Flux Cancelation: The Key to Solar Eruptions

Abstract

Solar coronal jets are magnetically channeled eruptions that occur in all types of solar environments (e.g. active regions, quiet-Sun regions and coronal holes). Recent studies show that coronal jets are driven by the eruption of small-scale filaments (*minifilaments*). Once the eruption is underway magnetic reconnection evidently makes the jet spire and the bright emission in the jet base. However, the triggering mechanism of these eruptions and the formation mechanism of the pre-jet minifilaments are still open questions. In this talk, mainly using SDO/AIA and SDO/HMI data, first I will address the question: what triggers the jet-driving minifilament eruptions in different solar environments (coronal holes, quiet regions, active regions)? Then I will talk about the magnetic field evolution that produces the pre-jet minifilaments. By examining pre-jet evolutionary changes in line-of-sight HMI magnetograms while examining concurrent EUV images of coronal and transition-region emission, we find clear evidence that flux cancelation is the main process that builds pre-jet minifilaments, and is also the main process that triggers the eruptions. I will also present results from our ongoing work indicating that jet-driving minifilament eruptions are analogous to larger-scale filament eruptions that make flares and CMEs. We find that persistent flux cancelation at the neutral line of large-scale filaments often triggers their eruptions. From our observations we infer that flux cancelation is the fundamental process for the buildup and triggering of solar eruptions of all sizes.
Flux Cancelation: The Key to Solar Eruptions

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OUTLINE

- Background
- Triggering of Jet-Driving Minifilament Eruptions
- Formation of Pre-Jet Minifilaments
- Triggering of CME-producing Filament Eruptions
- Summary
Coronal jets are frequent magnetically channeled narrow eruptions. They occur in various solar environments: quiet regions, coronal holes and active regions.

They are relatively short-lived features (of about 10 minutes; Shimojo et al 1996, Savcheva et al 2007) occur at a rate of ~60 per day in polar coronal holes (Savcheva et al 2007).
All coronal jets observed in EUV and X-ray images show a bright spire with a base brightening, also known as jet bright point (JBP). X-ray jets were first detailed study with Yohkoh satellite (Shibata et al 1992), later they were studied with Hinode satellite (Savcheva et al 2007, Cirtain et al 2007).

- There are two types of jets (Moore et al 2010, 2013): standard jets and blowout jets.
Emerging-flux jet model

**Solar Jet Models**

- Some studies suggested that flux emergence may lead to the jet eruptions (e.g. Shibata et al. 1992, 2007, Moreno-Insertis et al. 2008).

- Recent studies show that coronal jets are driven by small-scale filament eruptions (e.g. Hong et al. 2011, Shen et al. 2012, Adams et al. 2014, Sterling et al. 2015).

- **Sterling et al. 2015** did extensive study of 20 polar coronal hole jets and found that X-ray jets are mainly driven by the eruption of minifilaments.

- **What leads to these minifilament eruptions?**

- **How and when are minifilaments formed?**
(I) Triggering of Pre-Jet Minifilament Eruptions

Quiet region jets
  Coronal hole jets
  Active region jets
We examined the magnetic cause of 10 random on-disk quiet region jet eruptions by using SDO/HMI magnetograms and SDO/AIA images.

Measured parameters for the observed quiet-region jets:

