



High-resolution Imaging Spectroscopy of a Tiny Sigmoidal Minifilament Eruption

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Abstract

Minifilament eruptions producing small jets and microflares have mostly been studied based on coronal observations at extreme-ultraviolet and X-ray wavelengths. This study presents chromospheric plasma diagnostics of a quiet-Sun minifilament of size $\sim 2'' \times 5''$ with a sigmoidal shape and an associated microflare observed on 2021 August 7 17:00 UT using high temporal and spatial resolution spectroscopy from the Fast Imaging Solar Spectrograph (FISS) and high-resolution magnetograms from the Near InfraRed Imaging Spectropolarimeter (NIRIS) installed on the 1.6 m Goode Solar Telescope at Big Bear Solar Observatory. Using FISS $H\alpha$ and Ca II 8542 Å line spectra at the time of the minifilament activation we determined a temperature of 8600 K and a nonthermal speed of 7.9 km s^{-1} . During the eruption, the minifilament was no longer visible in the Ca II 8542 Å line, and only the $H\alpha$ line spectra were used to find the temperature of the minifilament, which reached $1.2 \times 10^4 \text{ K}$ and decreased afterward. We estimated thermal energy of $3.6 \times 10^{24} \text{ erg}$ from the maximum temperature and kinetic energy of $2.6 \times 10^{24} \text{ erg}$ from the rising speed (18 km s^{-1}) of the minifilament. From the NIRIS magnetograms we found small-scale flux emergence and cancellation coincident with the minifilament eruption, and the magnetic energy change across the conjugate footpoints reaches $7.2 \times 10^{25} \text{ erg}$. Such spectroscopic diagnostics of the chromospheric minifilament complement earlier studies of minifilament eruptions made using coronal images.

Unified Astronomy Thesaurus concepts: [Quiet Sun \(1322\)](#); [Solar chromosphere \(1479\)](#); [Solar filament eruptions \(1981\)](#); [Solar magnetic reconnection \(1504\)](#)

Materials only available in the [online version of record](#): animations

1. Introduction

Solar filaments are typically cool and dense plasma formed in the chromosphere along the polarity inversion line (PIL) during flux emergence (e.g., A. Bruzek 1967; P. Foukal 1971; C. Zwaan 1985; K. Shibata et al. 1989; S. Toriumi et al. 2017). The arch filament enveloped in the emerging magnetic bipole expands as it rises from the solar surface. The filament erupts as its configuration with surrounding fields is destabilized by reconnection in different scenarios, such as breakout, kink instability, and tether cutting (Y. Bi et al. 2015; P. Kumar et al. 2019; S. Kim & V. Yurchyshyn 2022). Solar filament eruptions are often associated with a wide range of dynamic solar activities from as large as coronal mass ejections (CMEs) to small-scale spicule activities by which free energy is transported to the corona from the chromosphere. In active regions, the sigmoid configurations, which are defined as S-shaped loop arcades of nonpotential magnetic field, have typical lengths of $100''$. Nonpotentiality of the kinked magnetic field flux ropes tend to drive eruption in the PILs of the sigmoidal regions by tether-cutting reconnection and form arcade loops (R. Liu et al. 2010; C. Liu et al. 2012). Strong nonpotential bipolar magnetic configuration is also identified in X-ray and extreme-ultraviolet (EUV) microsigmoids (C. H. Mandrini et al. 2005; N. E. Raouafi et al. 2010; R.-S. Zheng et al. 2013).

Minifilaments (MFs) are scale-down versions of solar filaments, which extend less than 25 Mm and last for about 50 minutes in $H\alpha$ images (J. Wang et al. 2000). Similar to large-scale filaments, the loop-like topology of MFs usually lies above the photospheric PIL of small-scale adjacent opposite-polarity magnetic fields, which are distinguished from “surge-like macrospicules” that emanating from network field concentrations on the same size scale. The earliest systematic studies of small-scale filaments utilizing $H\alpha$ observations from Big Bear Solar Observatory (BBSO) by L. M. Hermans & S. F. Martin (1986) discovered elongated dark features and characterized that: (1) with an occurrence rate of 600 day^{-1} , the average duration of eruptive phase was 26 minutes in a total lifetime of 70 minutes; (2) the majority of events are spatially related to canceling magnetic features; and (3) small-scale filament share similarities with large-scale filaments that often have one or both ends terminate at reconnection site. The total mass and bulk kinetic energy of MFs are estimated to be 10^{13} g and 10^{25} erg , respectively.

Eruption of MFs can also produce mini-CMEs, coronal jets, and microflares, and contribute correspondingly small transients to the coronal heating and solar wind acceleration (D. E. Innes et al. 2009; N. E. Raouafi et al. 2016). Observations of the roots of coronal heating in the chromosphere proved that it cannot be driven solely by energy deposition at coronal heights; instead, mass and energy supply from the lower atmosphere are required through ubiquitous upflows across the magnetic configuration in the heating process of the corona (B. De Pontieu et al. 2009; H. Tian 2017). Ejected cold material from filament eruptions in the chromosphere called surges have been observed in $H\alpha$



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filtergrams (R. A. Harrison et al. 1988; B. Schmieder et al. 1995, 2022; J. Chen et al. 2022) with bright/flaring points separating from footpoints of the surge during onset of eruptions. The brightening primarily observed in soft X-ray (SXR) wavelengths is located where the $H\alpha$ surges originate, in which magnetic reconnection between twisted cool loops and open field lines leads to the formation of surges that coincide with X-ray subflares (K. Shibata et al. 1992; D. Alexander & L. Fletcher 1999). Coronal counterparts of the erupted filament, jets, are observed in EUV filtergrams (Y. M. Wang et al. 1998; Z. F. Li et al. 2023), as well as at SXRs (D. E. Innes et al. 2016; A. C. Sterling et al. 2022). Observations of magnetic reconnection between a confined flux loop and the overlying field at different wavelengths suggest the formation of cool and hot ejecting components from MF eruptions (Y. Shen et al. 2017). Coronal bright points (CBPs) of network field configuration of opposite polarities are found to be heated to their brightness temperature maxima with the occurrence of MF eruptions (J. Hong et al. 2014).

A schematic model of MF eruptions that has characteristics different from the standard jet model (K. Shibata et al. 1992) was proposed by R. L. Moore et al. (2010), in which the sheared core field carrying cool plasma begins erupting when X-ray brightening in the base arch is observed. Such dynamic small-scale filament eruptions are often observed to initiate the blowout jet scenario through interchange reconnection at the boundary of open fields and closed flux loops (Y. Shen et al. 2012; M. Adams et al. 2014; X. Li et al. 2015), and show obvious asymmetric brightening in the loop called jet bright points (A. C. Sterling et al. 2015). External reconnection is driven by flux cancellation (N. K. Panesar et al. 2017; R. A. McGlasson et al. 2019; A. C. Sterling & R. L. Moore 2020) at the PIL and opens the filament field to allow plasma ejection through the undergoing internal reconnection (Y. Shen et al. 2012; M. Adams et al. 2014; N. K. Panesar et al. 2016, 2018). Recently, by reviewing jet-producing MF events and the flux cancellation model, A. C. Sterling & R. L. Moore (2020) proposed a possible mechanism for magnetic switchbacks in the solar wind detected by the Parker Solar Probe (PSP), in which the jetlets carry twist from flux cancellation during interplanetary propagation. In situ observations of the solar wind show an expansion of scale and duration of small-scale magnetic flux ropes during propagation (H. Chen et al. 2020), which inversely, are used to investigate their possible solar sources (S. D. Bale et al. 2021; J. Lee et al. 2022, 2024). The occurrence rate of small-scale solar eruptions of 0.02 per unit area per hour is arguably sufficient to heat the corona and generate Alfvénic pulses for switchbacks (J. Wang et al. 2022; N. E. Raouafi et al. 2023).

Toward the grand goal of understanding how small-scale MF eruptions can contribute to coronal heating, it is worthwhile to take an initial step of collecting the thermodynamic properties of an MF as small as can be observable. In this paper, we study a tiny MF observed with the Fast Imaging Solar Spectrograph (FISS) of the Goode Solar Telescope (GST) in the $H\alpha$ and Ca II 8542 Å lines, which are analyzed using the classical cloud model (J. M. Beckers 1964) along with the multilayer spectral inversion (MLSI) method (J. Chae et al. 2021a). It is the first time that this combination of spectral inversion methods is used to determine the temperature and density of an MF as tiny as $2'' \times 5''$ in the chromosphere, whereas most previous studies of erupting MFs were made

using coronal images at X-ray or EUV wavelengths and thus targeted relatively large ($\geq 10''$) MFs.

2. Observation and Data Reduction

On 2021 August 7, the GST (W. Cao et al. 2010) of BBSO detected a tiny MF in the quiet Sun while performing a ground-based support to PSP observations. The target was located at ($71''$, $450''$) before the ninth encounter of the PSP campaign passing through perihelion (2021 August 9 19:11 UT) on the far side.

