SOLAR MAGNETIZED “TORNADOES”: RELATION TO FILAMENTS

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ABSTRACT

Solar magnetized “tornadoes,” a phenomenon discovered in the solar atmosphere, appear as tornado-like structures in the corona but are rooted in the photosphere. Like other solar phenomena, solar tornadoes are a feature of magnetized plasma and therefore differ distinctly from terrestrial tornadoes. Here we report the first analysis of solar “tornadoes” (two papers which focused on different aspects of solar tornadoes were published in the Astrophysical Journal Letters and Nature, respectively, during the revision of this Letter). A detailed case study of two events indicates that they are rotating vertical magnetic structures probably driven by underlying vortex flows in the photosphere. They usually exist as a group and are related to filaments/prominences, another important solar phenomenon whose formation and eruption are still mysteries. Solar tornadoes may play a distinct role in the supply of mass and twist to filaments. These findings could lead to a new explanation of filament formation and eruption.

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

Online-only material: animations, color figures

1. SOLAR MAGNETIZED “TORNADOES”

The Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO) observes the Sun in high-temporal cadence (∼12 s) and spatial resolution (∼0.6 arcsec). This capability enables detailed observation of a new phenomenon in the solar corona, solar magnetized “tornadoes.” They appear as tornado-like magnetic structures and are widely distributed over the solar disk. Similar phenomena may have been seen (e.g., movie 13, “Tornadoes and fountains in a filament on 2000 August 2,” in http://soi.stanford.edu/results/SoLPhys200/Schrijver/TRACEsolarphysicsCD.html) in the observations from the Transition Region and Coronal Explorer (TRACE; Handy et al. 1999) but never been reported in scientific journals. Here we present the first study on solar magnetized “tornadoes” and their role in the formation and eruption of filaments/prominences, another type of solar phenomenon.

During 2011 June 22–23, a group of solar tornadoes developed on the solar northwest limb (Figure 1 and online movies). The “tornado” funnels appear as dark, cone-shaped column structures in the AIA Fe x x 171 Å (∼0.63 MK) passband (Figures 1(a)–(c)), connecting the surface and the prominence seen in the AIA He i 304 Å (∼0.05 MK) and Ca ii K3 (3934 Å) lines (Figures 1(d) and (f)). The largest tornado (located at [683, 628] in Figure 1(c)) has a height of about 60 arcsec (∼44,260 km) with a width of only ∼2 arcsec (∼1480 km) at the bottom and ∼10 arcsec (∼7380 km) at the top. The widths in AIA 304 Å, H-alpha and Ca ii K3 are about 2–3 times larger, suggesting that the core of tornadoes may have a lower temperature than that of the surrounding plasma.

AIA 171 Å movies (M1) reveal apparent rotating motions in the evolution of these structures. On 2011 June 22, several dark vertical structures appeared on the surface (Figure 1(a)) and grew to higher altitude. The motion of the attached branches indicates the rotation of the whole structure. The overlying prominence, which connected these tubes, became more prominent on 2011 June 23 (see movies in AIA 304 Å). We analyzed the dynamics of solar tornadoes using the time–distance diagrams (see Figure 2), known as stack plots. The dark sinusoidal features in these plots suggest that the dark vertical threads in the solar tornadoes were rotating. Four regions (a, b, c, and d) were selected to show the detail (the third and fourth rows in Figure 2). In particular, the features in region c appear to reveal two mutually rotating threads, which cause the upper part of the tornado to become highly twisted as indicated by the converging motion (with a speed of about 1.5 km s−1) shown in the time–distance plot (top panel of Figure 2). Sometimes, the dark threads in solar tornadoes also show divergence (second panel of Figure 2), which may suggest untwisting motions. If the sinusoidal features seen in time–distance plots are interpreted as rotating motions, we can estimate the rotating angular speed (ω) and linear speed (v) from the period (T) and amplitude (r) using ω = 2πr/T and v = 2πr/T. The periods are different for different tornadoes, suggesting that they rotated with different (angular) speeds. For the features in the four regions, their periods are measured to be about 70, 50, 70, and 30 minutes, and the estimated rotation speeds of the threads are about 8, 6, 7, and 6 km s−1.

However, oscillatory motions, which have been reported in previous works (see Isobe & Tripathi 2006; Ning et al. 2009; Tripathi et al. 2009; Bocchialini et al. 2011, and references therein), cannot be ruled out in our events. They may coexist with the rotational motion and cause the periodic variations seen in Figure 2 as signature of torsional Alfvén wave in the corona (Jess et al. 2009).

To investigate whether solar “tornadoes” rotate and whether they relate to the magnetized vortices detected in the solar photosphere and chromosphere (Bonet et al. 2008, 2010; Steiner 2012),...
et al. 2010; Wedemeyer-Böhm & Rouppe van der Voort 2009), we studied another group observed during 2010 October 18–21 by multiple spacecrafts at different locations (see Figure 3 and the associated online movies M2 and M3 for an overview of this event). The AIA 171 Å movie and selected frames in Figure 4 show rotating threads in one of the solar tornadoes (indicated by a white box in Figure 3) from 12:50 to 13:50 UT on October 19. By tracking the motions of magnetic elements on the solar surface using the DAVE method (Schuck 2006), a horizontal flow map is derived from the photospheric magnetograms observed by the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board the SDO around 13:11 UT (Figures 4(b) and (c)). It reveals vortex flows with velocity of up to a few hundred meters per second in the footpoint region of the tornado. The coincidence in position and timing suggests that the rotational motion in solar tornadoes has a close connection with the vortex flows in the photosphere.

