

Measurements of the Solar Coronal Magnetic Field Based on Coronal Seismology with Propagating Alfvénic Waves: Forward Modeling (Postprint)

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Abstract

Recent observations have demonstrated the capability of mapping the solar coronal magnetic field using the technique of coronal seismology based on the ubiquitous propagating Alfvénic/kink waves through imaging spectroscopy. We established a magnetohydrodynamic model of a gravitationally stratified open magnetic flux tube, exciting kink waves propagating upwards along the tube. Forward modeling was performed to synthesize the Fe xiii 1074.7 and 1079.8 nm spectral line profiles, which were then used to determine the wave phase speed, plasma density, and magnetic field with seismology method. A comparison between the seismologically inferred results and the corresponding input values verifies the reliability of the seismology method. In addition, we also identified some factors that could lead to errors during magnetic field measurements. Our results may serve as a valuable reference for current and future coronal magnetic field measurements based on observations of propagating kink waves.

Full Text

Preamble

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Sympathetic Solar Eruption on 2024 February 9

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Abstract

In this paper, we perform a follow-up investigation of the solar eruption originating from active region 13575 on 2024 February 9. The primary eruption of a hot channel generates an X3.4 class flare, a full-halo coronal mass ejection (CME), and an extreme-ultraviolet (EUV) wave. Interaction between the wave and a quiescent prominence (QP) leads to a large-amplitude, transverse oscillation of QP. After the transverse oscillation, QP loses equilibrium and rises up. The ascending motion of the prominence is coherently detected and tracked up to $1.68 R_{\odot}$ by the Solar UltraViolet Imager onboard the GOES-16 spacecraft and up to $2.2 R_{\odot}$ by the Solar Corona Imager (SCI_UV) of the Ly α Solar Telescope onboard the ASO-S spacecraft. The velocity increases linearly from 12.3 to 68.5 km s⁻¹ at 18:30 UT. The sympathetic eruption of QP drives the second CME with a typical three-part structure. The bright core comes from the eruptive prominence, which could be further observed up to $3.3 R_{\odot}$ by the Large Angle Spectroscopic Coronagraph onboard the Solar and Heliospheric Observatory mission. The leading edge of the second CME accelerates continuously from 120 to 277 km s⁻¹. The EUV wave plays an important role in linking the primary eruption with the sympathetic eruption.

Key words: Sun: flares – Sun: filaments, prominences – Sun: coronal mass ejections (CMEs)

Introduction

Filaments are widespread in the solar corona (Engvold 1998; Mackay 2010; Parenti 2014). They consist of very dynamic and dark threads observed in the H α line center (Martin 1998; Lin 2011). Above the limb, filaments are called prominences, which show bright features due to their strong emissions in H α (6562.8 Å), Ca II H line (3968 Å), H I Ly α (1216 Å), and He II (304 Å) wave bands (Berger 2008; Zhou 2023; Qiu 2024; Xue 2024). After being disturbed, the filament threads tend to deviate from their equilibrium positions and oscillate for a few cycles before calming down (Oliver 2002; Tripathi 2009; Arregui 2018).

According to the velocity amplitude, filament oscillations are divided into

small-amplitude ($\sim 10 \text{ km s}^{-1}$) oscillations (SAOs) and large-amplitude ($\sim 20 \text{ km s}^{-1}$) oscillations (LAOs). SAOs are frequently observed in quiescent prominences (QPs; Okamoto 2007; Ning 2009; Li 2018; Wang 2024). LAOs are occasionally detected in active region (AR) filaments as well as quiescent filaments (Shen 2014a; Luna 2018; Luna 2024). Based on the direction of oscillations, LAOs are further divided into longitudinal and transverse oscillations. The filament materials move along the threads during longitudinal oscillations (Jing 2003; Vrsnak 2007; Zhang 2012; Zhang 2017; Zheng 2017; Ni 2022). On the contrary, the filament threads swing back and forth perpendicularly to the spine during transverse oscillations (Isobe 2006; Hershaw 2011; Dai 2023; Zhang 2024). Shen 2014b discovered simultaneous transverse oscillations of one filament and longitudinal oscillations of another one induced by a single shock wave. Longitudinal and transverse oscillations before eruptions have been observed (Isobe 2006; Bi 2014; Zhang 2020; Dai 2021; Ni 2022), which make LAOs a credible precursor for filament eruptions considering that LAOs may represent a transition phase between the initial equilibrium and the eventual eruption (Chen 2008; Zhang 2012; Fan 2020).