High-resolution GST data were obtained taking advantage of a high-order adaptive optics system combining 308 subapertures and a reconstruction technique for solar speckle interferometric data (F. Wöger et al. 2008). Photospheric optical continuum images are obtained by the Broadband Filter Imager with a TiO filter (705.7 nm, 10 Å bandpass). Spectroscopic polarization measurement of the Fe I 1565 nm line (0.25 Å bandpass) is taken by the Near InfraRed Imaging Spectropolarimeter (NIRIS) with a round field of view (FOV) of $80''$ at $0''.24$ resolution and 42 s cadence. In addition, we utilize EUV images in the 171 Å, 193 Å, 211 Å, and 304 Å channels of the Atmospheric Imaging Assembly (AIA; J. R. Lemen et al. 2012) on board the Solar Dynamic Observatory (SDO) to observe the coronal brightening associated with the MF eruption at EUV wavelengths. In the quiet-Sun region, Milne–Eddington inversion for the magnetic field cannot be achieved with a relatively low signal-to-noise ratio (~ 2.1) in the linear polarization profiles. Line-of-sight (LOS) magnetograms are obtained by integration of the NIRIS measurements at around the maximum and the minimum of the Stokes V profile, then normalized to Gauss units by dividing the wavelength range (~ 1.58 Å) of the integral. We compared our measurements with a Helioseismic and Magnetic Imager (HMI) magnetogram of the same region and find overall agreement between the two sets of magnetograms. However, we found that for some small confined features, the field strength from NIRIS can be higher than that from HMI by up to 60%.

Spectral observation of the chromosphere is achieved with FISS, which is capable of recording via a dual-band echelle spectrograph the $H\alpha$ and Ca II 8542 Å lines simultaneously. Each $H\alpha$ spectrogram (slit image) consists of 256 spectral profiles that represent the spatial variation along the slit with a sampling of $0''.16$. The Ca II 8542 Å spectrogram consists of 250 spectral profiles after binning by a factor of 2 along the slit within one scan. Each $H\alpha$ (Ca II 8542 Å) spectral profile consists of 512 (502) wavelength points that cover 9.7 Å (12.9 Å) with a spectral resolution of 19 mÅ (25 mÅ). The position of the slit on the image plane was successively shifted with a step size of $0''.16$ so as one raster scan comprising 200 steps covered a $32'' \times 41''$ area in the FOV. The raster scan was repeated every 22 s for 1 hr and 40 minutes in the quiet Sun. We used data of half an hour with the best quality that cover the MF event in this study.

The FISS data are preprocessed. First, a reference profile is created by taking an average of the observed background region, which is then used to normalize all profiles by the maximum intensity (a proxy of the continuum intensity) of the reference profile. The data profiles are corrected to the reference profile by a multiplicative factor that is close to unity so that contrast in far wings vanishes while maintaining contrast accuracy in the $H\alpha$ line center. The stray light effect in

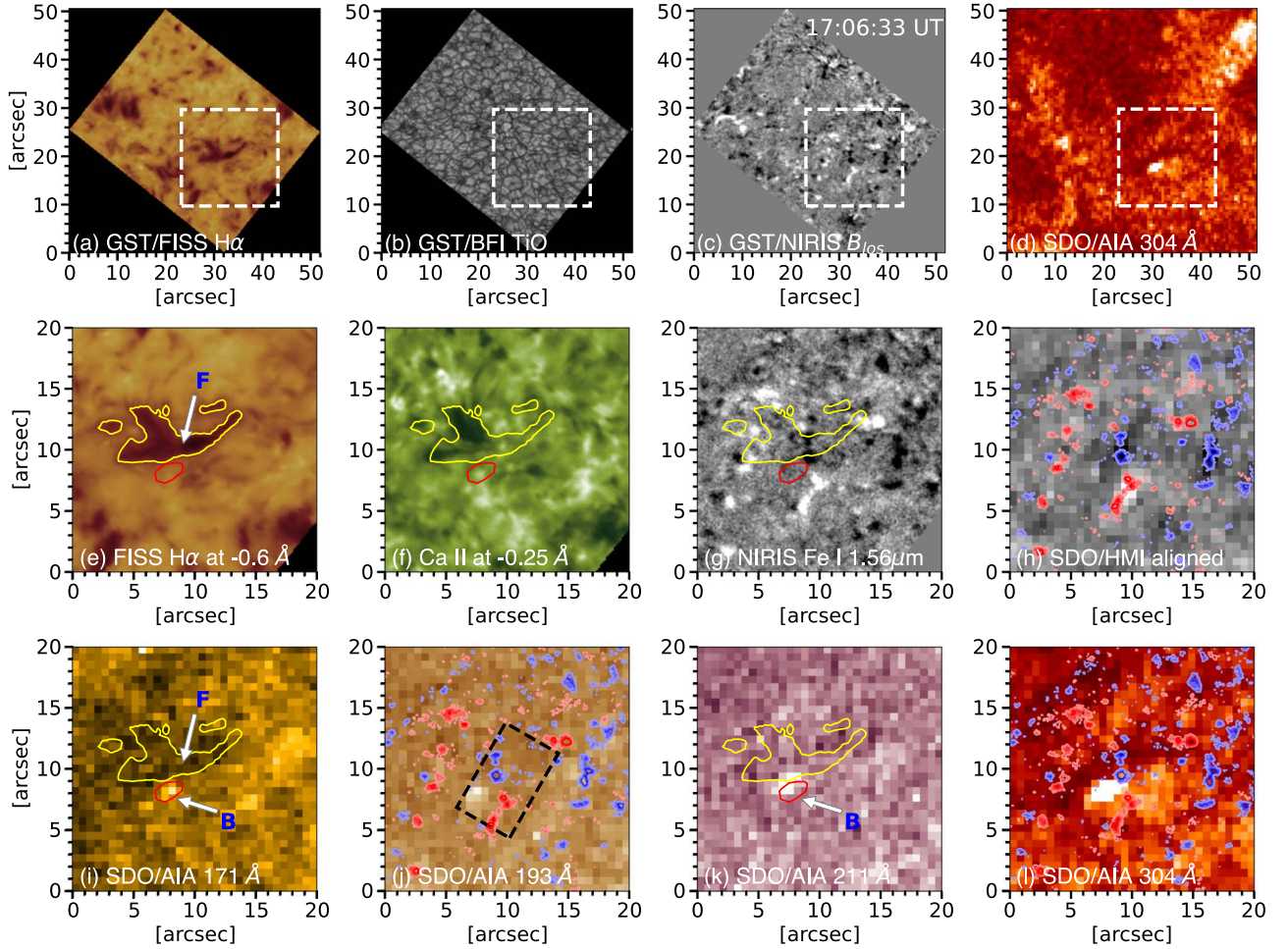


Figure 1. Observation of the tiny MF. (a–d) Full FOV of the FISS $H\alpha$ spectrographs, broadband TiO filtergrams, NIRIS magnetograms, and SDO/AIA 304 Å image obtained at around 17:06 UT. The dark feature in the blue wing of the $H\alpha$ (e) and Ca II 8542 Å (f) lines is identified as the MF. The outline of the MF as a yellow contour is overlaid on the NIRIS magnetogram (g) and EUV images (i, and k). The location of the 304 Å brightening is marked in the remaining panels in the form of a red contour. (h–l) The NIRIS LOS magnetogram is overlaid on the SDO/AIA 171 Å, 193 Å, 211 Å, and 304 Å channels in the bottom panels for the period of 16:40–17:15 UT. (An animation of this figure is available in the [online article](#).)

the observation is removed by following the calibration process of FISS (J. Chae et al. 2013b). The $H\alpha$ and Ca II 8542 Å line spectra of the MF are analyzed using the classical cloud model (J. M. Beckers 1964), which assumes that the profile of the background light incident on the feature of interest from below is the same as the reference intensity profile.

3. Results

We start with an overview of the eruption of the event and present the measurements of physical quantities from the Dopplergrams and magnetograms associated with the eruption. We then describe the spectroscopic analysis of the FISS data and the resulting temperature and velocity. Finally, we use these results to derive the kinetic and thermal energies carried by the MF.

3.1. Overview of the Minifilament Eruption

The MF eruption was detected by multiple instruments. In Figure 1, we show FISS $H\alpha$ and Ca II 8542 Å spectrograms, NIRIS magnetograms, and AIA EUV images of the event. The GST images are coaligned to the SDO/AIA and HMI images

(Figure 1(h)), and the x -axis is along the east–west direction in helioprojective Cartesian coordinates. Figures 1(a)–(c) show the GST observations of the MF, which erupted from spicular bundles between the opposite polarities of the magnetic bipole, with a zoomed-in FOV (white box) of the MF feature displayed in panels (e)–(l). The MF configuration is clearly observed in the $H\alpha$ image at -0.6 Å (-30 km s $^{-1}$) off the central wavelength, and in the Ca II 8542 Å image at -0.25 Å off the central wavelength (-10 km s $^{-1}$, see Figures 1(e) and (f)). The magnetic bipole in the MF central footpoints are shown in the NIRIS and HMI magnetograms (see Figures 1(g) and (h), respectively). Two parts of the arcade loops coincide at F ($9''$, $10''$), with EUV burst B (Figures 1(i)–(l)) appearing adjacent to the central region of the MF, and fan-spined dark features observed with $H\alpha$ at a -0.6 Å wavelength. Coronal counterparts of the MF are observed in the AIA 171 Å (630,000 K) and 304 Å (50,000 K) images (see Figures 1(i) and (l), respectively). Manifestation of a miniature version of the two-ribbon flare is observed in a supplementary movie of Figures 1(e)–(l). Contours of the longitudinal magnetic field at ± 150 G are superimposed on the AIA 193 Å and 304 Å images, with a positive (negative) field represented in red (blue).

