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Penumbral Waves Driving Solar Fan-shaped Chromospheric Jets

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Abstract

We use Hα imaging spectroscopy taken via the Swedish 1 m Solar Telescope to investigate the occurrence of fan-shaped jets at the solar limb. We show evidence for near-simultaneous photospheric reconnection at a sunspot edge leading to the jets appearance, with upward velocities of 30 km s⁻¹, and extensions up to 8 Mm. The brightening at the base of the jets appears recurrent, with a periodicity matching that of the nearby sunspot penumbra, implying running penumbral waves could be the driver of the jets. The jets’ constant extension velocity implies that a driver counteracting solar gravity exists, possibly as a result of the recurrent reconnection erupting material into the chromosphere. These jets also show signatures in higher temperature lines captured from the Solar Dynamics Observatory, indicating a very hot jet front, leaving behind optically thick cool plasma in its wake.

Key words: Sun: activity – Sun: chromosphere – Sun: oscillations – Sun: photosphere

Supporting material: animation

1. Introduction

Spicules and fibrils are well documented examples of chromospheric plasma motions appearing as thin, jet-like strands. Type I spicules and dynamic fibrils are thought to be driven by magnetoacoustic shocks formed by p-modes, while type-II spicules are thought to be driven by reconnection events (Hansteen et al. 2006; Tsiropoula et al. 2012) or via the release of magnetic tension (Martínez-Sykora et al. 2017).

Fan-shaped jets (also known as peacock jets—Robustini et al. 2016—and light walls—Yang et al. 2015) have been subject to much less study due to the rarity of observing such events. These jets were first reported by Roy (1973), who described them as solar surges appearing in the centers of active regions in the Hα line. They reported strong initial acceleration with peak velocities of 150 km s⁻¹ and extensions up to 50 Mm. Deceleration due to gravity eventually caused these surges to reverse direction and fall back toward the solar surface. Until the advent of high-resolution ground-based observatories, very little was added to this description. Asai et al. (2001) combined ground-based and space-borne instruments to note that fan-shaped jets were recurrent, and appear dark in the blue wings of the Hα line, and in the Fe IX 171 Å line, normally sensitive to transition region/coronal temperatures. They also found less extreme velocities of ~40 km s⁻¹, lengths of 15–20 Mm, and mean lifetimes of 10 minutes.

On-disk fan-shaped jets most often appear at light bridges (Roy 1973; Asai et al. 2001; Robustini et al. 2016), where the dominant magnetic field orientation in the photosphere changes from vertical to horizontal (Shimizu et al. 2009). This has led to the theory that fan-shaped jets are formed via shearing reconnection between the vertical and horizontal photospheric magnetic field lines at the light bridge–umbra interface (Robustini et al. 2017). Recently, Hou et al. (2016) reported a solar flare occurring along the same field lines as fan-shaped jets, causing them to incline and shorten.

Three-dimensional simulations have reinforced this theory, showing fan-shaped jets being formed during shearing reconnection between horizontal magnetic fields and a vertical current sheet, with the base of the jets corresponding to the location of magnetic reconnection (Jiang et al. 2011). While the initial acceleration of the jets is due to the magnetic tension, the kinematics following this are thought to be due to the gas pressure gradient created via the heating at the base of the jets (Li et al. 2016).

Yang et al. (2016) noted the bright fronts of the jets were coupled to recurrent brightenings at the jets’ base, and that these brightenings resulted in lengthening of the jets. This fits with the theory of recurrent photospheric reconnection causing this phenomenon. Zhang et al. (2017) suggest that these bright fronts are caused by propagating shocks due to p-modes leaking from the photospheric base.

On-disk fan-shaped jets appear dark in the wings of the Hα line, while appearing bright in the line cores. They also appear as brightenings in the Ca II (Shimizu et al. 2009) and Ca II 8542 Å lines (Robustini et al. 2017), while the fronts appear bright in the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (Lemen et al. 2012), 304 and 171 Å channels (Robustini et al. 2016), and the Interface Region Imaging Spectrograph (De Pontieu et al. 2014) 1330 Å channel (Yang et al. 2016; Tian et al. 2018).

In this paper, we report on observations of recurrent photospheric brightenings at a sunspot edge, resulting in the production of fan-shaped jets. We describe the observational setup in Section 2, while we discuss the appearance and dynamics of these jets in Section 3. Section 4 draws conclusions from these observations.

2. Observations

The observational data were obtained with the CRisp Imaging SpectroPolarimeter at the Swedish 1 m Solar Telescope (SST; Scharmer et al. 2003a, 2008) on La Palma. The target was an active region (NOAA 12126) at the limb (coordinates: X = 897″, Y = −184″, μ = 0.34). The observations took place on 2014 August 02 between 09:07 and 09:54.
UT. The observations comprised of Hα imaging spectroscopy. Each scan sampled 11 line positions, taken at ±1.450, ±1.087, ±0.815 Å, ±0.543 Å, ±0.317 Å, and line center. The Hα data had a post-reduction mean cadence of 3 s, and a pixel scale of 0″059 pix⁻¹.

The SST data were processed with the Multi-Object Multi-Frame Blind Deconvolution (MOMFBD) algorithm (Löfdahl 2002; van Noort et al. 2005). This includes tessellation of the images into 88 × 88 pixels² sub-images for individual restoration to preserve the assumption of invariance of the image formation models. An extended MOMFBD scheme that includes the reconstruction of auxiliary wide-band images, cotemporal with the narrowband wavelengths were used together with destretching (Shine et al. 1994) to reduce the impact of residual seeing on the profiles (Henriques 2012). The field of view (FOV) of the reconstructed data set is 59″ × 58″. Prefilter FOV and wavelength dependent corrections were applied to the restored images. More information relating to the SST reduction pipeline used in this manuscript is available in de la Cruz Rodríguez et al. (2015).

