Network Jets as the Driver of Counter-streaming Flows in a Solar Filament/Filament Channel

Navdeep K. Panesar 1, 2, Sanjiv K. Tiwari 1, 2, Ronald L. Moore 3, 4, and Alphonse C. Sterling 4

1 Lockheed Martin Solar and Astrophysics Laboratory, 3251 Hanover Street, Building 252, Palo Alto, CA 94304, USA; panesar@lmsal.com
2 Bay Area Environmental Research Institute, NASA Research Park, Moffett Field, CA 94035, USA
3 Center for Space Plasma and Aeronomic Research (CSPAR), UAH, Huntsville, AL 35805, USA
4 NASA Marshall Space Flight Center, Huntsville, AL 35812, USA

Received 2020 March 26; revised 2020 June 3; accepted 2020 June 5; published 2020 June 25

Abstract

Counter-streaming flows in a small (100″ long) solar filament/filament channel are directly observed in high-resolution Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) extreme-ultraviolet (EUV) images of a region of enhanced magnetic network. We combine images from SDO/AIA, SDO/Helioseismic and Magnetic Imager (HMI), and the Interface Region Imaging Spectrograph (IRIS) to investigate the driving mechanism of these flows. We find that: (i) counter-streaming flows are present along adjacent filament/filament channel threads for ~2 hr, (ii) both ends of the filament/filament channel are rooted at the edges of magnetic network flux lanes along which there are impinging fine-scale opposite-polarity flux patches, (iii) recurrent small-scale jets (known as network jets) occur at the edges of the magnetic network flux lanes at the ends of the filament/filament channel, (iv) the recurrent network jet eruptions clearly drive the counter-streaming flows along threads of the filament/filament channel, (v) some of the network jets appear to stem from sites of flux cancelation, between network flux and merging opposite-polarity flux, and (vi) some show brightening at their bases, analogous to the base brightening in coronal jets. The average speed of the counter-streaming flows along the filament/filament channel threads is 70 km s⁻¹. The average widths of the AIA filament/filament channel and the Hα filament are 4″ and 2″, respectively, consistent with the earlier findings that filaments in EUV images are wider than in Hα images. Thus, our observations show that the continually repeated counter-streaming flows come from network jets, and these driving network jet eruptions are possibly triggered by magnetic flux cancelation.

Unified Astronomy Thesaurus concepts: Solar filaments (1495); Solar chromospheric heating (1987); Solar magnetic fields (1503); Solar magnetic reconnection (1504); Jets (870); Solar corona (1483); Solar chromosphere (1479)

Supporting material: animations

1. Introduction

Solar filaments (on-disk), and/or solar prominences (off-limb) are mainly composed of cool and dense plasma, suspended in the hotter solar corona (Engvold 1976; Hirayama 1985; Tandberg-Hanssen 1995; Labrosse et al. 2010; Mackay et al. 2010; Parenti 2014). They lie above photospheric magnetic neutral lines (also known as polarity inversion lines: Babcock & Babcock 1955), i.e., between opposite-polarity magnetic field regions (Martin 1973). The cool filament plasma is trapped in highly sheared magnetic field lines (van Ballegooijen & Martens 1990; Martens & Zwaan 2001).

It is well known that the macroscopic filament structure is composed of several fine-scale threads (Engvold 1976; Engvold et al. 2001; Lin et al. 2005). The main body of a filament, known as the spine, runs horizontally along the photospheric neutral line. So-called “barbs” protrude from both sides of the spine and connect to the photosphere (Martin 1998); they supposedly tether the filament system (Engvold 1976). The presence of cool plasma flows along the spine of the filament, as well as in the barbs, have been observed in high-resolution images (Lin et al. 2003, 2005). Sometimes plasma flows in opposite directions (bidirectional flows) are seen along a filament thread or along adjacent filament threads.

Using Hα data from the Big Bear Solar Observatory (BBSO), Zirker et al. (1998) reported bidirectional/anti-parallel flows, which they named as “counter-streaming” flows, in the entire structure of the filament (including spine and barbs). They detected both blueshifts and redshifts in the wings of the Hα line, which indicate plasma flows toward and away from the observer. In their study, what drives the bidirectional flows remains unknown. Later, similar bidirectional flows were also reported by Lin et al. (2003), Lin et al. (2005), Chae et al. (2007), Schmieder et al. (2008), Panasenco & Martin (2008), and Ahn et al. (2010).

Alexander et al. (2013) reported counter-streaming flows in an active-region filament using high-resolution extreme-ultraviolet (EUV) 193 Å images from the High-resolution Coronal Imager (Hi-C) and they concluded that counter-streaming flows are not discernible in the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) data because of its larger pixel size in comparison to Hi-C. Recently, Diercke et al. (2018) reported anti-parallel flows in a quiescent filament using EUV images from SDO/AIA. However, the flows were not directly visible in the AIA images; Diercke et al. (2018) had to apply image-enhancement techniques and local correlation tracking (LCT) to the AIA images to detect the horizontal flows along the filament. The driving mechanism of the bidirectional flows are not investigated in any of the abovementioned studies.

A possible driving mechanism for the flows is magnetic reconnection at the ends of the filament. But until now, there have been no systematic observational studies of the origin of the bidirectional flows in filaments. In this Letter, we address
this key question: what drives the counter-streaming flows in solar filaments/filament channels?