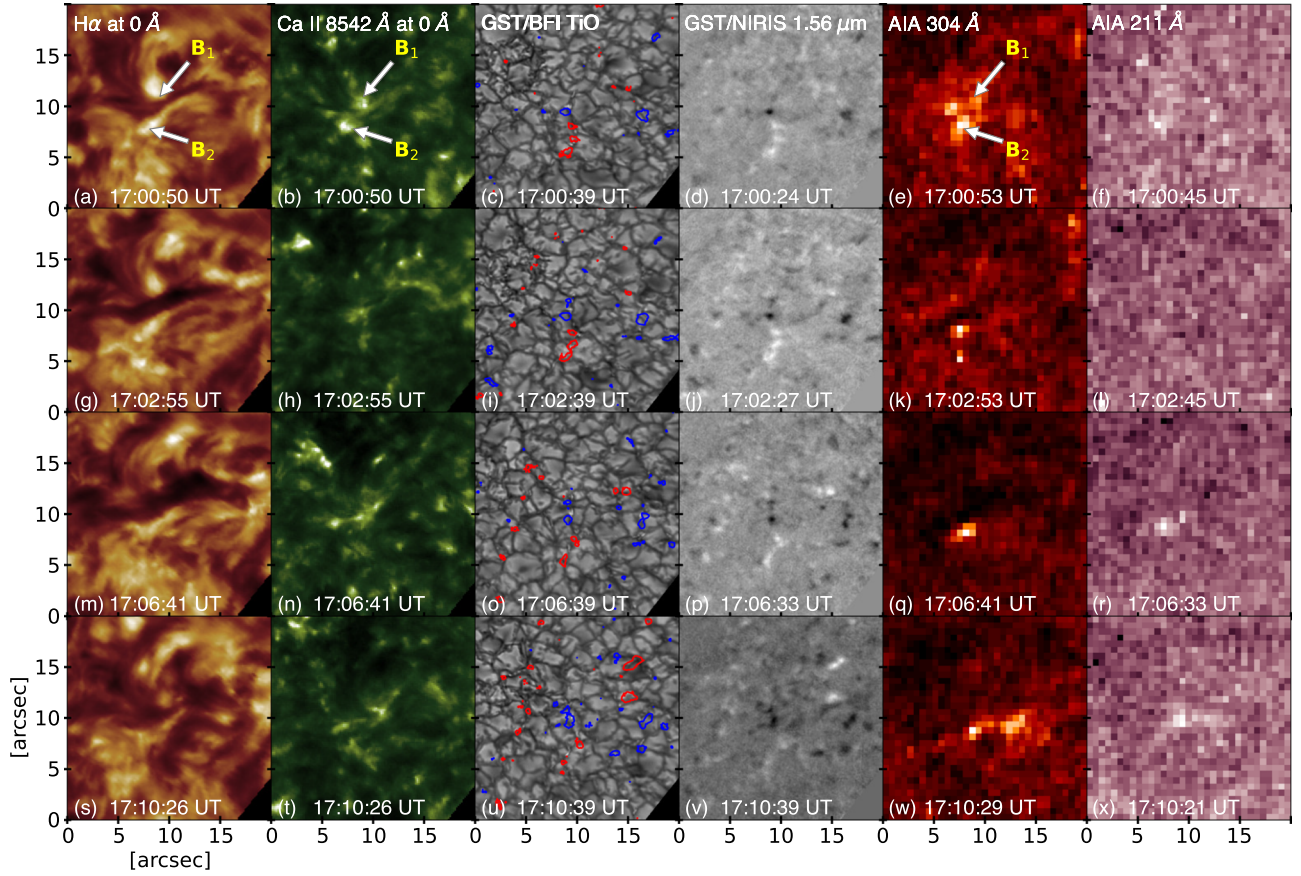


Figure 2. Evolution of the MF in the $H\alpha$ central wavelength, the $\text{Ca II } 8542 \text{ \AA}$ central line, the broadband TiO filtergrams, GST/NIRIS LOS magnetograms, and AIA 304 $\text{\AA}$ and 211 $\text{\AA}$ channels. The figure shows the MF feature at four times ranging from 17:00 UT (top) to 17:10 UT (bottom). An animated version of this figure is available in the online journal. This 10 s animation shows a time sequence of the above images in the six columns for the period of 16:40–17:15 UT.

(An animation of this figure is available in the [online article](#).)

The EUV bursts lie along the direction of the MF, which is between opposite polarities of strong magnetic elements.

The detailed eruption process of the MF is shown in Figure 2. A dark sigmoidal feature is shown in the $H\alpha$ images while only a short braid of the dark feature is observable at $\text{Ca II } 8542 \text{ \AA}$. Brightenings denoted B_1 and B_2 (B in Figure 1) on both sides of the sigmoid feature in the central footpoint are seen in the $H\alpha$, $\text{Ca II } 8542 \text{ \AA}$, and AIA 304 $\text{\AA}$ images. The footpoints of the emerging MF were preoccupied by spicule bundles surrounding the bright point as seen in $H\alpha$ line-center wavelength at 16:55:16 UT. The MF emerged from the bright points with one footpoint anchored in place, of which the rising flux formed two conjugated arcade loops that extend in opposite directions at 17:00:50 UT. The MF upflow is shown in the $H\alpha$ line at the same time as the appearance of the MF sigmoid structure. The eruptive activity of the rising sigmoidal MF is observed at 17:05:50 UT with bright points separating from the footpoints, followed by a prominent downflow 3 minutes later as seen in the $H\alpha$ images, as the rising MF vanishes.

3.2. Evolution of the Minifilament in the Extreme-ultraviolet Images

Figure 3 shows the time variation of the MF intensity at EUV wavelengths from the AIA 193 and 304 $\text{\AA}$ channels (Figure 3(a)). After subtracting the 3 minute background oscillation, we found the activation and rising of MF (t_1) is accompanied by a decrease of EUV intensity following a peak

of EUV brightening in the time profiles of the AIA 304 and 193 $\text{\AA}$ data. The time profiles of the EUV fluxes show a continuous decrease until 17:06 UT when lateral displacement of the erupting MF is observed in Figure 5(a), specifically, dimming in AIA 193 $\text{\AA}$ is seen after the start of the MF eruption (t_2) during this period of time. Figure 3(b) shows the time profiles of the $H\alpha$ flux (integrated intensity over the MF region denoted as a dotted box in Figure 1(j)) at the line core. The pseudo-Doppler flux is defined as $(F_+ - F_-)/(F_+ + F_-)$ where $F_{\pm}$ refers to the flux of $H\alpha \pm 0.6 \text{ \AA}$ integrated over the box in Figure 1(j). The pseudo-Doppler flux starts to increase 1 minute before the apparent rising time (t_1) and decreases back to the background level after 17:06 UT (t_p), when the $H\alpha$ line-center intensity is a minimum. During this period, the $H\alpha$ line-center flux continuously decreases. This indicates a transient upward motion of the MF at its activation. Figure 3(c) shows magnetic flux change within the box specified in Figure 1(j). The positive magnetic flux decreased by $1.8 \times 10^{17} \text{ Mx}$ through the MF eruption while the negative magnetic flux decreased by $2.5 \times 10^{17} \text{ Mx}$ from t_1 to t_2 .

Figure 4 shows the configuration around the erupting MF as detected in the multiple wavelengths together with the slits (yellow curves) used for constructing time–distance plots to study the dynamics of the MF. The NIRIS magnetogram shows a magnetic bipolar element (denoted as P) at the footpoint of the sigmoid. We set a slit (S1) along the spine of the erupting filament (MF) starting from the EUV bright point (B). Another

