Small-scale Turbulent Motion of the Plasma in a Solar Filament as the Precursor of Eruption

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Abstract

A filament, a dense cool plasma supported by the magnetic fields in the solar corona, often becomes unstable and erupts. It is empirically known that the filament often demonstrates some activations such as a turbulent motion prior to eruption. In our previous study, we analyzed the Doppler velocity of an Hα filament and found that the standard deviation of the line-of-sight velocity distribution in a filament, which indicates the increasing amplitude of the small-scale motions, increased prior to the onset of the eruption. Here, we present a further analysis on this filament eruption, which initiated approximately at 03:40 UT on 2016 November 5 in the vicinity of NOAA Active Region 12605. It includes a coronal line observation and the extrapolation of the surrounding magnetic fields. We found that both the spatially averaged microturbulence inside the filament and the nearby coronal line emission increased 6 and 10 hr prior to eruption, respectively. In this event, we did not find any significant changes in the global potential field configuration preceding the eruption for the past 2 days, which indicates that there is a case in which it is difficult to predict the eruption only by tracking the extrapolated global magnetic fields. In terms of space weather prediction, our result on the turbulent motions in a filament could be used as the useful precursor of a filament eruption.

Unified Astronomy Thesaurus concepts: Solar filament eruptions (1981); Quiet solar corona (1992); Solar coronal mass ejections (310); Solar magnetic fields (1503); Solar filaments (1495)

1. Introduction

A filament eruption, a spectacular erupting phenomenon of dense cooler plasma, often initiates on the solar surface. A filament is a dense (10^9–10^11 cm^{-3}) and cool (10^4 K) plasma floating in the solar corona (density ~10^9 cm^{-3}, and temperature ~10^6 K) supported by magnetic fields. The plasma is believed to be in equilibrium state owing to the balance between gravitational force and Lorentz force. Several models of the magnetic field configuration supporting the dense and cool plasma have been proposed (e.g., Tandberg-Hanssen 1995). The so-called Kippenhahn–Schülter (KS) model, first proposed by Kippenhahn & Schlüter (1957), suggested that the magnetic field topology has a concave-upward shape where the dense plasma is condensed. In another model called Kuperus–Raadu (KR), first proposed by Kuperus & Raadu (1974), the magnetic field has a helical configuration similar to a flux rope. In the KR model, the plasma is condensed at the bottom of the flux rope.

A filament eruption is often preceded by various dynamical motions called filament activations (Smith & Ramsey 1964; Tandberg-Hanssen 1995; Isobe & Tripathi 2006; Isobe et al. 2007; Gosain et al. 2009; Sterling et al. 2011; Parenti 2014). Slow ascending motion of a filament, typically with a velocity of a few kilometers per second and a duration of tens of minutes for active region filaments and hours for quiescent filaments, has been widely reported in studies prior to the eruption (e.g., Ohyama & Shibata 1997; Sterling & Moore 2004). A turbulent motion was also reported prior to a filament eruption (Tandberg-Hanssen 1995) and, more generally, a solar flare (e.g., Harra et al. 2001, 2009). Harra et al. (2001) observed that nonthermal velocity inside an active region coronal filament increased prior to the flare on 1993 October 3 and suggested that this is the indicator of turbulent changes in the active region.

In our previous study (Seki et al. 2017), we reported that the standard deviation of line-of-sight (LOS) velocity distribution of small-scale plasma motions inside a filament increased as the filament was reaching the eruption around 03:40 UT on 2016 November 5. By using the Solar Dynamics Doppler Imager (SDDI; Ichimoto et al. 2017) installed on the Solar Magnetic Activity Research Telescope (SMART; UeNo et al. 2004) at the Hida Observatory, we monitored the Doppler velocity map of the filament from 29 hr before the onset of the eruption. As a result, we determined that the standard deviation increased to 3–4 km s^{-1} 6 hr prior to the eruption, while it was 2–3 km s^{-1} from 29 to 21 hr prior to the eruption. The average LOS velocity was approximately constant around 0 km s^{-1}. Thus, we concluded that this broadening LOS velocity distribution (increase of the standard deviation) could reflect information on the preceding turbulent plasma motion inside a filament.