Recently, Panesar et al. (2018b, 2019) reported small-scale network jets (such as observed by Tian et al. 2014 and also known as jetlets; Raouafi & Stenborg 2014) that are proposed to be miniature versions of coronal jets, because they: (i) occur at the edges of magnetic network lanes between majority-polarity network flux and merging minority-polarity flux, (ii) show brightenings at their base, and (iii) are located at the feet of far-reaching coronal magnetic field. The magnetic flux cancelation between majority-polarity network flux and merging minority-polarity magnetic flux prepares and triggers the jetlet eruption that ejects plasma out along the pre-existing ambient far-reaching field, i.e., makes the jetlet spire. All of the above properties are observed in most coronal jets (see e.g., Panesar et al. 2016; McGlasson et al. 2019, and references therein).

Here, from high-resolution observations from SDO and the Interface Region Imaging Spectrograph (IRIS), we report counter-streaming plasma flows in a filament/filament channel, and the fact that they are driven by network jets. To the best of our knowledge, this is the first report of direct SDO/AIA observations of counter-streaming flows in a filament/filament channel displayed without using any image-enhancement techniques. By studying continually repeated counter-streaming flows for two hours in the filament channel, we find that counter-streaming flows come from repeated jetlets at both ends of the filament/filament channel. These network jets occur at sites of flux cancelation at edges of magnetic network flux lanes. We use the terms “network jets” and “jetlets” interchangeably throughout the Letter. On the basis of the similarity of the observed flows in our filament with those in previous works (e.g., Zirker et al. 1998; Alexander et al. 2013; Diercke et al. 2018), and to maintain consistency with the terminology in these papers, here we mostly use the term “counter-streaming” to describe the antiparallel/bidirectional flows.

2. Data Set

We used data from IRIS (De Pontieu et al. 2014), AIA (Lemen et al. 2012) and the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) from SDO (Pesnell et al. 2012), and Global Oscillation Network Group (GONG; Harvey et al. 1996). A small filament (100′ long) was observed in a region of enhanced magnetic network on the solar disk (330°, −175°) on 2016 January 8 by IRIS and SDO/AIA and HMI. IRIS captured the filament/filament channel for about an hour, from 07:50 to 08:47 UT. We study the same region for 2 hr (07:00–09:00) using SDO data.

IRIS provides both slit-jaw images (SJIs) and spectra of the Sun with high spatial resolution of 0′.16 pixel−1 and temporal cadence as high as 1.5 s in four different wavelengths (C II 1330, Si IV 1400, Mg II k 2796, and Mg II wing 2830). For study of the network jets, we used IRIS Si IV SJIs that have a temporal cadence of 21 s. Network jetlets show up better in Si IV SJIs than in the other SJIs. The field of view (FOV) that we investigate is not covered by the IRIS slit.

Simultaneously, we used EUV images from AIA on board SDO to study the filament/filament channel. AIA captures high spatial resolution (0′.6 pixel−1) full-Sun images, at 12 s temporal cadence, in seven different EUV channels. For our investigations, we used 304, 171, 193, and 211 Å images and we found that the counter-streaming flows were best seen in 171 Å images.

To study the photospheric magnetic field evolution of the filament ends and jetlets, we used line-of-sight (LOS) magnetograms from HMI on board SDO. HMI LOS magnetograms have spatial resolution of 0′.5 pixel−1, a temporal cadence of 45 s, and a noise level of about 7 G (Schou et al. 2012; Scherrer et al. 2012; Couvidat et al. 2016). We used GONG Hα data to confirm that the filament was visible in Hα filtergrams.

IRIS, AIA, and HMI data sets are co-aligned using SSW routines (Freeland & Handy 1998). To enhance the visibility of weak minority-polarity flux patches at the edges the magnetic network lanes, we summed two consecutive magnetograms at each time step. We have created movies, using IRIS, AIA, and HMI data, to follow the evolution of counter-streaming plasma flows and jetlets together with their underlying magnetic field. We have overplotted contours of ±20 G, of HMI LOS magnetograms. The white arrows and blue circles in the movies point to the jetlet spire and jetlet base, respectively. By westward or eastward flow, we mean plasma flows toward solar west or toward solar east, respectively.

3. Results

3.1. Overview

Figures 1(a) and (b) show the filament observed by GONG in Hα (see the white arrows in Figures 1(a)), and (c) shows the same filament in AIA 171 Å image. The white contour outlines the filament/filament channel in the Hα image, and the FOV of the white box is used for detailed analysis of SDO and IRIS data. The filament has a wider appearance in AIA EUV images than in Hα images, particularly in the middle segment. That the measured width of filaments is wider in EUV images than in Hα images has been reported by Heinzel et al. (2001), Aulanier & Schmieder (2002), Heinzel et al. (2003), Dudík et al. (2008), Parenti (2014), and Diercke et al. (2018).

The filament/filament channel in our study is similar to that reported by Alexander et al. (2013). Both in Alexander et al. (2013) and in our observations, the Hα filament (i) appears narrower than the filament/filament channel in AIA and Hi-C EUV images (Figure 1; see Figure 7 for our comparison of measured widths), and (ii) does not show the two-strand structure seen in EUV images that show the counter-streaming flows. On the basis of these strong qualitative similarities between our filament/filament channel and the filament/filament channel of Alexander et al. (2013), we believe that we are observing the same phenomenon as observed by Alexander et al. (2013), which they call “counter-streaming” flows. We therefore follow the same terminology. Further, because the middle segment of the filament in the AIA EUV images is wider than the filament in the Hα image, we use the term filament/filament channel for the two-stranded EUV structure that closely tracks the Hα filament.

