High-resolution Spectroscopy of an Erupting Minifilament and Its Impact on the Nearby Chromosphere

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Abstract

We study the evolution of a miniﬁlament eruption in a quiet region at the center of the solar disk and its impact on the ambient atmosphere. We used high spectral resolution imaging spectroscopy in Hα acquired by the echelle spectrograph of the Vacuum Tower Telescope, Tenerife, Spain; photospheric magnetic ﬁeld observations from the Helioseismic Magnetic Imager; and UV/EUV imaging from the Atmospheric Imaging Assembly of the Solar Dynamics Observatory. The Hα line proﬁles were noise-stripped using principal component analysis and then inverted to produce physical and cloud model parameter maps. The miniﬁlament formed between small-scale, opposite-polarity magnetic features through a series of small reconnection events, and it erupted within an hour after its appearance in Hα. Its development and eruption exhibited similarities to large-scale erupting ﬁlaments, indicating the action of common mechanisms. Its eruption took place in two phases, namely, a slow rise and a fast expansion, and it produced a coronal dimming, before the miniﬁlament disappeared. During its eruption, we detected a complicated velocity pattern, indicative of a twisted, thread-like structure. Part of its material returned to the chromosphere, producing observable effects on nearby low-lying magnetic structures. Cloud model analysis showed that the miniﬁlament was initially similar to other chromospheric ﬁne structures, in terms of optical depth, source function, and Doppler width, but it resembled a large-scale ﬁlament on its course to eruption. High spectral resolution observations of the chromosphere can provide a wealth of information regarding the dynamics and properties of miniﬁlaments and their interactions with the surrounding atmosphere.

Unified Astronomy Thesaurus concepts: The Sun (1693); Solar chromosphere (1479); Active solar chromosphere (1980); Active solar corona (1988); Solar ﬁlament eruptions (1981); High resolution spectroscopy (2096)

Supporting material: animations

1. Introduction

Filaments are elongated structures seen in absorption in strong chromospheric lines (see Mackay et al. 2010; Parenti 2014). These structures contain cool and dense plasma, suspended up to coronal heights by magnetic forces. Although outside active regions the magnetic concentrations are considerably weaker, they can support filaments over a large range of sizes, from giant ﬁlaments, which span across hundreds of megameters (e.g., Yazev & Khmyrov 1988; Kuckein et al. 2016; Diercke et al. 2018), to more compact active region ﬁlaments (see, e.g., Kuckein et al. 2012) and small-scale versions called miniature ﬁlaments, or, more commonly, miniﬁlaments (Hermans & Martin 1986; Wang et al. 2000).

Hermans & Martin (1986) were the ﬁrst to draw attention to these small-scale, elongated features, which were abundant in quiet-Sun Hα time-lapse ﬁlms. They detected 63 events in 32 days of observations taken from the Big Bear Solar Observatory (BBSO) and presented a detailed account of their characteristics. Their average length was 15″, their average lifetime was 70 minutes, and it was estimated that 600 of them appear on the Sun every day. Their evolution exhibited formation, a darkening phase, and an eruptive phase whereby they underwent lateral displacement and outward expansion until eventually disappearing. This early study also indicated that most of these small-scale eruptions were associated with sites of magnetic ﬂux cancellation and pointed out analogies in evolution with their large-scale counterparts. Wang et al. (2000) performed a similar study, but this time also employing magnetograms acquired by the Michelson Doppler Image (MDI; Scherrer et al. 1995) on board the Solar and Helio- sphereic Observatory (SOHO; Domingo et al. 1995). They introduced the term “miniﬁlament,” reported lengths and lifetimes around 19 Mm and 50 minutes, respectively, and emphasized that their loop-like morphology distinguished them from other quiet-Sun structures such as macrospicules.

The advent of space-borne UV and soft X-ray observatories facilitated multiwavelength observations of miniﬁlaments and the study of their evolution in the chromosphere and in the overlying corona. In Sakajiri et al. (2004) and Ren et al. (2008), Hα ﬁltergrams were combined with EUV imaging, showcasing the sequence of events during the formation and eruption of miniﬁlaments, namely, ﬂux cancellation at the photosphere, darkening and expansion of the chromospheric absorption features, rotating motions, and radial eruption of the whole or part of the structures. During this motion, brightenings and EUV/soft X-ray dimmings also occurred.

Subsequent studies demonstrated the close association between miniﬁlaments and other coronal eruptive events. Roughly a quarter of the quiet-Sun miniﬁlaments were involved in eruptions that produced mini-CMEs and even small-scale coronal waves (Innes et al. 2009; Podladchikova et al. 2010; Schrijver 2010). Moore et al. (2010), although not discussing miniﬁlaments per se, estimated that one-third of the coronal jets were produced by the eruption of sheared-core magnetic arcades, similarly to active regions. Raouafi et al. (2010) supported that microsigmoids are progenitors of coronal jets, which can explain the helical structure of the ejecta.
(Patsourakos et al. 2008) and the presence of mini-CMEs. Analysis of two-viewpoint observations of a filament eruption by Hong et al. (2011) supported that mini-CMEs and blowout jets may share a common origin, i.e., a core magnetic structure. Hong et al. (2014) found that brightness enhancements of coronal bright points were related to filament eruption events, which were attributed to reconnection due to flux convergence and cancellation below the loop structure. Sterling et al. (2015) presented more evidence on the role of filament eruption events in coronal ejecta and heating, while recent results indicate that more than two-thirds of the coronal jets in the quiet Sun and coronal holes were associated with filament eruption events (Kumar et al. 2019; McGlasson et al. 2019).

