Measuring three-dimensional shapes of stable solar prominences using stereoscopic observations from SDO and STEREO

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ABSTRACT

Aims. Although the real shapes and trajectories of erupting solar prominences in three dimensions have been intensively studied, the three-dimensional (3D) shapes of stable prominences before eruptions have not been measured accurately so far. We intend to make such a measurement to constrain 3D prominence models and to extend our knowledge of prominences.

Methods. Using multiperspective observations from the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory (SDO) and the Extreme Ultraviolet Imager on board the Solar Terrestrial Relations Observatory (STEREO), we reconstructed 3D coordinates of three stable prominences: a quiescent, an intermediate, and a mixed type. Based on the 3D coordinates, we measured the height, length, and inclination angle of the legs of these prominences. To study the spatial relationship between the footpoints of prominences and photospheric magnetic structures, we also used the Global Oscillation Network Group Hα images and magnetograms from the Helioseismic and Magnetic Imager on board the SDO.

Results. In three stable prominences, we find that the axes of the prominence legs are inclined by 68.6 ± 6 degrees on average to the solar surface. Legs at different locations along a prominence axis have different heights with a two- to threefold difference. Our investigation suggests that over 96% of prominence footpoints in a sample of 70 footpoints are located at supergranular boundaries. The widths of two legs have similar values measured in two orthogonal lines of sight. We also find that a prominence leg above the solar limb showed horizontal oscillations with larger amplitudes at higher locations.

Conclusions. With a limited image resolution and number of cases, our measurement suggests that the legs of prominences may have various orientations and do not always stand vertically on the surface of the sun. Moreover, the locations of prominence legs are closely related to supergranules.

Key words. Sun: filaments, prominences — Sun: UV radiation

1. Introduction

Solar prominences, also called solar filaments, consist of relatively cool and dense plasma (see, e.g., Labrosse et al. 2010, Parenti 2014). They are supported by helical magnetic flux ropes or sheared magnetic loops in the tenuous and hot solar corona above photospheric magnetic neutral lines (see, e.g., Mackay et al. 2010). Prominences in quiescent regions, known as quiescent prominences, often consist of several discrete pillar-like structures (Panesar et al. 2014) that are variously referred to as “legs” (Wedemeyer et al. 2013), “feet” (Aulanier & Demoulin 1998), “tornadoes” (Petit 1943), Su et al. 2012, Panasenco et al. 2014), and “barbs” (Martin 1998). These pillar-like structures are called legs in this paper. Prominence legs are often linked by a long continuous body, the so-called spine, in the upper part in a well-developed prominence, and the lower parts of the prominence legs become narrow and sharp when they approach the chromosphere (Martin 1998). Sometimes, especially in high-latitude regions or close to the solar limb when the line-of-sight (LOS) integration path through the spine is short, the spine of a prominence is almost invisible in the Hα line, and only prominence legs remain (Su et al. 2012, Li & Zhang 2013). The formation of filaments begins with a few individual legs, which later combine to form a continuous body (Pevtsov & Neidig 2005). Prominence legs appear to be fundamental building blocks of prominences. The location of prominence legs is likely related to supergranulation, which can be traced by the chromospheric network and the photospheric magnetic network (Simon & Leighton 1964). By comparing Hα prominence legs with Ca II K chromospheric network, Plociennik & Rompolt (1973) found that 90% of the footpoints of filament legs are located at boundaries of supergranular cells, which was confirmed by Pevtsov & Neidig (2005) using off-band Hα chromospheric network images. Lin et al. (2005) derived photospheric flow cells representing supergranular cells and found that about 65% of the endpoints of filament barbs are located at supergranular cell boundaries. Moreover, the endpoints of filament barbs may not be the footpoints of legs, as shown by Su et al. (2012) in their Figure 3 from two viewing angles at the same time, where some legs are present in side views but are hidden in top-down views, and barbs shown in top-down views are not visible in side views. The one-to-one correspondence between legs and barbs has been doubted, and some dynamic barbs may be due to longitudinal oscillations of filament threads high above the solar surfaces (Ouyang et al. 2020). Without 3D information, it is difficult to accurately identify the footpoints of the legs. The relation between supergranulation and prominence legs needs further investigation, which may shed light on the unclear magnetic structure of prominence legs.
Because the gravitational scale height of prominence plasma is shorter than the height of prominences, which means the gas pressure gradient cannot be the main support for prominence plasma, it is commonly accepted that prominence plasma is supported by the Lorentz force in magnetic dips (Mackay et al. 2010). Three-dimensional static force-free magnetic field models have been developed to interpret a filament barb as magnetic dips piled up from nearby parasitic magnetic elements on the solar surface to the main magnetic flux rope along the filament axis (Aulanier & Demoulin 1998). This interpretation of a leg as assembled lateral dips was supported by a high-resolution observation from one viewing angle of an active region filament, whose bars terminated above the small polarity inversion line dividing two close magnetic elements of opposite polarities (Chae et al. 2005). Gunär et al. (2013) filled the magnetic dips of thousands of magnetic field points from a 3D prominence force-free magnetic field model with hydrostatic prominence plasma (Gunär et al. 2013) and constructed radiative-transfer-based synthetic Hα images from a filament and prominence viewing angles. The authors found that the collected magnetic field lines showing magnetic dips up to a pressure scale height are similar to the synthetic Hα images in the filament view, but occupy a wider volume than the synthetic Hα structures in the prominence view. To verify and constrain realistic 3D prominence models, it is important to accurately measure the 3D shapes of prominences, including the legs. However, measurements like this have large uncertainties from projection effects and can only be improved by time-series images because the solar rotation changes the relative viewing angle of prominences (Rosa 1996) before 2006 when ground- and space-based telescopes were only able to observe from a single solar-terrestrial angle of view. Since 2006, when the Solar TERrestrial RELations Observatory (STEREO) Ahead (A) and Behïnd (B) spacecraft (Kaiser et al. 2008) were launched, the two satellites, allowing a stereoscopic vision of the Sun from multiple viewing angles, have started uncovering instantaneous 3D structures of solar activities through triangulation and reconstruction methods (Inhester 2006; Feng et al. 2007; Aschwanden et al. 2008; Thompson 2009). Using these stereoscopic techniques, 3D information of an erupting active region filament on May 19, 2007, were studied (Gissot et al. 2008; Liewer et al. 2009; Xu et al. 2010), when the separation angle between STEREO A and B was small, for instance, 8.5 degrees. Simultaneous heating of the rising filament and the chromosphere below were identified (Liewer et al. 2009). A four-hour slow-rising phase with an upward acceleration of the filament was found before its impulsive eruption (Xu et al. 2010; Temporad 2009) estimated the expansion factor in 3D of an erupting active region prominence and found that the early expansion is anisotropic and mainly in the radial direction, with an overall nonrotating ribbon-like shape. Liu et al. (2012) investigated the partial eruption of a double-decker active region filament with 3D reconstruction and inferred that the upper and lower branch of the filament had negative helicity. Zhou et al. (2017) tracked 3D structures from gradual to the impulsive phase of an erupting active region prominence and found a shape transformation of the prominence from a sigmoid shape to a loop arcade. All these studies are focused on 3D shapes of erupting active region filaments. The 3D shapes of nonerupting stable prominences, especially those in quiescent regions, have not been measured accurately, as far as we know.

