex of the axial field line of the flux rope. We find that the height at which the acceleration becomes persistently positive, which approximates the loss-of-equilibrium height, is significantly higher for the “PROM” case than that for the “non-PROM” case. The decay rate with height of the corresponding potential field at the height for the loss of equilibrium for the “PROM” case (see Figure 2 at the location marked by the black dashed line) is about 2.3, which is also significantly higher than the critical value (of about 1.5) for the onset of the torus instability for a toroidal current ring (e.g., Khem & Török 2006; Démoulin & Aulanier 2010). An analytic study by Jenkins et al. (2019), which models a flux rope as a line current confined in a background potential magnetic field, showed that the inclusion of the prominence weight increases the height at which the line current experiences loss of equilibrium. The basic reason is that the additional (constant with height) weight of the prominence causes the total confining force to decline more slowly with height, such that the flux rope needs to reach a higher height where the potential field has a steeper decline with height (than that which is needed in the absence of the prominence weight) for the loss of equilibrium or torus instability to take place. Our simulation result of the increased loss of equilibrium height for the flux rope with the formation of prominence is consistent with the result of the analytic model by Jenkins et al. (2019).

To further investigate the effect of prominence draining, we have carried out the “PROM-drain” simulation where we artificially initiate prominence draining at a time \( t = 17.15 \) hr during the quasi-static rise phase of the “PROM” simulation by reducing the pressure at the right footpoint of the flux rope, as described in Section 2. Figure 3 shows the subsequent evolution of the “PROM-drain” case (third and fourth columns) compared to the “PROM” case (first and second columns). An animation of this side-by-side comparison of the evolution is also available in the online version. As can be seen from the figure (and the movie), an earlier draining of prominence mass toward the right footpoint (Figure 3(d)) takes place owing to the lowered pressure at the right footpoint of the flux rope, while no draining has yet happened in the “PROM” case. As a result, the quasi-static rise is faster in the “PROM-drain” case, and it develops an earlier eruption (Figures 3(g), (h), (k), (i)). On the other hand, in the “PROM” case, prominence draining also takes place but significantly later, and the flux rope develops a later eruption with an associated prominence eruption (see the movie associated with Figure 3). Figure 4(a) shows the evolution of the prominence mass, evaluated as the total mass with temperature below \( 10^5 \) K, comparing the two cases. We see that starting from the time \( t = 17.15 \) hr (when the pressure at the right footpoint of the flux rope is lowered) the prominence mass for the “PROM-drain” case (the red curve) starts to decline, while the prominence mass for the “PROM” case continues to rise owing to continued convergence of mass toward the field-line dips (F18). The draining toward the right footpoint of the flux rope in the “PROM-drain” case starts an earlier decline of the
prominence weight, causing a faster rise of the flux rope as shown by the height–time curves of the tracked apex of the axial field line of the flux rope (Figure 4(c)). This allows the flux rope in the “PROM-drain” case to reach the loss-of-equilibrium height earlier and develop an earlier eruption by about 5 hr, resulting in a rapid acceleration, a significant magnetic energy release, and a significant kinetic energy increase (Figure 4(b)). We find that the loss-of-equilibrium height (marked by the dashed lines in Figure 4(c)), which we approximate as the height at which the acceleration at the tracked apex of the axial field line becomes persistently positive, is close for the two cases, with the “PROM-drain” case being slightly lower. Thus, prominence draining can initiate an earlier eruption of the flux rope by allowing it to rise to the loss-of-equilibrium height more quickly.