Another interesting aspect is the interaction of filaments with the ambient atmosphere and the effect of their eruptions on nearby solar structures. Earlier studies suggested that part of the erupting filament material returns to the chromosphere (Hermans & Martin 1986; Wang et al. 2000; Sakajiri et al. 2004). More recent studies based on high-resolution EUV imaging showed aspects of this interaction in the corona. When formed in the vicinity of active regions, filaments can interact with the large-scale magnetic field and reconnect with the large-scale magnetic field of active regions (Chen et al. 2019), or other filaments producing jets (Sterling et al. 2019; Yang et al. 2019a). Zheng et al. (2013) found that the eruption of a microsigmoid led to the propagation of a coronal wave, which interacted with nearby loops, producing downflows. Yang et al. (2019b) demonstrated how a filament interacted with large-scale magnetic loops of an active region, causing heating and a blowout jet. They found that the twist of the filament was partly transferred to the newly formed loops.

Based on the aforementioned studies and results, it is largely accepted that the formation and eruption of filaments are dictated by mechanisms common to the ones found in active region filaments. These involve magnetic footpoint motions and shears (Kumar et al. 2018), converging motions during flux emergence, and flux cancellation (Denker & Tritschler 2009; Hong et al. 2011, 2014; Panesar et al. 2017; McGlasson et al. 2019; Sterling et al. 2019). As such, the formation (i.e., bodily emergence of a twisted structure vs. gradual formation) and eruption of filaments (i.e., mechanisms driving the instability) are subject to the same uncertainties and ambiguities as active region filament eruptions (which can lead to flares and CMEs). Studying these structures offers the opportunity to study the same fundamental physical processes in smaller scales, rendering them an ideal target for meter-class (and beyond) telescopes, whose field of view (FOV) is limited.

During the past decade, the study of filament eruptions was mainly limited to high-quality observations of the Solar Dynamics Observatory (SDO; Pesnell et al. 2012), complemented by context Hα imaging. Therefore, the dynamic evolution of erupting filaments and the response of the ambient chromosphere have not been studied in detail yet. Here we present such a detailed study, using time series of high spectral resolution imaging in Hα, which were taken using a new observing setup in the Vacuum Tower Telescope, Tenerife, Spain (VTT; von der Lühe 1998). Spectrally resolved Hα observations of filaments are very few; those that exist are mostly context observations, and, to our knowledge, this is the first time such a study has been performed, showcasing the intriguing nature of filaments and the potential of high spectral resolution observations.

The paper is organized as follows. In Section 2, we describe the observing setup and the data reduction steps. In Section 3, we describe the evolution of the filament eruption and its impact on the nearby chromosphere, based on reconstructed maps of physical quantities, spectral properties, and cloud model (CM) parameters. These results are then discussed in the context of the existing literature in Section 4, where we also highlight our conclusions.

2. Observations and Analysis

The observations were obtained between 07:00 and 13:00 UT on 2019 May 26, from the VTT in Tenerife, Spain. They were part of a coordinated observing campaign, which included the VTT and the Interface Region Imaging Spectrometer (IRIS; De Pontieu et al. 2014). The latter was not used in the present study because the filament was located just outside the southern edge of the IRIS FOV. The target of the campaign was a quiet-Sun region at the solar disk center. The excellent seeing conditions enabled the Kiepenheuer Institute Adaptive Optics System (KAOS; Berkefeld et al. 2010) to lock on quiet-Sun granulation.

Three pco.4000 CCD cameras were mounted at the echelle spectrograph to simultaneously record spectra in three spectral regions, namely, Hα (λ6562.8 Å), Hβ (λ4861 Å), and the magnetic sensitive Cr I line (λ5781 Å). Broadband interference filters were used in front of each camera to block light from overlapping spectral orders. The binning of the cameras was ×4 in the spatial and ×8 in the spectral dimension, resulting in a pixel size along the slit equal to 0′′.36 and a 15 m A pixel−1 spectral resolution. The slit width of the echelle spectrograph was 80 μm, resulting in a scanning step equal to 0′′.36 on the solar surface. This setup offers the opportunity to obtain relatively fast time series of scans, from a few minutes down to a few tens of seconds, depending on the FOV, with very high spectral resolution. In this study we focused on the Hα time series of scans; at each of the 140 steps of the scan, one 70 ms exposure was taken, facilitating 50′′ × 216′′ consecutive scans with a 20 s cadence. This includes overhead for positioning the scan mirror inside the AO system, image acquisition and transfer, and writing the data to disk.