Based on stereoscopic observations from two viewing angles, we therefore report our measurement of 3D shapes of three stable prominences with a reconstruction of the 3D coordinates, and we further investigate the spatial relation between the footpoints of prominence legs and supergranular boundaries. After an introduction in Section 2 of the instruments and data we used, we describe the 3D reconstruction technique in Section 3. The results for the three prominences we selected are shown in Section 4. Conclusions are summarized and discussed in Section 5.

2. Instruments and data

To explore the effects of solar activity on the Earth, NASA launched a series of solar space telescopes, such as the STEREO and the Solar Dynamics Observatory (SDO) (Pesnell et al. 2012). The Atmospheric Imaging Assembly (AIA) (Lemen et al. 2012) on board the SDO provides full-disk images out to 1.5 solar radii with 1.5″ spatial resolution (0.6″ pixel size) and 12-second temporal resolution in seven extreme ultraviolet (EUV) and two ultraviolet wavebands and in one visible light waveband. We used AIA EUV images in 304 Å (0.05 MK), 171 Å (0.63 MK), and 193 Å (1.6 MK and 20 MK) wavelength bands. The Extreme Ultraviolet Imager (EUVI) (Wuelser et al. 2004) of the SECCHI instrument suite (Howard et al. 2008) on board the two STEREO spacecraft observes the Sun from two viewing angles in four EUV spectral channels with 1.6″ pixel size and a full-Sun field of view out to 1.7 solar radii. We used 171 Å (0.63 MK) EUVI images. We also used full-disk LOS photospheric magnetograms provided by the Helioseismic and Magnetic Imager (HMI) (Schou et al. 2012) on board the SDO with a 0.5″ pixel size and a cadence of 720 s.

To search suitable data for 3D reconstruction, we focused on the time at which prominences can be observed simultaneously from different angles by at least two spacecraft, including the SDO and STEREO A or B, and the angle between the lines of sight of the two spacecraft should be less than 130 degrees. We examined all data from October 2010 to March 2013, mainly looking at dark features of filaments in 171Å images of SDO/AIA and STEREO/EUVI, and in Hα full-disk images from the Global Oscillation Network Group (GONG). Because the available images have a limited resolution, we targeted relatively large stable prominences with clear structures. In the end, we selected three prominences that we call PA, a quiescent prominence on February 9, 2012; PB, which is an intermediate prominence on May 25, 2012; and PC, a quiescent-intermediate mixed prominence on November 19, 2011. PA was observed by STEREO A and SDO separated by 115.6 degrees in viewing angles. PB was observed by STEREO B and SDO separated by 115.85 degrees in viewing angles. PC was observed by STEREO A and SDO separated by 106.1 degrees in viewing angles.