In this paper, we present further detailed analysis on this event, including the extrapolation of the surrounding potential fields and the estimate of the intensity in coronal emission lines. Kliem & Török (2006) investigated the ideal magneto-hydrodynamic (MHD) instability called the torus instability...
first discussed in Bateman (1978) in the situation of low-beta magnetized plasma. They found that critical conditions to favor the instability were related to the so-called “decay index,” which is defined as the minus gradient of the unsigned horizontal component of the overlying magnetic field with respect to height. In this study, we investigated the decay index of potential fields surrounding the filament to see whether the torus instability was favorable to be initiated.

In addition, we performed an observational analysis using the SDO/AIA 94, 211, 171, 193, and 304 bands to investigate the variation of intensity in the coronal emission lines. The destabilization of a flux rope containing a filament by magnetic reconnections plays a key role in initiation of its eruption (Feynman & Martin 1995; Chen & Shibata 2000; Nogashima et al. 2007; Shibata & Magara 2011). If small-scale magnetic reconnections take place prior to the eruption, rising intensity in coronal (high-temperature) emission lines will be observable. Those SDO/AIA bands enable us to estimate high-temperature emissions such as Fe XIV (a few × 10^6 K) and Fe XVIII (~7 MK) (Del Zanna 2013).

This paper is organized as follows: In Section 2, we describe observations and methods used for our analysis with a brief overview of this event. In Section 3, we present the results of our decay index investigation and observational analysis in multiple wavelengths in SDO/AIA bands. In Section 4, we deliver some interpretations of the turbulent motions and the trigger and evolution of the eruption and the possibility of the application of our results to space weather prediction.

2. Observations and Methods

2.1. Data

In this study, we used a multiple-wavelength observation of the Sun by the Atmospheric Imaging Assembly (Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO). SDO/AIA captures the full-disk Sun routinely in 10 wavelengths, including 94, 211, 171, 193, and 304 Å, with a time cadence of 12 s and a spatial sampling of 0′′6 pixel ^{-1}. LOS magnetograms of the Sun taken by the Helioseismic and Magnetic Imager (HMI) on board the SDO (Scherrer et al. 2012) and a synoptic chart of the photospheric radial magnetic fields inputted by HMI LOS magnetograms were also used. SDO/HMI observes the solar full-disk LOS magnetogram with a time cadence of 45 s and a spatial sampling of 0′′5 pixel ^{-1}. Synoptic HMI charts are remapped “radial” components of magnetograms onto the Carrington coordinate grid. Here “radial” means that the observed HMI LOS magnetograms are assumed to be the LOS component of purely radial magnetic fields. Thus, for the computation of this imputed radial magnetic field component, the HMI LOS magnetograms are divided by the cosine of the angle from the disk center.

The full-disks images in Hα line center and its wings captured by the SDDI were used to see the morphology of the target filament and to compute its LOS velocity. The SDDI installed on the SMART (Ichimoto et al. 2017) at the Hida Observatory, Kyoto University, has been conducting routine observations since 2016 May 1. It captures the solar full-disks images in 73 wavelengths with a step of 0.25 Å from Hα line center—9.0 Å to Hα line center + 9.0 Å, i.e., at 36 positions in the blue wing, Hα line center, and 36 positions in the Hα red wing. Each image is obtained with a time cadence of 15 s and a spatial sampling of 1″23 pixel ^{-1}. A part of daily observational data (Hα center, ±2.0, ±1.25, ±0.5, and ±3.5 Å) is always available on the website from 2016 May 1 to the present.10

2.2. Overview

The observed filament first appeared from the solar east limb on 2016 October 28 as a prominence. Its highest spine was measured as 33 Mm above the limb. It was located at the latitude of N27 degree and in the vicinity of NOAA Active Region 12605 (see Figure 1), and it was tilted by an angle of approximately 45° with respect to the south–north direction. Its length was approximately 112 Mm measured in Hα center.

The filament started to erupt around 03:00 UT to the north on November 5 and totally disappeared in Hα line center around 03:40 UT. Two-ribbon brightening was observed in both Hα line center and the SDO/AIA 304 in the vicinity of the filament location after eruption (see Figures 3 and 6). This filament eruption was associated with a B1.1-class flare in the GOES soft X-ray, which peaked at 04:30 UT (see Figure 2 in Seki et al. 2017).

