High-resolution Observations of Downflows at One End of a Pre-eruption Filament

Qin Li\textsuperscript{1}, Na Deng\textsuperscript{1,2}, Ju Jing\textsuperscript{1,2}, and Haimin Wang\textsuperscript{1,2}

\textsuperscript{1} Space Weather Research Laboratory, New Jersey Institute of Technology, University Heights, Newark, NJ 07102-1982, USA; q247@njit.edu
\textsuperscript{2} Big Bear Solar Observatory, New Jersey Institute of Technology, Big Bear City, CA 92314-9672, USA

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Abstract

Studying the dynamics of filaments at the pre-eruption phase can shed light on the precursor of eruptive events. Such high-resolution studies (of the order of 0\textdegree 1) are highly desirable yet very rare. In this work, we present a detailed observation of a pre-eruption evolution of a filament obtained by the 1.6 m New Solar Telescope (NST) at the Big Bear Solar Observatory (BBSO). One end of the filament is anchored at the sunspot in the NOAA active region (AR) 11515, which is well observed by NST H\alpha off-bands from four hours before to one hour after the filament eruption. A M1.6 flare is associated with the eruption. We observed persistent downflowing materials along the H\alpha multi-threaded component of the loop toward the AR end during the pre-eruption phase. We traced the trajectories of plasma blobs along the H\alpha threads and obtained a plane-of-sky velocity of 45 km s\textsuperscript{-1} on average. Furthermore, we estimated the real velocities of the downflows and the altitude of the filament by matching the observed H\alpha threads with magnetic field lines extrapolated from a nonlinear force-free field model. Observations of chromospheric brightenings at the footpoints of the falling plasma blobs are also presented. The lower limit of the kinetic energy per second of the downflows through the brightenings is found to be \(\sim 10^{25}\) erg. Larger FOV observations from BBSO full-disk H\alpha images show that the AR end of the filament started ascending four hours before the flare. We attribute the observed downflows at the AR end of the filament to the draining effect of the filament rising prior to its eruption. During the slow-rise phase, the downflows continuously drained away \(\sim 10^{15}\) g mass from the filament over a few hours, which is believed to be essential for the instability, and could be an important precursor of eruptive events.

Key words: Sun: activity -- Sun: chromosphere -- Sun: filaments, prominences

Supporting material: animation

1. Introduction

Solar filaments (on disk)/prominences (on limb) have been studied for decades and their structures have become one of the well-known features in the solar atmosphere. They are comprised of numerous cool and dense plasma threads upheld by highly sheared and twisted magnetic fields in the chromosphere and coronae, and can last for days or even weeks in coronae until they disappear in situ or in violent eruptions (Martin 1973). Moreover, filament eruptions could be part of other dynamic and energetic events such as flares and coronal mass ejections (van Driel-Gesztelyi et al. 2012). Filament evolution can give insight into the local magnetic field structure that otherwise cannot be measured directly. For instance, filaments’ spatial evolutions disclose the surrounding magnetic field topologies as a flare evolves (Hirayama 1974).

A filament is composed of a spine, barbs, and two ends. They lie on a sheared arcade and above the magnetic polarity inversion line (PIL) (Kleint et al. 2015). According to some models, the structure of dipped field lines is responsible for dense matter accumulation (Demoulin et al. 1989). Such dip structures form in the magnetic configuration, allowing dense matter to accumulate, and tend to bend down at the top of arcades (Aulanier & Demoulin 1998). Filaments naturally involve radial outward magnetic force, so the weight of this dense matter balances out the upward Lorentz force and results in the filament equilibrium. Magnetic structure expulsion therefore was believed to be a consequence of an inability to confine the magnetic fields (Fong et al. 2002). During the eruption, downflows are expected to be present to drain away most of the filament material, and are accompanied by the upward transport of magnetic flux due to the magnetic field’s ascent (Petrie & Low 2005). A draining rate of \(10^{15}\) g per day in a quiescent filament was estimated by Liu et al. (2012). The magnetic energy that is required for the eruption could be as large as the weight of the removal materials that hold the entire magnetic structure in force equilibrium.