All steps of VTT reduction and analysis of the echelle spectra, namely, dark and flat-field correction, removal of the spectrograph tilt, and wavelength and intensity calibration, were performed in Interactive Data Language (IDL) routines, which are part of the sTools software library (Kuckein et al. 2017). The data reduction process includes principal component analysis (PCA) as a means to clean spectra from noise and blends with telluric lines, to facilitate further spectral analysis. After the process, the clean spectra were centered on the nominal Hα line center at 6562.8 Å, extending ±2.5 Å into the wings, and were then used to produce maps of quantities such as Doppler velocity, line core intensity, FWHM, equivalent width, bisector velocities, etc. For each scan a noise-stripped, average quiet-Sun profile, IQS, was calculated, and from all observed profiles, Iobs contrast profiles, (Iobs − IQS)/IQS, were constructed. From these, radiative transfer and line formation parameters were derived by means of CM inversions (Beckers 1964). We will discuss the CM and its derived parameters in more detail in Section 3.5. Further details on the reduction pipeline of this type of VTT
observations and the use of PCA to denoise spectra and derive CM parameters are given in Dineva et al. (2020).

Context UV and EUV observations were provided by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) of SDO. In this study we used time series of images recorded in the 1600 Å, 304 Å, 171 Å, and 193 Å channels. The cadence of the observations was 24 s for the 1600 Å channel and 12 s for the rest. Furthermore, we used the LOS magnetograms provided every 45 s by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012; Schou et al. 2012).

The region encompassing the minifilament eruption was scanned by the echelle spectrograph between 10:03 UT and 10:50 UT (Figure 1), thus capturing the eruption that took place around 10:25 UT. However, the evolution of the region before the formation and eruption of the minifilament was monitored using AIA and HMI, as well as slit-jaw (SJ) images of the echelle spectograph in Hα and Ca II K.

The co-alignment of the observations was performed first by comparing the SJ images of the echelle spectrograph in Ca II K with the AIA filtergrams at 1600 Å and, therefore, the rest of the AIA channels. The 1600 Å filtergrams were then co-aligned with the HMI magnetograms.

3. Results

3.1. Overview of the Minifilament Formation and Eruption

Figure 1 shows the quiet region near solar disk center as observed on 2019 May 26 by VTT and SDO. The minifilament was formed in the region between a slightly more extended negative magnetic polarity footpoint and some smaller positive ones. When fully formed, it had an S shape, with the southern, convex part being more extended than the northern, concave one. The Hα SJ images show the typical mottled appearance of the chromosphere, wherein the minifilament resides with a contrast similar to that of the other fine structures (mottles or fibrils). In 304 Å, the region showed the typical network emission, corresponding to small coronal bright points seen in the 171 Å channel.

An overview of the evolution of the region prior and during the eruption is presented in Figure 2. The photospheric magnetic field (bottom row) did not show any pronounced variation, e.g., flux emergence or cancellation, although it is possible that these mechanisms acted on a scale near or below the resolution and sensitivity limit of HMI, as the small-scale magnetic field was reconfiguring to produce the minifilament. Applying the Differential Affine Velocity Estimator (DAVE; Schuck 2006) method, we found persistent converging motions of the two magnetic polarities toward the neutral line. The green curve in Figure 2 (09:20 UT, bottom row) marks the minifilament as seen in the SJ images at that time and roughly indicates the region of the neutral line. On top of the aforementioned converging motion, the individual points exhibited apparent proper motions in smaller scale, rotating and shuffling. By the end of the observations, the negative polarity became more compact and the opposite-polarity footpoints approached each other. Converging motions of the footpoints, as the ones found here, are often considered to be the cause of minifilament eruptions (Hong et al. 2011, 2014; Kumar et al. 2018).

The EUV emission of the region exhibited intense variability. In the hotter emission channels (171 Å and 193 Å) a structure resembling a microsigmoid was visible at the beginning of the observations. This structure underwent changes in shape and brightness, giving the impression of an interaction between the bright loops that were initially connecting the magnetic footpoints of the region (08:43 UT).

The minifilament was gradually forming and eventually seen at 09:20 UT in the 171 Å and 304 Å channels, embedded in a bright envelope. At the same time, the minifilament appeared clearly in the Hα SJ images (not shown). The brightenings seen above and around the structure in EUV can be attributed to successive reconnection events. These can build up the magnetic flux and provide the minifilament with plasma, reconfiguring the overlying magnetic field to facilitate its eruption, similarly to what is observed in active regions. The entire minifilament is clearly discernible in EUV images after 10:10 UT, first in the 304 Å and then in the 171 Å and 193 Å channels. After the last brightening seen at the lower part of the minifilament (10:20 UT), it eventually erupted. This sequence of events supports a scenario where, upon its formation, the structure started to rise slowly, reconnected with the overlying magnetic field, and gradually made its way to eruption.

As seen clearly in the 193 Å and 171 Å filtergrams (Figure 2, first and second row), the minifilament did not erupt homogeneously. The northern part erupted first, became more opaque than the southern part, and traversed a much smaller distance, exhibiting a quasi-rotational motion in the east-to-west direction. Conversely, the southern part, which was more...
clearly visible in the chromosphere, had a conspicuous semicircular shape, and its expansion and eruption had a more pronounced horizontal component, sweeping the ambient atmosphere and producing more extended dimmings in all EUV channels. Based on these observations, we conjecture that the northern part of the mini-filament had a significant propagation component along the LOS while the southern part had also a predominant horizontal expansion component. The H\(\alpha\) spectroscopic observations described in the following section will corroborate the latter conjecture.