3.2. Eruption Preceded with LAL Oscillations and Draining of Prominence

Figure 5 and the associated online movie show the evolution of the 3D magnetic field and the synthetic SDO/AIA 304 Å emission from the “PROM-LALO” simulation, in which we initiate prominence oscillations by imparting an initial parallel velocity (parallel to the magnetic field lines) to the cool prominence mass at a time instance during the quasi-static phase in the original “PROM” simulation. We see that with the initial velocity imparted to the prominence plasma at $t = 17.15$ hr, the prominence as a whole develops large-amplitude oscillations (panels (b), (e), (c), (f)) with a period of roughly 2 hr, with the magnetic field also showing horizontal swinging oscillations of the entire flux rope (see the movie associated with Figure 5). These large-amplitude oscillations are strongly damped and die out after about two to three periods. They are then followed by episodes of prominence draining toward either footpoint as the flux rope continues to rise quasi-statically (panels (g), (h), and (i) and the movie), until eventually it erupts with an associated prominence eruption (panels (j), (k), and (l)). As can be best seen in the movie of Figure 5 (the on-disk view of the synthetic AIA 304 Å images), the displacements of the prominence condensations during the oscillations are not exactly aligned with the prominence spine.
Figure 6 and the associated movie show the evolution of two tracked prominence-carrying field lines colored in temperature, traced from two fixed left footpoints on the lower boundary. They show the oscillation motions of the two cool prominence condensations at the dips of these two field lines. It can be seen that the motions of the condensations are mainly along the magnetic field lines, and the field lines are not rigid, with the field line themselves showing swinging motions. It can also be seen from the movie that the motions of the two condensations gradually become out of phase, with the condensation in the higher shallower dip showing a slightly longer oscillation period than that in the lower deeper dip. Figure 7 shows the parallel velocity (parallel to the magnetic field) as a function of time of the two prominence condensations shown in Figure 6. The velocity is measured at the temperature minimum on the tracked field lines. We have fitted an exponentially decaying sinusoidal function to the measured velocity:

\[ v(t) = A_0 \sin \left( \frac{2\pi}{P} (t - t_0) - \phi_0 \right) \exp \left( -\frac{t - t_0}{\tau} \right), \]  

(1)

where \( t_0 = 17.15 \) hr is the time for which the initial velocity is imparted to the prominence plasma, and \( A_0, \phi_0, P \) and \( \tau \) are the fitted initial amplitude, initial phase, oscillation period, and e-folding decay time, respectively. We obtain oscillation period \( P = 1.94 \) hr (\( P = 1.82 \) hr) and decay time \( \tau = 2.45 \) hr (\( \tau = 2.20 \) hr) for the motion of the higher (lower) dip prominence concentration. These values are within the observed ranges for the period and the decay time for LAL oscillations of prominences (e.g., Jing et al. 2006; Tripathi et al. 2009; Luna & Karpen 2012; Luna et al. 2018). Luna & Karpen (2012) constructed the “pendulum model” to explain the prominence LAL oscillations, in which the projected gravity along the magnetic field is the restoring force for the oscillatory motions of the prominence condensations along the magnetic dips. In this model the oscillation period is given by

\[ P_{\text{pendulum}} = 2\pi \frac{R_c}{g}, \]  

(2)

where \( R_c \) is the radius of curvature of the magnetic field-line dip and \( g \) is the gravitational acceleration. We estimate a mean \( R_c \) for the field-line dip by averaging the radius of curvature over a length from the bottom of the dip that corresponds to the initial peak displacement of the oscillations. Then, the theoretical period based on the estimated \( R_c \) is found to be \( P_{\text{pendulum}} = 1.76 \) hr (\( P_{\text{pendulum}} = 1.30 \) hr) for the higher (lower) dip. The actual period \( P \) found in the simulation above is significantly greater than the period estimated from the pendulum model by about 10% (40%) for the prominence condensation in the higher (lower) dip. Higher periods for LAL oscillations (by up to 20%) than what are estimated from the pendulum model are also found in the 3D MHD simulation by Zhou et al. (2018). A probable explanation of this discrepancy is that the magnetic field lines supporting the prominence are not rigid, as assumed in the pendulum model, but deform with the oscillations, which change the curvature radius dynamically (Zhou et al. 2018). Figure 8 illustrates this deformation by showing a tracked prominence-carrying field line at two time instances, at \( t_1 \), when the prominence condensation is at the bottom of the dip, and at \( t_2 \), when the prominence has moved to

but are at a small acute angle from the prominence spine. This is because the motion of the prominence mass is mainly along the magnetic field, and magnetic field lines supporting the prominence at the dips are at a small acute angle relative to the apparent orientation (spine) of the prominence concentrations (F17, Luna et al. 2018; Zhou et al. 2018). It can also be seen from the movie of Figure 5 (the middle synthetic AIA 304 Å images) that the prominence oscillations are showing out-of-phase displacements, with the upper part of the prominence exhibiting a slightly longer oscillation period than the lower part. The amplitude of the oscillations is also greater for the upper part than the lower part.

