Increase in the Amplitude of Line-of-sight Velocities of the Small-scale Motions in a Solar Filament before Eruption

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Abstract

We present a study on the evolution of the small-scale velocity field in a solar filament as it approaches the eruption. The observation was carried out by the Solar Dynamics Doppler Imager (SDDI) that was newly installed on the Solar Magnetic Activity Research Telescope at Hida Observatory. The SDDI obtains a narrowband full-disc image of the Sun at 73 channels from Hα − 9.0 Å to Hα + 9.0 Å, allowing us to study the line-of-sight (LOS) velocity of the filament before and during the eruption. The observed filament is a quiescent filament that erupted on 2016 November 5. We derived the LOS velocity at each pixel in the filament using the Becker’s cloud model, and made the histograms of the LOS velocity at each time. The standard deviation of the LOS velocity distribution can be regarded as a measure for the amplitude of the small-scale motion in the filament. We found that the standard deviation on the previous day of the eruption was mostly constant around 2–3 km s⁻¹, and it slightly increased to 3–4 km s⁻¹ on the day of the eruption. It shows a further increase, with a rate of 1.1 m s⁻², about three hours before eruption, and another increase, with a rate of 2.8 m s⁻², about an hour before eruption. From this result we suggest that the increase in the amplitude of the small-scale motions in a filament can be regarded as a precursor of the eruption.

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

1. Introduction

Dark filaments, or prominences, which are dense cooler plasmas supported by a magnetic field in the solar corona, often become unstable and erupt. Filament eruption is associated with various phenomena such as flares, coronal mass ejections (CMEs), and giant arcade formations in the quiet Sun. Despite their diversity in size, morphology, and emitting radiation spectrum, they are considered different aspects of the common magnetohydrodynamical processes that involve plasma ejection and magnetic reconnection (Shibata & Magara 2011).

Filament eruptions often follow the slow rise (Sterling & Moore 2004; Sterling et al. 2011), plasma motions (Isobe & Tripathi 2006; Gosain et al. 2009), weak heating (Chifor et al. 2006), and increased internal motions (Tandberg-Hanssen 1995) in the filament. In the more general context of the solar eruptions, various kinds of "precursors" have been proposed, including emerging magnetic flux (Feynman & Martin 1995; Chen & Shibata 2000; Kusano et al. 2012), magnetic reconnection at various magnetic configurations (Antiochos et al. 1999; Moore et al. 2001), and helicity injection (Magara & Tsuneta 2008; Harra et al. 2009). Of particular interest for the present study is the pre-flare increase in the non-thermal velocity. Via a spectroscopic observation in the coronal line, Harra et al. (2001) found non-thermal line broadening before the increase in the X-ray flux and the electron temperature, suggesting an increase in the turbulent motion taking place before the onset of the flare.

In this Letter, we report the observation of a quiescent filament eruption by the Solar Dynamics Doppler Imager (SDDI; Ichimoto et al. 2017) newly installed on the on the Solar Magnetic Activity Research Telescope (SMART; Ueno et al. 2004) at Hida Observatory, Kyoto University. The SDDI takes full-disc solar images at 73 wavelength positions around Hα, which allows us to monitor the Hα line profile of the filament prior to and during an eruption.

2. Observation

The SDDI installed on the SMART at Hida Observatory of Kyoto University has been conducting a routine observation since 2016 May 1. It takes the solar full-disc images of 73 channels at every 0.25 Å from the Hα line center −9.0 Å to the Hα line center +9.0 Å, i.e., at 36 positions in the blue wing, the Hα line center, and 36 positions in the Hα red wing. Each image is obtained with a time cadence of 15 seconds and a pixel size of about 1.2 arcsec.

In this Letter we used the SDDI images taken from 23:00UT on 2016 November 3 to 7:00UT on 2016 November 4 and from 22:00UT on 2016 November 4 to 5:00UT on 2016 November 5. Figure 1 shows the full-disc image at the Hα center at 00:22:46UT on November 5.

The filament was located in the quiet Sun in the northern hemisphere, and it erupted around 3:30UT on November 5. There are weak active regions, including NOAA 12605 on the Sun, but the overall solar activity was very low. Thanks to the low activity, the eruption can be barely identified as a B1-class event in the GOES soft X-ray flux, shown in Figure 2.

The gradual enhancement starting around 4:00UT and peaking around 4:50UT corresponds to the filament eruption. In the EUV images from the SDO/AIA (Lemen et al. 2012), formation of a giant arcade after the filament eruption can be found (not shown in the figures). The erupted filament eventually became a slow CME, which seems to be the cause...
of the moderate disturbance of the geomagnetic field from November 9 to 10.

We applied the Beckers’s cloud model (Beckers 1964; Mein & Mein 1988) to the SDDI data. By applying the model to the images taken at multiple channels around Hα we can determine source function, Doppler width, Doppler shift, and optical depth of filaments. The plane-of-sky motion in the images and the Doppler shift derived from the model can be used to calculate the three-dimensional velocity of erupting filaments (Morimoto & Kurokawa 2003a, 2003b; Morimoto et al. 2010; Cabezas et al. 2017). The wide wavelength coverage and the high spectral resolution of the SDDI allow us to determine the physical parameters precisely, even when the line profile shifts from the nominal line center (6563 Å) significantly. From the Doppler shift, we obtain the line-of-sight (LOS) velocity at each pixel in the filament, and the LOS velocity images are shown in Figure 3.