Figure 2 shows the same Hα filament observed with AIA and IRIS images (see the white arrows). It is an intermediate filament (Gaizauskas et al. 1997; Gaizauskas 1998) in the enhanced network remnant of decayed active region AR 12476, with east foot anchored in negative-polarity magnetic flux, and the west foot rooted in positive polarity. The Hα filament resides above a weak magnetic neutral line, the northern/
southern side of which has dominant positive/negative magnetic polarity (see Figure 2(c)).

During one hour of IRIS coverage, we noticed several network jetlets at the east end of the filament (EEF; see Figure 2(d)) that occur at the edges of the magnetic network lane between the majority-polarity negative magnetic flux of the network lane and a merging weak minority-polarity (positive) magnetic flux patch. At the same time, these jetlets also appear in AIA images but not...
as clearly as in IRIS SJIs (see the animated version of Figure 2). We use AIA 171 and 304 Å images to study the jetlets at the west end of the filament (WEF) because the WEF is not covered by the IRIS FOV (Figure 2(d)). The properties of these jetlets are similar to the jetlets observed by Panesar et al. (2018b, 2019). In Table 1, we list 10 randomly selected network jetlets that occur at the two ends of the filament. Here, we present jetlets (2 and 5) from the EEF/filament channel and jetlets (8 and 9) from the WEF/filament channel.

3.2. Counter-streaming Flows and Network Jetlets at the EEF/Filament channel

Jetlet-2: Figures 3(a) and (d) show the example of jetlet-2, from Table 1, observed by IRIS and AIA. The accompanying movies (animated Figures 2 and 3) show the complete evolution of the jetlet. At 07:57:38, the jetlet spire starts to rise (animated Figures 2 and 3) and it continues to grow until 08:00:49. We also see brightening in SiIV SJIs at the base of the jetlet at about 07:58:21 (see blue circle at 07:59:25 in the

Figure 2. Overview of the filament/filament channel observed on 2016 January 8. (a) AIA 171 Å image of the filament/filament channel. The white arrows point to the filament. (b) AIA 304 Å image of the filament. (c) HMI magnetogram showing the photospheric magnetic field of the same region. (d) IRIS Si IV SJIs covering most of the same region. The black boxes show the locations of network jetlets at the east end of the filament (EEF) and at the west end of the filament (WEF), and are the FOVs analyzed in detail in Figures 3 and 4. The WEF is not covered by the IRIS FOV (the white region in d). In (b) and (d), ±20 Gauss green and black contours (at 08:00:23UT) outline the positive- and negative-polarity flux patches, respectively. The animated images run from 07:00 to 08:59 UT, except the IRIS Si IV SJIs data, which cover from 07:50 to 08:47 UT. The white arrows in the animations point to the jetlets that are listed in Table 1.

(An animation of this figure is available.)

The Astrophysical Journal Letters, 897:L2 (11pp), 2020 July 1 Panesar et al.
Key Data of Jetlets at the Ends of the Filament/filament Channel

| Event No. | East End Jetlet Timing | Base Brightening | Base Brightening | Base Brightening | Base Brightening | Base Brightening | Base Brightening |
|-----------|------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 1.        | 07:36:34               | No               | Yes              | Yes              | No               | Yes              | No               |
| 2.        | 07:59:25               | Yes              | Yes              | Yes              | No               | Yes              | No               |
| 3.        | 08:21:22               | Yes              | Yes              | Yes              | No               | Yes              | No               |
| 4.        | 08:38:01               | Yes              | Yes              | Yes              | No               | Yes              | No               |
| 5.        | 08:42:16               | Yes              | Yes              | Yes              | Yes              | Yes              | Yes              |
| 6.        | 08:44:23               | Yes              | Yes              | Yes              | Yes              | Yes              | Yes              |
| 7.        | 07:14:10               | Yes              | Yes              | Yes              | No               | Yes              | No               |
| 8.        | 07:37:22               | Yes              | Yes              | Yes              | No               | Yes              | No               |
| 9.        | 07:45:22               | No               | Yes              | Yes              | No               | Yes              | No               |
| 10.       | 08:43:46               | No               | Yes              | Yes              | No               | Yes              | No               |

Notes.

a Timing of the visibility of the jetlet spire at the east end of the filament using IRIS Si IV SJIs.

b Whether a brightening at the base of the jetlet is discernible in IRIS Si IV SJIs.

c Whether minority-polarity flux is discernible at the base of the jetlets.

d Whether this jetlet is observed by IRIS.

e This jetlet occurs before the start of the IRIS observations (07:50:33–08:47:33).

f IRIS has some bad frames (due to south atlantic anomaly) so the jetlet is not visible at this time. Therefore, we use AIA 171 Å images for timing of this event.

g Minority-polarity flux is visible near the base of the jetlet but is not as near as in the other eight events.

h Timing of the visibility of the jetlet spire at the west end of the filament using AIA 171 images (Figure 4).

i Whether a brightening at the base is discernible in AIA 171 Å.