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Date</th>
<th>Time (UT)</th>
<th>Location x,y (arcsec)</th>
<th>Jet Speed (km s⁻¹)</th>
<th>Jet Dur. min.</th>
<th>Jet-base Width (km)</th>
<th>Minifil. length (±1700 km)</th>
<th>Φ values 10¹⁹ Mx</th>
<th>% of Φ reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>2012 Mar 22</td>
<td>04:46</td>
<td>-470,-100</td>
<td>100±30</td>
<td>15±5</td>
<td>10500±500</td>
<td>9800</td>
<td>1.6</td>
<td>52 ± 5.8</td>
</tr>
<tr>
<td>J2</td>
<td>2012 Jul 01</td>
<td>08:32</td>
<td>-44, 285</td>
<td>100±10</td>
<td>10±2</td>
<td>27000±500</td>
<td>25000</td>
<td>4.0</td>
<td>18 ± 6.8</td>
</tr>
<tr>
<td>J3</td>
<td>2012 Jul 07</td>
<td>21:31</td>
<td>-192, -180</td>
<td>120±15</td>
<td>14±3</td>
<td>16500±400</td>
<td>10500</td>
<td>- i</td>
<td>-</td>
</tr>
<tr>
<td>J4</td>
<td>2012 Aug 05</td>
<td>02:20</td>
<td>-485, 190</td>
<td>140±35</td>
<td>10±3</td>
<td>22000±1000</td>
<td>31000</td>
<td>1.5</td>
<td>21 ± 6.0</td>
</tr>
<tr>
<td>J5</td>
<td>2012 Aug 10</td>
<td>23:03</td>
<td>-168, -443</td>
<td>125±15</td>
<td>15±2</td>
<td>16000±400</td>
<td>10000</td>
<td>0.9</td>
<td>57 ± 5.4</td>
</tr>
<tr>
<td>J6</td>
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<td>22:56</td>
<td>-158, -486</td>
<td>35±5</td>
<td>9±2</td>
<td>20000±500</td>
<td>36000</td>
<td>2.0</td>
<td>23 ± 4.6</td>
</tr>
<tr>
<td>J7</td>
<td>2012 Sept 21</td>
<td>03:33</td>
<td>-115, -485</td>
<td>135±30</td>
<td>12±1</td>
<td>17500±500</td>
<td>15000</td>
<td>1.0</td>
<td>36 ± 7.2</td>
</tr>
<tr>
<td>J8</td>
<td>2012 Sept 22</td>
<td>01:25</td>
<td>-338, 103</td>
<td>110±45</td>
<td>11±1</td>
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<td>5700</td>
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<td>50 ± 5.1</td>
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<tr>
<td>J9</td>
<td>2012 Nov 13</td>
<td>04:21</td>
<td>-28, -307</td>
<td>55±5</td>
<td>9±3</td>
<td>18000±1000</td>
<td>25000</td>
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<td>34 ± 3.2</td>
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<tr>
<td>J10</td>
<td>2012 Dec 13</td>
<td>10:36</td>
<td>26, 50</td>
<td>65±20</td>
<td>10±2</td>
<td>9500±500</td>
<td>12500</td>
<td>1.2</td>
<td>38 ± 5.0</td>
</tr>
</tbody>
</table>

Quiet region jet (J7)

- A minifilament (length ~15000 km) is present in the jet-base region prior to jet eruption.
- It resides over the neutral line between the opposite-polarity flux patches.
- The JBP occurs at the pre-eruption location of the minifilament.
- The jet spire extends upward with an average speed of 135±30 kms$^{-1}$.
The minifilament was present at the neutral line for 34 hours before the jet eruption.

The jet-producing eruptions and JBP$^*$s are similar to typical solar flare eruption, in which a flare arcade grows over the neutral line in the wake of the filament.
Flux cancelation leading to minifilament eruption

- Both polarities approach towards the neutral line, and eventually cancel with each other just before the eruption. Flux cancelation continued until the minority-polarity flux patch completely disappeared.
- We find in each of the ten jets that opposite polarity magnetic flux patches converge and cancel, with a flux reduction of 20-60 % until jet erupts.
- The minifilaments show a slow-rise, followed by a fast-rise as they erupt, analogous to larger-scale filament eruptions.
I) Triggering of Pre-Jet Minifilament Eruptions