Filament eruptions are intimately related to solar flares (Fletcher 2011) and coronal mass ejections (CMEs; Forbes 2006; Chen 2011) in the standard flare model, namely the CSHKP model (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp 1976). Owing to magnetic connectivity between two filaments, the eruption of a primary filament may considerably affect the environment of another filament and lead to a second eruption, which is considered a sympathetic eruption. The most commonplace condition for a sympathetic eruption is that multiple filaments are supported by a common, overlying magnetic system. Successful eruption of the first filament may significantly reduce the constraint on the adjacent filaments and trigger a second or even a chain of eruptions (Sterling 2004; Cheng 2005; Cheng 2013; Shen 2012; Yang 2012; Lynch 2013; Joshi 2016; Wang 2016; Wang 2018; Dacie 2018; Hou 2020; Song 2020; Zhou 2021). Torok 2011 performed a three-dimensional (3D) magnetohydrodynamics (MHD) simulation to explore possible magnetic trigger mechanisms for sympathetic eruptions. In their model, two magnetic flux ropes (MFRs) are located within a pseudo-streamer and the third one is located nearby. The eruption of the third rope gives rise to consecutive eruptions of the two MFRs, which could excellently explain the observed twin filament eruptions and CMEs on 2010 August 1 (Titov 2012). Shen 2012 studied two sympathetic filament eruptions including a partial and full MFR eruption in a quadrupolar magnetic configuration on 2011 May 12. A schematic model is proposed to illustrate the whole process. Breakout magnetic reconnection occurs after the first filament rises up, which finally evolves into a CME. The adjacent filament undergoes a partial eruption, with the top part evolving into a blob.

Impulsive eruptions are likely to drive coronal extreme-ultraviolet (EUV) waves (Thompson 1998; Chen 2002; Patsourakos 2009) or chromospheric Moreton waves (Moreton 1960; Eto 2002), which propagate away at speeds of hundreds of km s^{-1} to $\sim 1000 \text{ km s}^{-1}$. Interactions between these global waves and

remote filaments may result in LAOs (Gilbert 2008; Hershaw 2011; Asai 2012; Liu 2013; Dai 2023; Zhang 2024) or direct eruptions. Jiang 2011 investigated three successive filament eruptions from different locations on 2003 November 19. The first eruption originates from AR 10501 and generates a CME. The CME-related coronal dimmings propagate outward and interact with two quiescent filaments, leading to the second and third eruptions and related flares. It is concluded that the dimming process in the first eruption results in weakening and partial removal of the large-scale, overlying magnetic fields on the two remote filaments, which facilitate sympathetic eruptions. Dai 2021 studied the sympathetic eruption of a very long quiescent filament excited by the eruption of a nearby smaller filament on 2015 April 28. The two parallel filaments are ~ 250 Mm apart. *Prior to the sympathetic eruption, the huge filament undergoes both longitudinal and transverse oscillations.* The combination of LAOs and mass drainage indicates that the filament is losing equilibrium gradually.

Until now, a complete process of LAOs and the subsequent sympathetic eruption of a prominence excited by EUV waves has not been reported. Using multiwavelength observations of the Atmospheric Imaging Assembly (AIA; Lemen 2012) onboard the Solar Dynamics Observatory (SDO; Pesnell 2012), Zhang 2024 (hereafter Paper I) studied two successive EUV waves and the induced transverse oscillation of a QP on 2024 February 9. The EUV waves are separately driven by a fast halo CME (hereafter CME1) as a result of a hot channel (HC) eruption and by a fast coronal jet originating from AR 13575. QP is close to the solar south pole and is more than 380 Mm away from the flare site.