3. 3D reconstruction and data analysis

When the apparent positions of an object are determined in two images observed by two known observers from different viewing angles, then the 3D coordinates of the object can be derived with the tie-pointing method (Thompson 2006; 2009). A 3D reconstruction program using the method is ready to use in the SolarSoftWare (SSW) (Freeland & Handy 1998). We used scc_measure.pro in SSW to manually obtain the 3D coordinates and image pixel positions of features of the prominences. The specific steps are as follows. First, we opened the two 171 Å images, called A and B, from AIA or EUVI. Second, we selected a feature of the targeted image in image A. The LOS of image A that passes through this point then shows up as a straight line in image B. Third, we selected a point that was most likely...
the same structure in the line in image B. In the end, the program calculates and outputs the solar Carrington heliographic coordinates of the structure and its pixel positions in the two images. When the LOS of image A passes through a thick filament structure in image B, then it is hard to determine the corresponding point in the filament segment on the line. Filament structures closer to the underlying chromosphere usually have narrower extension and therefore smaller attached uncertainty in a 3D reconstruction. We therefore marked all distinguishable filament footpoints. However, dark structures of the chromosphere near filament footpoints sometimes obscured the identification. Because low filament footpoints in images A and B are expected to have nearly the same Carrington coordinates, we plot Carrington coordinates latitude and longitude lines through the footpoints. To plot the same Carrington coordinate latitude and longitude lines on two images from different viewing angles, we used hel2arcmin.pro in SSW to calculate the angular distance from the given Carrington coordinates to the center of a given image. We used one pixel size of a STEREO/EUVI image, that is, 870 km, as the uncertainty to estimate the error of the 3D reconstruction, which entered all quantities derived from 3D reconstructed coordinates.

4. Results

4.1. Quiescent prominence: PA

Prominence PA was observed on May 25, 2012, when the STEREO A and SDO had a difference in viewing angles of 115.6 degrees. As shown in Figure 1, the prominence was close to the west solar limb in the SDO/AIA 171 Å image, while it appeared at the east solar limb in the STEREO/EUVI 171 Å image, which is shown in log scale to present the details of dark filament structures. The prominence consisted of more than seven dark legs distributed along the magnetic neutral line from northeast to southwest, and a sparse filament spine linked these legs. The legs are easier to distinguish in the SDO view by watching the flank of the prominence than in the STEREO A view, which looked down at the prominence along its axis. Based on the method described in section 3, we determined the 3D coordinates of several features of the prominence. These features are marked with small circles in different colors. Small circles with the same color in the two images correspond to the same prominence structure. Five distinguishable legs of the prominence are represented by their footpoints and top points. The footpoints are labeled F1, F2, F3, F4, and F5, and the corresponding top points are labeled T1, T2, T3, T4, and T5. The legs are labeled F1-T1, F2-F2, and so on. In the STEREO A image, the legs F4-T4 and F3-T3 almost overlap, so they are not labeled to avoid confusion. Four blue circles between F1 and F2 represent the bottom parts of the filament segment where the corresponding top parts are hard to identify in the EUVI image because of the low resolution and the disturbance from nearby dark chromospheric patches.

Using information from the 3D reconstruction, we can evaluate the true spatial sizes of the prominence without uncertainties from the projection effect. In Table 1 we list the length of the prominence legs, the inclination angle of the legs, the height of the top points of the legs, and the height of the footpoints of the legs for all three prominences. The length of each leg is evaluated as the distance between the footpoint and the top point of the leg. The inclination angle of each leg is calculated as the angle between the foot-to-top line and the solar surface. When a leg is vertical to the solar surface, its inclination angle is 90 degrees. The average inclination angle of the five legs of PA is about 69 degrees. The least inclined leg F4-T4 has an inclination angle of 82±8 degrees. The most inclined leg F1-T1 has an inclination angle of 54±12 degrees. The axes of legs F2-T2, F3-T3, and F4-T4 are not straight, with an apparent bending near footpoints in the AIA image. These legs did not stand perpendicular to the solar surface, for instance, leg F4-T4 is inclined to the north and leg F3-T3 is inclined to the east. The highest point T3 of the PA has a height of 30,964±745 km. By accumulating the distances between the footpoints, we find that the overall length of the prominence is about 558,000 km.

To understand the magnetic field environment of the prominence legs, we compared the HMI photospheric magnetogram around PA with the AIA 171 Å, 193 Å, and 304 Å images in the same field of view, as shown in Figure 2 The magnetogram is shown with saturation values of ±45 G. The four reconstructed footpoints F2, F3, F4, and F5 seem to be located near polarity-mixed magnetic flux elements on supergranular boundaries. F1 is almost on the solar limb of the magnetogram. The errors in magnetic field and projected position are too large.