Quiet region jets
Coronal hole jets
Active region jets
**Coronal Hole Jets**

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Date</th>
<th>Time (UT)</th>
<th>Location</th>
<th>Helio. Cord.</th>
<th>Jet Speed (km s(^{-1}))</th>
<th>Jet Dur. (minutes)</th>
<th>Jet-Base Width (km)</th>
<th>XRT Coverage</th>
<th>(\Phi) values (10^{19}) Mx</th>
<th>% of (\Phi) Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>2012 Jul 02</td>
<td>02:11</td>
<td>N21, W07</td>
<td></td>
<td>65±1.5</td>
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<td>22500±1500</td>
<td>No</td>
<td>1.5</td>
<td>33±4.5</td>
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<tr>
<td>J2</td>
<td>2015 Aug 18</td>
<td>13:07</td>
<td>N27, E02</td>
<td></td>
<td>40±20</td>
<td>12±3</td>
<td>9700±1000</td>
<td>Yes</td>
<td>0.9</td>
<td>31±10</td>
</tr>
<tr>
<td>J3</td>
<td>2015 Dec 28</td>
<td>09:54</td>
<td>N36, E19</td>
<td></td>
<td>110±40</td>
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<td>13000±900</td>
<td>No</td>
<td>0.9</td>
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<tr>
<td>J4</td>
<td>2015 Dec 28</td>
<td>16:02</td>
<td>N37, E03</td>
<td></td>
<td>35±7</td>
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<td>12000±2500</td>
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<td>52±4.8</td>
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<tr>
<td>J5</td>
<td>2015 Dec 30</td>
<td>15:14</td>
<td>N36, W23</td>
<td></td>
<td>70±30</td>
<td>7±1</td>
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<tr>
<td>J6</td>
<td>2015 Dec 31</td>
<td>19:04</td>
<td>N43, W34</td>
<td></td>
<td>27±4</td>
<td>6±1</td>
<td>6600±500</td>
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<td>41±8.3</td>
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<tr>
<td>J7</td>
<td>2016 Jan 01</td>
<td>11:45</td>
<td>N08, E30</td>
<td></td>
<td>30±5</td>
<td>8±1</td>
<td>18500±3500</td>
<td>No</td>
<td>0.7</td>
<td>52±6.6</td>
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<tr>
<td>J8</td>
<td>2016 Jan 01</td>
<td>18:11</td>
<td>N41, E39</td>
<td></td>
<td>204±70</td>
<td>4±1</td>
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<td>0.5</td>
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<tr>
<td>J9</td>
<td>2016 Apr 21</td>
<td>06:15</td>
<td>S01, E12</td>
<td></td>
<td>240±70</td>
<td>8±1</td>
<td>10500±700</td>
<td>Yes</td>
<td>_</td>
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<tr>
<td>J10</td>
<td>2016 Sep 15</td>
<td>23:36</td>
<td>S06, E00</td>
<td></td>
<td>_k</td>
<td>6±1</td>
<td>19000±2000</td>
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<tr>
<td>J11</td>
<td>2017 Jan 03</td>
<td>14:59</td>
<td>N20, E02</td>
<td></td>
<td>105±30</td>
<td>6±1</td>
<td>18700±6000</td>
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<td>1.6</td>
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<tr>
<td>J12</td>
<td>2017 Jan 04</td>
<td>09:26</td>
<td>N24, W03</td>
<td></td>
<td>92±30</td>
<td>15±3</td>
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<td>2.0</td>
<td>73±5.0</td>
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<tr>
<td>J13</td>
<td>2017 Jan 04</td>
<td>17:08</td>
<td>N19, W10</td>
<td></td>
<td>103±30</td>
<td>4±1</td>
<td>7000±500</td>
<td>Yes</td>
<td>0.9</td>
<td>21±8.0</td>
</tr>
</tbody>
</table>

A minifilament resides (1 hour before the eruption) over the neutral line between the opposite-polarity flux patches.

The JBP occurs at the pre-eruption location of the minifilament.

The jet spire extends upward with an average speed of $105\pm30\ \text{kms}^{-1}$. 

Coronal hole jet (J11)
Flux cancelation leading to minifilament eruption

- The positive flux continuously decreases with time, which is clear evidence of flux cancelation at the neutral line of the minifilament.
- HMI time-distance map shows the convergence and cancelation of the jet-base polarities.
- We find in each of the 13 jets that opposite polarity magnetic flux patches converge and cancel, with a flux reduction of 20-75 % until jet erupts.
Coronal hole jet (J1)
The minifilament (blue) initially resides in sheared/twisted field between patches of majority (positive) and minority (negative) flux.

These two flux patches converge and cancel with each other. Continuous flux cancelation at the neutral line eventually destabilizes the filament field to erupt outwards and undergo external reconnection with the surrounding coronal field.

The external reconnection opens the erupting closed field, allowing hot reconnection-heated material and cool minifilament material to escape along the far-reaching field as the jet spire.

(I) Triggering of Pre-Jet Minifilament Eruptions

Quiet region jets
Coronal hole jets
Active region jets
Active Region Jets

Active Region Jet

AIA 171 movie

HMI movie
Flux cancelation leading to the jet eruption
(II) Minifilament Formation
### Quiet Region Minifilament Formation