Figure 3 animation). At 07:58:21, a faint brightening at the base also appears in 171 Å images (animated Figure 3). Soon after the start of the jetlet spire, plasma begins to flow along the filament/filament channel strands (shown by the arrows in Figure 3(e) and the online animation). The westward flow shows that the filament/filament channel is made up of several horizontal threads, like those in the filament studied by Alexander et al. (2013).

The EEF/filament channel is rooted at the west end of a negative-polarity-network patch of magnetic flux (Figures 2(b), (c)). IRIS and HMI movies show network jetlets that originate from that edge of the negative-network flux patch. We observe an opposite-polarity weak magnetic flux patch present near that edge of the negative-polarity network flux patch, and the flow-driving jetlet (jetlet-2) erupted from the neutral line between the negative-polarity network flux patch and the weak positive flux patch (see the red arrow in Figures 3(b), (c)), which was merging into the negative-network flux patch and evidently canceling with it.

Figure 5(a) shows the minority-polarity (positive) flux plot of the region that is bounded by the yellow box of Figure 3(b). The positive flux decreases between 07:55 and 07:58 UT, presumably due to flux cancelation that prepares and triggers the eruption of jetlet-2 (see the online animation). During the same time, there also appears to be a decrease in negative flux at the adjacent edge of the negative-network flux patch (see the red arrow in Figures 3(b), (c)), and this suggests that flux cancelation is occurring. Presumably, the flux cancelation prepares and triggers the eruption of the jetlet, and that jetlet drives the westward-streaming flow in the filament/filament channel strand. Large-scale coronal jet eruptions (Panesar et al. 2016, 2017, 2018a; Sterling et al. 2017; McGlasson et al. 2019) and jetlets (Panesar et al. 2018b, 2019) are also seen to be prepared and triggered by flux cancelation at an underlying neutral line.

To estimate the uncertainty in the measured flux plotted in Figure 5(a), we selected an apparently flux-free region (outlined by the magenta box in Figure 3(b), which is of the same size as the yellow box in which the flux for the plot in Figure 5(a) was measured) that has no visibly discernible non-noise magnetic flux in it throughout the time period of the flux plot in Figure 5(a). The uncertainty (from magnetogram noise) in the flux measured in the yellow box was estimated by smoothing (by a factor of two) and adding up the total unsigned flux in all of the pixels in the magenta box in each frame. We then averaged the values of total unsigned flux over time. The half of this value is $3.6 \times 10^{16}$ Mx, which is plotted in Figure 5(a) as error bars for positive magnetic flux. The error bar for Figure 5(b) and the uncertainty in the Figure 4 magnetogram field strength were estimated in the same way, using the magenta box in Figure 4(g): we obtained $\pm 0.4 \times 10^{16}$ Mx for the error bars in Figure 5(b) for negative magnetic flux. Note that the measured flux (the solid curve) in Figure 5(a) and in (b) is above zero by more than the downward extents of the error bars for the entire time interval of each of the two plots; this demonstrates that the flux in each of the two measured minority flux patches is definitely above noise, and hence that each of these minority flux patches is real, not just noise.

Jetlet-5: Figures 3(g)–(j), and accompanying movies (animated versions in Figures 2 and 3), show the example of jetlet-5 from Table 1. The white arrow points to the jetlet spire, which was visible between 08:41:54 and 08:43:19 in Si IV SJIs (Figures 2 and 3 animations), as well as in AIA images. IRIS images also show base brightening during the onset of the jetlet, but the AIA images do not show any corresponding brightening at the base of the jetlet. In the Figure 2 animation, we can clearly see that westward flow in the filament originate from this jetlet (the direction of the flows in shown in Figure 3(k)).

Jetlet-5 is rooted at the edge of a negative-polarity network magnetic flux lane (Figures 3(g) and (h)). There is a minority-polarity magnetic flux patch present near the base of this jetlet, although not as strong as in jetlet-2. We also see a decrease in flux at the edge of the negative-polarity network flux lane from where the jetlet starts from before to after the jet erupts.

Similarly, there are other jetlets that come from the same network flux lane (see Table 1). The Figure 2 animation shows the complete evolution of all the jetlets and westward-streaming flows in the filament that come from the jetlets. Jetlets (2–6) show base brightening during the eruption onset; these base brightenings are clearly visible in the IRIS images. All the jetlets are rooted at the edge of the negative magnetic network flux lane. Right after a jetlet starts, usually flow along a filament/filament channel thread stemming from the jetlet begins to move westward along the thread. Figure 6(a) shows a running-difference time-distance map along the northern dashed line of Figure 3(l). It shows obvious westward flows in the filament’s threads; some of the flows are highlighted with red dashed arrows (see Section 3.4). These examples clearly
show that the flows are apparently driven by network jetlet eruptions at sites of magnetic flux cancelation.

3.3. Counter-streaming Flows and Network Jetlets at the WEF/Filament channel

Jetlet-8: Figure 4(a) shows jetlet-8 in an AIA 171 Å images. Note that the WEF/filament channel is not covered by IRIS. The accompanying animations (Figure 2 and 4) show the complete evolution of jetlet-8. AIA 171 Å images show faint base brightening in jetlet-8 (at 07:32:34, Figure 6). The jetlet spire starts to rise at about 07:34:58 and continues to grow (the white arrow in the animated Figure 4). Shortly after the onset of the jetlet spire, plasma starts to move eastward along a filament/filament channel thread stemming from the site of the jetlet (see the white arrows in Figure 4(b) and the Figure 2 animation).