The dark filament structures in the 171 Å and 193 Å EUV channels are mainly caused by absorption of background EUV emission by neutral hydrogen, neutral helium, and singly ionized helium of filament plasma through photoionization, with a minor contribution from the volume-blocking effect for on-disk features (Anzer & Heinzel 2005). Compared to the 171 Å image, the legs on the solar disk are hardly visible in the 193 Å image, with very poor contrast because of the strong foreground emission that is caused by the large coronal emission scale height (Parenti et al. 2012). However, the absorption features above the solar limb around leg F1-T1 is very similar in the 171 Å and 193 Å images. The bright structure on the top of leg F1-T1 in the 171 Å channel is due to the emission of Fe IX 171.07 Å line from the prominence-corona transition region (PCTR) around 400,000 K (Parenti et al. 2012; Del Zanna et al. 2011). In the 304 Å image, the dark legs on the disk are vaguely visible due to dark chromospheric features nearby. The 304 Å channel is dominated by the He II 303.78 Å line from 50,000 K plasma (O’Dwyer et al. 2010), which is the PCTR covering prominence plasma. Cold prominence plasma shown as dark legs above solar limb in the 171 Å and 193 Å channels is hidden behind the emission from the large PCTR region in the 304 Å channel. Above T1, the top of the 171 Å dark prominence, there are additional 304 Å bright prominence structures. Wang et al. (1998) found a similar phenomenon with additional He II 303.78 Å emissions above Hα emissions and 195 Å absorptions in a quiescent prominence. Because of the high optical thickness of the He II 303.78 Å line, the 304 Å structures are located in a layer of PCTR in front of the prominence with a spatially extended shape (Günár et al. 2014), where the low optical thickness Hα line may render the contrast too high to be visible because the difference in integral depth along the LOS is too poor.

Because the LOS magnetogram around the prominence on May 25, 2012, close to the west solar limb, shows projection effect and large errors, we looked back in time of the previous four days when the prominence was closer to the disk center and used Hα images from GONG to locate the prominence legs. We label their footpoints with small circles in Figure 5 For each day, we plot the AIA 171 Å images and the HMI LOS magnetograms in the same field of view at the closest time of the Hα images and plot circles with coordinates found in the Hα footpoints. Circles with the same color in the three panels of a row have the same coordinates. The footpoints are labeled G1, G2, and so on from...
Fig. 1. Prominence PA in the SDO/AIA 171 Å image (left) and STEREO A/EUVI 171 Å image (right) at the same time on May 25, 2012. The EUVI image is in log-scale for clarity. Different features are marked with circles in different colors, and circles of the same color in the two images represent the same structures. The diameter of these circles is 8 arcsec (about 5,800 km). The dotted lines are the Carrington coordinate latitude and longitude lines, using the latitudes and longitudes of the three points F1, F2, and F3. The LOS of STEREO A in the left picture is along the latitude, and the dashed lines and arrows in the right image show the LOS of SDO.
Fig. 2. HMI magnetogram, AIA 171 Å, 193 Å, and 304 Å images with the same field of view looking at prominence PA on May 25, 2012. Feature points of the prominence are marked with circles in different colors for all images. The diameter of these circles is 8 arcsec (about 5,800 km). The magnetogram is shown in gray saturated at ±45 G.
west to east from the top to the bottom row with consecutive numbering because we do not mean to follow the time evolution of prominence legs with this low time cadence. The 171 Å images are in log scale to highlight dark structures. The filament legs in Hα images correspond well with the filament legs found in 171 Å images. We applied a Gaussian smooth filter on the HMI magnetograms to reduce noise in weak-field regions and highlight strong magnetic elements. We outline the supergranular boundaries presented by magnetic network near the polarity-inversion line (PIL) with dashed lines connecting strong magnetic elements in the HMI magnetograms. In the first row on May 20, four out of five footpoints except for G3 are at supergranular boundaries. In the second row on May 21, five out of six footpoints except for G8 are at supergranular boundaries. In the third row on May 22, all seven footpoints are at supergranular boundaries. In the last row on May 23, nine footpoints except for G19, which is close to the solar limb with large errors of magnetic field measurement, are at supergranular boundaries. In this case, we find that about 93% (25 out of 27) of the recognizable footpoints are located at supergranular boundaries around the PILs. There are separations of about one to three supergranular cells between two neighboring footpoints.

To investigate the shape of the cross-sections of prominence legs, we measured the apparent width of the PA legs F3-T3 and F4-T4 in two viewing angles at the same time. The LOS of SDO, in the right panel of Figure 4, is roughly perpendicular to the neutral line, while the LOS of STEREO A is along the neutral line. As shown in Figure 4, we drew two lines that cut perpendicular through the middle of two legs and plot the intensity curves along the white cutting lines. We applied the following procedure to determine the width of the legs. First, we evaluated the maximum and minimum from the left half and the right half of the intensity curve separately. Second, we recorded the smaller of the two maxima and the smaller of the two minima. Third, we calculated the arithmetic mean of these two values and plot it as a horizontal line in the intensity curve plot. The two intersection points between the horizontal line and the intensity curve are treated as the boundaries of the prominence leg. The distance between two boundaries along the cutting line is counted as the apparent width of the leg. This measurement of the width is also known as the full width at half minimum (FWHM), which was used to measure the width of filament threads (Lin et al. 2005). The apparent widths of the two legs in the AIA image are of the same value of 8.6" (6,230 km). The apparent width of the two overlapped legs in the STEREO A image is 8.9" (6,450 km), which is the upper limit because of the overlapping in the LOS. The width of the legs that appeared in the LOS along the neutral line is comparable to or smaller than the width that appeared in the LOS perpendicular to the neutral line.