Given the time of its first unambiguous detection in H\(\alpha\) and the time of its eruption, it is estimated that the lifetime of the mini-filament was of the order of 1 hr, similarly to what was reported by Wang et al. (2000) and Hermans & Martin (1986). However, the entire formation process could not be monitored by the H\(\alpha\) spectroscopy because these observations started at 10:03 UT, when the mini-filament was already formed. Instead, we were able to monitor the later stages of evolution toward the eruption of the southern, convex part, which we will describe in detail in the next section.

3.2. Slit-reconstructed Maps of H\(\alpha\) Spectral Characteristics

The FOV of the echelle spectrograph contained the southern part of the mini-filament and its eruption. In the following we will be referring to this part as the "mini-filament," for brevity. In Figure 3 we present the slit-reconstructed maps of some key spectral parameters of the H\(\alpha\) line, namely, the Doppler-shift-compensated minimum intensity (simply: core intensity), the Doppler velocity (derived through a Gaussian fit), the FWHM, and the bisector velocity measured at the half-maximum of the profile (BVHM). Although the line formation processes of H\(\alpha\) are complicated, it can be considered that each of these parameters represents a different type of information encapsulated in the H\(\alpha\) profiles. The core intensity and Doppler velocity characterize the highest chromospheric layers of line formation, while the FWHM is associated with heating and the BVHM characterizes motions, both seen at lower chromospheric heights (Cauzzi et al. 2009; Leenaarts et al. 2012). We study these maps along with the images in 304 Å and 171 Å, to get a closer and more detailed view of its evolution across all atmospheric layers.

As seen in the top two rows of Figure 3, this part of the mini-filament became darker, became thicker, and started expanding radially after 10:11 UT. Nine minutes later, it erupted almost radially, producing a dimming that swept across the nearby atmosphere. This dimming and its propagation were more pronounced in the coronal 171 Å emission, extending out to 20–25 Mm from its origin, and less in the upper chromospheric 304 Å emission. Behind the dark rim of the propagating dimming, coronal and chromospheric brightenings appeared, near both “footpoints” of the mini-filament. These EUV brightenings are common in mini-filament eruptions (see, e.g., Hong et al. 2011) and can be attributed to the reconnection with the magnetic field of the source region.

The third row of Figure 3 shows the evolution of the H\(\alpha\) line core intensity. In these maps we see more clearly the chromospheric counterpart of the thickening, darkening, and...
eruption. Brightenings peek out behind the structure, corresponding to the ones seen in the hotter channels of AIA. At 10:30 UT an arc-like structure is protruding from the main body of the minifilament (“1”), which was fully formed 3 minutes later as a second arc-shaped absorption structure ahead of the main body of the minifilament. Five minutes later (10:38 UT) the chromospheric counterpart of the minifilament was already fragmented, leaving behind only its lower arm (“2”). From 10:33 UT to 10:38 UT this part of the minifilament evolved from an apparent homogeneous cylindrical into a wider spiral shape (see Figure 3 and accompanying movie), indicating that the minifilament was a twisted structure. After the eruption, this remaining spiral arm eventually moved laterally, its fragments dissolving into the chromospheric Hα background. Both the protruding arc and the dissolving arm support that the minifilament consisted of finer threads.

The Doppler velocity maps in Figure 3 (fourth row) show that initially the minifilament exhibited a bulk upward motion with velocity in excess of 5 km s⁻¹. After this initial bulk motion, the southern part of the structure moved downward (see, e.g., 10:30 UT), while the northern part maintained its upward motion. The secondary arc-like structure that

Figure 3. Overview of the minifilament eruption. From top to bottom are the AIA filtergrams in 171 Å and 304 Å (for context), the Hα Doppler-shift-compensated core intensity, Doppler velocity (scaled between ±5 km s⁻¹), FWHM, BVHM (scaled between ±5 km s⁻¹), and HMI photospheric magnetograms. To facilitate comparison, the cutouts are aligned to the reference system defined by the slit orientation and scan direction of the echelle spectrograph. Numbers and arrows denote features of interest (see text). The Cartesian axes at the top left indicate the orientation of the solar north and west directions. The animation of this figure shows the entire time series of reconstructed Hα maps and coaligned AIA filtergrams/HMI magnetograms, in a horizontal configuration, between 10:11 UT and 10:49 UT. (An animation of this figure is available.)
developed after 10:30 UT continued the upward motion until its disappearance from the Hα maps. Interestingly, at the lower part of this secondary, blueshifted arc strong downflows are found (10:33 UT “3”), which indicate interaction with the neighboring small-scale magnetic structures of the quiet Sun. The spiral-shaped arm that remained from the eruption exhibited strong alternating upward and downward motions (10:38 UT, “4”), further supporting a spiral structure of the minifilament. Strong downflows are also found in some of the minifilament footpoints, which coincide with the intense brightenings seen in 171 Å and 304 Å. The Doppler velocity maps at 10:47 UT and 10:48 UT indicate that after the eruption strong downflows were located ahead of the erupting minifilament and at its footpoints. We will further discuss these in the following description of the FWHM and BVHM maps.