The jetlet erupts from the east edge of the majority-polarity (positive) network flux lane (Figures 4(a), (c)). The red arrows in Figures 4(c), (d) point to the weak minority-polarity negative flux patch that converges toward the positive flux patch and plausibly prepares and triggers the jetlet eruption. Figure 5(b) shows a plot of the negative flux patch versus time during the onset time of jetlet-8 (the first red line in Figure 5(b)). Although, the animated Figure 4 shows flux cancelation more clearly, as mentioned before, the error bars in Figure 5(b) are

Figure 3. Jetlets at the east end of the filament/filament channel. Panels (a) and (d) show the IRIS Si IV SJI and AIA 171 Å images of the onset of jetlet-2; the white arrows point to the jetlet spire. Panels (b) and (c) show the HMI magnetograms of the same region; the red arrow in each magnetogram points to the minority-polarity canceling flux patch, the yellow box shows the area that is used to calculate the flux evolution plot shown in Figure 5(a), and the magenta box shows the area that is used to estimate the noise in the measured flux plotted in Figure 5(a). Panels (e) and (f) show AIA 171 images of the filament and have the same FOV as in Figure 2. The white arrows show the direction of the westward flow that is driven by the jetlet shown in a and d; the black box shows the FOV displayed in panels (a)–(d), and the white lines (1–3) in (f) show the cuts across the filament threads used for measuring the intensity for the plot shown in Figure 7. In panels (a) and (d) HMI contours (of level ±20 G) of 07:49:33 are overlaid, where green and black represent positive and negative polarities, respectively. Panels (g) and (j) show the IRIS Si IV SJI and AIA 171 Å images of jetlet-5 from the same region. The black box in (k) shows the FOV displayed in panels (g)–(j). The white dashed lines in panel (l) show the two east-west cuts for the two time-distance maps in Figure 6. In panels (g) and (j) HMI contours (of level ±20 G) of 08:42:23 are overlaid, where green and black represent positive and negative polarities, respectively. Other annotated features are the same as above. The animated images run from 07:50 to 08:47 UT. The white arrows and blues circles in the animations point to the jetlet spire and jetlet base, respectively. (An animation of this figure is available.)
large, suggesting only marginal flux cancellation at the base of the jetlet.

**Jetlet-9**: In Figure 4(e), we show an AIA 171 Å image of jetlet-9. The detailed evolution of the jetlet and its photospheric magnetic field evolution can be seen in the animated Figures 2 and 4. A faint jetlet spire extends outward at 07:45:22 (shown with an arrow in Figure 4(e) and the online animation). Immediately after the appearance of the spire, eastward flow begins to move in the filament’s thread, along a thread stemming from the site of the jetlet. The white arrows in Figure 4(f) highlight the eastward flow in the thread of the filament/filament channel. Unlike for jetlet-8, we do not see any brightening at the base of jetlet-9.

Figures 4(g), (h) display the photospheric magnetic field evolution of the base of the jetlet. The jetlet is rooted at the neutral line between a majority-polarity (positive) network flux lane and minority-polarity (negative) weak flux patch (red arrows in Figures 4(g), (h)). Figure 5(b) shows the minority-polarity flux patch versus time. It shows a magnetic flux evolution during the eruption of jetlet-9 (second red line).

It is clear that the eastward-streaming flows from the WEF/filament channel are also driven by jetlets, similar to the westward flows from the EEF. The timings of significant jetlets are listed in Table 1. Just after each of these jetlets, plasma starts to flow eastward along the filament/filament channel thread. Figure 6(b) displays clear evidence of the eastward flows in the southern thread of the filament. Some of the stronger flows are highlighted with red dashed arrows.
Figure 5. Magnetic flux plots for jets (2, 8, and 9) of Table 1. Panel (a) shows the positive flux plot as a function of time computed inside the yellow box of Figure 3(b). Panel (b) shows the negative flux plot as a function of time computed inside the blue box of Figure 4(g). The three red vertical lines mark the onsets of the three jetlet spires. Error bars in each panel represent the uncertainty in the measured magnetic flux from magnetograph noise, as estimated in the way described in Section 3.2.

3.4. Flow Speed

Figure 6 shows horizontal flows in the northern thread and in the southern thread of the filament/filament channel. To present a clear picture of counter-streaming flows, we made a running-difference time-distance map from along each of the two white dashed lines of Figure 3(l). These two maps clearly show the plasma flows in opposite directions along the filament/filament channel threads (see the red arrows). In the northern thread the plasma travels toward solar west whereas in the southern thread the plasma travels toward solar east. Thus, these are counter-streaming flows.

One can clearly see the persistent and continuous counter-streaming flows in the two strands from 07:54 to 08:15 UT (in the Figure 2 animation) in 171 Å images. The observed counter-streaming flows are similar to the flows that are reported by Alexander et al. (2013) in two adjacent strands of a filament in HI-C 193 Å images. The counter-streaming flows are sporadic at times, particularly in the beginning of the movie (animated Figure 2), in the manner of the counter-streaming flows reported by Diercke et al. (2018).

We also observed additional flows in the filament/filament channel that are not on the path of either of these two selected time-distance cuts. For example in Figure 6(b), some strong eastward flows that are driven by jetlets (7, 8) (between 07:15 and 07:40 UT) and are not discernible due to the selection of this time-distance cut.