A coronal mass ejection (CME) was observed at 04:36 UT on November 5 in the SOHO/LASCO C2 (Brueckner et al. 1995) with a linear speed of 403 km s ^{-1}. A moderate geomagnetic disturbance on November 10–11, which peaked at −59 nT in Dst (Nose et al. 2015) at 18:00 UT on November 10, was also observed. According to Richardson & Cane Catalogue (Cane & Richardson 2003), an interplanetary CME shock was first detected on 2016 November 9 at 06:04UT, which is consistent with the estimated arrival time of the CME (2016 November 9 11:44UT) derived from the simple empirical model provided by Gopalswamy et al. (2000). After the arrival of the shock, the interplanetary CME plasma and the magnetic fields were observed by the Faraday Cup instrument of the Solar Wind Experiment on board the Wind spacecraft (Kasper 2002) from 2016 November 10 00:00 UT to 2016 November 10 16:00 UT on the basis of the occurrence of abnormally low proton temperature and the reduced fluctuations and organization in the interplanetary magnetic fields (Cane & Richardson 2003). Thus, this geomagnetic disturbance can be attributed to the CME associated with the filament eruption.

2.3. Extrapolation of Magnetic Fields

To investigate the decay index surrounding the filament, we computed potential fields from the radial magnetic field components of the photosphere. The decay index calculated from potential fields is commonly used for the stability analysis (e.g., Filippov 2013; Joshi et al. 2014a, 2014b; Li et al. 2016). In this study, we set the critical decay index as 1, above which the torus instability is considered to be more favorable, following previous observational studies (Filippov 2013; Joshi et al. 2014b).

It should be noted that it was necessary to compute potential fields for the whole Sun, unlike other cases of decay index analysis in which potential fields are extrapolated only for a subregion of the Sun (e.g., Filippov 2013), because the volume to be considered is too large to ignore the sphericity of the Sun. Moreover, for the objective of tracking the temporal evolution of the global magnetic fields with a time cadence of 1 day, a

9 https://www.hida.kyoto-u.ac.jp/SMART/T1.html

10 The full version of the data (73 wavelengths) is also available. Please contact us (data_info@kwasan.kyoto-u.ac.jp) if you are interested in using it.
A synoptic chart is not suitable for the boundary condition of potential field source surface (PFSS) extrapolation, because it is provided once in $\sim 27$ days (rotation period of the Sun). Therefore, assuming that the unobservable hemisphere was equivalent to the HMI synoptic map, we used “patched HMI synoptic charts” (described later) as a boundary condition for the PFSS extrapolation.

Here, we describe how to construct a boundary image used for extrapolation. There are three steps: First, we inputted the radial component of magnetic fields from an HMI LOS magnetogram, assuming that HMI measures the LOS component of a purely radial magnetic field. Second, we extracted a region of a magnetogram between heliocentric latitudes and longitudes of $\pm 60^\circ$. Third, we patched the region in the form of a heliocentric spherical coordinate to the HMI synoptic chart for Carrington Rotation 2183.

We used the Potential Field Source Surface Solver provided by A. R. Yeates to extrapolate potential fields (van Ballegooijen et al. 2000). This Python-based code solves the basic equations for magnetic fields by using a finite-difference method with an assumption that the electric currents are negligible in a spherical shell. For more details, see https://

\[ \text{Figure 1. Left: H}_\alpha \text{ center images observed by SDDI at three different times superimposed by the photospheric PIL (red line). The cyan line in each panel corresponds to the cross section of the right panel. Yellow and green contours indicate the HMI LOS magnetogram at $\pm 100$ G. For EFR, see Figure 5. Right: side view of three-dimensional distribution of decay index. Each digit at the bottom axis corresponds to the digit on the cyan line of the left panel. White and black lines correspond to the approximate height of the filament (30 Mm) and the contour where decay index is 1, respectively.} \]
where GitHub.com/antyeates1983/pfss. We chose 2.0 solar radius above the photosphere and 7 Mm as the height of source surface and the grid size of radius (height), respectively. Grid sizes of zenith and azimuth angle were taken to be \(0.5^\circ\).