Filament dynamics have been studied in H\alpha and EUV observations through the analysis of the paths of absorption features and Doppler shift (Parenti & Vial 2014). Tracing features of time-sequence images and analyzing spectral line profiles reveal two complementary components: plane-of-sky velocity and line-of-sight (LOS) motion of mass flows. Counter-streaming mass flow along interleaved threads of filaments was first observed through a H\alpha Doppler map with a speed of \(5 \sim 20\text{ km s}\textsuperscript{-1}\) (Zirker et al. 1998). Individual barbs stretched from a quiescent filament spine in Ca\textsc{II} and H and H\alpha lines show a horizontal speed of \(10\text{ km s}\textsuperscript{-1}\) and a downward speed of \(35\text{ km s}\textsuperscript{-1}\) (Kucera 2015). The mass flow of \(25\sim 30\text{ km s}\textsuperscript{-1}\) plane-of-sky velocity from the spine that led to barb formation was also reported by Joshi et al. (2013). In an earlier review by Mackay et al. (2010), downflow blobs moved along the vertical threads in \(\sim 10\text{ km s}\textsuperscript{-1}\). On average, these flows have velocities that are lower than the sound speed of \(20\sim 40\text{ km s}\textsuperscript{-1}\) for prominence plasma (Parenti 2014). But in EUV observations, the flow motion in a filament is faster than that in H\alpha observations, e.g., the counter-steaming flow motion in an active filament can reach \(100\text{ km s}\textsuperscript{-1}\) in the EUV 193 Å band (Alexander et al. 2013). As suggested by Kucera (2015), EUV observations of the moving plasma features have been shown to be faster than what is considered normal in H\alpha. This
is because the hot plasma as observed in EUV is not visible in Hα.

Threads of filament mass flow are to some extent analogous to coronal rain, which can be described as plasma moving along the magnetic field lines (Antolin et al. 2012). The mechanism accountable for filament formation also resembles that of coronal rain due to condensation, yet at a different rate. The filament mass is maintained by condensation at a high rate of $10^{10} \text{g s}^{-1}$ (Liu et al. 2012). In coronal rain the temperature transition of coronal loops along their height and the falling sunward blobs could be observed through AIA 171 Å and 304 Å off-limb observation (Vashalomidze et al. 2015). Compared to coronal rain blobs, which are relatively loose and faint, those threads of filament downflows are much more continuous and dense.

Filament drainage is a common phenomenon in the quiescent phase and eruption phases. They are parts of the coronal cycle (Berger et al. 2010), balanced by the ubiquitous upflows and condensation. Their speeds can be as low as 5 km s$^{-1}$ (Parenti & Vial 2014). Strong draining can be observed in the eruption phase. Huang et al. (2014) observed filament drainage in the pre-eruption phase. Such drainage in the pre-eruption phase has also been reported by Bi et al. (2014). Large-amplitude filament oscillation was observed in the pre-eruption phase, and followed by substantial material drainage prior to eruption. The authors suggested that drainage could play a role in the slow-to-fast transition of filament eruption.

Fine-structure (<500 km) filament drainage can help us understand the eruption mechanism, but it has been rarely observed due to the lack of high spatial resolution observations. In this paper, high-resolution Hα data are from the 1.6 m New Solar Telescope (NST) at the Big Bear Solar Observatory (BBSO), which achieves 0″1 spatial resolution. We observe one end of a small filament in an active region (AR). During the five hour observation period, we see the filament ascending, and see strong consequential downflows toward this end. Unfortunately, the LOS velocity from Doppler measurement cannot be deduced due to the lack of a Hα red wing observation, but we can still find out the characteristics of the strong downflows before eruption by considering the local magnetic field topology, and we can identify the potential role of the drainage as a pre-eruption precursor.

2. Observation and Data Description

The main data source is Hα images from the Visible Imaging Spectrometer (VIS) at NST. In the earlier years of its operation, NST was operated with the 76-element Adaptive Optics System (Goode et al. 2010). In the visible wavelengths, NST achieved a spatial resolution around 0″05 after using 100 frames for speckle reconstruction. The cadence of data is 15 sec. On 2012 July 5, the Hα observations were made through a tunable filter at two wavelengths: the Hα line center (λ6562.808 Å) and 0.75 Å off-band in the blue wing. NST has a limited FOV around 50′′ × 50′′, therefore it only covers a fraction of the targeted AR 11515. In addition, observations were also made in the TiO band (a proxy for the continuum photosphere at 7057 Å). The full-disk Hα line center images were also obtained at BBSO with a separate telescope, with a cadence of one minute and a pixel size of the order of 1″. A small AR filament is visible; one end of the filament is located in the NST FOV at the edge of the largest sunspot of the region (see Figure 1). It is worth noting that a M1.6 flare occurred at 21:39 UT, covered by NST observations.