2. SOLAR TORNADOES AND FILAMENTS

Strikingly, we found that solar “tornadoes” are often correlated with filaments, another important phenomenon in the solar corona. Filaments are dark channels filled with relatively cool (around 10^4 K) and dense plasma suspended in the hot (~1 MK) and tenuous corona. When they appear above the solar limb, they are recognized as bright structures called prominences. Filaments and prominences may erupt from the solar surface to become coronal mass ejection (CME) and produce solar flares.

Therefore, they are important for understanding the nature of solar activities and predicting the space weather on Earth. How filaments form and evolve to eruption is still a big mystery, although various models have been proposed (see Labrosse et al. 2010 and Mackay et al. 2010 for a review). Filaments are believed to be helical magnetic flux ropes (Rust & Kumar 1994). The source of dense, cold plasma and twists in the filament, however, is still unclear.

The spine and barbs are the two structural components of a filament. The spine is the highest, horizontal part of a filament. Filaments are thought to be helical magnetic flux ropes (Rust & Kumar 1994). The source of dense, cold plasma and twists in the filament, however, is still unclear.

The association with solar “tornadoes” and filaments has been shown in the 2011 June 23 event. In the event on 2010 October 18–21 (Figure 3), their relations are revealed more clearly using observations from two simultaneous views with a separation angle of 80° between the Solar Terrestrial Relations Observatory (STEREO-B/EUVI; Wuelser et al. 2004) and SDO/AIA (aided with ground-based H-alpha observations). The association with solar tornadoes may provide a new key to understand the formation and eruption of filaments.

Below is what we learned from this event: (1) barbs appear earlier than the filament spine itself and may act as supporting stands during the evolution of the filament. Only three dark blobs (barbs) were visible in H-alpha on October 18. One day later...
Figure 2. Dynamics of solar tornadoes on 2011 June 22 and 23. First and second panels: time–distance diagrams (stack plots) along “cut1” and “cut2” in Figure 1(b) (with start point at the north end). Third and fourth panels: four regions a, b, c, and d were selected to show the details of the periodic variations (white solid lines connect the minima in brightness at different times).

(October 19), line structures (spine fields) were seen between barbs in H-alpha and 171 Å images (Figure 3), especially between the two southern barbs. On October 20, the filament with three major barbs was clearly visible in the H-alpha spectral line. (2) The filament barbs, as viewed from side, are the vertical tornado structures and appear in projection as viewed from Earth. Previous studies have found counterstreaming flows as evidence for vertical magnetic structure in filaments (Zirker et al. 1998). Here we present in Figure 3 (October 18 and 19) the good agreement in spatial relation between the filament barbs (H-alpha) and the solar “tornadoes” (AIA 171 Å). Figure 3 (October 20) in particular shows that the locations of barbs as viewed on-disk have no corresponding horizontal features when viewed from the side (STEREO-B), but have vertical tornado structures. The best evidence for projection effects is given by the most northern tornado. Its coronal part, as viewed from Earth, maps to the most northern on-disk barb location. (3) Solar tornadoes can erupt with the associated filament. The movies recorded in SDO/AIA 171 (M2) and STEREO-B 195 Å (M3) show the filament formation and eruption. Two ribbons and bright loops are seen on October 22 after the eruption (online movie M2), which are similar to that produced in a solar flare. However, no significant X-ray emission was detected.

Figure 5 shows additional examples for the eruption of solar tornadoes and associated filaments. In the first example, the tornadoes started to form not later than 2010 October 15 and erupted on 2010 October 26. In the second example, a group of large tornadoes was associated with a giant filament across the solar disk, which appeared in the SDO field of view on 2011 November 7. A partial eruption cleaned out the eastern part of the filament on 2011 November 14. These eruptions show a common feature that a major tornado in the group appears to rise first, together with the overlying filament and cavity. The erupting filament then “pulls up” other tornadoes. However, a recent study by Régnier et al. (2011) showed that the eruption of a cavity and filament is a two-stage process composed of a slow rise phase and an acceleration phase. Thus, it cannot exclude the possibility that the rising tornado is a consequence of filament eruption. In any case, the continuous rotation of solar tornadoes can effectively build up twists in the filament structure (the slow rising phase) and finally lead to their eruption due to MHD instability.