Some of the counter-streaming flows are highlighted with red dashed arrows and their speeds are noted in Figure 6. The westward and eastward flows move with an average speed of $73 \pm 16$ km s$^{-1}$ and $73 \pm 13$ km s$^{-1}$, respectively. Note that our measured speeds are lower limits on the full speeds of the 3D flows because only the projected (proper-motion) speed is measured; the full speed is the rms of proper-motion speed (which we measure) and the speed along the LOS (which speed we do not measure, but we expect it to be small compared to the proper-motion speed in our case because the filament is on the central disk and the field in it is roughly horizontal). The observed flow speeds are in agreement with the speeds ($70$ km s$^{-1}$) obtained by Alexander et al. (2013) for an active-region filament, using HI-C data, whereas Zirker & Cleveland (1994) and Zirker et al. (1998) reported flow speeds in the range of $5$–$20$ km s$^{-1}$ for quiet-region filaments, using H$\alpha$ data.

3.5. Thread Width

We have measured the widths of the filament/filament channel (using AIA 171 Å and H$\alpha$ images in Figure 1), from the intensity–distance plots from transverse cuts at three places along the filament/filament channel (Figures 7). In the plots from the AIA image, the first peak (Figures 7(a)–(c)) corresponds to the northern thread of the filament/filament channel, and the second peak corresponds to the southern thread of the filament/filament channel. There is a decrease in intensity in between the two threads in the gap between the two threads. Similarly, HI-C observations (Alexander et al. 2013) also show a gap between adjacent threads. According to Zirker et al. (1998), counter-streaming in filament threads might be either superimposed along the LOS on the same thread, or there is a separation between filament threads having opposite flows. Figures 7(d)–(f) show the measured widths of the filament in the H$\alpha$ image. These plots confirm the visual impression from Figure 1 that in the middle of the filament/filament channel (well away from each end), that the H$\alpha$ filament is narrower than the AIA EUV filament/filament channel.

The average widths (using AIA images) of the northern and southern threads are $3\prime\prime7 \pm 3\prime\prime$ and $4\prime\prime0 \pm 2\prime\prime$, respectively. The observed AIA thread widths are wider than the widths (0\prime\prime8) obtained by Alexander et al. (2013), using high-resolution 193 Å images from HI-C, and the widths (0\prime\prime3) observed by Lin et al. (2005), using high-resolution H$\alpha$ images from SST. Apparently the filament threads seen in our AIA 171 Å images are bundles of a few finer threads of narrower widths such as seen in higher-resolution H$\alpha$ images of other filaments.
4. Discussion

We have investigated the driving mechanism of counter-streaming flows in a solar filament/filament channel using SDO and IRIS data. We show the first direct observations of counter-streaming flows in a filament/filament channel from AIA, without using any image-enhancement techniques. We find that (i) opposite ends of the filament/filament channel are at opposite-polarity magnetic network flux lanes, (ii) repeated small-scale jets (jetlets) erupt from the flux-lane edges where the ends of the filament/filament channel are rooted, (iii) the jetlet eruption at the two ends drive the observed counter-streaming flows in the filament/filament channel, (iv) some of the jetlets appear to erupt from sites of flux cancelation between majority-polarity network flux and merging minority-polarity flux, reminiscent of coronal jets, and (v) IRIS Si IV SJJs show brightening at the base of the jetlets; this brightening is similar to the base brightening in coronal jets.

According to Chen et al. (2014), longitudinal oscillations (when they are not in phase) in filament threads in Hα observations could appear as bidirectional flows. Whereas Low & Petrie (2005) suggested that bidirectional flows occur due to non-equilibrium in magnetic forces at the footpoints of filament threads. Shen et al. (2015) argued that counter-streaming flows are possibly caused by magnetic reconnection at a separator between the prominence bubble and the overlying-magnetic-field dips. Wang et al. (2018) presented high-resolution Hα observations of counter-streaming flows that are obviously flows of plasma along a filament’s fibrils.

Our observations clearly show that plasma flows in the filament/filament channel threads are driven by network jets. The AIA 171 Å movie shows clear evidence of continuous counter-streaming flows throughout the filament structure (they are not localized to some places), and that the flows originate from the two ends of the filament. The counter-streaming flows travel along two different strands, and move with a speed of about 70 km s⁻¹ in both threads. These flows are similar to the counter-streaming flows observed by Hi-C (Alexander et al. 2013), where the authors suggested that the oppositely directed flows were in separate strands (threads) of the same filament, and they observed flow speeds in both threads similar to those in the present observations. The AIA filament/filament channel threads that we observe are wider than those observed by Lin et al. (2005) and by Alexander et al. (2013), perhaps mostly due to AIA’s lower spatial resolution. The average width of our filament/filament channel threads is 4″, whereas Lin et al. (2005) obtained 0″3 using Swedish Solar Telescope (SST) Hα images and Alexander et al. (2013) reported 0″8 using Hi-C data. Thus, our observations provide information on counter-streaming flows in wider filament threads (or perhaps in bundles of threads) than found from those higher-resolution observations.
The cool plasma moves with an average speed of about $70 \text{ km s}^{-1}$ in both threads. The observed EUV flows have higher speeds than the flows observed using Hα data in quiet-region filaments. For example, Zirker et al. (1998) and Lin et al. (2003) obtained plasma flows speeds between 5 and $20 \text{ km s}^{-1}$ and $8 \text{ km s}^{-1}$, respectively, using Hα observations of quiet-region filaments. Our measured flow speeds are in agreement with the EUV observations reported by Labrosse et al. (2010) and Alexander et al. (2013), who observed velocities of $70 \text{ km s}^{-1}$ along individual threads of active-region filaments, similar to that seen in our observations of an intermediate filament.