We also analyze the EUV images obtained from the AIA on board the Solar Dynamic Observatory (SDO), in particular, the EUV images at the wavelengths of 171 Å and 304 Å, which correspond to the corona and upper chromosphere of the Sun, respectively. The 171 Å band is mainly from the Fe IX line, with a characteristic temperature of $10^{5.8}$ K, while the 304 Å is a He II line, with a characteristic temperature of $10^{4.7}$ K (Lemen et al. 2012).

To understand the magnetic structure, we analyzed the vector magnetograph data from HMI on board SDO by conducting nonlinear force-free field (NLFFF) extrapolation. The NLFFF extrapolation model assumes that the corona is static and free of Lorentz force: $\mathbf{j} \times \mathbf{B} = 0$. And the currents must be aligned with the magnetic field: $\nabla \times \mathbf{B} = \alpha \mathbf{B}$, where $\alpha$ is the nonlinear coefficient. Under NLFFF approximation, by assuming the Lorentz force is negligible, $\alpha$ varies in space, and the field evolves slowly through a series of quasi-equilibrium states (Metcalf et al. 2008).

We used hmi.sharp_cea_720s series data, which are disambiguated vector magnetograms with a pixel size of 0″5. It converts data as $(B_r, B_\theta, B_z)$ in a heliocentric spherical coordinate corresponding to $(B_x, -B_y, B_z)$ in the heliographic coordinates (Sun 2013) through cylindrical equal area projection. We congrid the magnetograms to 2″25 pixel and preprocess the data toward a suitable boundary condition to achieve nearly force-free conditions (Wiegelmann et al. 2006). An optimization code with a weighting function was also conducted (Wiegelmann 2004). The extrapolation was performed within a computational domain of 256 × 100 × 200 uniform grid points, corresponding to $\sim$450 × 175 × 350 Mm$^3$.

The most important part of data processing is tracing the flow speed of plasma motions based on Hα observations. We assume that the plasma motion follows magnetic field lines. This is generally true when the plasma pressure is much less than the magnetic pressure. The procedure to track the flows, including the correction of the projection effect, will be discussed in detail in the next section.

3. Results

3.1. Downflowing Threads at the Filament End

Figure 1 shows the filament in NOAA AR 11515 on 2012 July 05, as seen in Hα (Figures 1(a) and (b)), and AIA 171 Å (Figure 1(c)), and 304 Å (Figure 1(d)). In particular, the FOV of the NST/VIS high-resolution Hα observation covers one end of the filament (Figure 1(a)) from 16:41 to 22:22 UT. The filament eruption was associated with a flare at 21:39:00UT. In Figures 1(c) and (d), the filament is seen in AIA 304 Å as a dense loop consisting of dark materials, which shows the low-temperature property of the filament. A rapid temperature transition from 1 MK to 0.05 MK was observed by Vashalomidze et al. (2015). For this event, however, no clear temperature transition can be determined, which may imply a different driver mechanism. The sunspot contours are obtained from HMI white light images. The downflow trajectories are marked by green lines. NST data provide details on the filament threads (white box) and the green lines’ footpoints (red circles; Figure 1(a)). The FOV of NST data is marked in red in Figure 1(b). We observe persistent downflows along the filament threads four hours before the eruption. In Figure 2,
we used the moving plasma blobs as a tracer of the downflow threads and tracked the trajectories of the head (or tail) of these blobs as shown in Figures 2(a)–(h). In this example, about 15 points on average are pinned to determine each trajectory over a period of $\sim 150$ s. The trajectories of four sample downflow threads are shown in Figures 2(e)–(h).

Figures 1(i)–(l) show spacetime diagrams of the curved trajectories of the downflow blobs. We fit the trajectories with a linear function. The slope represents the average plane-of-sky velocity. Acceleration is hard to see in the diagrams, indicating a nearly constant plane-of-sky velocity of the blobs. The upper thread has a larger velocity than the lower thread, which implies that the outer threads hold faster downflows than inner threads. We further estimate the real velocity and acceleration in Section 3.2.