3. SUMMARY AND DISCUSSION

Thanks to two space missions, SDO and STEREO, we obtained direct images of solar magnetized “tornadoes” from two different angles. The observations show possible connections among different solar features, such as solar tornadoes, vortices, cavities, and filaments. The results are summarized below.
1. Solar “tornadoes” are rotating magnetic structures in the solar atmosphere. Their lifetime could be from hours to weeks (small-scale tornadoes with shorter lifetimes may also exist but could be difficult to detect\(^7\)). They usually exist as a group of tornadoes due to their magnetic connections. It is unknown whether or not isolated tornadoes exist. Vortex flow is found at the foot of solar tornado as evidence for the rotational motion of magnetic structures. The driver of solar “tornadoes” is very likely associated with vortices at granule and supergranule boundaries in the photosphere. The period is about tens of minutes and the rotation speed about 5–10 km s\(^{-1}\). One of the measured tornadoes seems to show acceleration in (angular) speed with time.

2. A group of solar tornadoes exists below the filament spine and evolves with it, from formation to eruption (a short-lived event may show no appearance of a filament). Barbs are actually the projections of the tornado funnels as viewed from Earth. They appear before the filament spine forms (contains enough cold plasma that absorbs radiation from below to be visible as dark structures). Solar tornadoes can erupt with the filament spine. These eruptions generally produce two ribbons and loops, similar to those in a solar flare, but no significant enhancement in \(\text{GOES}\) soft X-rays. The evolution of the filament indicates that cold plasma and twists may be transported from the surface into the filament spine through rotating tornado funnels to make the filament visible as a dark structure in the H-alpha line.

These observations may suggest a filament model in which magnetized tornadoes (or vortices in the photospheric networks) play a central role in filament formation and eruption. The vortex flows converge and twist the magnetic tubes which connect different vortices. As they rotate, cold plasma and twists could be transported into the filament spine through tornado funnels. Barbs then appear first on the surface, and the spine afterward. The filament becomes highly twisted and unstable. It may erupt eventually with these underlying tornado funnels.

This picture needs to be further tested by observations and simulations. Some challenges to this interpretation are the

\(^7\) Wedemeyer-Böhm et al. (2012) did find solar tornadoes with lifetimes of about 10 minutes.
Figure 4. Evidence for rotational motion in a solar tornado on 2010 October 19. (a) Selected AIA 171 Å images from 12:59 to 13:23 UT. The white box in the image at 13:11 UT indicates the location of the region shown on the right. (b) and (c) Horizontal velocity field (longest arrow represents 600 m s\(^{-1}\)) superimposed on SDO/HMI white-light continuum image (b) and SDO/HMI LOS magnetic field (c) map. Red arrows stand for positive magnetic field and blue for negative. The velocities are derived from HMI magnetic measurements around 13:11 UT (10 minute cadence) and the DAVE method (with a window size of 10 pixels). (An animation and a color version of this figure are available in the online journal.)

following. (1) The model requires some upflows in the vortices for the mass supply while most observations (Bonet et al. 2008, 2010) and simulations (Kitiashvili et al. 2011, 2012; Moll et al. 2011, 2012; Shelyag et al. 2011, 2012; Shelyag et al. 2011) show downflows in the vortex core (the so-called sinkhole) at photosphere height. These researches also show signatures for some upflows in the surrounding area of vortex core. Besides, upflow was seen in the vortex at chromospheric height (Wedemeyer-Böhm & Rouppe van der Voort 2009). There are also reports on upflow at the feet of the filament (Zirker et al. 1998; Cao et al. 2010). These results may suggest height-dependent vertical flows in vortices.\(^8\)

(2) The lifetime of solar tornadoes is much longer than that of the small-scale vortices related to granules (on the order of several minutes). It is possible that larger vortices with longer lifetimes exist in the supergranule scale as observed before (Attie et al. 2009; Tian et al. 2010). What we observed in the corona may relate to some of the “solar cyclones,” which are also rotating magnetic structures with relatively long lifetime of more than 10 hr (Zhang & Liu 2011). (3) The magnetic vortices could exist anywhere in the photospheric networks while filaments always form above polarity inversion lines (PILs; Zirker et al. 1998). One explanation for the fact that solar tornadoes prefer to form as a group may be that the emergence of a twisted flux rope (Okamoto et al. 2010; Berger et al. 2011) below the surface during filament formation produces a group of vortices (and tornadoes).

Continuous measurements of Doppler velocity in the “tornado” structures from spectrographic instruments that cover at least several hours are needed for future studies. However, it should be pointed out that rotating motion revealed from Doppler signal may not necessarily be an indicator of the existence of tornado structure. A “magnetized tornado” refers to rotating magnetic structures or magnetic funnels while plasma  

\(^8\) New observations reported by Wedemeyer-Böhm et al. (2012) provided evidence for upflow in tornado structures with a typical speed of 4 km s\(^{-1}\) at chromospheric height.
flows along static helical flux ropes could generate an equivalent Doppler feature.

The connection with other solar features through the magnetic field is the most important characteristic of solar tornado, like other solar phenomena. However, it is unknown whether or not all filaments are associated with solar tornadoes. What we report here may provide an important clue to the future development of models and simulations on filaments and magnetized tornadoes themselves.

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Figure 5. Two examples for the eruption of solar tornadoes and associated filaments. The images were taken at SDO/AIA 171 Å on 2010 October 24–26 and 2011 November 13 and 14, respectively. (A color version of this figure is available in the online journal.)
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