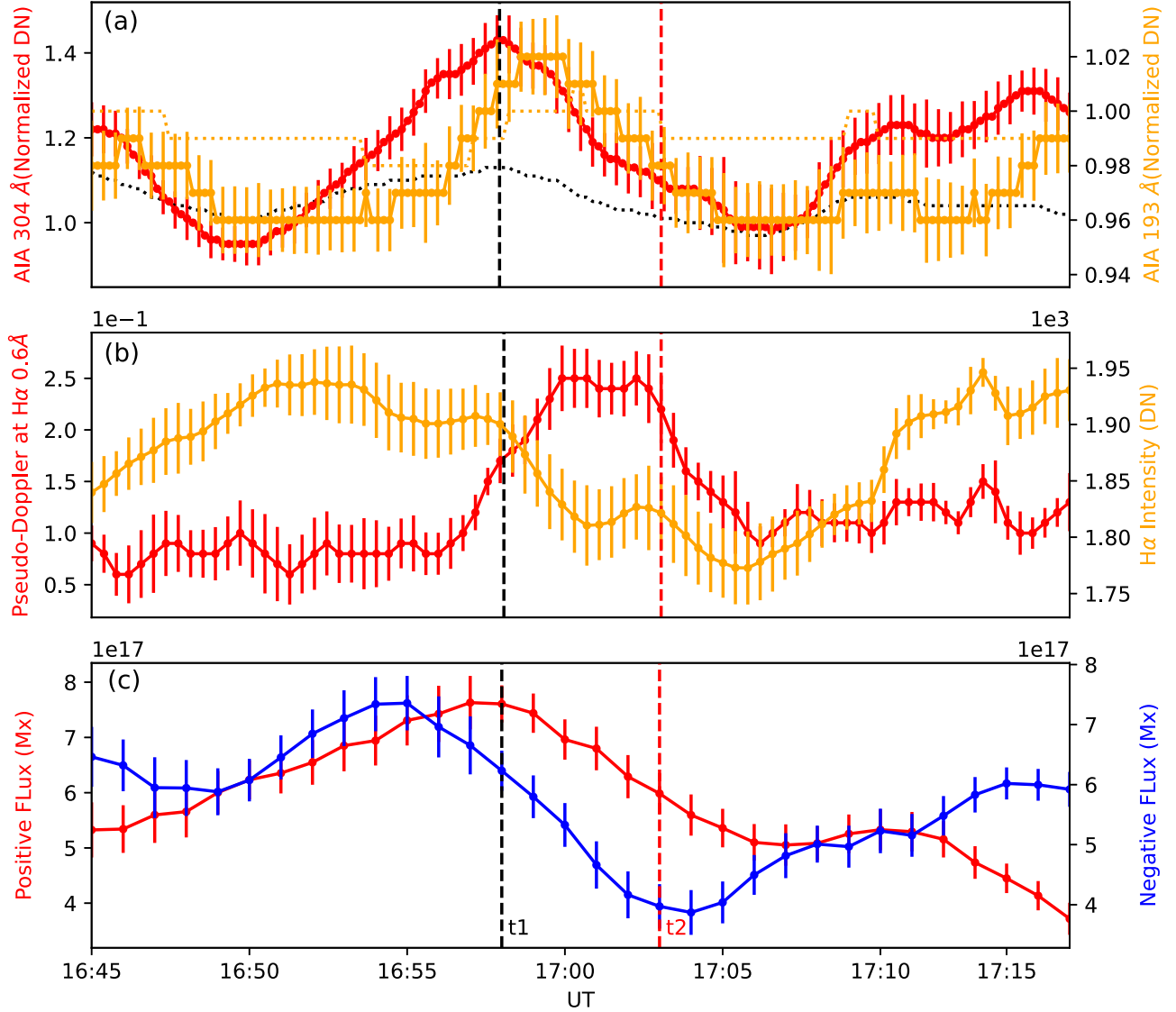


Figure 3. Time profiles of the MF event in the EUV, the $H\alpha$ line, and magnetograms obtained from the dashed box in Figure 1(j). Red and yellow curves in (a) show the EUV intensity of the MF core region in the 304 Å and 193 Å channels, respectively. Panel (b) shows changes of the normalized $H\alpha$ intensity at -0.5 Å and -0.8 Å from the absorption line center. Panel (c) shows changes of the positive (red) and negative (blue) magnetic flux of the magnetic bipole corresponding the brightening in B1 and B2 in Figure 2. Black, red, and green dashed lines mark the time of MF activation (t_1 : 16:58:21 UT) at the $H\alpha$ center line, the start time of the MF eruption (t_2 : 17:03:28 UT), and peak of the MF eruption (t_p : 17:06:33 UT), respectively. The error bars in each profile indicate the estimation of errors at 3σ deviation.

slit, S2, is set to cut through the MF and magnetic bipole. They are used to detect motions along the magnetic bipole direction and along the MF sigmoid trace, respectively.

Figure 5 shows time–distance diagrams of the MF constructed using the two slits set in Figure 4. Figure 5(a) shows the motion of the bright point and the following dark feature along the MF sigmoid (denoted in Figure 4(c)). The apparent speed of the bright point is $38\text{--}54\text{ km s}^{-1}$, and the speed of the dark feature seen in Figures 5(a) and (b) is $22 \pm 3\text{ km s}^{-1}$. Figure 5(c) shows the transverse motion of the magnetic footpoint at a speed of $2.5 \pm 0.3\text{ km s}^{-1}$. Figure 5(d) shows the lateral displacement of the MF perpendicular to the sigmoid spine at a speed of $36 \pm 5\text{ km s}^{-1}$.

The magnetic flux in the negative polarity is almost stationary while the positive polarity patches emerge and migrate toward the negative polarity in the rising phase of the MF. The field strength in the positive (negative) polarity decreases by $\sim 30\%$ ($\sim 24\%$) during the MF eruption (see

Figure 3(c)). With accurate coalignment between the $H\alpha$ images and AIA 193/304 Å images, we could find this MF eruption identified with FISS spectra at the location of its coronal counterparts in the AIA EUV images. This enables us to study the thermodynamic properties of the MF eruption from the characteristics of the spectra and their connection with the coronal dynamics. We focus our spectral analysis of the $H\alpha$ line during the transient part of the MF which sustained for ~ 10 minutes in the $H\alpha$ images.

3.3. Spectroscopic Analysis of the Minifilament

In Figure 6 we show the spectroscopic data of the MF and the bright point obtained at 22 s cadence between 16:52:47 UT and 17:15:26 UT together with raster images of the $H\alpha$ (Figures 6(a) and (b)) and Ca II 8542 Å line center (Figures 6(c) and (d)) at 17:00:50 UT and 17:07:06 UT, where we marked the locations of the spectral sampling with diamond symbols. The $H\alpha$ images display an ϵ -shaped MF structure near the

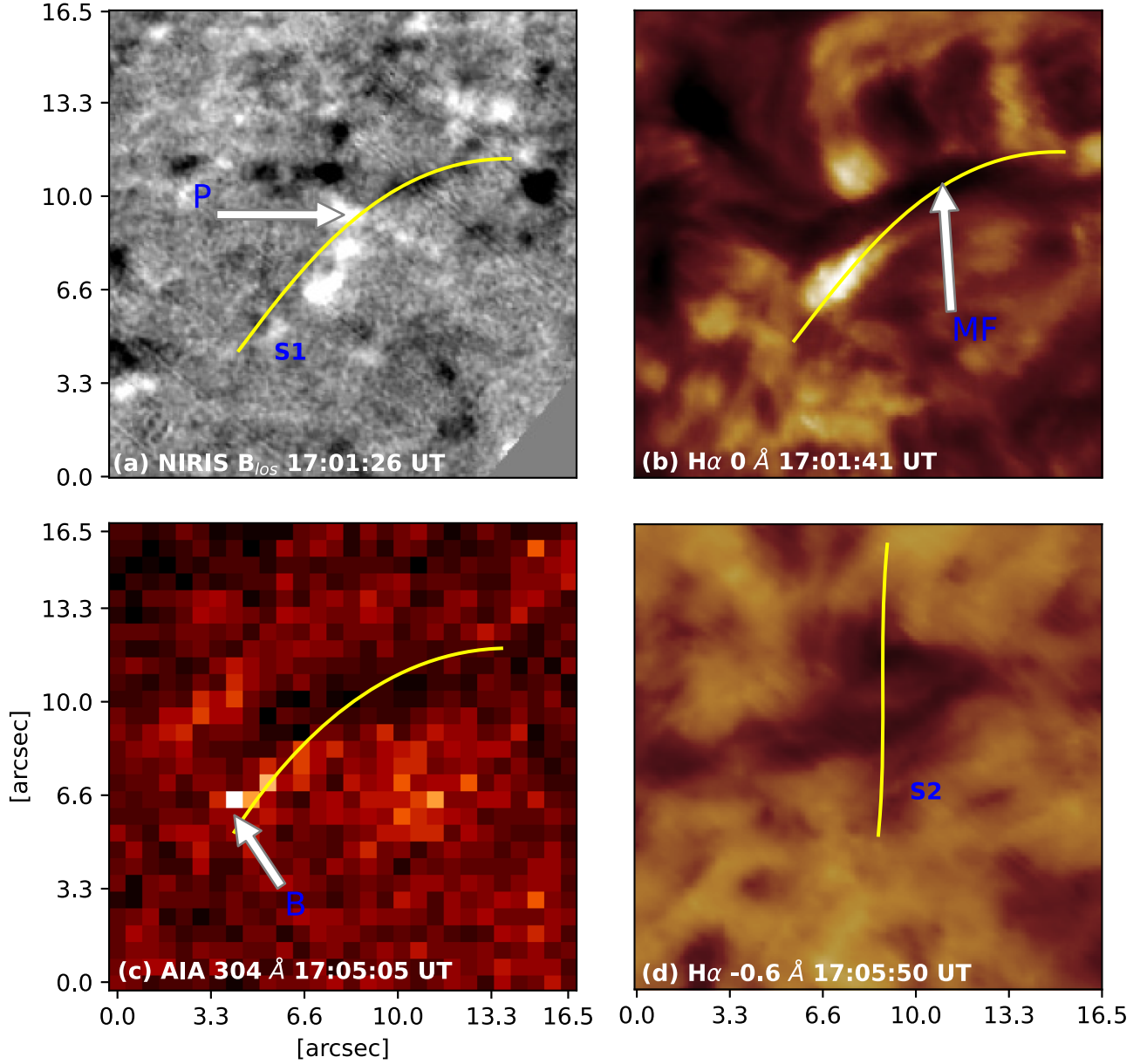


Figure 4. The MF eruption detected in the multiple wavelengths. (a) A bipolar magnetic element at the footpoint of the MF sigmoid at the time of the maximum positive flux. (b, d) The brightenings at the footpoints (marked as B1 and B2 in Figure 2(a)) and the MF at the $H\alpha$ line center and $-0.6 \text{ \AA}$, respectively. (c) The flaring ribbon along the MF in the AIA 304 $\text{\AA}$ channel. The yellow curves in (a) and (b) denote the slit, S1 across the MF, and the yellow curve in (c) denotes the slit along the MF sigmoid.

center of the FOV, with two J-shaped arms reaching $\sim 5''$ from the junction by $\sim [8''.0, 7''.5]$. Two locations are selected to represent the prominent rising arm (denoted by blue diamonds) of the MF structure as well as bright points (red diamond) in the vicinity. In the $H\alpha$ wavelength–time diagram, strong blueshifted absorption is detected from 17:00:50 to 17:02:30 UT. The Ca II 8542 $\text{\AA}$ spectral profiles show narrow absorption at the line center, with corresponding brightening fibrils spanning $\sim [8''.0, 7''.0]$ in the raster images (Figure 6(g)). At 17:07:06 UT, the MF feature at low opacity broadens in the northwest direction, with Ca II 8542 $\text{\AA}$ bright fibrils ceding underneath the MF loop. The wavelength–time diagrams of both the $H\alpha$ and Ca II 8542 $\text{\AA}$ lines in the bright point show a periodic blue-to-redshift evolution during $\sim 16:55\text{--}17:06$ UT, while at the MF location, the blue-to-redshift change is only visible before the rising of the MF in the Ca II 8542 $\text{\AA}$ line and

vanished after 17:00:50 UT. Such a blue-to-redshift change indicates a shock ridge, which is interpreted as manifestation of a magneto-acoustic wave in the chromosphere (M. Carlsson & R. F. Stein 1997; J. Chae et al. 2015).