Figure 3 plots the statistical distribution of all the detectable blobs velocities within the NST FOV. We detected 81 blobs in total from 4 hours to 10 minutes before the eruption. It is not
easy to trace the blobs during the flare eruption due to dramatic intensity enhancement. The downflow velocity ranges from 28 to 63 km s\(^{-1}\), with a mean velocity of 45 km s\(^{-1}\). The outer threads host faster downflows than the inner threads. The low-velocity part is from 28 to 40 km s\(^{-1}\), within the range of other filament plane-of-sky velocities (see Joshi et al. 2013; Parenti & Vial 2014; Kucera 2015). The materials with high velocities, in the range of 50–63 km s\(^{-1}\), occupy the outer threads. This may suggest that the high velocities are augmented by the general upward motion associated with the slow-rise phase. The velocity of downflows does not vary dramatically during the four hours before the eruption, from a large-scale
perspective. The small-scale inconstancy of the velocity distribution can help explain the merge and split of those dark materials when they are moving along designated paths.

### 3.2. Filament Foot Real Velocity

We use NLFFF extrapolation to deduce the local magnetic field. The spatial scale of NLFFF is $2''25$, much coarser than that of high-resolution Hα images. In Figure 4, extrapolated field lines at 18:48:00 UT are selected to fit ballistic trajectories of downflows. The ballistic trajectory matches extrapolated fields within the FOV of the high-resolution Hα data. We see many dense materials moving along the field lines. We chose these five NLFFF lines because their footpoints are close to brightening zones (BZs) and hence can help us identify whether these downflow threads are actually landing upon BZs.

The peak height of the field lines ranges from 5 Mm to 15 Mm, which could be the lower limit of the altitude of the filament spine. Assuming the mass motion follows NLFFF lines, we find that the de-projected velocity ranges 40–80 km s$^{-1}$, with a mean of 56 km s$^{-1}$. Both inner threads and outer threads have faster downflows than those in the quiescent phase (Parenti & Vial 2014; Kucera 2015). Due to a high level of activity before or during the eruption, the local field topology may lead to a nonuniform distribution of the velocity. Figure 5 shows the location of the filament over an SDO/HMI LOS magnetogram. The spine of the filament lies along the PILs, while the materials at the end move along the magnetic field lines and tend to cross the PILs. This suggests that the dense materials may accumulate as the magnetic field dips above the PIL, and then slide off along the filament end.

To calculate the total kinetic energy (KE) of the downflows directly flowing into BZs, we assume that the trajectory is a tilted axisymmetric cylinder when flows are close to surface. The electron density of the filament is $10^9$–$10^{11}$ cm$^{-3}$ (Hirayama 1985; Labrosse et al. 2010); here we choose the lower limit of the electron density $n_e = 8 \times 10^9$ cm$^{-3}$ for erupting filaments, and proton mass $m_p = 1.67 \times 10^{-24}$ g. Mass density $\rho_0 = n_e m_p = 1.33 \times 10^{-14}$ g cm$^{-3}$. Area $A = 1.32$ Mm$^2$ was chosen from the lower limit of the BZ’s area, which is determined by the 95% peak intensity. The KE per second of downflow reaching the BZ is estimated to be $5.6 \times 10^{21} \sim 4.5 \times 10^{22}$ erg. $5.6 \times 10^{21}$ erg is regarded as the lower limit of the KE per second through the BZs:

$$KE = \frac{A \rho_0 v^2}{2}.$$ 

### 3.3. Filament Drainage

Figure 6 shows the temporal evolution of the filament before eruption. We can see one end of the filament anchored at the sunspot (AR 11515) ascend, while the other end and the spine part remain stationary. Arch-like expansion is one of the main
procedures that an entire pre-flare filament may undergo (Ramsey & Smith 1963). In a case study by Kleint et al. (2015), a filament shows blueshifted Doppler velocities of 1–10 km s\(^{-1}\) at the pre-eruption phase. Since the downflow threads are confined to the magnetic fields, the expansion and ascent of the filament arcade lead to more radial magnetic field lines and downflowing thread injections. Therefore, more dense materials can be poured downward back to a lower chromospheric layer, resulting in drainage.

The slit image shown in the left panel of Figure 7 is derived from SDO/AIA 304 Å images along the dashed line shown in Figure 1(d). The right panel shows the GOES X-ray flux of the M1.6 flare peak at 21:45 UT. The filament started to ascend from \(\sim15:10\) UT until the eruption at \(\sim21:30\) UT. The slow-rise phase started from \(\sim15:10\) UT with an average plane-of-sky velocity of 0.8 km s\(^{-1}\) and the fast-rise phase started at \(\sim20:20\) UT until the eruption, with a final plane-of-sky velocity of 12 km s\(^{-1}\). It is worth mentioning that the rising velocities are probably severely underestimated due to projection effects.