2.4. Cloud Model

To compute the LOS velocity and the microturbulence inside a filament, we utilized a cloud model first proposed by Beckers (1964). Assuming that (1) the source function is constant along the wavelengths and (2) along the LOS direction and that (3) the line absorption coefficient is a Gaussian shape, this model enables us to determine four physical parameters of the plasma cloud: the source function, the Doppler width, the Doppler shift, and the optical depth (Morimoto & Kurokawa 2003a, 2003b; Morimoto et al. 2010; Cabezas et al. 2017; Seki et al. 2017, 2019; Sakaue et al. 2018). The LOS velocity (\(v_{\text{los}}\)) and the microturbulence (\(\xi\)) at each pixel were calculated from the Doppler shift (\(\Delta \lambda_0\)) and the Doppler width (\(\Delta \lambda_0\)), respectively, based on the equations below (Morimoto & Kurokawa 2003a):

\[
v_{\text{los}} = c \frac{\Delta \lambda_x}{\lambda_0}, \quad (1)
\]

\[
\Delta \lambda_0 = \frac{\lambda_0}{c} \sqrt{s^2 + \frac{2k_B T}{m_p}}, \quad (2)
\]

where \(c\), \(\lambda_0\), \(k_B\), \(T\), and \(m_p\) are the velocity of light, the wavelength of H\(\alpha\) line center (6562.808 Å), Boltzmann’s constant, a fixed temperature of \(10^4\) K in the filament, and the mass of protons, respectively.

(For further information, refer to our previous works (Seki et al. 2017, 2019).)

3. Result

3.1. Decay Index

Figure 1 demonstrates the decay index distribution in the vicinity of the filament on November 3, 4, and 5 at 00:00 UT. Left panels show H\(\alpha\) images superimposed by the photospheric polarity inversion lines (PILs) denoted by red lines and the cross sections of the right panels depicted as cyan lines. Each right panel exhibits the side view of the three-dimensional decay index along the cyan line in the left panel. From top to bottom, we can recognize a similar decay index distribution with time. Generally, the decay index had larger values in the higher location. In the vicinity of the filament, the decay index was always below one. Note that the filament in H\(\alpha\) laid between the positions 2 and 3 on November 3 and 4, while it was located between 1 and 2 on November 5. The emerging flux region (EFR; see Figure 5) appeared in the vicinity of position 3. The height of the filament was assumed to be 30 Mm because its highest spine was measured to be 33 Mm above the limb as a prominence on 2016 October 28.

3.2. Microturbulence

Figure 2 shows the temporal evolution of the spatially averaged microturbulence of the filament derived from Equation (2). The average was taken for the entire main body of the filament. (For the methodology to determine the main body of the filament, see Seki et al. 2017.) The horizontal dotted line indicates a microturbulence of 15 km s\(^{-1}\). Although the mean microturbulence had been around 12 km s\(^{-1}\) until 21 hr prior to eruption, it increased to around 14 km s\(^{-1}\) at 22:00 UT on November 4 (6 hr prior to eruption). It continued increasing to around 25 km s\(^{-1}\) until the total disappearance of the filament in the H\(\alpha\) line.

3.3. Coronal Line Emission

Figure 3 shows the temporal evolution of the spatially averaged counts per pixel in Fe XIV (a few \(\times 10^6\) K) from a linear combination of AIA 211, 171, and 193 passbands (Del Zanna 2013) estimated by

\[
I(\text{Fe xiv}) = I(211 \, \text{Å}) - \frac{I(171 \, \text{Å})}{17} - \frac{I(193 \, \text{Å})}{5}. \quad (3)
\]

White rectangles are located between the two ribbons. These locations were in the vicinity of the stable filament seen in H\(\alpha\) center. To improve the signal-to-noise ratio, we temporally averaged the AIA data over 5 minutes. We can observe rising...
intensities inside rectangles 3 and 4 approximately from 18:00 UT, while those in the other regions did not exhibit such an ascent. Note that the location of EFR in Figure 5 corresponds to rectangle 2.

Figure 4 exhibits the same temporal evolution except the emission line of Fe XVIII (∼7 MK) estimated by the equation (Del Zanna 2013)

$$I(\text{Fe xviii}) = I(94 \text{ Å}) - \frac{I(211 \text{ Å})}{120} - \frac{I(171 \text{ Å})}{450}. \quad (4)$$

Inside any rectangles, the counts did not exhibit the rising feature except the sudden increase around 13:00 UT. This is due to a B-class flare at NOAA AR 12605 (see Figure 1).