We use the latest MLSI code (J. Chae et al. 2021a) to analyze the $H\alpha$ and Ca II 8542 $\text{\AA}$ line spectra, as briefly described in the Appendix. In the present case, the top layer is actually the MF, which can be treated like a cloud, and it is adequate to use the three-layer MLSI to calculate the background intensity coming below the cloud. In Figure 7 we plot an example of the spectral fitting to the $H\alpha$ and Ca II 8542 $\text{\AA}$ line profiles using the MLSI three-layer model and a cloud model at 16:56 UT. At this time, the MF started to rise and is observable in both lines, which we treat as a cloud. In the spectra of the MF, a prominent blueshift is seen in the $H\alpha$ line at $\sim 17:00$ UT and $\sim 17:03$ UT, and in the Ca II 8542 $\text{\AA}$ line

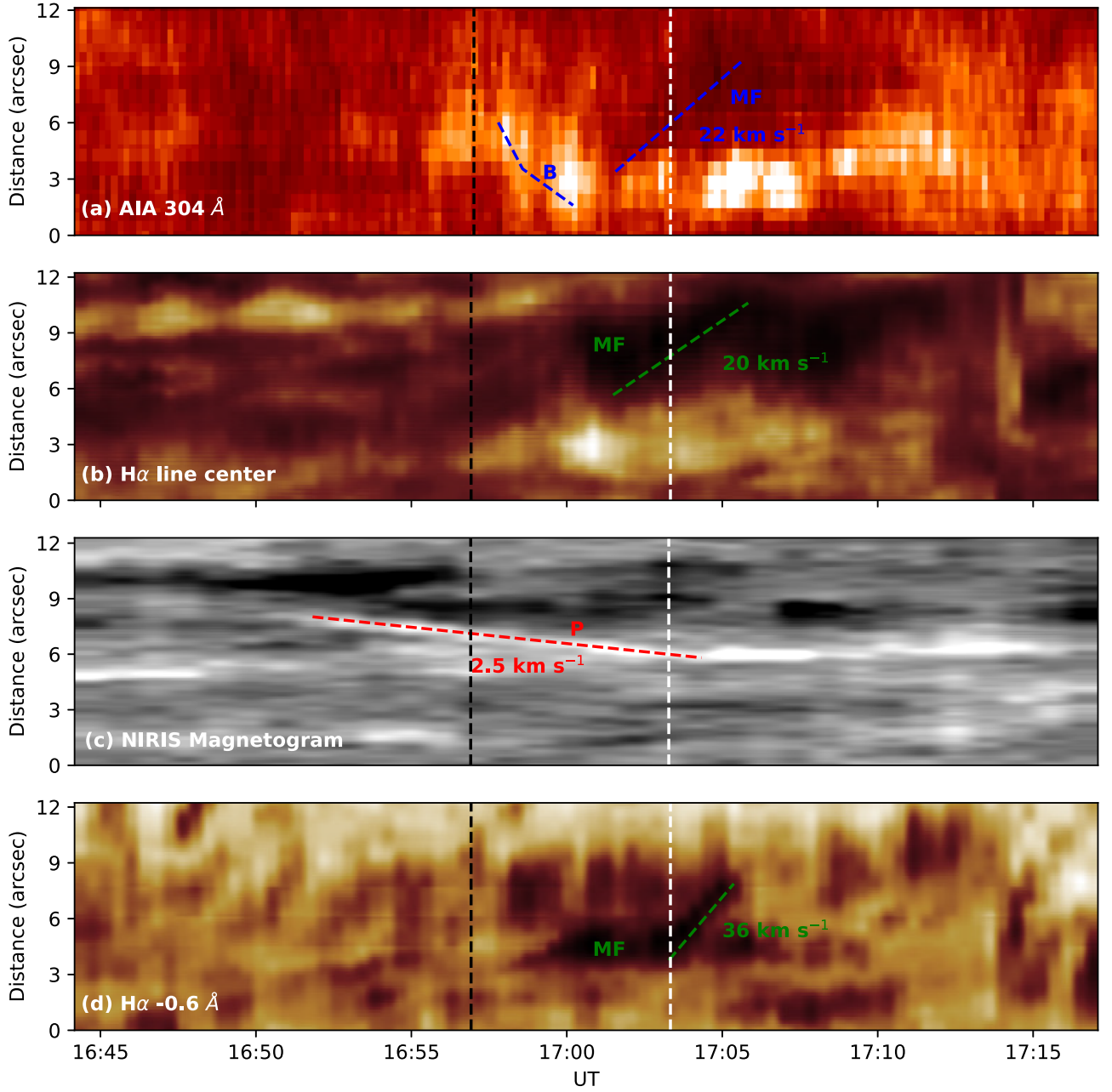


Figure 5. Time–distance diagrams for the MF, flare ribbon, and associated brightening constructed along the curved slits set in Figure 4. (a) Intensity variation of the AIA 304 Å channel along slit S1. Blue dashed lines during 16:57 UT–17:00 UT and 17:03 UT–17:05 UT indicate motions across the bright points and that of the MF, respectively. (b) FISS H α line-center intensity along S1 shows enhanced lateral motion of the MF (green dashed line). (c) NIRIS magnetic field along S1 shows diverging motion of the positive magnetic flux at the MF footpoint (red dashed). (d) FISS H α offline intensity along S2 shows the MF motion along S2 (green dashed). The vertical black dashed line marks the time of MF activation (t_1) and the vertical white line, the start time of the MF eruption (t_2 in Figure 3(c).)

the blueshift is seen when the shock ridge terminates. Since the source function and opacity are variable along the chromospheric height, MLSI may return composite spectral parameters representing different layers.

Figure 8 shows the cloud model fitting to the H α and Ca II 8542 Å line profiles from the MF at 16:56 UT. At this time, the MF started to rise and is observable in both lines, and we could determine both the temperature and nonthermal speed of the MF while treating it as a cloud feature. For the reference spectrum, I_{ref} we used I_0 in Figure 7 instead of using the ambient spectrum, because the latter is less reliable. We can notice that the upflow motion is accelerated at this moment as indicated by the enhanced blueshift of the H α line

(Figure 3(b)), and the Doppler velocity is estimated to reach 7.9 km s^{-1} using the lambdameter method (J. Chae et al. 2013a) on the H α line profile. The Ca II 8542 Å line profile shows enhanced intensity with redshift, indicating that the bright fibrils are associated with the rising MF.

3.4. Evolution of the Temperature and Doppler Velocity

We derive the temperature and density of the MF by treating it as a cloud on top of the chromosphere represented by the three layers. To determine the line width of the H α cloud spectrum, we subtracted from the observed line profile, the incident line profile, I_0 , determined from the three-layer MLSI