Figure 4. (a) Temporal evolution of the cool prominence mass in the corona evaluated as the total mass with temperature below \( 10^5 \) K; (b) temporal evolution of the total magnetic energy \( E_m \) and total kinetic energy \( E_k \); (c) height vs. time tracked at the apex of the axial field line of the emerged flux rope. In each panel, the red (black) solid curve shows the result for the “PROM-drain” (“PROM”) case. The red (black) dashed line in panel (c) marks the loss-of-equilibrium height for the “PROM-drain” (“PROM”) case, which is approximated by the height at which persistently positive acceleration begins.
Figure 5. Evolution from the “PROM-LALO” simulation. The left column shows snapshots of the 3D magnetic field lines, and the middle and right columns show the synthetic SDO/AIA 304 Å emission images as viewed from two different perspectives, with the middle column being of the same perspective as the field-line snapshots and the right column being for an on-disk view from above. An animation of the evolution from the time the oscillation is initiated until the prominence eruption \((t = 17.15–39.64 \, \text{hr})\) is available in the online version of the paper.

(An animation of this figure is available.)
the rightmost position in its oscillation. We find that with the motion of the prominence to the right, the field line also slightly swings to the right, with the dip location tending to follow the prominence such that the prominence does not rise as high as it would have if it had moved strictly along the original field-line curve. This effectively reduces the curvature experienced by the prominence-moving trajectory, thus increasing the oscillation period, which is also found in the 2D simulations by Zhang et al. (2019). This effect is expected to be significant if the magnetic dips supporting the prominence are significantly non-force-free because of the prominence weight (Zhou et al. 2018), which is the case for our simulated prominence-carrying flux rope (F18). The “pendulum model” is a first approximation for the LAL oscillations, and there are other complications, for example, the effect of gas pressure gradient as an additional restoring force (Luna et al. 2012; Adrover-González & Terradas 2020), although that effect would tend to reduce the oscillation period.

Figure 8. Prominence-carrying field line at two time instances \((t_1\) and \(t_2\)) during the oscillation of the prominence, illustrating the deformation of the field line.

Figure 7. Temporal evolution of the parallel velocity (parallel to the magnetic field) of the prominence condensation in the higher (black diamonds) and the lower (red diamonds) dips of the two tracked field lines shown in Figure 6. The black and red solid curves are the fitted exponentially decaying sinusoidal functions to the black and red points.

Figure 6. Snapshots of two tracked prominence-carrying field lines (traced from two fixed left footpoints) colored in temperature, showing the oscillation motions of the prominence condensations (mainly) along the field lines. The left and right columns show two different perspective views. An animation of the evolution of the two tracked field lines is also available in the online Journal. The animated view runs from \(t = 17.15\) to 22.60 hr.

(An animation of this figure is available.)
aligned component of the gravity force

two

the rate of work done to the prominence by the field-aligned component of the pressure gradient force (blue curve),

\[ W_{\parallel} = \int f_p \cdot v \, dV_{\text{prom}}, \] (5)