The FWHM maps of the region (Figure 3, fifth row) show that the minifilament consisted mostly of plasma with narrower Hα absorption profiles. During the expansion, this plasma was found mostly around the apex, while toward the “footpoints” (i.e., the region closer to the edge of the FOV and in the vicinity of the photospheric magnetic elements), FWHM values were considerably higher. This was more pronounced at the locations where the brightenings are seen at the upper part of the minifilament. A larger FWHM is also detected at the site of interaction between the secondary arc and the nearby quiet-Sun magnetic fields, as well as at locations of strong downflows that followed the eruption.

The reconstructed maps of the BVHM (Figure 3, sixth row) largely follow the velocity pattern exhibited by the Doppler velocity, but with some notable differences. After the eruption, they show very pronounced redshifts, over more extended patches on the FOV (10:38 UT, “5”). These are attributed to strong downflows after the eruption and indicate that the corresponding spectral profiles are not only redshifted but also highly asymmetric. Since the BVHM is sensitive to motions lower in the chromosphere (Dineva et al. 2020; Verma et al. 2020), these strong downflows are attributed to the interaction of the minifilament material with the chromosphere below. In the following, we will discuss these profiles in detail and the regions where they occurred.

3.3. Spacetime Slices and High-resolution Spectra of the Minifilament Apex

In Figure 4 we plot spacetime (X–t) slices, to study the motion of the apex and the lower spiral arm of the minifilament. These 2°-wide slices were taken along the horizontal lines seen in Figure 3 (top row, 10:30 UT). Overall, the traces of the minifilament in 171 Å are considerably thicker than the ones in 304 Å and Hα, showing the much more extended impact of the eruption to the coronal environment. The shift between the traces of the eruption in Hα and the hotter channels is also a result of different formation heights, as the eruption is more extended in the higher layers. The Hα Doppler velocity maps show how the initial upward bulk motion is followed by intense downflows at the apex of the minifilament. Although the minifilament then disappeared from the X–t slices of core intensity, patches of large FWHM and intense downflows are seen along the extension of its...
Figure 5. Evolution of Hα line profiles and spectral characteristics along the trajectory of the minifilament apex. (a–b) Evolution of the original spectral line profiles and the PCA-denoised contrast profiles, respectively. (c–f) Evolution of the corresponding line core intensity, Doppler velocity, FWHM, and BVHM. The horizontal lines in panels (c) and (e) denote quiet-Sun averages, derived from observations.

The X–t slices of the arm (Figure 4, bottom row) show an overall thicker and more complicated trace. As already mentioned previously, this part exhibited an apparent (un)twisting and lateral motion until eventually fading. The corresponding X–t slices show an alternating upward and downward velocity pattern, supporting this interpretation. Next, we examine the spectra and spectral characteristics along the trace of the apex, which was determined in Figure 4. Panels (a) and (b) of Figure 5 contain two different representations of the evolution of these Hα line profiles, one as overplotted profiles, where time is denoted by colors from blue to red, and one as stacked contrast profiles, where time is the vertical axis. In panel (a) we have also included a time-average quiet-Sun profile (plotted in black), taken in a region of the FOV with no pronounced absorption features. The Hα profiles (Figure 5(a)) vary with time, first becoming blue-shifted, deeper, and narrower and then redshifted, shallower, wider, and clearly asymmetric. The contrast profiles (Figure 5(b)) show more clearly the progression of the velocity of the opaque minifilament material of the apex. Dark patches, which correspond to increased absorption, shift from the blue wing (10:20–10:30 UT) to the far red (Δλ > 1 Å), after the eruption and breakup of the structure.

A parametric representation of the temporal variation of the spectral profiles of the apex is given in panels (c)–(f) of Figure 5. In panels (c) and (e) we have also marked the level of time-averaged quiet-Sun Hα core intensity and FWHM, calculated in a region with no pronounced absorption features. The core intensity (Figure 5(c)) decreases continuously until 10:30 UT, as the filament darkens and thickens, from 0.15 · b_{back} to 0.11 · b_{back}, which corresponds roughly to a 25% change in line core intensity during the darkening phase of the minifilament. After that, the line core intensity reaches and surpasses the quiet-Sun levels by about 15%, as the...
minifilament disappears. This increase resulted from the impact of the minifilament material on the nearby chromosphere. Similarly, the upward Doppler velocity, observed clearly until 10:25 UT, gradually turns downward, eventually leading to strong downflows observed after the eruption (Figure 5(d)). The temporal variation of the FWHM and BVHM (Figures 5(e) and (f)) is not very pronounced until 10:30 UT. The FWHM is lower compared to the average quiet Sun, indicating that the minifilament contains cool chromospheric material, but the FWHM increases rapidly after 10:35 UT (reaching ∼1.9 Å). The bisector velocity, although it qualitatively follows the evolution of the core velocity, is not very sensitive to macroscopic motions of the minifilament, hence the very low negative values until 10:25 UT. It is, however, exhibiting a steep rise, reaching as high as 10 km s⁻¹, when the minifilament material impacts on the nearby lower chromospheric structures.