Network jetlets tend to erupt repeatedly at the edges of strong magnetic network flux clumps are at the boundaries of supergranule convection cells (Tian et al. 2014; Panesar et al. 2018b, 2019). Jetlets (1, 2, 3, 5, and 6) occur at the sites of discernible flux cancellation, and base brightening appears at the canceling neutral line. In jetlet-4 we do see a signature of minority-polarity flux at the base of the jetlet but do not observe clear evidence of flux cancellation. In this jetlet, we do observe brightening at the base. It is possible that a weak minority-polarity flux is present there at the edge of the network flux, but not detected by HMI. Since IRIS FOV does not cover the WEF, there we use only AIA 171 Å images to study the jetlets and their base brightenings. Jetlets (7 and 8) each show base brightening and each brightening occurs at a canceling neutral line, similar to the IRIS jetlets observed at the EEF. These results are apparently consistent with flux cancellation at the neutral line (between majority-polarity network flux and a minority-polarity flux patch) preparing and triggering multiple jetlet eruptions (Panesar et al. 2018b, 2019). The base brightening that occurs at a canceling neutral line and/or at the edge of network flux is possibly a miniature version of the jet-base brightening that occurs at a canceling neutral line before and during coronal jets (Panesar et al. 2016, 2017). The discernible flux cancellation plausibly prepares and triggers the multiple jetlets at the both ends of the filament/filament channel that drive continually repeated counter-streaming flows in the filament/filament channel.

If these jetlets are miniature versions of coronal jets then the base brightenings would result from the internal reconnection (it occurs within the legs of erupting minifilament flux rope and its enveloping field; Sterling et al. 2015), and the spire would result from the external/interchange reconnection (when the erupting flux-rope envelope and flux rope reconnect with encountered far-reaching magnetic field). In the present case,
the jetlets shoot out horizontally along the horizontal magnetic field (in the filament/filament channel). We infer that the plasma flows are injected into the filament threads via the external reconnection that makes the jetlet spire. The counter-streaming flows may be further magnetically driven by magnetic-twist waves from the external reconnection of the erupting flux rope if that flux rope contains twist (Moore et al. 2015).

Jets and jetlets are also seen to occur at other sites of flux cancelation (sometimes accompanied, or preceded, by flux emergence and/or flux coalescence) in mixed polarity photospheric flux at the base of far-reaching coronal loops (e.g., Panesar et al. 2019; Tiwari et al. 2019) and they might contribute to heating of coronal loops. In polar crown prominences, upflows have been observed in prominence pillars/barbs rooted at sites of flux cancelation (Panesar et al. 2014). Similarly, our network jetlets (evidently prepared and triggered by flux cancelation) at both feet of the filament/filament channel are driving the flows in the filament’s threads. As in filament threads, blueshifts and redshifts in coronal loops might be due to explosive events at the base (e.g., Srivastava et al. 2020). Whether such flows in coronal loops come from jetlet eruptions remains to be established.

Our SDO and IRIS observations show examples of recurrent counter-streaming flows along filament/filament channel threads, and that these counter-streaming flows are clearly driven by network jetlet eruptions that occur at both ends of the filament/filament channel. The network jetlets erupt from the edges of magnetic network flux lanes and therefore plausibly are small-scale versions of the larger jetlets and coronal jets, most or all of which are prepared and triggered to erupt by flux cancelation.

There have been several numerical models of larger-scale jets (e.g., Cheung et al. 2015; Wyper et al. 2018, and references therein), but formation of small-scale jets, i.e., network jets/jetlets, have not been well simulated. It will be interesting to see whether in a suitable magnetic configuration such counter-streaming flows as reported here are produced by simulated jetlets erupting from the ends of a filament field.

We thank an anonymous referee for constructive comments. N.K.P. acknowledges support from NASA’s SDO/AIA (NN04EA00C) and HGI grant (80NSSC20K0720). S.K.T. gratefully acknowledges support by NASA contracts NNG09FA40C (IRIS), and NNM07AA01C (Hinode). R.L.M. and A.C.S. acknowledge the support from the NASA HGI program. We acknowledge the use of IRIS, SDO/AIA, SDO/HMI, and GONG data. AIA is an instrument on board the Solar Dynamics Observatory, a mission for NASA’s Living With a Star program. IRIS is a NASA small explorer mission developed and operated by LMSAL with mission operations executed at NASA Ames Research Center and major contributions to downlink communications funded by ESA and the Norwegian Space Centre. This work has made use of NASA ADSABS and Solar Software.