In this paper, using EUV observations of the Solar UltraViolet Imager (SUVI; Seaton 2018; Tadikonda 2019; Darnel 2022) onboard the Geostationary Operational Environmental Satellite (GOES-16) and ultraviolet (UV; 121.6 ± 10 nm) observations of the Solar Corona Imager (SCI_UV) of the Ly α Solar Telescope (LST; Feng 2019; Li 2019; Chen 2024) onboard the Advanced Space-based Solar Observatory (ASO-S; Gan 2019; Gan 2023), we reanalyze the event, focusing on the sympathetic eruption of QP and the related CME (hereafter CME2). Characteristics of these instruments are summarized in Table 1. In Section 2, we briefly describe the data analysis of these instruments. In Section 3, we first show the primary eruption, which leads to an X3.4 flare, CME1, and an EUV wave. Then, we show the sympathetic eruption of QP, which leads to CME2 without a flare. Discussions and a brief summary are arranged in Sections 4 and 5, respectively.

2. Data Analysis

SDO/AIA takes full-disk images in seven EUV (94, 131, 171, 193, 211, 304, and 335 Å) and two UV (1600 and 1700 Å) wavelengths. The level_1 data are calibrated using the standard program `aia_prep.pro` in the Solar Software package. The full-disk GOES-16/SUVI images in 171 and 304 Å are rotated and slightly shifted to align with the AIA images (Zhang 2024). The Ly α images from ASO-S/SCI_UV are primarily processed through the correction of flat

fields and dark currents, along with the normalization of exposure times. To suppress stray light signals, we subtract the daily-minimum background from the images. Following this, the images are rotated, scaled, and aligned by overlapping structures in the field of view (FOV) with the AIA 304 Å images. The high cadence and large FOV of ASO-S/SCI_UV provide a great opportunity to track the erupting prominence from 1.1 to $2.2 R_{\odot}$ in Ly α wavelength. The white-light (WL) images of CMEs are obtained from the C2 and C3 coronagraphs of the Large Angle Spectroscopic Coronagraph (LASCO; Brueckner 1995) onboard the Solar and Heliospheric Observatory (SOHO) mission as well as the COR2 coronagraph onboard the ahead Solar TERrestrial RELations Observatory (Kaiser 2008).

3.1. Primary Eruption

As shown in Figures 3 and 5 of Paper I, the HC is exclusively observed in 131 and 94 Å of SDO/AIA, undergoes a slow rise phase and a fast rise phase, the latter of which starts from 12:53:53 UT and lasts for 10 minutes before escaping the FOV of AIA. In Figure 1(a), the soft X-ray (SXR) light curve of the flare in 1–8 Å recorded by the GOES-16 spacecraft is plotted with a magenta line. The SXR emission increases from 12:53 UT and peaks at 13:14 UT before declining gradually.

Figure 2 shows four running-difference images observed by STA/COR2, which had a separation angle of 7.6° with the Sun–Earth connection on 2024 February 9. In panel (a), the yellow arrow points to CME1 when it first appears at 13:23:30 UT. CME1 propagates in the southwest direction and expands rapidly to form a full-halo CME (panels (b)–(d)). In panels (a)–(c), the blue arrows indicate the propagation direction and heliocentric distances of the CME leading edge, which are plotted with cyan pluses in Figure 1(a).

As is shown in the bottom panels of Figure 3 in Paper I, CME1 was also observed by SOHO/LASCO. The height variation of CME1 with time in the FOV of SOHO/LASCO is plotted with red circles in Figure 1(a). A linear fitting is performed between 13:25 UT and 14:45 UT, which is displayed with a blue dashed line. The apparent speed of CME1 reaches 2782 km s^{-1} in the plane of the sky.