3.4. Interaction with the Nearby Chromosphere

The analysis presented so far indicates that a defining characteristic of the impact of the minifilament material on the nearby chromosphere is not the line core absorption but the BVHM. As already mentioned, this velocity refers to lower chromospheric heights than the Doppler velocity of the line core and is associated with asymmetric profiles. We utilize this to study the spatial distribution and extent of this effect. We used a threshold of 3 km s⁻¹, corresponding to the 3σ level from the average BVHM (which was calculated over the entire FOV and time series, and it was equal to 0 km s⁻¹). Then, we located the points that exhibited a maximum BVHM higher than this threshold, after 10:35 UT.

In Figure 6, these locations are found over the projected expansion of the minifilament, after its eruption (see the black contour provided for context). They are not homogeneously distributed within the FOV; instead, they are strongly associated with, or adjacent to, nearby, small-scale magnetic concentrations. Since these are connected via small-scale, low-lying magnetic loops (see, e.g., Kontogiannis et al. 2018), the observed pattern is the result of the interaction between the returning minifilament material and the chromospheric magnetic loops. The color of the locations in Figure 6 ranges from black to red, showing also the “propagation” of this effect, from locations closer to the minifilament to sites located farther away. The strongest effect is directly around the apex (“1” in Figure 6) and covers a distance of more than 10 Mm. The remaining spiraling arm of the minifilament also has an impact, as indicated by the high-BVHM patches at “2,” seen toward the end of the time series when the corresponding part of the minifilament dissolves into the chromospheric background. A smaller patch can be associated with the upper arm of the minifilament at “3.” These findings provide conclusive evidence to the conjecture made by Wang et al. (2000), that part of the material of the minifilament returns to the chromosphere and provides an explanation of the downflows detected in Hα line-wing filtergrams by Sakajiri et al. (2004) and Ren et al. (2008).

3.5. Cloud Model Analysis of the Minifilament

The CM can be used to invert spectra from a chromospheric structure, under the simplifying assumption that the structure is suspended in the atmosphere like a cloud of plasma, absorbing the background radiation (see Tziotziou 2007, for a review). The model assumes that the emerging spectral line profile can be fully represented by four parameters, namely, the optical depth τ, the source function S (as a fraction of the background irradiation), the Doppler velocity vD, and the Doppler width ΔλD, which are constant along the line of sight (LOS) within the structure. Furthermore, the optical thickness has a Gaussian dependence on wavelength, while the source function is wavelength independent. The parameters are derived by inverting the contrast profiles of the structure, which are taken in reference to an average absorption profile taken from a nearby quiet-Sun region, free from prominent absorption structures (see, e.g., the black line in Figure 5(a)). Typical structures that have been treated with CM are chromospheric mottles or fibrils (see, e.g., Tsiropoulou & Schmieder 1997; Tziotziou et al. 2003), filaments (e.g., Kuckein et al. 2016), arch-filament systems (González Manrique et al. 2017), and surges (Verma et al. 2020). In this study, as already mentioned, contrast profiles were processed by applying an iterative PCA process to remove noise before feeding the CM inversion scheme.

To follow the evolution of the minifilament as it expands and erupts, a threshold on the absolute contrast value of the Hα profiles over the entire FOV is not sufficient, because other quiet-Sun network regions may satisfy this condition and be erroneously counted as part of the minifilament. We set a threshold in the contrast value that generously covered the minifilament and refined it by manually setting an ROI, which contained the minifilament as it expanded, excluding the nearby atmosphere. The drawback of this method is that the investigated region grew with time, but we base it on the assumption that the imprint of the evolving structure within this region will be more easily recognizable, instead of using the entire FOV. For these masks we kept only the good fits and discarded the bad ones (see Dineva et al. 2020, for the set of criteria that were used to identify good fits).

Using these masks, we plot maps of the four CM parameters in Figure 7. At 10:25 UT, i.e., just before its eruption, the minifilament already has high optical depth and low source
function and Doppler width. Therefore, it consists of optically thick, cool, and dense plasma, with the exception of the footpoints, which exhibit high Doppler width and are consequently associated with heating. At this instance, the minifilament exhibits a bulk upward motion, with velocities exceeding 10 km s\(^{-1}\). The velocities calculated with CM are always higher than the Doppler shifts shown in the maps of Figure 3 (Chae et al. 2006; Kuckein et al. 2016; Dineva et al. 2020).