To investigate the apparent motion of fine structures in prominence legs, we drew two fixed cutting lines H0 and H1 across the leg F1-T1 above the solar limb in AIA 171 Å images and plot the time-distance maps of the cuts in Figure 5. Both maps show apparent oscillations of the leg in the horizontal direction nearly perpendicular to the leg axis. The oscillations in the higher part of the leg show larger amplitudes than the oscillations in the lower part, which was also found in a shock-driven case of prominence transverse oscillations in previous work (Shen et al. 2014). This result indicates that the upper part of prominence legs may have shallower magnetic dips than the lower part, which agrees with the 3D linear force-free magnetic field model of Gunar et al. (2018), assuming that the prominence plasma is moving along magnetic field lines.

Table 1. Geometrical properties of prominence legs obtained by 3D reconstruction.

| prom. legs | length (km) | Inclination (°) | T height (km) | F height (km) | F projection (km) |
|------------|-------------|----------------|---------------|--------------|------------------|
| PA F1-T1   | 21,438±4,430| 54±12          | 22,852±111   | 5,375±132   | 5,281            |
| PA F2-T2   | 15,146±586 | 67±05          | 15,812±647   | 1,852±487   | 1,611            |
| PA F3-T3   | 18,257±459 | 70±04          | 17,310±633   | 118±557     | 100              |
| PA F4-T4   | 25,813±493 | 73±03          | 30,964±745   | 5,828±585   | 4,602            |
| PA F5-T5   | 27,122±788 | 82±08          | 30,637±842   | 3,746±786   | 2,812            |
| PB F1-T1   | 22,435±3,035| 52±08          | 21,014±647   | 3,391±690   | 2,439            |
| PB F2-T2   | 21,330±683 | 86±09          | 21,331±800   | 1,825±960   | 1,233            |
| PB F3-T3   | 62,581±1,831| 65±04         | 60,181±1,051 | 3,330±587   | 1,883            |
| PB F4-T3   | 62,887±2,203| 60±04         | 60,181±1,051 | 5,270±646   | 3,083            |
| PC F1-T1   | 32,191±1,593| 61±06          | 37,607±738   | 9,409±801   | 6,391            |
| PC F2-T2   | 26,590±1,518| 63±08          | 31,250±724   | 7,513±1,155 | 5,156            |
| PC F3-T3   | 25,710±1,203| 76±08          | 29,913±954   | 4,950±863   | 3,428            |
| PC F4-T4   | 24,252±152 | 81±03          | 28,395±835   | 4,400±696   | 3,076            |
| PC F5-T5   | 23,753±2,339| 61±08          | 21,320±800   | 473±835     | 340              |
| PC F6-T6   | 50,203±1,905| 68±04          | 45,468±821   | 1,065±814   | 813              |
| PC F7-T7   | 41,055±1,476| 26±02          | 34,237±369   | 15,652±473  | -                |

1 The angle between a leg axis and the solar surface in units of degree.
2 The projected distance on HMI magnetograms of a prominence footpoint.

4.2. Intermediate-type prominence: PB

In addition to quiescent prominences, we also investigated the 3D structure of an intermediate-type prominence PB that was observed on February 9, 2012, when the STEREO B and SDO were separated with a viewing angle difference of 115.85 degrees. As shown in Figure 6, the prominence was located in the east part of AIA 171 Å images and overlapped legs in the STEREO B image are at supergranular boundaries. The LOS perpendicular to the neutral line is comparable to or smaller than the width that appeared in the LOS along the neutral line. However, from the STEREO B/EUVI LOS looking from the side, the prominence shows mul-
Fig. 3. Time sequence of prominence PA in GONG Hα images, AIA 171 Å images in log scale, and Gaussian smoothed HMI LOS magnetograms on May 20 ((a)-(c)), May 21 ((d)-(f)), May 22 ((g)-(i)), and May 23 ((j)-(l)) in 2012. The small circles in different colors show the location of the footpoints of the prominence legs. The diameter of these circles is 8 arcsec (about 5,800 km). The magnetograms are shown in gray saturated at ±30 G. Supergranular boundaries are indicated by dashed lines in different colors connecting strong magnetic elements in the HMI magnetograms.
**Fig. 4.** Measurement of the width of two legs of prominence PA. (a) two prominence legs in the SDO/AIA 171 Å image and two cutting lines in white. (b) Intensity curve along the left cutting line in (a). (c) Intensity curve along the right cutting line in (a). (d) Two overlapping prominence legs in STEREO A 171 Å image with a line cut in white. (e) Intensity curve along the line cut in (d). The horizontal solid lines in (b), (c), and (e) are the inner boundaries of the leg boundaries and indicate the widths of the legs with the intersection points.
Fig. 5. Transverse oscillations in a leg of prominence PA. The left panel presents the AIA 171 image of partial spine and legs of PA two dotted horizontal lines H0 and H1 cutting across a prominence leg above the solar limb. The right panels are time-distance maps for cuts H0 and H1; the 12-second cadence covers about five hours on May 25, 2012.
tiple discontinuous internal structures, in which we mark four legs as F1-T1, F2-T2, F3-T3, and F4-T3. The prominence forks to the leg F3-T3 and the leg F4-T4 at the T3 point, which is the highest point of the whole prominence. Two blue circles mark the middle parts of leg F3-T3 and leg F4-T4, respectively. Reconstructed true sizes of the prominence can be found in Table[1] The leg F2-T2 is almost vertical to the solar surface (86 degrees), while the legs F1-T1, F3-T3, and F4-T4 have smaller inclination angles relative to the solar surface, around 60 degrees. The highest point T3 has a height of 60,181±1,501 km, and the total length of the prominence is about 297,000 km.