4. Discussion

4.1. Turbulent Motion

In our previous work (Seki et al. 2017), we found that the standard deviation of the LOS velocity distribution in a filament, which indicates the amplitude of the small-scale motions, increased prior to the onset of the eruption. As seen in Figure 2, the mean microturbulence inside the filament also demonstrated an increase with time, which should reflect the turbulent motion of the plasma even within a spatial scale of 1 pixel. It should be noted that the estimate of LOS velocity assumes only one moving component of plasma blob along the LOS, whereas the microturbulence considers the unresolved plasma motion. To derive a more realistic LOS velocity distribution, we need further investigation to improve the model, but that is out of the focus of this study.

Here, we suggest two possible origins for the preceding turbulent motions: one is the magnetic Rayleigh–Taylor instability, and the other is small-scale reconnections. The small-scale vertical motions of plasma are often observed in quiescent prominences with high-resolution observations (Berger et al. 2008, 2011). Hillier et al. (2011) carried out three-dimensional MHD simulations to analyze how the magnetic flux rope (KS model) is stable to the magnetic Rayleigh–Taylor instability, and they reconstructed the upflows of the plasma with constant velocities. The dependences between initial parameters of the ideal MHD simulations and the evolution of the instability were also discussed in Hillier et al. (2012). In their studies, the maximum velocity of a rising plume reached 5.9 and 2.5 km s⁻¹ under the conditions of plasma β = 0.5 and 0.2, respectively. The terminal velocity of the rising plasma plume is determined by the balance among the Lorentz force, the gravitational force, and the gas pressure gradient at the top of the plume. At the beginning of the rising, the plume experiences an acceleration due to the buoyancy dominant force. It continues until the magnetic fields are transported by the flow and sufficiently accumulated at the top of the plume to balance the gravitational force, the magnetic tension, and the magnetic and gas pressures. As a magnetic flux rope containing a filament is reaching eruption, it is expected that the flux rope expands, and the magnetic fields become weaker. Thus, it will take more time to realize the force balance at the top of the plume, resulting in the faster terminal velocity of the plume and the more active small-scale motions in the filament.

The other possibility is due to the small-scale reconnections below the filament. In this study, we observed rising intensities in the coronal line in the vicinity of the filament (see Figure 3). These increasing profiles could denote the continuous occurrence of small-scale reconnections below the flux rope, which could lead to destabilizing it and result in a disturbance of the small-scale plasma inside the filament. Chifor et al. (2006) observed an EUV brightening feature (∼10⁶ K) at the footpoint of a prominence ∼20 minutes prior to the eruption. In their study, they concluded that this suggestive brightening denoted the onset of “tether-cutting reconnection,” in which, once reconnections below a flux rope are initiated, it will ascend owing to cutting off the anchoring magnetic fields, and more reconnections will be induced (Moore et al. 2001). The observation of the continuous enhancement in Fe XIV could be attributable to this positive feedback process, and the evolution of this event could be explained by this scenario.
Note that during this period there was no increase in the Fe XVIII line (see Figure 4), which indicates that there were no substantial flares causing high temperatures.

4.2. Trigger and Evolution of the Eruption

An emerging flux was observed around 9 hr before eruption, and this emerging flux could be the trigger of the eruption. In fact, several studies showed that the existence of EFR plays a key role in the initiation of a filament eruption from the observational and theoretical points of view (Feynman & Martin 1995; Chen & Shibata 2000; Kusano et al. 2012). Figure 5 shows the location of a bipole in comparison with that of the filament and the snapshots of EFR observed by HMI. One can recognize that from 19:00 UT on November 4 the bipole evolved with time. The two polarities were separated with time, which is characteristic of an emerging flux. Kusano et al. (2012) found that there are several types of small magnetic structures that should appear in the vicinity of the PIL in order to favor the onset of solar eruptions. Especially, one of them is called reversed-shear-type (RS-type), in which small-scale magnetic field (such as emerging flux) is injected into preexisting large-scale sheared magnetic field with a certain rotation angle with respect to large-scale potential field (see Figures 1 and 5 in Kusano et al. 2012). Figure 6 shows solar subimages observed by AIA 304 and HMI at 03:41 UT on November 5 superimposed by the blue dotted line indicating the edge of the two ribbons (left and middle). We can notice that the large-scale magnetic field surrounding the filament was sheared in clockwise. The right panel shows the schematic diagram of the top view of the large-scale and small-scale magnetic structures. This magnetic field configuration corresponds to RS-type configuration for negative shear (clockwise rotation) introduced in Kusano et al. (2012). Thus, we conclude that the filament eruption could be triggered by the emerging flux observed at 18:00 UT.