During the eruption (10:30–10:33 UT), the optical depth of the minifilament near the apex decreases, as the plasma becomes thinner along the LOS, as a result of the expansion of the structure. However, the arms still maintain their optical thickness. Along the entire minifilament, the source function does not present any notable changes during the eruption. The Doppler width increases in progressively larger parts of the structure, mostly closer to the footpoints, indicating heating of the plasma that constitutes the minifilament. The Doppler velocity maps show that mostly the middle part continues to move upward, while the footpoints start receding. At 10:33 UT, the velocity map indicates a more complex flow pattern along the minifilament. Although the middle part maintains the upward motion, the lower part exhibits a pattern of alternating red- and blueshifts, which persist (10:38 UT). This pattern is indicative of a three-dimensional motion of the body of the minifilament, possibly exhibiting twisting and writhe as it is stretched owing to its eruption. At 10:38 UT, the shape of this lower part resembles a spiral-like structure, whose decreasing optical depth indicates that it has already started to fade. The Doppler width is higher at the outer parts of the arm than at the middle, which also supports the presence of a complex three-dimensional twisting flow pattern. At the outer parts of the arm, where motions of the spiraling plasma will be roughly along the LOS, velocity gradients will contribute to the Doppler width. In contrast, along the main axis, where these motions are roughly perpendicular to the LOS, this contribution will be much lower. Finally, the regions of the nearby chromosphere ahead of the apex of the minifilament and its upper footpoint are more optically thick, with higher source function, high Doppler width, and predominant strong downflows.

Using the minifilament masks constructed for each scan, we calculated the two-dimensional density distribution functions of the four CM parameters in the parameter space over time, in 2-minute-wide bins (Figure 8). As already mentioned, the area of the masks, and hence the number of pixels they contained, increased with time, following the expansion of the minifilament. Therefore, we express the density as a percentage of the number of pixels contained in each mask.

The distribution functions of the CM parameters (Figure 8) show clear evolutionary trends of the erupting minifilament within the density distribution of the background pixels. These trends are visible after 10:20 UT, when the structure is more clearly seen in the H\(_\alpha\) scans. As the minifilament appears in the FOV, the source function density distribution shifts to lower values and then increases during the eruption (after 10:20 UT), before subsiding gradually to the quiet-Sun background of the masks. Conversely, the optical depth exhibits a slight increase, but the distribution functions are highly skewed toward high values, as per the appearance of optically thick plasma, reaching values as high as two. These values then tend to decrease during the eruption. The Doppler velocity, initially with no pronounced preferred direction, was predominantly upward after 10:20 UT, with upward motions in excess of 10 km s\(^{-1}\). This upward motion was followed by a bulk downward motion of the minifilament material, which then led to the strong downflows with velocities up to 20 km s\(^{-1}\), as discussed also in the previous sections. The Doppler velocities derived with the CM are more representative of the actual motions of the downflowing material. The evolutionary signature of the minifilament is also seen in the density function of the Doppler width. Initially, the minifilament is characterized by narrower absorption profiles than the average quiet Sun, with Doppler widths equal to \(\Delta \lambda = 0.3\) Å, with the exception of its footpoints (\(\Delta \lambda > 0.5\) Å). During and after the eruption, spectral profiles with higher Doppler width are more abundant. The profiles associated with the strong downflows are predominantly wider, with Doppler widths exceeding \(\Delta \lambda = 0.4\) Å.

It is useful to see how the measured CM parameters of the minifilament compare with other H\(_\alpha\) absorption structures. For example, Tziotziou et al. (2003) find that chromospheric mottles have optical depth, source function, and Doppler widths around 1.00, 0.15, and 0.45 Å, respectively, which roughly agree with the ones also reported earlier by Tsiropoula & Schmieder (1997). The corresponding average values for arch-filament systems reported by González Manrique et al. (2017) were 1.19, 0.12, and 0.41 Å, while Kuckein et al. (2016) found that the giant filament of their study had corresponding values equal to 1.59, 0.07, and 0.39 Å. These values, along with the density distributions of Figure 8, indicate that minifilaments are closer to quiet-Sun structures when they form, but they acquire more filament-like properties during their evolution toward eruption. In that sense, minifilaments stand out from the chromospheric fine-structure contrast background (i.e., fibrils) when they are on their course to eruption, as already noted by Hermans & Martin (1986).
4. Discussion and Conclusions

A new observing setup at the VTT allowed us to acquire high spectral resolution scans of extended regions with a fast cadence equal to 20 s. Using this setup, we were able to capture the eruption of a quiet-Sun minifilament, revealing hitherto-unnoticed aspects of their dynamic evolution in the chromosphere and their interaction with neighboring structures.

Spectroscopic inversions based on the CM (Beckers 1964) were performed for the first time for such a structure. The inferred values were close to those of other chromospheric structures, but these values started to differ notably when the expansion/eruption process was initiated. Then, the minifilament stood out from the chromospheric "forest" and started resembling its large-scale counterparts.

Initially, it contained cool chromospheric plasma and exhibited increasing opacity along with radial expansion. In the chromosphere, we measured a projected speed equal to 2.2 km s\(^{-1}\) for the slow expansion and a faster speed of 17.6 km s\(^{-1}\) for the eruptive phase. These values are comparable to speeds derived by Panesar et al. (2020) for a number of jet-like events involving minifilament eruptions. The two phases of eruption, which are also common in active region filaments, were also supported by the Doppler velocities of the high-resolution H\(\alpha\) spectra. During the slow expansion phase, the minifilament was moving upward as a single structure, before exhibiting a more complicated velocity pattern during the eruption. This pattern comprised alternating blue- and redshifted patches, which we interpreted as the result of a three-dimensional motion with twisting and writhing components. This intricate velocity structure points to the minifilament being a twisted structure, possibly a small-scale flux rope. The distributions of FWHM and Doppler width, derived via CM inversions, also support this interpretation. However, detailed analyses of more observations in the future can shed more light on the structure and development of flows and instabilities in minifilaments.