In Figure 3, panels (a)–(c) show base-difference images in AIA 211 Å during 13:05–13:09 UT (see also Figure 6 in Paper I). QP is signified by black rectangles. Panel (d) shows the GOES-16/SUVI 304 Å image at 13:09:06 UT, featuring the columnar QP near the south polar region. The quick expansion of CME1 generates an EUV wave front (WF1), which is indicated by black arrows. WF1 propagates in the southeast direction at a speed of 835 km s^{-1} and arrives at the prominence at 13:09 UT (panel (c)).

The left panels of Figure 4 show the QP with a position angle (PA) of 196° , which is observed by SUVI 304 and 171 Å around 12:49 UT. The width and height of QP in 304 Å are 17.4 Mm and 188 Mm, respectively. Therefore,

the aspect ratio of QP is ≈ 11 .

The strong impact of WF1 excites a transverse oscillation of QP. In the left panels of Figure 4, a straight slice (S1) perpendicular to the prominence is selected to study the oscillation. Time–distance diagrams of S1 in 304 and 171 Å are displayed in the left panels of Figure 5. The magenta and cyan dashed lines indicate peak times (13:21 UT and 13:43 UT) of the transverse oscillation. It is clear that QP swings back and forth for two cycles with an initial amplitude and a period of 27 Mm and 25 minutes respectively. It is worth mentioning that variations of the initial amplitudes, velocities, and periods with the prominence height are demonstrated in Figure 10 of Paper I.

3.2. Sympathetic Eruption of QP

The transverse oscillation lasts for up to 60 minutes until 14:09 UT. Then, QP breaks into two pieces. The top part lifts off to form CME2, while the lower part remains and collapses gradually. Base-difference images in SUVI 304 and 171 Å during 14:30–16:33 UT are displayed in panels (a2)–(a5) and panels (b2)–(b5) of Figure 4 respectively (see also the online movie anim1.mp4 available as Supplementary material). It is obvious that as QP rises up, a fraction of plasmas falls back to the solar surface. The leading edges of QP in 304 Å are marked with white crosses. In Figure 1(b), the magenta diamonds correspond to the heliocentric distances of the prominence leading edges, which increase from $1.40 R_{\odot}$ to $1.68 R_{\odot}$ during 14:30–16:50 UT.

In Figure 4(b3), a wide slice (S2) is selected along the propagation direction of QP. It is evident that QP propagates non-radially with an inclination angle of 23° with respect to the local vertical direction (Zhang 2022). Time-slice diagrams of S2 in 304 and 171 Å are displayed in the right panels of Figure 5. It is seen that QP is accelerating during the eruption. As is shown in Table 1, SUVI has an FOV of $1.6 R_{\odot}$. The erupting QP becomes blurred and fades out after 16:50 UT in SUVI images. Fortunately, it is captured by the ASO-S/SCI_UV coronagraph with a much larger FOV of $2.5 R_{\odot}$ and a much higher time cadence. Figure 6 shows QP observed by SCI_UV during 14:30–18:20 UT (see also the online movie anim2.mp4 available as Supplementary material).

The shape of the prominence changes from a column to a hook as it ascends. Likewise, temporal evolution of the heliocentric distances of QP in the FOV of SCI_UV are drawn with brown pluses in Figure 1(b) and excellently fitted with a quadratic function where t_0 is set to be 14:30:12 UT. h_{QP} increases slowly from $1.37 R_{\odot}$ and accelerates to $2.18 R_{\odot}$ at 18:29:27 UT.

The apparent speed of QP is

$$v_{QP}(t - t_0) = 12.3 + 3.9 \times 10^{-3}(t - t_0) \text{ km s}^{-1}.$$

Hence, v_{QP} increases slowly from 12.3 km s^{-1} at 14:30 UT to 68.5 km s^{-1} at 18:30 UT.