Figure 1 shows that the decay index nearby the filament was smaller than 1, meaning that the flux rope was stable against the torus instability. It should be noted that in Kliem & Török (2006) they assumed the shape of the flux rope as a ring. On the other hand, Ishiguro & Kusano (2017) found that the ideal MHD instability can be initiated even in the torus-stable condition, i.e., decay index is less than 1, if the magnetic loop has a double-arc-shape configuration. They called this critical condition for the eruption under a certain geometry the double arc instability (DAI). The DAI-favored magnetic configuration can be produced in the “tether-cutting reconnection” scenario (Moore et al. 2001). Additionally, this scenario agrees with the result of Kusano et al. (2012). The evolution of this event could be explained by this scenario (see the previous section), and the magnetic field configuration could be the DAI-favored one.

4.3. Space Weather Application

Quiescent filament eruptions occasionally drive large CMEs and cause severe geomagnetic disturbances (e.g., Cliver et al. 2009). Thus, in terms of space weather prediction, it is also of great importance to predict filament eruptions (e.g., Joselyn & McIntosh 1981). McAllister et al. (1996) reported a large polar crown filament eruption on 1994 April 14. Although this event was not associated with any significant flares, we experienced a severe geomagnetic disturbance (Dst ~ −200 nT) within a few days of the eruption. Isobe et al. (2019) investigated the records of aurora display in the middle magnetic latitudes (China and Japan) during the Maunder minimum in 1653, which indicates the presence of a great geomagnetic disturbance, although the solar activity at that time must have been very quiet. With a simple theoretical discussion, they concluded that this
A geomagnetic storm was extremely intense ($\text{Dst} < -300 \text{ nT}$) and can be driven by a quiescent filament eruption.

Our result implies that it would have been impossible to predict the filament eruption only from the photospheric magnetic fields and the extrapolated potential fields for this event because the photospheric magnetic fields scarcely changed over the past several days of the eruption. From Figure 1, we cannot recognize any significant changes in the global magnetic field configuration that lead to the onset of the eruption. Moreover, the region to be considered around the

![Figure 5](image1)

**Figure 5.** Top: Hα image taken by the SDDI superimposed by the contours of $+100 \text{ G}$ (yellow) and $-100 \text{ G}$ (green) of the HMI LOS magnetogram. Bottom: the HMI LOS magnetograms inside the white rectangle in the top panel at four different times. To enhance visualization, the magnetograms are shown with a scale of lower and upper limits of $\pm100 \text{ G}$.

![Figure 6](image2)

**Figure 6.** Left and middle: solar subimages observed by SDO/AIA 304 and SDO/HMI at 03:41 UT on November 5. The blue dotted line corresponds to the edge of the flare ribbon. The white arrow indicates the EFR. To enhance visualization, the magnetogram is shown with a scale of lower and upper limits of $\pm200 \text{ G}$.

Right: the schematic diagram of the top view of the large-scale and small-scale magnetic structures. Cyan and red arrows indicate the small-scale magnetic field and the possible large-scale overlying field, respectively. White and black regions correspond to the positive- and negative-polarity regions, respectively. Blue dotted lines and P1–4 are simple expressions of those in the middle panel. This magnetic field configuration corresponds to RS-type configuration for negative shear (clockwise rotation) introduced in Kusano et al. (2012).
filament is a global quiet one, and we can hardly expect to obtain precise vector–magnetic field data. That is why it is difficult to extrapolate more realistic magnetic fields such as nonlinear force-free fields for this event. This illustrates that there is a case in which it is difficult to predict and monitor when a filament will erupt only from the global magnetic field configuration. Thus, we suggest that the internal turbulent motion in a filament can also provide useful clues to predict filament eruptions (UeNo et al. 2007; Seki et al. 2018, 2019).

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Software: Potential Field Source Surface Solver (created by A. R. Yeates, https://github.com/antyeates1983/pfss), SunPy (The SunPy Community et al. 2015).

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