To derive the LOS velocity at each pixel, we conducted three automatic steps to determine the binary images, which can cover most of the pixels inside the filament (we call them “masks”). First, we determined the positions of the pixels where the intensities are lower than $I_m - 2\sigma_I$ ($I_m$ is the average of the intensities inside the black square area shown in Figure 1 and $\sigma_I$ is their standard deviation) for each wavelength image and got all the positions together to obtain a binary image whose pixels at the same positions have 1 and the other pixels have 0. After that, we smoothed the obtained images by taking the average of $5 \times 5$ pixels around each pixel and selecting the pixels whose values are 1. The last step was to conduct the “dilation” and “erosion” processes. Dilation is a process in which, if at least one of the surrounding pixels is 1 for a certain pixel, the pixel will become 1, i.e., it will be 0 only if all the 8 pixels around it are 0. On the other hand, erosion is the opposite process, in which a certain pixel will be 1 only if all the surrounding 8 pixels are 1. By utilizing this fundamental morphological image processing, we performed 4 processes, erosion–dilation–erosion–dilation–erosion in that order, on the images after the second step. The last 2 steps (the smoothing process and the erosion–dilation–dilation–erosion process) are necessary to remove the spot noises appearing in the images after the first step because of the spicules in the images of ±0.5 Å.

These three steps gave us masks that cover most of the filament, and we operated the cloud model fitting to the pixels inside the mask for each image. In this study we will focus on the LOS velocity and not use the other parameters derived from the model.

Figure 3 shows the time series of the SDDI images. From the top to the bottom: the Hα center, +0.5 Å, −0.5 Å, −1.0 Å, and the LOS velocity.

The field of view is indicated as the black square in Figure 1. The filament was stable and only the small portions were barely visible at ±0.5 Å, before 00:00UT on November 5. However, from ~00:30UT the small-scale motions in the filament became noticeable in the wing images as well as the LOS velocity. The amplitude of the small-scale motion showed a further increase after ~2:30UT, and finally the filament erupted around 3:30UT.

In order to quantify the small-scale motions in the filament prior to the eruption, we made the histograms of the LOS velocity.

3. Results

Figure 4 shows the examples of the histograms and the corresponding LOS velocity images at 22:49UT on November 4, 1:05UT, 3:07UT, and 3:22UT on November 5.

The mean velocity and the standard deviation are also shown in the figure. One can recognize that the histograms are quite symmetric before the eruption, but the standard deviation increases with time and the histograms themselves become asymmetric.

Figure 5 shows the temporal profile of the standard deviation of the histogram and the mean LOS velocity.
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4. Discussion

The SDDI/SMART allowed us to obtain the LOS velocity
inside a filament with unprecedented detail. The evolution of
the standard deviation of the histogram for LOS velocity as
the filament approaches the eruption provides unique
information on the physical state of the filament and may
be regarded as a precursor of the eruption that can be used for
the prediction of the eruption. The increase of the standard deviation with a rate of 2.8 m
s\(^{-2}\) during 2:30–3:10UT before the eruption may correspond
to the slow-rise phase commonly observed before filament
eruptions (Sterling & Moore 2004; Isobe & Tripathi 2006).
By investigating the Hα center images in Figure 3 one can
recognize the global drift of the filament toward the northwest
in the plane of the sky. On the other hand, the weaker (1.1 m
s\(^{-2}\)) increase in the standard deviation starting around
00:00UT is not associated with a global drift of the filament.
This may be regarded as a precursor of the onset of the slow-
rise phase.

It should be also noted that the standard deviation during
22:00–00:00UT is almost constant, but its absolute value is
slightly larger than that from the previous day. Here we
present a possible interpretation of this. Small-scale vertical
motions have been commonly found in the high-resolution
observations of quiescent filaments (Berger et al. 2008, 2011).
Their physical origins are still uncertain, but one promising
mechanism is the magnetic Rayleigh–Taylor instability
(Hillier et al. 2011, 2012). In the nonlinear phase of the
instability, the termination velocity of the rising plumes and
sinking spikes is determined by the balance of the buoyancy
(gravity) force and the drag force from the ambient plasma. It
is likely that as the filament evolves toward the eruption, it
expands and the magnetic field becomes weaker. This results
in the decrease of magnetic drag on the plumes and spikes and
thus an increase in the average small velocity inside the
filament. This hypothesis may be verified by statistical
analyses of the quiescent filaments that show the vertical
motions.

From a space weather point of view, filament eruptions can
cause geomagnetic storms that have societal and economical
impacts. It should be noted that the eruptions of quiescent
filaments far from active regions, which cannot be detected as
flares in soft X-rays, may produce geomagnetic storms
(McAllister et al. 1996). Therefore, the prediction of filament
eruptions is highly important for mitigating the hazards of
space weather.

The increase in the small-scale velocity found in the
present study may be regarded as a precursor of the filament
eruptions. Combining it with the other diagnostics for
eruption, such as the height of the filaments (Filippov &
Den 2001; Nagashima et al. 2007), period of oscillatory
motion (Isobe & Tripathi 2006; Isobe et al. 2007; Foullon
et al. 2009), and the decay index of the coronal magnetic
field (Kliem & Török 2006; McCauley et al. 2015), will improve
the prediction capability of solar eruptions. We emphasize
that it is very important that Hα observation can be done from
ground-based telescopes.

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Figure 4. Left: the histograms of the LOS velocity images. Each histogram corresponds to the right image. The word “Std. Dev.” means standard deviation. Right: four LOS velocity images inside the black squares of Figure 3.
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