and the sum of the two (red dashed curve). In the above, \( f_p = -\rho (GM_\odot / r^2) \mathbf{r} \) is the gravity force and \( f_p = -\nabla p \) is the pressure gradient force. It can be seen that, except at the very beginning, immediately after the initial velocity is imparted (at about \( t = 17.15 \) hr), the rate of change of the parallel kinetic energy of the prominence (black curve) is in approximate agreement with the sum of the rate of work done by the parallel component of the gravity and pressure gradient forces, \( W_{\parallel \parallel} + W_{\parallel \parallel} \) (red dashed curve), during the periods of the LAL oscillations. The gravity part \( W_{\parallel \parallel} \) (green curve) shows both positive and negative rate of work done to the prominence, roughly in phase with the rate of change of the parallel kinetic energy \( \dot{E}_{\parallel\parallel} \) (black curve), indicating that it acts as a restoring force of the oscillations, whereas the pressure gradient part \( W_{\parallel \parallel} \) (blue curve) shows only negative rate of work to the prominence and is significantly out of phase with the rate of change of the kinetic energy, indicating that it is mainly a dissipative force of the oscillations and can account for most of the dissipation over the oscillation periods (except at the very beginning). At the beginning, immediately after the initial velocity is imparted (at about \( t = 17.15 \) hr), the dissipation of the kinetic energy \( \dot{E}_{\parallel\parallel} \) (black curve) is significantly greater than the sum of the rate of work by the field-aligned gravity and pressure gradient \( W_{\parallel \parallel} + W_{\parallel \parallel} \) (red dashed curve). The initial strong dissipation of the kinetic energy is most likely due to the strong numerical viscosity in the code produced by the discontinuous initial velocity field imparted to the prominence. However, the agreement between \( \dot{E}_{\parallel\parallel} \) and \( W_{\parallel \parallel} + W_{\parallel \parallel} \) and the fairly close in-phase relation between \( \dot{E}_{\parallel\parallel} \) and \( W_{\parallel \parallel} \) during the LAL oscillations indicate that the field-aligned gravity is the main restoring force of the LAL oscillations with the field-aligned pressure gradient acting mainly as a drag or dissipation, consistent with the “pendulum model” of Luna & Karpen (2012).

The damping role of the field-aligned pressure gradient on the LAL oscillations of the prominence is further illustrated in Figure 10, which shows an approximate antiphase relation between the parallel kinetic energy \( E_{\parallel\parallel} \) (in the top panel) and the rate of work by the parallel pressure gradient \( W_{\parallel \parallel} \) (in the bottom panel). The consistent negative sign of \( W_{\parallel \parallel} \) and its antiphase relation with \( E_{\parallel\parallel} \) show that the field-aligned pressure gradient is always acting against the velocity direction, and its amplitude is well correlated with the magnitude of the velocity, making it behave like a frictional force. This result is in agreement with the findings from the simulations by Zhang et al. (2019), who showed that with the inclusion of the nonadiabatic effects, the pressure gradient becomes a predominantly frictional force instead of a restoring force.

The top panel of Figure 10 also shows that the perpendicular kinetic energy of the prominence,

\[ E_{\perp} = \frac{1}{2} v_{\perp}^2 \, dV_{\text{prom}}, \] (6)

where \( v_{\perp} = \mathbf{v} - (\mathbf{v} \cdot \mathbf{B}) \mathbf{B} / B^2 \) is the velocity component perpendicular to the magnetic field, remains very small compared to the parallel kinetic energy \( E_{\parallel\parallel} \). In other words, there is not a significant excitation of the prominence transverse oscillations due to the LAL oscillations. We have also evaluated the rate of work done to the prominence mass by the Lorentz force \( f_L \) (which is itself perpendicular to the magnetic field line),

\[ W_L = \int f_L \cdot \mathbf{v} \, dV_{\text{prom}}, \] (7)
and the rate of work done to the prominence by the perpendicular component of the gravity force,

$$W_{g\perp} = \int f_g \cdot \mathbf{v}_l \, dV_{\text{prom}}$$

(8)

and by the perpendicular component of the pressure gradient force:

$$W_{p\perp} = \int f_p \cdot \mathbf{v}_l \, dV_{\text{prom}}$$

(9)

