Two Solar Tornadoes Observed with the Interface Region Imaging Spectrograph

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Abstract

The barbs or legs of some prominences show an apparent motion of rotation, which are often termed solar tornadoes. It is under debate whether the apparent motion is a real rotating motion, or caused by oscillations or counter-streaming flows. We present analysis results from spectroscopic observations of two tornadoes by the Interface Region Imaging Spectrograph. Each tornado was observed for more than 2.5 hr. Doppler velocities are derived through a single Gaussian fit to the Mg II k 2796 Å and Si IV 1393 Å line profiles. We find coherent and stable redshifts and blueshifts adjacent to each other across the tornado axes, which appears to favor the interpretation of these tornadoes as rotating cool plasmas with temperatures of $10^4$–$10^5$ K. This interpretation is further supported by simultaneous observations of the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory, which reveal periodic motions of dark structures in the tornadoes. Our results demonstrate that spectroscopic observations can provide key information to disentangle different physical processes in solar prominences.

Key words: Sun: corona – Sun: filaments, prominences – Sun: UV radiation

Supporting material: animations

1. Introduction

Solar prominences are cool and dense materials embedded in the hot corona above the solar limb. On the disk, they often show up as dark filament structures in Hα and extreme ultraviolet observations. Morphologically, solar prominences consist of spines, legs, and barbs (e.g., Martin 1998; Parenti 2014; Shen et al. 2015). It has long been known that some parts of a subset of prominences show signs of rotation. Edison Pettit first noticed these types of prominences and categorized them as tornadoes (Pettit 1943). More recently, the term “tornado” has also been used to describe some other rotating solar phenomena including the macrospicules with rotating motions (Pike & Mason 1998; Curdt & Tian 2011), chromospheric swirls that may channel energy to the corona (Wedemeyer-Böhm & van der Voort 2009; Wedemeyer-Böhm et al. 2012; Yang et al. 2015), and fast-evolving tornado-like erupting structures (Chen et al. 2017). Other rotating structures, such as coronal cyclones rooted in the rotating network magnetic field (Zhang & Liu 2011) and rotating jet-like structures (e.g., Shen et al. 2011, 2012), have also received attention in recent years. In this paper, the term “solar tornadoes” refers to the barbs or legs of some prominences that show an apparent rotating motion.

Many solar tornadoes have been identified since the launch of the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) and Hinode. Through observations of the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board SDO, Li et al. (2012) found the formation of a solar tornado and its relationship with the coronal cavity above. Su et al. (2012) found that the rotating solar tornadoes observed with SDO/AIA have a connection with prominences. The possible relationship between a solar tornado and coronal mass ejections (CMEs)/flares from the surrounding active region has also been reported (Panasenco et al. 2013). Wedemeyer-Böhm et al. (2013) performed a statistical analysis of tornadoes using SDO/AIA observations and found that these solar tornadoes, which they called giant tornadoes, have a close relationship with prominences, share some similar characteristics with barbs, and may serve as the plasma source of some prominences. Attempts of plasma diagnostics and magnetic field measurements have also been made for solar tornadoes (e.g., González et al. 2016; Levens et al. 2016b, 2017). A theoretical investigation by Luna et al. (2015) suggests that the cool and dense plasma in these tornadoes can be supported by the Lorentz force if the associated magnetic structure is sufficiently twisted or strong poloidal flows are present.

There are different interpretations for the apparent rotating motion of solar tornadoes, including rotation, oscillation, and counter-streaming. Su et al. (2014) and Levens et al. (2015) analyzed a solar tornado observed by the EUV Imaging Spectrometer (EIS; Culhane et al. 2007) on board Hinode, and found split redshifts and blueshifts across the tornado. They interpreted this result as the rotational motion of plasma in the tornado. However, the emission lines that they used are formed at coronal temperatures. Thus, this observational signature can only be explained as the rotation of the hot coronal plasma surrounding the tornado, and might not reflect the motion of the cool tornado materials. On the contrary, some researchers believe that the apparent rotating motion is not real rotation. For instance, Panasenco et al. (2014) mentioned that such apparent motion is a visual illusion caused by the projection of oscillating plasma or counter-streaming flows. Using observations of two tornadoes with the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014), Levens et al. (2016a) found no evidence of rotation through an analysis of the Mg II k Doppler shift. More recently, Schmieder et al. (2017) analyzed a solar tornado observed with Hα and found an alternation between redshifted and blueshifted regions, revealing a possible irregular periodicity of about 1 hr. Such behavior is not supposed to be caused by rotation. It is unclear how frequent such oscillations are in solar tornadoes.
Obviously, more high-resolution observations, especially spectroscopic observations, are required to disentangle these different scenarios for solar tornadoes. Here we present analysis results from IRIS observations of two solar tornadoes. IRIS has several strong emission lines formed in the temperature range of $10^4$–$10^5$ K. Observations with these lines provide information about the motion of the cool tornado materials instead of the hot coronal plasmas in the surrounding environment. Both of our IRIS observations lasted for more than 2.5 hr, which is sufficient to detect possible oscillations with a period of ∼1 hr (Schmieder et al. 2017). Our analysis of the IRIS spectra appears to support the scenario of rotation for these two tornadoes.