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Minifil. formation time (UT)</th>
<th>Minifil. eruption time (UT)</th>
<th>Location</th>
<th>Duration of eruption (hrs)</th>
<th>Width of minifil. (km)</th>
<th>No. of Jets</th>
<th>$\Phi$ values</th>
<th>% of $\Phi$ reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>2012 Mar 21 22:46</td>
<td>2012 Mar 22 04:46</td>
<td>S09, E29</td>
<td>6</td>
<td>2000±500</td>
<td>1</td>
<td>1.6</td>
<td>20 ± 6.8</td>
</tr>
<tr>
<td>J2</td>
<td>2012 Jul 01 05:58</td>
<td>2012 Jul 01 08:29</td>
<td>N12, E02</td>
<td>2.5</td>
<td>1500±200</td>
<td>1</td>
<td>1.9^h</td>
<td>20 ± 7.3</td>
</tr>
<tr>
<td>J4</td>
<td>2012 Aug 04 05:14</td>
<td>2012 Aug 05 01:58, 2012 Aug 05 02:20</td>
<td>N07, E30</td>
<td>21</td>
<td>2500±500</td>
<td>2</td>
<td>5.8</td>
<td>14 ± 4.6</td>
</tr>
<tr>
<td>J5</td>
<td>2012 Aug 10 19:43</td>
<td>2012 Aug 10 23:03</td>
<td>S31, E11</td>
<td>3.2</td>
<td>1500±200</td>
<td>1</td>
<td>0.9</td>
<td>27 ± 6.1</td>
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<tr>
<td>J6</td>
<td>2012 Sept 19 17:15</td>
<td>2012 Sept 20 22:52</td>
<td>S34, E11</td>
<td>34</td>
<td>2500±500</td>
<td>2</td>
<td>3.0</td>
<td>9 ± 5.3</td>
</tr>
<tr>
<td>J7</td>
<td>2012 Sept 21 00:51</td>
<td>2012 Sept 21 03:33</td>
<td>S34, E08</td>
<td>3.5</td>
<td>2500±500</td>
<td>1</td>
<td>1.7</td>
<td>38 ± 2.6</td>
</tr>
<tr>
<td>J8</td>
<td>2012 Sept 21 23:55</td>
<td>2012 Sept 22 01:25</td>
<td>N01, E20</td>
<td>1.5</td>
<td>1500±500</td>
<td>1</td>
<td>0.9</td>
<td>38 ± 5.5</td>
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<tr>
<td>J10</td>
<td>2012 Dec 13 08:06</td>
<td>2012 Dec 13 10:11, 2012 Dec 13 10:36</td>
<td>S01, W01</td>
<td>2.5</td>
<td>1600±200</td>
<td>2</td>
<td>1.2</td>
<td>7.0 ± 8.3</td>
</tr>
</tbody>
</table>

Minifilament Formation (J2)
Minifilament Formation (J2)

- Duration of minifilament ~ 2.5 hours.

- Brightenings appear at the location where the minifilament subsequently forms.
Minifilament Formation and Flux Cancelation
Homologous Jet Eruptions

- We also observe more than a single jet from the same neutral line. A minifilament erupts and drives a jet, reforms/reappears at the same location, and then again erupts, driving the next jet.

- This process occurs as flux cancelation is ongoing and continues until all the minority-polarity flux vanishes. Eventually, the neutral line disappears, no more minifilaments and homologous jets are produced.
Origin of Minority-Polarity Flux Patch

We found the three scenarios:

- In some events tiny grains of flux coalesce to make a minority-polarity flux clump.

- The minority-polarity foot of a newly-emerged bipole became the minority-polarity flux patch.

- In some cases the minority-polarity clump preexisted as it rooted onto the Earthward side of the Sun 2-3 days before our observations began.
Continuous flux cancelation between a minority-polarity flux clump and a majority-polarity flux clump builds a highly sheared minifilament field.
**Flux rope model**

- Footpoints get displaced along the PIL due to the differential rotation of the Sun.
- Footpoints come closer, due to the flux convergence at the PIL.
- Reconnection at the footpoints lead to the formation of longer helical field lines which carried the prominence plasma.

*van Ballegooijen and Martens (1989)*
Polar Crown Prominence Observed on 13 Feb 2011
Magnetic Field Structure

The interaction between two unconnected bi-poles, one is older and diffused which is at higher latitude, the other polarity is at lower latitude.

This results in the highly sheared field at the PIL. Thus, after the many repetitions of this process, it forms the long helical structures that can partly or fully cover the polar region of the Sun.

Martens and Zwaan (2001)
(III) CME-producing Filament Eruptions
Filament Observed on 04 May 2013

AIA 193 movie

HMI Magnetogram movie
Flux Cancelation at the Neutral line

4-May-2013 00:33:36

4-May-2013 00:32:07

4-May-2013 02:42:06

Positive Flux (10^{19} Mx)


Start Time (03-May-13 21:53:29)
Continuous flux cancelation at the neutral line of the filaments often triggers their eruptions. This corresponds to the finding that persistent flux cancelation at the neutral is the cause of jet-producing minifilament eruptions.

Thus our observations support coronal jets being miniature versions of CMEs.
Summary

- We examined in detail random on-disk quiet-region jets and coronal hole jets. In each event a cool-transition-region material, a minifilament, initially resides at a neutral line inside the jet-base region.

- Our observations suggest that flux cancelation is usually the trigger of coronal jets.

- We found that flux cancelation is the key agent responsible for building a highly sheared minifilament field, leading to the formation of minifilaments.

- All the jet-producing eruptions are similar to typical solar flare eruptions, where a solar flare arcade forms during the filament eruption along the neutral line along which the filament resided prior to its eruption.

- Thus our observations support coronal jets being miniature versions of CMEs.