During the eruption, a secondary arc protruded from the minifilament, which continued to move upward before disappearing, implying a thread-like structure of the minifilament. The southern end of this structure interacted with a nearby small-scale structure, causing strong downflows and broadening in the H\(\alpha\) profiles. The rest of the minifilament started disappearing, first around its apex and then more toward its footpoints. Part of the material returned to the chromosphere, interacting with nearby small-scale magnetic structures. This was evident by the high values of the BVHM and the FWHM at the wake of the eruption. The corresponding line profiles at these regions were highly asymmetric with broad shoulders in the red wing, indicating strong downflows and velocity gradients, as the minifilament material collided with the low-lying chromospheric structures. CM inversions showed that at these sites downflow velocities exceeded 10 km s\(^{-1}\) and Doppler widths surpassed 0.5 Å.

The minifilament was associated with brightenings near its apparent footpoints, another common feature reported in the literature (e.g., Ren et al. 2008; Hong et al. 2011; Chen et al. 2018b). Some of these were seen in EUV, more brightly in 304 Å, before the start of the slow expansion. Others appeared gradually as the minifilament expanded, before the fast motion. They were also detected in the H\(\alpha\) core intensity and were associated with large FWHM and strong downflows. Such a brightening was also evident at the northern part of the minifilament. These brightenings can be attributed to reconnection below the minifilament as a result of tether cutting, as the structure stretched the field lines of the constraining magnetic field (see, e.g., the observations of an erupting active region filament in Chen et al. 2018a). More likely, however, they can be due to the interaction between the minifilament and the small-scale magnetic fields, as the former expanded above them, leaving the neutral line region. These reconnection
events can act as a driver for the fast expansion that followed (Sterling & Moore 2005; Panesar et al. 2020).

Regarding the origin of the minifilament, our EUV observations and context Hα SJ images suggest that the structure formed during the observations and did not emerge bodily. No magnetic flux emergence of the scale that would justify the appearance of the structure took place at least 3 hr before the observations. The morphological evolution of the region in EUV suggests a transition from sheared loops to a sigmoid structure. This means that the structure was gradually building up through successive reconnection events. However, lack of Hα scans across the entire structure did not allow us to monitor the processes that led to the formation of the minifilament.

Recent studies attest to the critical role of minifilaments in the dynamics of the quiet Sun and support that common physical mechanisms act in both large-scale and miniature filaments. Similarly to active regions, but at a considerably smaller scale, the magnetic field of the quiet Sun can produce complicated magnetic configurations, amenable to the same instabilities as their active region counterparts, which can, in turn, give rise to various eruptive phenomena. Findings regarding the abundance of sigmoidal structures in the quiet Sun and the nonpotentiality of the small-scale magnetic fields (Chesny et al. 2013, 2015, 2016) support this analogy, albeit coming from a different standpoint. Another pertinent example is the finding that the quiet-Sun magnetic fields of the network obey a fundamental free energy—magnetic helicity relationship (Tziotziou et al. 2014), similarly to active regions, although in the quiet Sun magnetic helicity builds mainly because of the action of the shuffling motions on small-scale magnetic fields (Tziotziou et al. 2015). Chen et al. (2018b) attributed the formation of a minifilament to such motions, resulting in helicity injection after emergence of small-scale magnetic flux. The persistent converging motions of the magnetic footpoints of the region also seem to be involved in the formation and destabilization of the minifilament presented here. This implied analogy between large- and small-scale phenomena may extend to even smaller (perhaps granular) scales (see, e.g., Sterling et al. 2020). The high spatial and temporal resolution, together with unprecedented multiwavelength capabilities, of the new generation of solar telescopes, such as the Daniel K. Inouye Solar Telescope (DKIST; Tritschler et al. 2016) and the European Solar Telescope (EST; Jurčák et al. 2019), will play an important role in better understanding the small-scale nature of minifilaments.

A future goal is to capture the evolution of minifilaments during their formation and along their entire length. Further high-quality, multiwavelength observations are needed to decipher their structure, flow fields, and intricate interactions with the chromosphere and corona. To this end, we anticipate the contributions not only from the new facilities underway but also from observing setups such as the one used in this study. Such a configuration offers very high spectral resolution combined with fast temporal coverage and good spatial resolution; not only can it provide invaluable insight into the processes that take place in the chromospheric and photospheric environment, but it also offers a more accurate and reliable reference for future magnetohydrodynamics and radiative transfer modeling efforts.

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Software: SolarSoft IDL (Bentley & Freeland 1998; Freeland & Handy 1998), sTools (Kuckein et al. 2017; Dineva et al. 2020).

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