Figure 7 shows five original images observed by LASCO-C2 during 17:00–20:12 UT. CME2 presents a typical three-part structure (Illing 1985; Song 2022). The bright front of CME2, which is pointed out by the yellow arrow, turns up at 17:00 UT and propagates in the south direction with a PA of 190° (panels (a)–(b)). At 18:12 UT, the bright core of CME2 appears. Considering that CME2 is driven by the erupting QP, QP is exactly the core of CME2, which is pointed out by an orange arrow (panel (c)). Afterwards, QP and the bright front of CME2 move outward together (panels (d)–(e)). In Figure 1(b), temporal evolution of the heliocentric distances of QP in the FOV of LASCO-C2 is plotted with blue circles. It is obvious that QP evolves coherently in the FOVs of SCI_UV and LASCO-C2. The slight difference in height during 18:12–18:30 UT is probably due to the different wavelengths. QP is observed in UV (121.6 ± 10 nm) by SCI_UV and in WL by LASCO-C2. The advantages of passband and large FOV of SCI_UV enable us to track erupting prominences completely from their early phases up to $\approx 2.5 R_\odot$. In Figure 1(b), temporal evolution of the heliocentric distances of the bright front is plotted with orange circles.

Similarly, the trajectory is satisfactorily fitted with a quadratic function where t_2 is set to be 17:00:00 UT. Likewise, the apparent speed of CME2 is

$$v_{CME2}(t - t_2) = 120.4 + 6.5 \times 10^{-3}(t - t_2) \text{ km s}^{-1}.$$

Therefore, v_{CME2} increases gradually from 120.4 km s^{-1} at 17:00 UT to 277.2 km s^{-1} at 23:42 UT.

The whole sequence of events, including the X3.4 flare, CME1, coronal jet, EUV wave fronts (WF1 and WF2), QP, and CME2, is illustrated in a schematic cartoon in Figure 8. It is clear that the EUV waves, especially WF1, play an essential role in linking the primary and sympathetic eruptions.

4. Discussion

Kolotkov 2016 proposed a model of the global transverse oscillations and stability of QPs, which are supported by magnetic dips. The periods of transverse oscillations with small amplitudes are derived analytically. Considering that LAOs are frequently observed (Hershaw 2011; Shen 2014a; Shen 2014b; Dai 2023), Kolotkov 2018 investigated the effects of finite amplitudes on the transverse prominence oscillations. It is revealed that a metastable equilibrium of the prominence exists. The prominence is stable for small-amplitude displacements. However, it becomes unstable in the horizontal direction when the amplitude is large enough to exceed a threshold value. In our study, the maximal displacement amplitude reaches ≈ 34 Mm and the maximal velocity amplitude reaches $\approx 143 \text{ km s}^{-1}$, which is close to the acoustic speed of the corona (≈ 1.5 MK) (see Figure 10 in Paper I). After the oscillation, QP starts to rise up and evolves into the bright core of CME2 (see Figure 7). Therefore, both the transverse oscillation and subsequent eruption of QP might be explained by their analytical model. The large amplitudes of the transverse oscillation of QP may exceed

a threshold so that the prominence loses equilibrium and erupts, which provides a new piece of evidence for the conclusion that large-amplitude transverse oscillation is one of precursors for prominence eruptions (Chen 2008).

A similar metastable equilibrium may exist for a longitudinally oscillating prominence as well. Using one-dimensional hydrodynamic numerical simulations with the MPI-AMRVAC code (Keppens 2023), Zhang 2013 carried out a parameter survey of longitudinal prominence oscillations along magnetic dips. It is found that the prominence is limited in the dips when the initial amplitudes are not so large. Nevertheless, a fraction of the prominence reaches and overshoots the shoulders of dips, leading to mass drainage along the legs of the prominence and a possible eruption when the initial amplitude is large enough (see their Figure 8). Fan 2020 performed 3D MHD simulations of large-amplitude, longitudinal oscillations of a prominence supported by a twisted coronal flux rope. It is revealed that the oscillations are quickly attenuated after a few cycles, which are followed by significant mass drainage and eventual eruption of the prominence. From this point of view, LAOs of prominences, including transverse and longitudinal polarizations, are considered as a conceivable precursor of prominence eruptions.