To investigate the magnetic environment of prominence PB, we plot the HMI magnetogram around it, together with AIA 171 Å, 193 Å, and 304 Å images in the same field of view in Figure[7] The magnetogram is Gaussian smoothed and saturated at ±30 G to clearly show the magnetic network indicated by colored dashed curves near the PIL. All four reconstructed footpoints F1, F2, F3, and F4 are located at supergranular boundaries as shown in magnetic network in the polarity inversion region, where network magnetic fluxes with opposite polarities mix and neutralize. In the 171 Å image, a continuous dark filament is outlined by bright emission edges against a broad dark lane sandwiching the filament. These bright edges may be caused by the emission of Fe IX 171.07 Å line from the PCCTR around 400,000 K. But, there are no such bright edges around the filament in the 193 Å image, since the PCCTR temperature is far away from 1.6 MK, which is the dominant line formation temperature for the 193 Å channel (O’Dwyer et al. 2010). The dark filament in the 304 Å channel apparently has a larger lateral extension compared to the filament in 171 Å channel, especially around point T3.

Using the FWHM measurement described in Section[4.1] we obtained intensity curves along two lines cutting across the filament spine in the AIA 171 Å image in Figure[8]. The lower cut TH1 gives a thickness of 5″ (3,625 km), and the upper cut TH2 gives a thickness of 4.8″ (3,480 km). The rest of the spine, except for the southern bifurcated part, shows a similar thickness as viewed by eye. We repeated the width measurement of the filament spine in AIA 193 Å image and AIA 304 Å image. The TH1 cut gives 6.5″ and the TH2 cut gives 6.7″ in the 193 Å image, which is about 35% larger on average than the cuts in 171 Å. The TH1 cut gives 6.4″ and the TH2 cut gives 6.3″ in the 304 Å images. The light curves of the cuts in 304 Å image show both emission and absorption in the filament spine, and the width measurement has large uncertainty caused by the dark chromospheric structures around the filament spine in the 304 Å channel. The overall structure of the prominence, except for the southern bifurcated part, is reminiscent of in a vertical slab with detailed arch-like structures.

4.3. Compound-type prominence: PC

In the third case, we present a 3D reconstruction of the mixed-type prominence PC, which was observed on November 19, 2011, when STEREO A and SDO were separated by 106.1 degrees. As shown in Figure[9] the prominence has a straight distribution extending from the northeast quiescent region to the southwest active region, which is characterized by multiple coronal loop systems. The northeast part of the prominence is composed of six legs, like typical quiescent prominences, while the southwest part is dominated by a quasi-continuous spine similar to intermediate-type prominences. One leg is labeled F7-T7 at the southwest end. The leg is apparently vertical in the AIA image, but actually very oblique with a small inclination angle of 19±2 degrees, which may be caused by a strong magnetic field of the coronal loops to its east. The legs in the northeast part with a weaker magnetic field environment are more vertical with an inclination angle in the range of 60-80 degrees, as listed in Table[1]. The highest point of the prominence is T6 with an altitude of 45,468±821 km. The overall length of the prominence is about 736,000 km. There are several dark patches and bright features in the chromosphere near the prominence, so we mark them with crosses to distinguish them from prominence dark features.

We also plot the HMI photospheric magnetogram around PC with the AIA 171 Å, 193 Å, and 304 Å images in the same field of view in Figure[10]. Within seven reconstructed footpoints, six footpoints from F1 to F6 are clearly located at supergranular boundaries and the footpoint F7 is very close to the limb, with a large uncertainty in the magnetogram, and it shows a large projection effect. Similar to PA, the filament legs are hardly visible in the 193 Å image, with very poor contrast because the strong foreground emission accumulated through the coronal loops, except for leg F7-T7 because its background is bright. Above the dark chromospheric patches marked with crosses, the filament spine labeled with purple to blue circles consists of horizontal threads in the 171 Å channel. In the 304 Å channel, the dark threads have lower contrast and extend above the top of the 171 Å filament spine because of the high optical thickness, as discussed in Section[4.1].