2. Observations

Since its launch in 2013, IRIS has been obtaining spectra and slit-jaw images (SJIs) with a high spatial resolution and cadence. The slit-jaw imager has four passbands sampling mainly the C II 1334 Å/1335 Å lines, the Si IV 1393 Å/1400 Å lines, the Mg II k 2796 Å line, and the photospheric continuum around 2832 Å, respectively. The spectrograph has two wavelength bands in the far-ultraviolet (FUV; 1332 Å–1358 Å and 1389 Å–1407 Å) and one wavelength band in the near-ultraviolet (NUV; 2783 Å–2834 Å; De Pontieu et al. 2014). Here we analyze two tornado-like prominences (T1 and T2) observed by IRIS.

2.1. First Tornado (T1)

The first solar tornado was observed with IRIS using a sit-and-stare observation mode from 5:50 to 8:21 UT on 2014 April 9. The pointing coordinate of the telescope was (−638'', −764'') and the slit was rolled by −48°. The spatial pixel size was 0''167. With an exposure time of 8 s, 960 exposures were taken at a cadence of 9.4 s. SJIs in the filters of 1400 Å and 2796 Å were taken alternatively, with a field of view (FOV) of 119'' × 119'' and a cadence of 19 s for each passband. We use calibrated level 2 data for our analysis. Dark current subtraction, flat field, and geometrical corrections have all been applied to the data (De Pontieu et al. 2014).

We mainly use the Si IV 1393.755 Å and Mg II k 2796.347 Å lines for spectral analysis, as the formation temperatures of these two strong lines fall in the temperature regime of prominences (∼0.1 MK for Si IV and ∼0.01 MK for Mg II). These two lines are among the strongest spectral lines in the IRIS spectrum, and thus they provide an excellent tool for prominence diagnostics. We take the average line centers above the solar limb as the rest wavelengths and calculate the Doppler shift of each line at each spatial pixel of the tornado.

2.2. Second Tornado (T2)

The second observation was a 16-step raster scan made from 00:09 to 03:40 UT on 2017 March 12. The pointing coordinate of the telescope was (702'', 748''). The spatial pixel size was 0''167. The FOV of the spectral observation was 30'' × 174'' and each raster covered 16 2'' steps. The cadence was 31.6 s, and the step cadence was 502 s. SJIs in the filters of 1400 Å and 2796 Å were taken alternatively. The FOV of the SJIs was 167'' × 174'', and the cadence was 63 s for each passband. Also, the level 2 data are used.

The same Si IV and Mg II k lines are used for our spectral analysis. The orbital variation (both the thermal component and

Figure 1. IRIS SJIs of the 2796 Å (left) and 1400 Å (right) passbands for T1. The white vertical line in each image marks the location of the IRIS slit. The range between A and B is the range of the y-axis of Figure 2. The numbers 1–9 indicate nine different positions where the line profiles are presented in Figures 3 and 4. (An animation of this figure is available.)
the spacecraft velocity component has been subtracted in the level 2 data (Tian et al. 2014). However, we find that there is still a residual orbital variation. To avoid misinterpretation of the data, we derive the average line centroid of the Ni I 2799.474 Å line on the solar disk as a function of time through a Gaussian fit. The average value is then subtracted from this trend. Afterward, the resultant relative variation is subtracted from the Doppler shift of the Mg II k 2796.347 Å line. Because the residual (in the unit of Å) is anti-correlated between NUV and FUV lines (De Pontieu et al. 2014), we can also apply the result derived from the Ni I 2799.474 Å line to the Si IV 1393.755 Å line. For absolute wavelength calibration in the FUV wavelength band, we assume that the Fe II 1392.817 Å line has no Doppler shift on average on the solar disk. For absolute wavelength calibration in the NUV band, several strong absorption lines are assumed to be at rest on the solar disk.