**ORCID iDs**

Navdeep K. Panesar @ https://orcid.org/0000-0001-7620-362X
Sanjiv K. Tiwari @ https://orcid.org/0000-0001-7817-2978
Ronald L. Moore @ https://orcid.org/0000-0002-5691-6152

Alphonse C. Sterling @ https://orcid.org/0000-0003-1281-897X

**References**

Ahn, K., Chae, J., Cao, W., & Goode, P. R. 2010, ApJ, 721, 74
Alexander, C. E., Walsh, R. W., Régnier, S., et al. 2013, ApJL, 775, L32
Aulanier, G., & Schmieder, B. 2002, A&A, 386, 1106
Babcock, H. W., & Babcock, H. D. 1955, ApJ, 121, 349
Chae, J., Park, H.-M., & Park, Y.-D. 2007, JKAS, 40, 67
Chen, P. F., Harra, L. K., & Fang, C. 2014, ApJ, 784, 50
Cheung, M. C. M., de Pontieu, B., Tarbell, T. D., et al. 2015, ApJ, 801, 83
Couvidat, S., Schou, J., Hoeksema, J. T., et al. 2016, SoPh, 291, 1887
De Pontieu, B., Title, A. M., Lemen, J. R., et al. 2014, SoPh, 289, 2733
Diercke, A., Kuckein, C., Verma, M., & Denker, C. 2018, A&A, 611, A64
Dudik, J., Aulanier, G., Schmieder, B., Bommier, V., & Roudier, T. 2008, SoPh, 248, 29
Engvold, O. 1976, SoPh, 49, 283
Engvold, O., Jakobsson, H., Tand berg-Hanssen, E., Gurman, J. B., & Moses, D. 2001, SoPh, 202, 293
Freeland, S. L., & Handy, B. N. 1998, SoPh, 182, 497
Gaizauskas, V. 1998, in ASP Conf. Ser. 150, IAU Coll. 167: New Perspectives on Solar Prominences, ed. D. F. Webb, B. Schmieder, & D. M. Rust (San Francisco, CA: ASP), 257
Gaizauskas, V., Zirker, J. B., Sweetland, C., & Kovacs, A. 1997, ApJ, 479, 448
Harra, L. K., & Wing, J. E. 2005, SoPh, 229
Lin, Y., Engvold, O., Roupe van der Voort, L., Wing, J. E., & Berger, T. E. 2005, SoPh, 226, 239
Lin, Y., Engvold, O. R., & Wiik, J. E. 2003, SoPh, 216, 109
Low, B. C., & Petrie, G. J. D. 2005, ApJL, 626, 551
MacKay, D. H., Karpen, J. T., Ballester, J. L., Schmieder, B., & Aulanier, G. 2010, SSRv, 151, 333
Martens, P. C., & Zwaan, C. A. 2001, ApJL, 558, 872
Martins, S. F. 1973, SoPh, 31, 3
Martin, S. F. 1996, SoPh, 182, 107
McGlasson, R. A., Panesar, N. K., Sterling, A. C., & Moore, R. L. 2019, ApJ, 882, 16
Moore, R. L., Sterling, A. C., & Falconer, D. A. 2015, ApJ, 806, 11
Panasenco, O., & Martin, S. F. 2008, in ASP Conf. Ser. 383, Topological Analyses of Symmetric Eruptive Prominences, ed. R. Howe et al. (San Francisco, CA: ASP), 243
Panesar, N. K., Innes, D. E., Schmit, D. J., & Tiwari, S. K. 2014, SoPh, 290, 2971
Panesar, N. K., Sterling, A. C., & Moore, R. L. 2017, ApJ, 844, 131
Panesar, N. K., Sterling, A. C., & Moore, R. L. 2018a, ApJ, 853, 189
Panesar, N. K., Sterling, A. C., Moore, R. L., et al. 2018b, ApJL, 868, L27
Panesar, N. K., Sterling, A. C., Moore, R. L., et al. 2019, ApJL, 887, L8
Panesar, N. K., Sterling, A. C., Moore, R. L., & Chakrapani, P. 2016, ApJL, 832, L7
Parenti, S. 2014, LRSP, 11, 1
Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, SoPh, 275, 3
Raouafi, N.-E., & Stenborg, G. 2014, ApJ, 787, 118
Scherrer, P. H., Schou, J., Bush, R. L., et al. 2012, SoPh, 275, 207
Schmieder, B., Bonmier, V., Kitai, R., et al. 2008, SoPh, 247, 321
Schou, J., Scherrer, P. H., Bush, R. L., et al. 2012, SoPh, 279, 229
Shen, Y., Liu, Y., Liu, Y. D., et al. 2015, ApJL, 814, L17
Srivastava, A. K., Rao, Y. K., Konkol, P., et al. 2020, ApJ, 894, 155
Sterling, A. C., Moore, R. L., Falconer, D. A., & Adams, M. 2015, Natur, 523, 437
Sterling, A. C., Moore, R. L., Falconer, D. A., Panesar, N. K., & Martinez, F. 2017, ApJ, 844, 28
Tandberg-Hanssen, E. (ed.) 1995, The Nature of Solar Prominences, Astrophysics and Space Science Library, Vol. 199 (Dordrecht: Kluwer)
Tian, H., DeLuca, E. E., Cranmer, S. R., et al. 2014, Sci, 346, 125711
Tiwari, S. K., Panesar, N. K., Moore, R. L., et al. 2019, ApJ, 887, 56
van Ballegooijen, A. A., & Mullan, P. C. H. 1990, ApJL, 361, 283
Wang, H., Liu, R., Li, Q., et al. 2018, ApJL, 852, L18
Wyper, P. F., DeVore, C. R., & Antiochos, S. K. 2018, ApJ, 852, 98
Zirker, J. B., & Cleveland, F. M. 1994, SoPh, 153, 245
Zirker, J. B., Engvold, O., & Martin, S. F. 1998, Natur, 396, 440

11