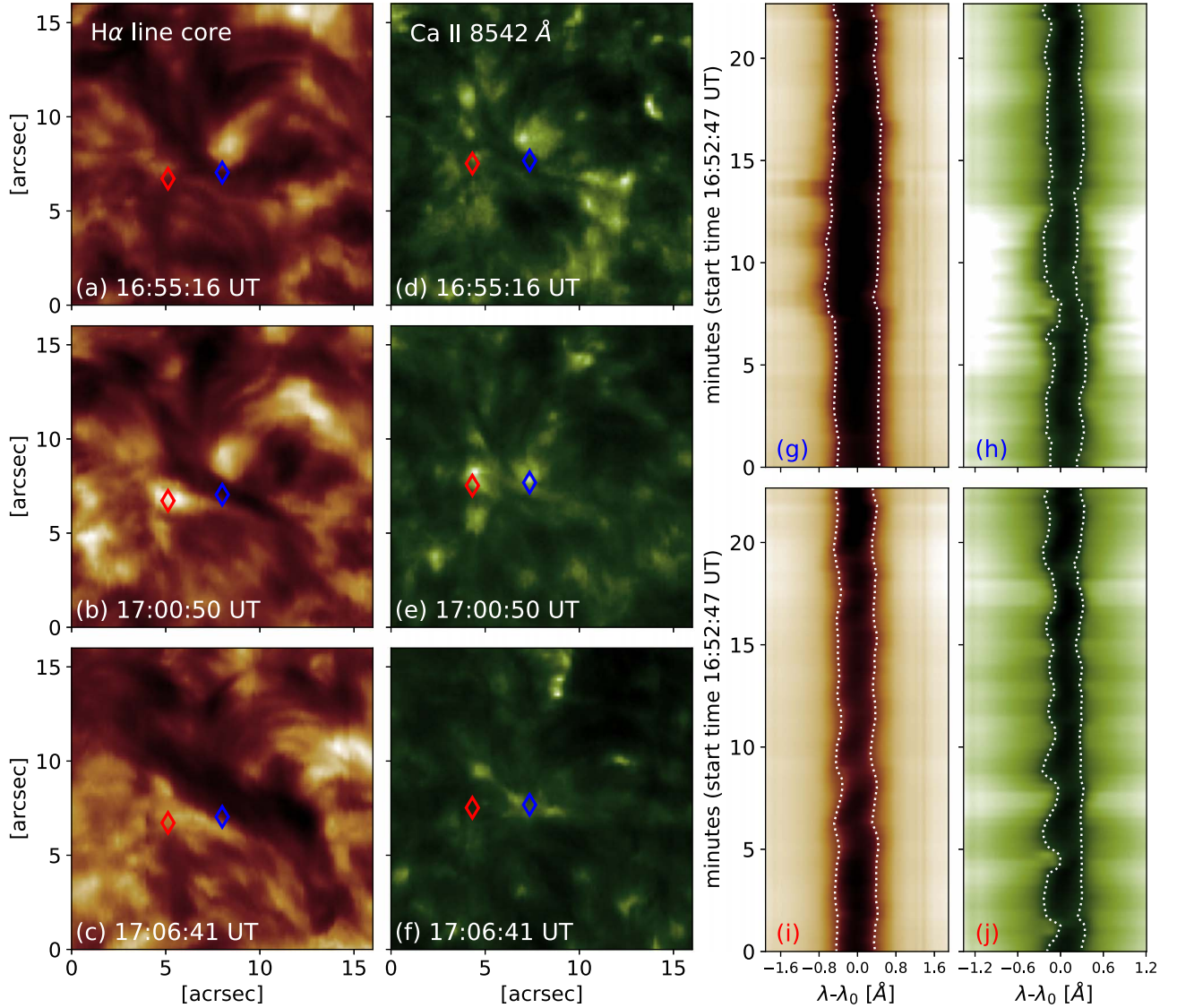


Figure 6. FISS detection of the MF and bright point in the $H\alpha$ and $\text{Ca II } 8542 \text{ \AA}$ lines. (a), (b), and (c) $H\alpha$ center line images at 17:00 UT and 17:07 UT, respectively. (d), (e), and (f) $\text{Ca II } 8542 \text{ \AA}$ center line images at the corresponding times. The MF and the bright point are marked with blue and red diamond symbols, respectively. (g) and (h) Time variations of the $H\alpha$ and $\text{Ca II } 8542 \text{ \AA}$ spectra at the location of the MF. (i) and (j) Spectra of the bright point at the corresponding times. The white dotted curves delineate the FWHM of the spectral line profiles.

model taken as the reference profile I_{ref} . Once the Doppler width of the absorption line $\Delta\lambda_D$ of the cloud is determined, we convert it to temperature, T , and nonthermal speed, ξ , using

$$\Delta\lambda_D = \frac{\lambda_0}{c} \sqrt{\frac{2kT}{m} + \xi^2}, \quad (1)$$

where λ_0 is the line-center wavelength, c , the speed of light, and m , the atomic mass. To determine these two variables, we need two lines that originate from the same atmospheric layer. We must, however, note that the MF is only partially visible in the $\text{Ca II } 8542 \text{ \AA}$ line whereas it always appears in the $H\alpha$ line (see Figures 2 and 6). Since the $\text{Ca II } 8542 \text{ \AA}$ line opacity is dominated by collisions and is more sensitive to density than the $H\alpha$ line opacity, our interpretation is that the $\text{Ca II } 8542 \text{ \AA}$ line opacity rapidly decreases with the rise of the MF to make the MF invisible in the line. We choose to proceed with the $H\alpha$ line data only, utilizing the nonthermal speed, ξ determined when the MF is detected in both lines. Specifically, we use $\xi = 7.9 \text{ km s}^{-1}$

determined at 16:55 UT as the base turbulent velocity for the entire time range under investigation. We will estimate the uncertainty range of the resulting temperature due to possible variation of ξ immediately after the temperature is calculated.

In Figure 9, we plot the temperature and the Doppler velocity of the MF as functions of time from 16:56:58 UT to 17:07:28 UT. The error bars are determined from the MLSI algorithm and they do not include the aforementioned uncertainty of the cloud model itself. The temperature of the MF shows a continuous increase from the time of the MF rise (16:57:49 UT) to its eruption time (17:05:19 UT), which is then followed by a rapid decrease after 17:05:00 UT. The maximum temperature is reached at 17:05:46 UT when the eruption occurs and the filament structure ejects laterally (Figure 2(m)). We now check the uncertainty range of this temperature estimation due to the approximation of keeping $\xi = 7.9 \text{ km s}^{-1}$. Supposing a possible variation of $\Delta\xi/\xi$ by $\pm 50\%$ we find the resulting uncertainty in our temperature estimation lies in the range $12\% \leq \Delta T/T \leq 26\%$ at the time of the maximum temperature.

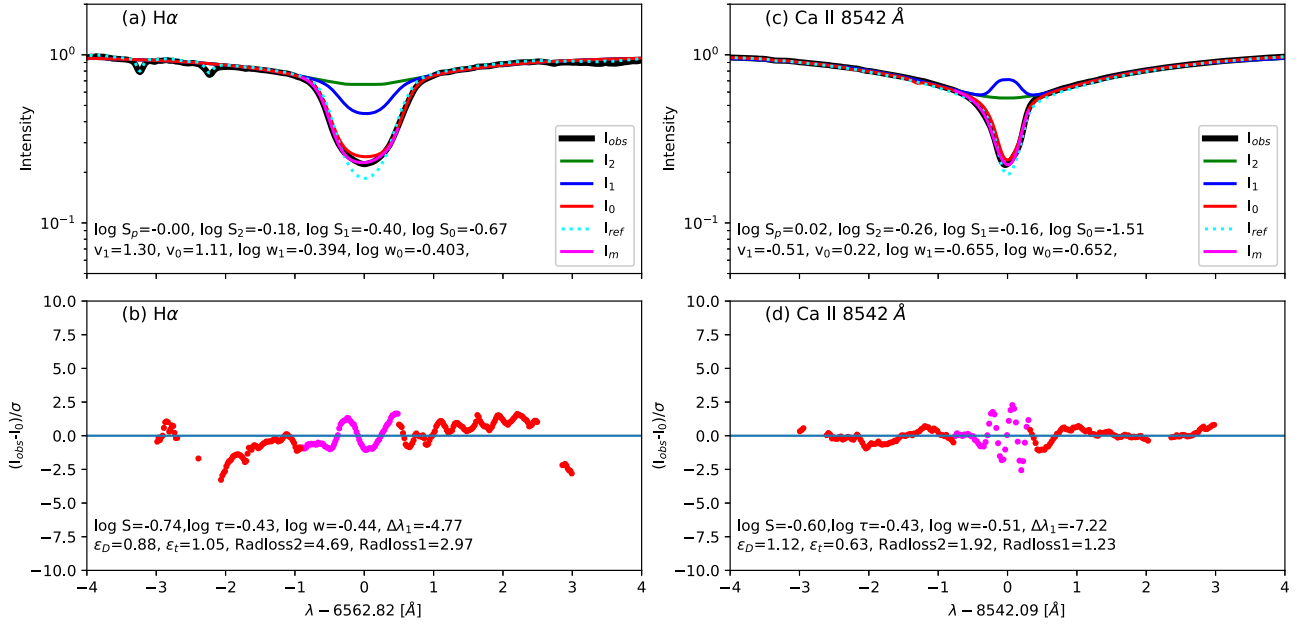


Figure 7. MLSI fitting of the H α and the Ca II 8542 Å line spectra in the MF at its activation time (17:00:50 UT). Top panels: the layers of the spectral fitting are denoted as 0 (top layer), 1 (middle layer), and 2 (bottom layer) in the chromospheric heights. Black curves indicate observed spectra at the selected feature point, F. The reference profile is represented with a dotted cyan curve, and fitting results are represented by red, blue, and green curves from the top to bottom layers, respectively. The purple lines should be compared with the observed profiles. Bottom panels: goodness of the spectral fitting is shown in terms of the difference $(I_{obs} - I_0)$ relative to the photon noise σ as defined in the Appendix. Purple points are the wavelengths used for the cloud model: $[-0.9, 0.5]$ Å for the H α line and $[-0.7, 0.3]$ Å for the Ca II 8542 Å line.

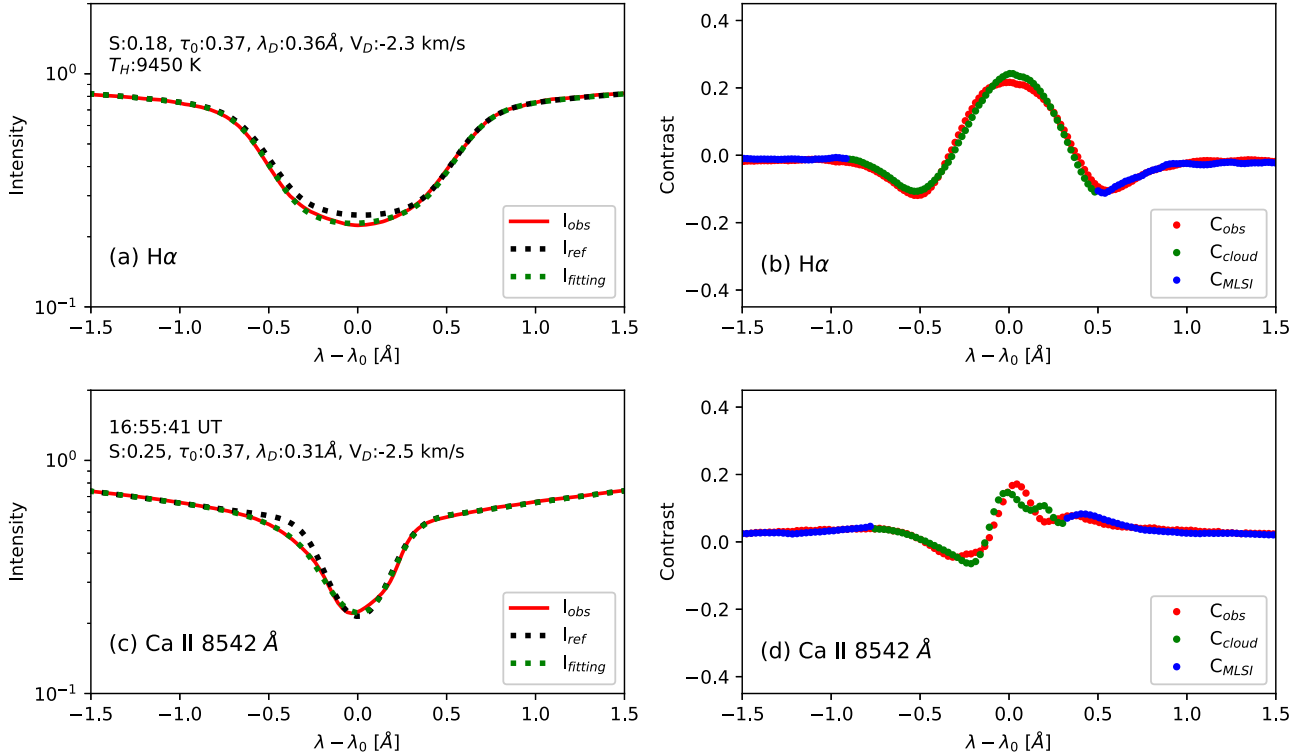


Figure 8. Absorption and contrast profiles of the cloud feature at the fast rising phase of the MF (16:56:06 UT). Left column: the dotted black curves and red solid curves represent background profiles and observation data of the absorption line profiles, respectively. The green curves represent the cloud features of the MF at wavelengths between ± 1.5 Å. Right column: blue and red curves are the contrast profiles for the cloud model, MLSI model, and observed intensities as distinguished by the colors.