To determine the relation between the prominence legs and the underlying magnetic features, we again looked back in time to the previous four days and plot the Hα images, AIA 171 Å images, and LOS magnetograms side by side, focusing on prominence PC in Figure[11]. The 171 Å images are in a logarithmic scale to highlight dark structures. A Gaussian smooth filter is applied on the HMI magnetograms to reduce noise and highlight strong magnetic elements. The filament legs in Hα images correspond well with the filament legs found in 171 Å images. We again outline the supergranular boundaries with dashed lines connecting strong magnetic elements on the HMI magnetograms. We mark the tips of bars and the southern end of legs as footpoints with small circles in different colors and ordered labels, as we did for prominence PA. After carefully checking the circles on the magnetograms, we find that all 29 footpoints in the four snapshots are at supergranular boundaries, that is, eight footpoints in the first row on November 15, six footpoints in the second row on November 17, seven footpoints in the third row on November 18, and eight footpoints in the last row on November 19.

5. Discussion and conclusions

We have used a 3D reconstruction technique on image data of simultaneous observations from different viewing angles to study three stable prominences: a quiescent, an intermediate, and a mixed type. In this section we present our conclusions on the main findings followed by further discussion.

We obtained 3D coordinates of the footpoints and top points of prominence legs of the three prominences in their stable phase. From these coordinates, we derived the inclination angles of the legs relative to the solar surface for the first time. These legs are highly inclined and not perpendicular to the solar surface, although some of them apparently stand radially at some viewing angles. The average inclination angle of the 15 legs, except for the biased PC F7-T7 leg, of the three prominences...
Fig. 6. Prominence PB observed on February 9, 2012, by SDO/AIA (left) and STEREO B/EUVI (right) in 171 Å channel. The EUVI image is in log-scale for clarity. Different features are marked with circles in different colors, and circles of the same color in two images represent the same feature. The diameter of these circles is 6 arcsec (about 4,350 km). Dashed white lines are the Carrington latitude and longitude lines according to the latitudes and longitudes of points F1 and F3.
Fig. 7. HMI magnetogram, AIA 171 Å, 193 Å, and 304 Å images with the same field of view looking at prominence PB on February 9, 2012. Prominence features are marked with circles in different colors for all AIA images. Only footpoints of the prominence are marked with circles in the magnetogram, which is shown in gray saturated at \( \pm 30 \) G. Circles of the same color in these images represent the same feature. The diameter of these circles is 8 arcsec (about 5,800 km).
Fig. 8. Measuring the thickness of the spine of prominence PB. (a) Prominence spine in the SDO/AIA 171 Å image and two lines in blue. (b) Intensity curve along the upper line in (a). (c) Intensity curve along the lower line in (a).
Fig. 9. Prominence PC observed on November 19, 2011, by SDO/AIA (left) and STEREO A/EUVI (right) in the 171 Å channel. The EUVI image is in log-scale for clarity. Different features are marked with circles in different colors, and two circles of the same color in the two images represent the same feature. The diameter of these circles is 8 arcsec (about 5,800 km). The dashed white lines are the longitude and latitude lines of the Carrington coordinates of F4 and F5. The crosses mark some dark patches and small bright spots in the chromosphere near the prominence to avoid confusion.
Fig. 10. HMI magnetogram, AIA 171 Å, 193 Å, and 304 Å images with the same field of view looking at prominence PC on November 19, 2011. Prominence features are marked with circles in different colors for all AIA images. Only footpoints of the prominence are marked in the magnetogram, which is shown in gray saturated at ±40 G. The diameter of these circles is 8 arcsec (about 5,800 km). The crosses mark some dark patches and small bright spots in the chromosphere near the prominence to avoid confusion.
Fig. 11. Time sequence of prominence PC in Hα images, AIA 171 Å images in logarithmic scale, and LOS magnetograms on November 15 ((a)-(c)), November 17 ((d)-(f)), November 18 ((g)-(i)), and November 19 ((j)-(l)) in 2011. The small circles in different colors show the locations of the footpoints of prominence legs. The diameter of these circles is 8 arcsec (about 5,800 km). The magnetograms in gray are Gaussian smoothed and saturated at ±30 G. Supergranular boundaries are indicated by dashed lines in different colors connecting strong magnetic elements in the HMI magnetograms.
is 68±6 degrees. When the legs from intermediate prominence PB and leg F7-T7 of PC are excluded, the average inclination angle of the 11 legs of the quiescent prominence is 68.7±6 degrees. Depending on the relative angle with the vertical plane of spines, these inclined legs may appear to be laterally protruding bars if the prominences were viewed from the top. This picture is consistent with the 3D force-free prominence model of Gunar et al. [2018], in which two laterally protruding filament bars appear as two inclined prominence legs from the synthetic Hα prominence view with a LOS perpendicular to the prominence axis. The accuracy of our 3D reconstruction is limited by the spatial resolution of the STEREO EUVI images, and 3D information about fine structures such as filament threads is beyond the scope of this study because the resolutions of the AIA and EUVI images are limited.