and these are shown in Figure 11. It is found that the rate of work done by the Lorentz force on the prominence (black curve) is mainly counteracting that by the perpendicular component of the gravity force (green curve). Overall, the sum of the rate of work done by all of the perpendicular forces ($W_{g\perp} + W_{p\perp} + W_{L\perp}$) on the prominence, shown as the red curve in Figure 11, is of a significantly smaller amplitude compared to the sum of the rate of work done by the field-aligned forces (the red dashed–dotted curve in Figure 9), which can account for most of the rate of change of the kinetic energy of the prominence (the black dashed–dotted curve in Figure 9). Thus, the damping of the LAL oscillation kinetic energy is mainly through the friction-like field-aligned pressure gradient force and also the numerical viscosity at the beginning. We note that future higher-resolution 3D simulations that significantly reduce the numerical diffusion are needed to see how well the above result in regard to the damping of the LAL prominence oscillations in a 3D configuration holds.

We find in this simulation that the flux rope is very stable to the introduction of the LAL oscillations and remains in a stable quasi-static rise after the oscillations are damped out (Figure 5 and the associated movie). The LAL oscillations are followed by episodes of asymmetric prominence draining toward either footpoint, as the quasi-static rise makes some of the prominence dips sufficiently shallow. Figure 12 shows the temporal evolution of the prominence mass and the total magnetic and kinetic energies for the “PROM-LALO” case compared to the original “PROM” case without the introduction of the oscillations. We find that although the temporal and spatial patterns of the prominence draining episodes are changed (see the movie for Figure 5) compared to the “PROM” case (shown in the movie for Figure 1), there is not a significant enhancement of the draining of the total prominence mass with the introduction of the LAL oscillations in the “PROM-LALO” case compared to the “PROM” case (Figure 12(a)). As a result, the flux rope rises quasi-statically to the loss-of-equilibrium height and develops an eruption with a significant release of the magnetic energy and increase of kinetic energy, at approximately the same time for the two cases (Figure 12(b)). We also note that since the prominence LAL oscillations are damped out quickly during the stable phase before the onset of eruption in our “PROM-LALO” simulation, we do not find a significant increase of the LAL oscillation period with time as was found in the observational study by Bi et al. (2014). This is because over the course of the LAL oscillations in our simulation, the prominence-carrying field-line dips have not risen significantly to produce a significant change of the radius of curvature and hence a significant change of the oscillation period. However, the fact that we see a larger oscillation period for the higher part of the prominence in the shallower dips than the lower part in the deeper dips suggests that one may see the coupling between the oscillation period and the rise of the prominence if the oscillations are less damped to last through the significant rise, or if they are introduced at a later phase when the magnetic field configuration is changing more rapidly as it approaches eruption. Further 3D simulations are needed to study the coupling between LAL oscillations and the eruption.
4. Summary and Discussion

In this paper, we have expanded on a previous study of the eruption of prominence-forming coronal flux rope (F18) and carried out further simulations to investigate the role of prominence draining and prominence LAL oscillations. In the previous study of F18, by comparing simulations with and without the formation of the prominence (the “PROM” and “non-PROM” simulations in F18), it was shown that prominence weight can suppress the development of the kink instability of the flux rope and delays its rise to the loss-of-equilibrium height to develop an eruption. Further comparison of those two simulations in this paper shows that the prominence weight also causes a significant increase of the loss-of-equilibrium height of the flux rope, consistent with the prediction from an analytical model by Jenkins et al. (2019). The reason is that the addition of the prominence weight causes the total confining force of the flux rope to decline more slowly with height, such that the flux rope needs to rise quasi-statically to a higher height where the corresponding potential field has a steeper decline rate (than that which is needed in the absence of the prominence weight) for the loss of equilibrium or torus instability to take place. A further simulation (the “PROM-drain” simulation in this paper), where we artificially initiate prominence draining during the quasi-static rise phase of the previous “PROM” simulation, shows that a significant reduction of the total prominence mass compared to the “PROM” case allows the flux rope to rise more quickly to the loss-of-equilibrium height and develop a dynamic eruption significantly earlier (by about 5 hr). This process of prominence mass unloading, which causes a speedup of the slow rise of the flux rope to the loss-of-equilibrium height to then develop a dynamic eruption, is consistent with the evolution seen in the multiple-viewpoint observation of the CME event described by Seaton et al. (2011).