Figure 1. Region of interest (ROI) showing fan-shaped jets with coaligned SDO AIA data, with dimensions 17″7 × 17″7. Top: Hα −0.814, +0.000, +0.814 Å. Middle: AIA 1600, 1700, 304 Å. Bottom: AIA 171, 94, 193 Å. The green lines shows curvilinear slices of example jets. The red box shows the brightened region, while the blue boxes indicate the regions used to measure the penumbra.

(An animation of this figure is available.)
Figure 2. Light curves of the recurrent photospheric brightening (solid), averaged from the red box in Figure 1. Periodic sine waves are also created based on the peak period from the global wavelet transforms of Figure 3 (dashed).

Coaligned SDO AIA and Helioseismic and Magnetic Imager (Schou et al. 2012) data were created using Rob Rutten’s alignment software, available on his website.5 The region of interest is shown in Figure 1, and consists of a sunspot, with a nearby pore also visible. The fan-shaped jets appear between the umbra of the main sunspot and the pore. Throughout the time series, coronal rain can be seen in the background, along with numerous Ellerman Bombs erupting in the surrounding photosphere. The footpoint of an overlying loop structure is visible in the high temperature AIA171 Å and AIA193 Å images.

3. Results and Analysis

The jets can be clearly seen as brightenings in the Hα core relative to the background, while appearing dark in the Hα red

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5 https://www.staff.science.uu.nl/~rutte101/rridl/
While the emanation of the jet fronts appears identical in the \( \text{H} \alpha \) line core and blue wing, in the \( \text{H} \alpha \) red wing, a contraction can be seen. The \( \text{H} \alpha \) red wing appears to show the falling of jets back to the solar surface rather than the presence of new bright jets, indicating a line-of-sight effect and that the jets are slightly tilted toward the observer. Doppler velocities have been estimated via fitting of a double Gaussian to the line profiles. However, our spectral sampling limits the Doppler velocity resolution to \( \pm 14 \text{ km s}^{-1} \). The falling jets appeared to have a Doppler shift of \( \sim 30 \text{ km s}^{-1} \), while the emanating jets do not appear to show any Doppler motion. This implies the emanating jets are propagating along the plane of sky, while the falling jets are slightly angled toward the observer (up to \( 20^\circ \) from the plane of sky). This could be due to the emanating jets traveling along the orientation of the field lines (Jiang et al. 2011), while the falling jets will be falling due to gravity. Using the \( \text{H} \alpha \) time slices, the jet front appears to propagate upward at a consistent speed of \( 28\text{–}30 \text{ km s}^{-1} \), and does not appear to decelerate until almost at peak length. The apparent falling of the same jet front in the red wing of \( \text{H} \alpha \), however, appears to show a constant deceleration due to solar gravity of \( \sim 0.3 \text{ km s}^{-2} \), reaching downflow velocities \( >100 \text{ km s}^{-1} \). The blue dashed line of Figure 5 shows the polynomial fitting of the falling material, while the green dashed line shows the linear fitting of the rising jet front. The pink dotted line shows the manual trace of the propagating jet front. Both the quadratic

Figure 3. Wavelet power transforms computed for the SDO 1700Å channel. The crossed regions show regions in the diagrams outside of the cone of influence. Left: the brightening (red box in Figure 1). Middle: the local sunspot penumbra. Right: nearby quiet-Sun reference.

Figure 4. Top: \( \text{H} \alpha \) line core images showing the progression of the jet fronts. Bottom: cotemporal \( \text{H} \alpha -0.814\text{ Å} \) images showing the eruption of material from the photospheric brightening into the jets. The scale is identical to Figure 1. The red arrow shows the direction of bright material erupting into the chromosphere (left of the arrow).
and linear functions appear to fit the jet front, and so \( \chi^2 \) values were calculated. The \( \chi^2 \) values of the linear and polynomial fitting against the rising jet front are 15.36 and 947.15, respectively, validating that the rising jet front appears to emanate with a constant velocity.

4. Discussion and Conclusions

We have investigated recurrent fan-shaped jets at the solar limb. The formation of the fan-shaped jets occur near-simultaneously with the occurrence of a corresponding photospheric brightening. The peak frequency of the recurrent photospheric brightening matches the peak frequency of the penumbra of the nearby large sunspot, suggesting that running penumbral waves could be triggering this form of reconnection.

The peak extensions of the jets (∼7–8 Mm) and their apparent peak velocities are shorter than those reported for fan-shaped jets over light bridges. However, the acceleration of the jets back to the solar surface does match with previous deceleration and velocity measurements. One possible explanation for the jets maintaining a steady extension velocity is that they are being constantly driven by the eruptive processes at the base, which counteracts the effects of solar gravity, rather than emanating with a fast (∼100 km s\(^{-1}\)) burst that decelerates due to gravity.

The jets appear with bright fronts in the SDO AIA171 and 304 Å channels, while in the passbands sensitive to much higher temperatures (including 171 Å), a darkness is left in the wake of the protruding jet front. This darkening is most likely optically thick plasma caused by strong absorption due to an increased density of hydrogen and singly ionized helium (Anzer & Heinzel 2005). This will absorb any emission from the higher energy Fe lines from behind the event, along the same line of sight.

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