We must therefore note that in the presence of enhanced nonthermal motion during the dynamic phase of the eruption, the result presented here could overemphasize the temperature rise during the MF eruption to that extent.

The MF has a prominent upflow from the rising phase (17:00:50 UT) to eruption (17:05:00 UT) reaching a peak speed of 18 km s^{-1} when the dark feature becomes visible in the H α blue-wing images (see Figure 2(a)). The upflow

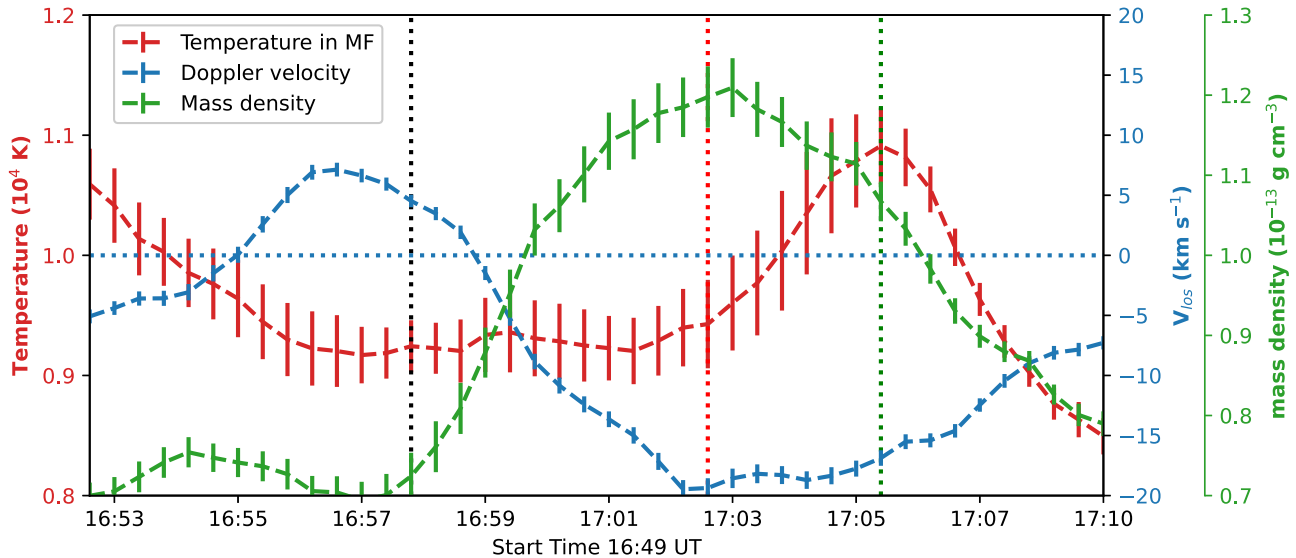


Figure 9. Temporal evolution of the thermal and kinetic parameters of the MF derived using the classical cloud model and the MLSI method. The cloud model gives the temperature (red) and the Doppler velocity (blue) of the cloud feature, both of which decrease after 17:05 UT. After the start of the MF eruption, only the H α line is used in the cloud model, and the nonthermal speed is fixed to 7.9 km s $^{-1}$ as determined at 16:55 UT.

(Figure 9) is closely associated with photospheric flux cancellation (Figure 3(c), t_1 – t_2). The upflow speed reaches its maximum when the magnetic flux is partly canceled. On the other hand, a time discrepancy is found between the temperature rise of the MF feature and flux cancellation but is cotemporal with the following magnetic flux increase. We interpret this relation that the continuous emergence of flux (Figures 2(i) and (o)) brings the MF to upper chromospheric heights through reconnection-driven acceleration.

We also determined the mass density from the cloud model. First, we determined the optical depth of the cloud at the line center, τ_0 , the Doppler width $\Delta\lambda_D$, and an independently estimated height d . This allows us to determine N_2 , the number density of hydrogen atoms in the second quantum level from the expression of the optical depth (G. Tsiropoula & B. Schmieder 1997, Equation (4)). N_2 is then converted to N_H using a scaling law between N_H and N_2 (A. Poland et al. 1971). The mass density is given by $\rho \approx 1.34 m_H N_H$ where m_H is the mass of the hydrogen atom (G. Tsiropoula & B. Schmieder 1997, Equation (12)). As a result, we find the mass density increases until the MF eruption and then decreases afterward (green curve in Figure 9).

Figure 10 shows Dopplergrams and temperature maps of the MF event. At a position of [8'', 8''] on the Dopplergrams (Figures 10(a), (d), and (g)) and the temperature maps (Figures 10(b), (e), and (h)), a prominent upflow is found along the MF sigmoid associated with the temperature burst near the central region (see F in Figures 10(d) and (e)). The scatterplots at the activation time, 16:57:49 UT, in Figure 10(c) show the temperature in the MF region is ~ 9700 K with cool materials of 7500 K rising at a Doppler speed of 10 km s $^{-1}$. Then, with the enhanced blueshift observed at the start of the eruption in the Dopplergram (Figure 10(d)), a segment of high-speed area (I2) that is over 10 km s $^{-1}$ appears in the scattered distribution, while the temperature does not show a prominent change. At the posteruption time of 17:05:25 UT, the scatterplot (Figure 10(i)) shows a 2D Gaussian-like distribution centered at 9800 K. We observed that for upflow speeds greater

than 10 km s $^{-1}$ the temperature is 9500 K, about 2000 K higher than the temperature at the start of the MF eruption.

3.5. Energy of the Minifilament

To estimate the kinetic energy of the MF, we need the mass of the MF most of all. In a cloud model, one can estimate the cloud density from the optical depth at the line center and an independently estimated height (G. Tsiropoula & B. Schmieder 1997, their Equations (11)–(12)). The mass density is estimated as 1.1×10^{-13} g cm $^{-3}$ as shown in Figure 9. For the volume of the MF, we use the AIA 304 Å and GST/FISS H α line-center images to estimate the dimension of the MF as 12'' in length and 2''.5 in width. We use these quantities to calculate the kinetic energy associated with the rising motion of the MF as 2.6×10^{24} erg. We also estimate the thermal energy associated with the MF eruption from the fitted thermodynamic properties obtained in Section 3.4. The thermal energy accumulated inside the MF is 3.6×10^{24} erg, resulting in a total energy of 6.2×10^{24} erg at the time of the maximum temperature. From the photospheric magnetograms, we find the magnetic energy change is $\sim 7.2 \times 10^{25}$ erg across the PIL of converging opposite magnetic elements. This is consistent with our previous study of quiet small-scale Sun eruptions where magnetic flux cancellation at granule scale provides sufficient free energy to heat the corona (J. Wang et al. 2022).

4. Summary and Discussions

In this paper, we investigated the chromospheric thermodynamics of an erupting tiny filament and an associated microflare in the quiet Sun, using high-cadence spectral data of the H α line from GST/FISS, and high-resolution magnetograms from GST/NIRIS. We analyzed the spectral data of the H α and Ca II 8542 Å lines to trace the temperature and energy of the MF at the location of a small-scale CBP observed in the SDO/AIA 193 and 304 Å channels, and the associated microflare in the vicinity of the MF. Overall this miniscale event resembles an eruptive two-ribbon flare at a larger scale.