We also use the SDO/AIA data to study the second tornado. We have analyzed images taken in the AIA 193 Å passband. The pixel size of AIA 193 Å images is ~0"6, and the cadence is 12 s.

3. Results and Discussion

3.1. First Tornado (T1)

Figure 1 and the associated online animation show the first solar tornado observed in the 2796 Å and 1400 Å passbands. The IRIS slit (white vertical line) crossed one leg of a prominence. The width of the leg is about 30" (~22 Mm). The IRIS 2796 Å and 1400 Å passbands mainly sample the Mg II k 2796 Å line formed at a temperature of about 0.01 MK and two Si IV lines formed at a temperature of ~0.1 MK, respectively. From the image sequences of both passbands, there seems to be an apparent rotating motion of the prominence materials around the rotation axis. However, the rotation direction cannot be easily inferred by just looking at the intensity images. Spectroscopic observations are required to determine whether real rotation exists and what is the rotation direction in this prominence.

To reveal the line-of-sight (LOS) velocities of this prominence leg or solar tornado, we have performed a single Gaussian fit (SGF) for the Si IV 1393 Å line profiles observed
in the tornado. The line profile of this optically thin line is generally Gaussian in the tornado. The Mg II \(k 2796 \text{ Å} \) line is formed under the optically thick regime, and usually shows a reversal at the line core. However, in prominences the central reversal of Mg II is absent or very shallow (Schmieder et al. 2014), which is also the case in our observations. For this type of line profile, the line centroid derived from the fitting should reflect the velocity of the bulk motion. In addition, we are mainly interested in the change of Doppler shift across the tornado axis. Thus, a single Gaussian fit has also been applied to the profiles of this line observed in the tornado. The similar trend of Doppler shift found in both the Mg II and Si IV lines also confirms the validity of this method.

Through the SGF we have obtained the peak intensity and Doppler shift of each line at every pixel along the slit during the sit-and-stare observation. Figure 2 shows the temporal evolution of the Doppler velocity and intensity along the slit for both the Mg II and Si IV lines. The range of the y-axis is from A to B, across the tornado, as shown in Figure 1. A persistent and split redshifts and blueshifts at two sides of the tornado can be seen from Figure 2. The absolute value of the maximum Doppler velocity is about 10 km s\(^{-1}\). During the whole ∼2.5 hr observation period, the sign of the Doppler velocity is not changed on each side of the tornado.

Examples of the Mg II and Si IV line profiles are presented in Figures 3 and 4. The measurement error of IRIS includes mainly two components: the photon counting error and CCD readout noise. The errors shown in the plots of line profiles are derived by adding the two in quadrature. The photon counting error is calculated as the square root of the photons. For the
Si IV line each DN corresponds to \( \sim 4 \) photons and for the Mg II line one DN represents \( \sim 18 \) photons. The readout noise is \( \sim 3.1 \) DN for Si IV and 1.2 DN for Mg II, which is related to the dark current uncertainty (De Pontieu et al. 2014).

The nine Mg II profiles marked as 1–9 in Figure 3 are observed at nine different positions along the slit (across the tornado, from one side to the other), as marked in Figure 1. The Doppler velocity changes from about \(-12 \) km s\(^{-1}\) (blueshift) on one side to nearly zero in the center of the tornado, and then to about \(11 \) km s\(^{-1}\) (redshift) on the other side.

Due to the weak signal on the far sides of the tornado, we only plot Si IV line profiles at six positions across the tornado (Figure 4). The single Gaussian fit works well with the Si IV 1393 Å line. Again the Doppler velocity changes from negative (blueshift) on one side of the tornado to positive (redshift) on the other side.

Figure 5 presents the change of the intensity and Doppler velocity of Si IV across the tornado. The Doppler velocity (solid line) and peak intensity (dashed line) are averaged over the whole observation period. The average Doppler velocity gradually changes from negative (blueshift) on one side of the tornado to positive (redshift) on the other side of the tornado. Meanwhile, the highest intensity appears near the center of the tornado, where the LOS velocity is \( \sim 0 \) km s\(^{-1}\). Because the Si IV line is optically thin, the intensity is proportional to the integrated emission along the LOS. Assuming a rotating cylinder or a helical flow/rotating plasma surrounding a central static structure with a uniform density, the integrated intensity should reach the peak value in the center as the integration length is the largest there; also, the velocity of the toroidal motion should have no component along the LOS at the center. The result presented in Figure 5 appears to be consistent with this scenario. The
We also plot the temporal evolution of the average Doppler velocity and peak intensity of Si IV 1393 Å on each side of the tornado. In Figure 6, the top panel shows the temporal evolution of the average Doppler shift (solid line) and intensity (dashed line) in the whole blueshifted region. The bottom panel presents the same for the redshifted region. During the 2.5 hr period of the observation, the average Doppler velocity in the blueshifted region remains negative, and that in the redshifted region remains positive. There is no sign change for the Doppler shift in either the blueshifted or redshifted region, which might not be easily explained by the oscillation scenario.