We note that the total prominence mass in the “PROM” and “PROM-drain” simulations reaches a peak value of about $4.5 \times 10^{15}$ g and $3.5 \times 10^{15}$ g, respectively during the quasi-static phase of the evolution. These values are of the same order of magnitude as the high end of the observed prominence mass range, $\sim 10^{14}$–$2 \times 10^{15}$ g (e.g., Parenti 2014). We have found that the suppression of the kink instability and the delay of onset of eruption depend on the total prominence mass. We have performed a simulation similar to the “WL-S” case in F17, where the constant of proportionality $C$ used for the base pressure in Equation (18) in F17 is smaller, such that a much smaller prominence formed in the emerged flux rope (see Figure 10 in F17), with the peak prominence mass reaching about $3.6 \times 10^{14}$ g, closer to the lower end of the observed range of prominence mass. In this case, with a much less massive prominence in the same emerged flux rope compared to the “PROM” and “PROM-drain” cases, we find that the onset of eruption is only slightly delayed (by about 0.5 hr) compared to the “non-PROM” case, i.e., the stability and the onset of eruption are not significantly altered by the prominence mass. This result suggests that even though locally the prominence-carrying field is significantly non-force-free, the total prominence mass formed also needs to be sufficiently large for it to significantly affect the stability and the onset of eruption of the flux rope. More extended simulations exploring different flux rope and confining field configurations are needed to study this necessary prominence mass given the field strength of the flux rope.

We have also carried out a simulation (the “PROM-LALO” simulation in this paper) where we excite LAL oscillations by adding an initial velocity (parallel to the magnetic field) of 100 km s$^{-1}$ to the prominence plasma (with temperature $T < 10^4$ K) at a time instant during the quasi-static phase of the “PROM” simulation and study the subsequent evolution in comparison to the original “PROM” simulation. We find that prominence LAL oscillations develop with an oscillation period of roughly 2 hr. The prominence shows differential motions, with the upper part of the prominence in shallower dips showing a slightly longer oscillation period than that in the lower, deeper dips. The oscillation periods are found to be longer (by about 10%–40%) than those estimated based on the “pendulum model” (Luna & Karpen 2012) using the mean radius of curvature of the field-line dips. The 3D simulation of LAL oscillations by Zhou et al. (2018) has also found longer periods than expected by the pendulum model. A probable cause for this is that the magnetic field lines supporting the prominence are not rigid as assumed in the pendulum model but deform with the oscillations. The deformation tends to drag the dip location along with the prominence motion, effectively reducing the curvature experienced by the trajectory of the moving prominence condensation and hence increasing the oscillation period. This effect needs to be taken into account when one uses the observed LAL oscillation periods to estimate the curvature radius and the magnetic field strength for the field-line dips supporting the prominence based on the pendulum model (Luna & Karpen 2012; Bi et al. 2014). It would tend to give an overestimate of the magnetic field strength. It is found that the rate of change of the parallel kinetic energy of the prominence during the LAL oscillations can be well described by the sum of the work done by the parallel components of the gravity force and the pressure gradient force, with the gravity force acting as the main restoring force and the pressure gradient mainly as a dissipation. The oscillations are found to be strongly damped and die out after about two to three oscillation periods. The flux rope is stable with the introduction of the LAL oscillations and remains in the quasi-static rise after the oscillations are damped out. It develops subsequent episodes of prominence draining with spatial and temporal patterns different from that in the original “PROM” case, but the overall draining of the total prominence mass is not significantly enhanced, and it develops the final eruption at approximately the same time as that in the “PROM” case. Thus, even though both the LAL oscillations and draining develop prior to the eruption, as is found in the observation of Bi et al. (2014), the oscillations do not significantly alter the overall rate of prominence draining and the initiation of eruption in this case.

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