From the LOS both along and perpendicular to the prominence axis, the apparent widths of the two legs of PA have similar values of about 6,000 km, which are consistent with statistic results found by Wedemeyer et al. [2013]. The cross-section of the legs is therefore more likely to have a roundish or semicircle shape than a thin-sheet shape. The overlapping of the two legs in the LOS along the filament axis may cause an overestimation of the width. Another leg of PA at the solar limb shows apparent horizontal oscillations with larger amplitude at the higher location, indicating that the upper part of prominence legs may have shallower magnetic dips than the lower part. The cross-section of the legs was studied in only two cases with drawbacks from overlap, and the horizontal oscillations were studied in a single case. Therefore a broader study is needed to verify the statistical significance of these findings.

By comparing the heights of the top points, we find that different locations along a prominence axis have different heights with a two- to threefold difference, which indicates that the hosting magnetic flux rope may have fluctuating heights along its axis. The length of the intermediate prominence PB (about 290,000 km) is shorter than the quiescent prominence PA (about 560,000 km) and the compound quiescent prominence PC (about 730,000 km). Because the footpoints may not be immediately beneath a prominence axis, the accumulated distances between footpoints may overestimate the true length of the prominence.

To justify the choice of 171Å channel images to measure the real filament sizes, we present a visual comparison of filament sizes in different spectral bands, for example, AIA 171Å, 193Å, 304Å in Figure [2] and Figure [7] and Hα. AIA 171Å in Figure [3] and Figure [11]. The sizes of 171Å filaments are similar to the sizes of Hα filaments, and the overall structures appear to be sharper in AIA 171Å images given that the AIA 171Å images have a better resolution than the Hα images. Thin filament structures shown in Hα images may not be visible in the 171Å channel with poor contrast due to little absorption of background light. No simultaneous observations in Hα or other chromospheric spectral lines from multiple view angles are available, therefore the best choice for us is to use the absorption features in 171Å images to represent filaments. The AIA 304Å channel collecting optically thick emission from plasma at about 50,000 K shows a layer of PCTR in front of prominences, therefore prominence images in 304Å channel above the solar limb occupy a larger volume than the actual prominence plasma does, which was also shown by Berger et al. [2011] in their Figure 1.

By checking the footpoint positions in the magnetograms, we find that almost all of the footpoints in a sample of 70 of the three prominences are located at or very close to the supergranular boundaries that are traced by magnetic network. This result confirms the previous finding by Plocieniak & Rompolt [1973], who suggested that the cool prominence plasma in prominence legs is preferentially located at some condensed magnetic structure associated with supergranular boundaries. Based on 3D reconstruction, we find that all 14 footpoints (excluding the 2 footpoints near the solar limb) of the three prominences are at supergranular boundaries. To quantify the uncertainty caused by the projection effect due to the height difference between the footpoints and the magnetograms, we calculated the projected distance (the distance between the apparent position and the radially projected point) of the footpoints in the magnetograms, as listed in Table[1] using the heights and heliocentric angles of the footpoints. If we were to consider the projection effect, the footpoints would shift by less than a marking circle size (about 5,800 km) toward the solar center because projected distances are comparable to or smaller than the diameter of the marking circles. This means that the projection effect does not change our conclusion that the footpoints of the three prominences are located near supergranular boundaries. About 96% (54 out of 56) footpoints of the PA and PC based GONG Hα images are also found to be at supergranular boundaries. The result based on 3D reconstructed footpoints is more reliable than the result based on Hα images because footpoints found in single viewing angle Hα images cannot exclude uncertainties from projection effects. In order to understand the magnetic structure of quiescent filament legs, a further dedicated study based on high-resolution observations is needed to determine the locations of filament footpoints in photospheric magnetograms and investigate possible magnetic flux cancellation near filament footpoints. Previous evolutive magnetic flux rope models of quiescent prominences (Mackay & Van Ballegooijen 2006; Xia et al. 2014; Xia & Kepens 2016) with a smooth magnetic topology along the PIL need to consider the effect of supergranulations to further explore possible magnetic substructures around prominence legs.

We have measured the inclination angle, the height of top points and footpoints, and the length of prominence legs for three prominences. Because the legs of PA and PC are typical and representative of legs of quiescent prominences in general, the new knowledge we obtained from them is likely to be approximately valid for other quiescent prominences. Although the legs of the intermediate prominence PB are not so clearly separable as the legs of quiescent prominences, combining the results from PB can help us to understand general properties for non-active-region stable prominences. With new space telescopes, such as the Solar Orbiter ( Müller et al. 2020) and the Advanced Space-based Solar Observatory (ASO-S) ( Gan et al. 2019) observing in different viewing angles in the same waveband, for example, Lo images, 3D reconstruction of prominences will give us more accurate and detailed 3D information of solar prominences.

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