3.2. Second Tornado (T2)

The way we process and analyze the data of the second solar tornado is basically the same as for the first one. Figure 7 and the associated online animation show the second solar tornado observed in the 1400 Å and 2796 Å passbands. The IRIS slit crossed one leg of a prominence, which appears to experience rotating motion around the rotation axis. The six white vertical lines that cross the solar tornado mark six selected slit locations along the slit in the 16-step repeated raster scans.

Again we perform a single Gaussian fit to the Si IV 1393 Å and Mg II k 2796 Å line profiles, and obtain the Doppler velocities and peak intensities of the two emission lines at different spatial locations and different times. Figures 8 (A)–(F) present six sets of intensity and Doppler shift images of the Mg II k line, corresponding to the six slit locations. Split redshifts and blueshifts across the tornado axis can be found in all six Dopplergrams. Such a type of Doppler pattern is coherent and stable during the whole 3.5 hr period of the observation, possibly suggesting a coherent rotating motion of the cool tornado plasma.

We present several profiles of the Mg II line and their fitting results in Figure 9. These nine profiles were observed at nine different locations across the tornado, from one side to the other. Consistent with the Doppler signature depicted in Figure 8, the Doppler velocity changes from blueshift to redshift across the solar tornado.

The intensity and Doppler shift images for the Si IV 1393 Å are presented in Figure 10. Similar to Figure 8, the Si IV Dopplergrams also reveal adjacent redshifts and blueshifts across the axis of the tornado, without any change of sign throughout the observation. In Figure 11, six line profiles obtained from six different positions across the tornado reveal a similar trend of the Doppler shift: from blueshift on one side of the tornado to redshift on the other side.

We also present the average Doppler velocity (solid line) and intensity (dashed line) of the Si IV line along the slit in Figure 12. At each spatial pixel, the Doppler velocity and peak...
intensity are averaged during the whole observing period. The six panels correspond to the six slit locations. At all six slit locations, the average Doppler velocity exhibits the trend that it changes from blueshift on one side of the tornado to redshift on the other side. The maximum value of the average intensity is found at the location where the velocity is \( \sim 0 \) km s\(^{-1}\) (the center of the solar tornado). As stated in Section 3.1, this result is consistent with the scenario of a rotating tornado.

Figure 8 shows the temporal evolution of the average Doppler velocity (solid line) and intensity (dashed line) in the IRIS Mg II 2796Å line for T2. The six rows show the results for the six different slit locations marked in Figure 7. The peak intensities are shown in logarithmic scale. The range of the y-axis in each panel corresponds to the range between A and B as marked in Figure 7. The dark horizontal lines in the images correspond to the fiducial mark on the IRIS slit.
blueshifted and redshifted regions for the Mg II and Si IV lines. Again, no sign reversal can be identified from the Doppler shift on either side of the tornado.

We have also analyzed the images taken with SDO/ALa for the second solar tornado. Figures 14(C)–(E) shows three spacetime diagrams of the AIA 193 Å intensity. The three diagrams are obtained at the first three slit locations of IRIS as shown on the left panel of Figure 14. We obtain a result similar to that of Su et al. (2014). Although the motion of the darkest feature is hard to track, we can still find crossing dark structures with less absorption. The crossed dark structures on each spacetime diagram, as marked by the yellow dashed lines, are a sign of periodic motion. Such crossed structures can be caused either by the rotation of cold materials or periodic oscillation, but it may not be easily explained by counter-streaming.

Because the oscillation scenario is likely not consistent with our spectroscopic observations, this result can only be explained by the rotation of cool materials in the tornado.

4. Summary

Previous analyses of solar tornadoes led to different interpretations about the apparent motion of the tornadoes: rotation, oscillation, and counter-streaming. With spectroscopic observations of the cool tornado materials by IRIS, we demonstrate that the apparent rotating motion of the two tornadoes studied here is most likely caused by the rotating plasma in the tornado.