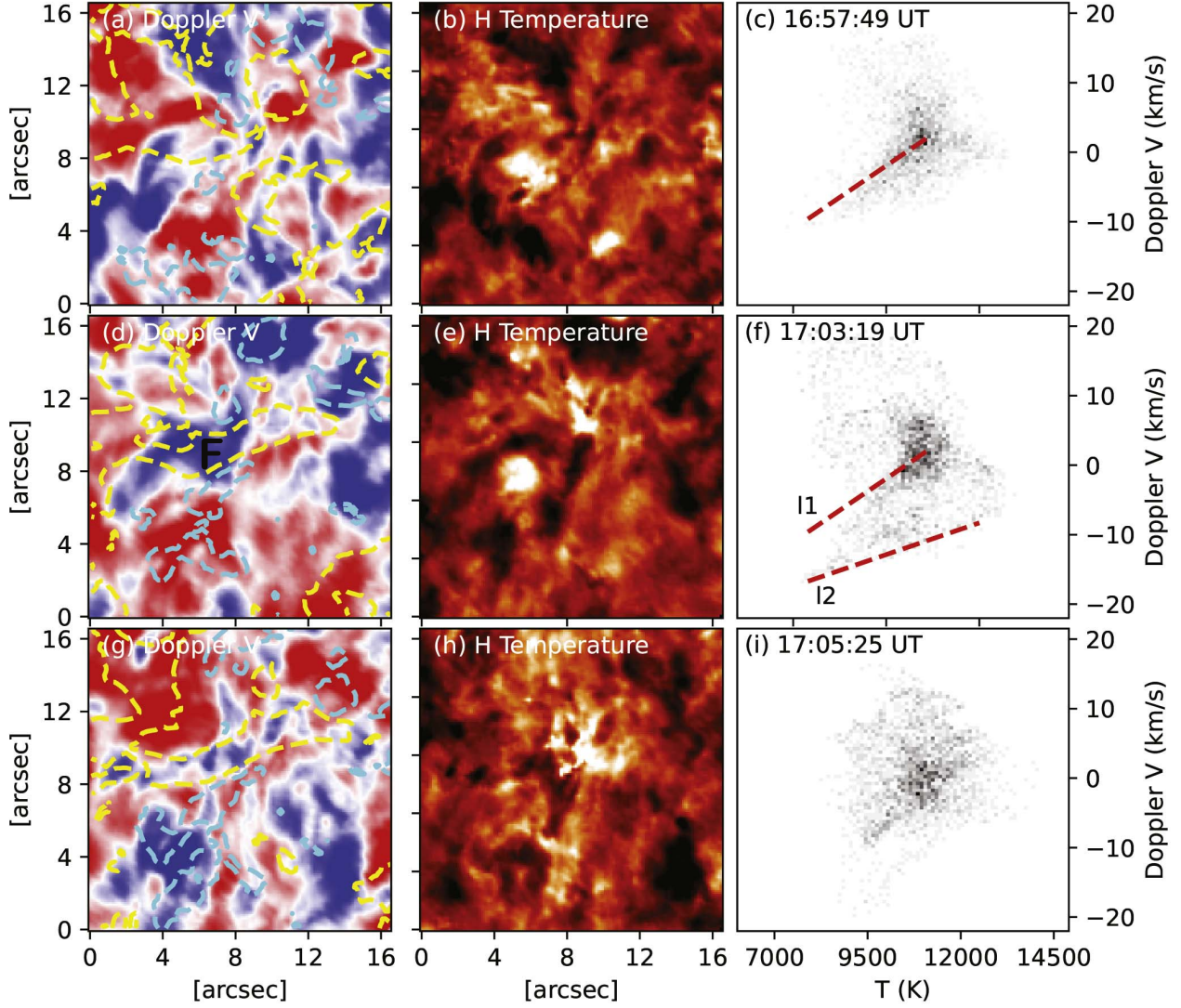


Figure 10. Dopplergrams and temperature maps of the MF event. From top to bottom, features at three selected times are shown: MF activation (t_1 , 16:57:49 UT), start time of the eruption (t_2 , 17:03:19 UT), and posteruption time (t_3 , 17:05:25 UT). Left column: dopplergrams with the yellow and blue contours indicating the brightening features in the $H\alpha$ line center and $-0.6 \text{ \AA}$ off the line center, respectively. Middle column: temperature maps. Right column: scatterplots of the temperature vs. the Doppler velocity of the MF event.

Key structural and dynamic properties of the event are summarized as follows.

1. We used a cloud model for the FISS $H\alpha$ and $\text{Ca II } 8542 \text{ \AA}$ line spectra at the time of the MF activation, determining a temperature of 8600 K and nonthermal speed of 7.9 km s^{-1} . Afterward, the temperature of the MF was traced using the $H\alpha$ line data only as the MF was no longer visible in the $\text{Ca II } 8542 \text{ \AA}$ line. The temperature keeps increasing to reach $1.8 \times 10^4 \text{ K}$ at the eruption and rapidly decreases after the eruption. The density of the MF also drops significantly as the eruption progressed, as evidenced by the disappearance of the $\text{Ca II } 8542 \text{ \AA}$ absorption line from the MF. Both the drop of the temperature and that of the density are considered to be due to expansion of the MF.
2. We estimated a thermal energy of $3.6 \times 10^{24} \text{ erg}$ from the maximum temperature and a kinetic energy of $2.6 \times 10^{24} \text{ erg}$ from the rising speed of 18 km s^{-1} of the MF. From the NIRIS magnetograms we found

cancellation of a magnetic bipole in the footpoints of the MF coincident with the eruption of the MF found in the NIRIS magnetograms, and the magnetic energy change across the conjugate footpoints is $7.2 \times 10^{25} \text{ erg}$. This amount of energy could belong to the lower end of MF eruption and is comparable to that of enhanced spicules.

3. A wave-like phenomenon in the form of a periodic shift of the FISS spectra is found at the location of the brightening near the MF. This phenomenon is similar to the shock waves expected from a train of upward-propagating acoustic shocks (M. Carlsson & R. F. Stein 1997; J. Chae et al. 2015). It seems that the shocks developed before the fast rising of the MF, and diminished as the magnetic structure above the intergranular lanes changed after the flux cancellation.
4. The associated $H\alpha$ microflare is also visible in the AIA $304 \text{ \AA}$ images as a j-shaped dark feature along the PIL in the photosphere. In the eruptive phase, the sigmoid appears to be heated, which may result from energetic

particles produced by the microflare (L. Frogner et al. 2020). This microflare is not associated with any jet/jetlet in its vicinity, while coronal brightening is observed along the trajectory of the MF eruption. The microflare ribbon motion in the EUV data and H α image at -0.6 Å off center show high speeds in the transverse direction, which could be due to heating and evaporation in the chromosphere.

- Using the high-resolution NIRIS magnetograms, we found that the weak fields emerging in the granules reinforce a flux supply to the existing fields. It is followed by the cancellation of the newly emerging negative polarity flux with the footpoint flux in the positive polarity and the MF eruption, implying a causal relationship between them.

These results demonstrate that a combination of spectral data from GST/FISS and magnetic information from GST/NIRIS can shed light on the possible relationship between energy released through magnetic flux emergence and cancellation in the chromospheric height. Specifically, the temperature rise after the onset of eruption predicted by existing models (F. Chen et al. 2017; A. J. Kaithakkal et al. 2023) is found in our spectral analysis, which provides a new piece of information regarding recurrent heating in the low solar atmosphere associated with the MF eruption. Acceleration of the MF up to speeds over 10 km s^{-1} , much higher than previously known speeds (A. C. Sterling et al. 2016; N. K. Panesar et al. 2020), suggests an explosive upward motion of the MF, which should be essential in defining the runaway reconnection at the internal current sheet present in the eruption.

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Appendix

We briefly describe the MLSI method, which was developed to derive the physical parameters of chromospheric plasmas from the FISS data of strong absorption lines, specifically, the H α and the Ca II 8542 Å lines. In both the original version (J. Chae et al. 2020) and the latest version (J. Chae et al. 2021a) of the MLSI, the radiative transfer is treated in three layers: two layers for the chromosphere and one for the photosphere. The photospheric layer extends from continuum opacity $\tau_c = 1$ to 0, above which the lower chromospheric layer (layer 2) starts with chromospheric opacity τ_0 and extends to the top of the upper chromospheric layer (layer 1) with $\tau_0 = 1$; layers 1 and 2 are divided at the interface with opacities of $\tau_0/2$. The chromospheric absorption line profiles are assumed to follow Gaussian functions, which are simply specified by v_2 and w_2 in the lower chromosphere and by v_1 and w_1 in the upper chromosphere. However, the line profile in the photosphere follows a Voigt function, which is specified by not only v_p and w_p but also a , a

dimensionless damping parameter. In the original version, the variation in the source function, S_0 , S_1 , S_2 , and S_p are specified by constant gradients, dS_i/dt_λ . In each layer, the absorption profile is fixed. Another parameter, the line-center-to-continuum opacity ratio, η , is needed to connect the chromosphere to the photosphere. We thus need a total of 13 parameters to specify the model.

In the updated version of MLSI, the absorption profiles are allowed to vary with optical depth in each layer, by which the profiles can continuously change across the interface of two adjacent layers. The parameters v_1 and w_1 representing the middle of the upper chromosphere in the original MLSI refer to the values at the bottom of the upper chromosphere in the updated version. The new parameters v_0 and w_0 are introduced to represent the top of the upper chromosphere. Thus, the updated model is specified by a total of 17 parameters. It is found in a subsequent study (J. Chae et al. 2021b) that the Doppler widths of the two lines inferred using this updated MLSI yields reasonable estimates of the temperature and nonthermal velocity in the chromosphere.

We determine the parameters using constrained least-squares fitting to the observed H α and Ca II 854.21 nm lines. Specifically, we require the model intensity $I_{\lambda,k,0}(\mathbf{p})$ calculated with parameters $\mathbf{p}$, and the observed intensity $I_{\lambda,k,\text{obs}}$ at the k th wavelength λ_k to satisfy the condition

$$\frac{|I_{\lambda,k,\text{obs}} - I_{\lambda,k,0}(\mathbf{p})|}{\sigma_k} \leq 1, \quad (\text{A1})$$

for every k ranging from 1 to N , the total number of parameters. σ_k controls the tightness of this constraint in each data point, for which we adopt the photon noise

$$\sigma_k = \sigma_c \sqrt{I_{\lambda,k,\text{obs}}}, \quad (\text{A2})$$

which is equal to σ_c in the continuum $I_{\lambda,k,\text{obs}} = 1$, and to $0.5\sigma_c$ in the core with $I_{\lambda,k,\text{obs}} = 0.25$. The goodness of the model for data requirement is also checked by the standard error in the model fitting.

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