After developing a new technique for tracking CMEs in the FOV of LASCO, Sheeley 1999 divided their sample into two types, gradual CMEs and impulsive CMEs. Impulsive CMEs are usually associated with flares and Moreton waves, while gradual CMEs are formed when prominences and their cavities rise up from below coronal streamers. Besides, impulsive CMEs are generally faster and tend to decelerate during propagation, while gradual CMEs are relatively slower and tend to accelerate.

In Table 2, we compare the primary eruption and sympathetic eruption in detail. The former results from an HC eruption at 12:49 UT from AR 13575, while the latter results from a prominence eruption at 14:10 UT from the quiet region, which is delayed by 80 minutes. *The HC eruption is characterized by a slow rise and a fast rise phase (Zhang 2023; 2024).* The final speed of CME1 is almost 10 times higher than that of CME2. In brief, the primary and sympathetic eruptions exhibit remarkably different properties.

Zhang 2004 explored the kinematic properties of three CMEs associated with flares. It is found that there is close correlation both between the CME velocity and the SXR flux of the flare and between the CME acceleration and derivative of the SXR flux. In our study, CME2 undergoes continuous acceleration for nearly seven hours. However, it is not related to a flare underneath. In Figure 9, the left panel shows large-scale magnetic field lines obtained by the potential-field source surface (PFSS; Schatten 1969; Schrijver 2003) modeling at 12:04 UT. The open and closed fields are indicated by magenta and white lines, respectively. The right panel shows the AIA 211 Å image at 13:09:45 UT. Close to the south polar region, the coronal hole (CH) is fainter than the surrounding quiet region and is associated with the footpoints of open field lines in the left panel. Since QP is also close to the south polar region, the slow CME

is probably pushed by the fast solar wind during its propagation (Hassler 1999; Tu 2005).

Using He II 304 Å observations with the Full Sun Imager (FSI) of the Extreme Ultraviolet Imager (EUI; Rochus 2020) onboard the Solar Orbiter (SolO; Muller 2020) mission, Mierla 2022 reported a fast prominence eruption up to $>6 R_{\odot}$ on 2022 February 15–16. The velocities of the leading edges of prominence and associated CME are 1700 and 2200 km s^{-1} , respectively. Using combined observations with the EUI/FSI in 174 and the SolO/Metis (Antonucci 2020) in visible light, Bemporad 2022 studied a CME followed by a prominence eruption and a long current sheet on 2021 February 12. The prominence was tracked by Metis from 3 to $5.4 R_{\odot}$, while the early phase of the prominence was not observed due to the occulting disk. In our case, the prominence is completely tracked by ASO-S/SCI_UV from 1.1 to $2.2 R_{\odot}$ in Ly α wavelength, which is crucial to study the kinematics.

5. Summary

In this paper, we perform a follow-up investigation of the solar eruption originating from AR 13575 on 2024 February 9. The main results are summarized as follows.

The primary eruption of an HC results in an X3.4 class flare, a full-halo CME (CME1), and an EUV wave (WF1). Interaction between WF1 and QP leads to a large-amplitude, transverse oscillation of QP, which has been described in our previous paper (Paper I). After the transverse oscillation, QP becomes unstable and lifts off. The rising motion of the prominence is clearly detected and tracked by GOES-16/SUVI until $1.68 R_{\odot}$ and by LST/SCI_UV onboard the ASO-S spacecraft until $2.2 R_{\odot}$. The velocity increases linearly from 12.3 to 68.5 km s^{-1} at 18:30 UT. The sympathetic eruption of QP drives the second CME (CME2) with a typical three-part structure. The bright core comes from the eruptive prominence, which could be tracked further until $3.3 R_{\odot}$ by SOHO/LASCO-C2. The leading edge of CME2 accelerates continuously from 120 to 277 km s^{-1} . The EUV wave serves as a causal link between the primary and sympathetic eruptions. The advantageous cadence and FOV of ASO-S/SCI_UV provide a great opportunity to track an erupting prominence from 1.1 to $2.2 R_{\odot}$ in Ly α wavelength.

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