The Doppler shifts of the Mg II k 2796 Å and the Si IV 1393 Å lines reveal crucial information about the nature of the motion in solar tornadoes. Split redshifts and blueshifts across the tornado axis are found in both observations. In the second
observation, a similar Doppler pattern is found at different locations along the tornado axis. A similar Doppler pattern for hot coronal lines has been previously found by Su et al. (2014) and Levens et al. (2015), and was interpreted as rotating motion of the million-degree plasma surrounding the tornado. The Doppler shifts that we obtained reflect the mass motion of the cool tornado materials, as the Mg II and Si IV lines are formed at a temperature of ~0.01 MK and ~0.1 MK, respectively.

Both observations lasted for more than 2.5 hr, a duration that is long enough to identify possible periodic oscillation (alternation of redshifts and blueshifts) with a ~1 hr period as identified by Schmieder et al. (2017). However, during the
observations these adjacent redshifts and blueshifts appear to be persistent, and they do not show any sign change of the Doppler shift. Thus, the apparent rotating motion in our observations is likely not dominated by oscillations. However, we may not rule out the possibility of oscillations in tornado structures. For instance, some type of oscillation with a relatively small amplitude could be superimposed on the overwhelming rotating motion.

In both observations, the average Doppler velocity changes gradually from the blueshift on one side of the tornado to nearly zero in the center, and then to redshift on the other side. The gradual change of the Doppler shift across the tornado axis might not be easily explained by counter-streaming flows, unless there are strong interactions between the oppositely directed flows. The maximum intensity of the Si IV line is generally found around the center of the tornado, where the LOS velocity is nearly zero. Such behavior is consistent with the scenario of rotating plasma.

The AIA observation of the second tornado may rule out the possibility of counter-streaming flows. The crossed dark structures in the spacetime diagrams of AIA 193 Å intensity are a sign of periodic motion: either rotation of cool plasma, or oscillation of plasma in solar tornadoes. It appears difficult to explain this periodic motion by counter-streaming flows.

In summary, analysis results from our IRIS and AIA observations of solar tornadoes appear to provide evidence to the viewpoint of cool rotating materials in the two tornadoes studied here. There may be two different scenarios: the entire magnetic structure of a tornado is rotating (magnetic tornado; Su et al. 2012), or cool materials are flowing along a static helical magnetic structure. If the entire magnetic structure of a tornado is rotating, we can estimate the time used for the coronal field lines to be dragged by one turn, which is \( \sim 1.3 \) hr if we use a rotation speed of \( \sim 10 \) km s\(^{-1}\) and a width of \( \sim 20^\circ\). Considering the fact that the two tornadoes we study here are seen to exist for around a week close to the solar limb from AIA observations, the magnetic field lines of these tornadoes would be wound around by more than 100 turns. Such highly twisted magnetic structures are obviously unstable and would inevitably lead to eruptions before so many rotations. Thus, the continuous rotation of the entire magnetic structures associated with the tornadoes makes it difficult to explain the observed long lifetimes of the tornadoes. On the other hand, the scenario of cool materials flowing along a relatively stable helical magnetic structure is not in contradiction with the existence of these structures for weeks. However, due to the lack of precise measurement of the magnetic fields in the tornadoes, we cannot confidently comment upon whether or not this scenario is correct.

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Figure 11. Similar to Figure 9 but for the Si IV 1393 Å line profiles at six positions marked in Figure 7. We have added nine to the observed counts for the purpose of illustration.
Figure 12. Change of average Doppler velocity (solid line) and intensity (dashed line) along the slit (across the tornado) for T2. The Doppler velocity and intensity are derived by applying an SGF to the Si IV 1393 Å line profiles. The six panels represent results derived at the six slit locations marked in Figure 7.

Figure 13. Temporal evolution of the average Doppler velocity (solid line) and intensity (dashed line) in the blueshifted (top) and redshifted (bottom) regions at the first selected slit location (see Figure 7) for T2. The Doppler velocity and peak intensity are derived from an SGF to the Mg II k 2796 Å (A)–(B) and Si IV 1393 Å (C)–(D) line profiles.
Figure 14. (A)–(B): An IRIS 1400 Å image (top) coaligned with an AIA 193 Å image (bottom). The three dark vertical lines indicate the first three slit locations as shown in Figure 7. (C)–(E): Spacetime diagrams for these three lines. The yellow dashed lines mark crossed dark structures, indicating periodic motion. (An animation showing the image sequence of AIA 193 Å is available.)

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