In a limb event where projection effects are less pronounced (McCaulay et al. 2015), the average slow-rise and fast-rise velocities of a prominence are 2.1 and 106 km s\(^{-1}\), respectively, both of which are higher than our results, 0.8 and 12 km s\(^{-1}\). The high-resolution H\(\alpha\) observation starts from 16:41:47 UT to 22:44:47 UT, and the effective duration for tracking downflow blobs starts from 16:41:47 UT to 20:41:47 UT, which mostly covers the slow-rise phase. Considering cross-sectional area \(A\) to be \(\sim300\) Mm\(^2\), we estimated the mass draining rate \(A \cdot \ell_0 \cdot v\), which is \(2.2 \times 10^{11}\) g s\(^{-1}\) and \(4.0 \times 10^{15}\) g for 5 hr continuous draining during the filament slow-rise phase. This is comparable to the filament clump mass \(\sim10^{15}\) g reported by Bi et al. (2014). The draining rate is faster than \(\sim10^{15}\) g day\(^{-1}\) in a non-eruptive filament studied by Liu et al. (2012). It drains away a certain fraction of the filament mass that is required to confine the magnetic structure, and thus may trigger the transition into the fast-rise phase. As some models indicated (Fong et al. 2002; Low et al. 2003; Petrie & Low 2005), filament drainage...
facilitates the eruption. The flare begins after the slow-to-fast rise phase transition. It may rule out the flare as a potential trigger for the filament eruption. This is different from the event reported by Nagashima et al. (2007), in which a C2.9 flare that occurred when the filament was close to the critical point for loss of equilibrium led to the filament eruption. It should be noted that though the potential roles of the torus and kink instabilities are not discussed here, they can still be responsible for triggering the fast-rise phase. In this way, the persistent downflows may make the filament rise further to meet the critical point for the instabilities.

3.4. Chromospheric Brightening

Gilbert et al. (2013) reported the chromospheric brightenings as the response to the impact of falling material from a partial filament eruption. It was proposed that the plasma compression is the dominant mechanism responsible for the observed brightenings. Here, small-scale BZs are also observed as being associated with the filament downflows from 16:41:47 UT to 21:19:24 UT in the high-resolution observation. Three main BZs of characteristic lengths of ∼1″ are marked in Figures 1(a) and 8. The BZs reside at the footpoints of numerous downflow threads, which are marked by dashed
The BZs may result from plasma heating due to the kinetic energy of the falling material. Unfortunately, the BZs that are just barely resolved in AIA images are shaded by dark filament features, which makes it difficult to derive the radiated energy of the BZs from DEM. Figure 9 shows the temporal evolution of the total Hα intensity over the area of BZs with/without subtracting background contrast. Background fluctuation does not affect the timing of brightenings. The sizes of these BZs keep relatively constant. In addition, these BZs recur successively, with an average lifetime of 20 minutes. Both the lifetimes and sizes of these BZs are 1 order of magnitude greater than those of the brightening footpoints of post-flare downflows, as reported by Jing et al. (2016).

4. Conclusion

To summarize, high-resolution NST Hα observations of NOAA AR 11515 have revealed strong unidirectional downflows toward one end of the filament at the pre-eruption phase of the filament. The ballistic trajectories of downflows keep steady except for a gradual ascent before the filament eruption. The extrapolated NLFFF lines near the AR end match well with the ballistic trajectories of the downflow threads, which helps estimate the real velocities of the downflow threads. Since our high-resolution observation started after the onset of the slow-rise phase, we are unable to identify whether filament drainage facilitates the onset of the slow-rise phase or vice versa. However, because the persistent drainage accompanied the slow-rise phase as early as at least ~4 hr before jumping into the fast-rise phase, we believe that the drainage not only contributes to the filament slow-to-fast-rise phase transition (e.g., Bi et al. 2014; Huang et al. 2014), but that it also maintains or even accelerates the slow-rise phase. The slow-rise phase is often attributed to increasing twist in the flux rope (Fong et al. 2002; Low et al. 2003) that results in an upward force, which is essential for the eventual loss of equilibrium. Pre-eruptive drainage accompanying the slow-rise phase can be regarded as a precursor to the eruption. Successive brightenings were observed on the chromosphere when impacted by the falling material. The plasma heating due to the dissipation of KE into the chromosphere via compression is a more accountable mechanism for the observed brightenings. We speculate that downflows toward one filament footpoint result from the draining effect of the ascending filament prior to its eruption, and might be a precursor to eruptive events.

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