Flux Cancelation: The Key to Solar Eruptions

Navdeep K. Panesar

(NASA, Marshall Space Flight Center, Huntsville, AL)

(Visiting researcher at Stanford University, Palo Alto, CA)

Collaborators

Alphonse Sterling (NASA), Ronald Moore (NASA), Davina Innes (MPS), BC Low (HAO),
Bart De Pontieu (LMSAL), Sanjiv Tiwari (LMSAL), Aimee Norton (Stanford), Don Schmit (Maryland)

Students

Roxana Popescu, Prithi Chakrapani
Riley McGlasson, Ellis Avalone, Abigail Harden

NASA

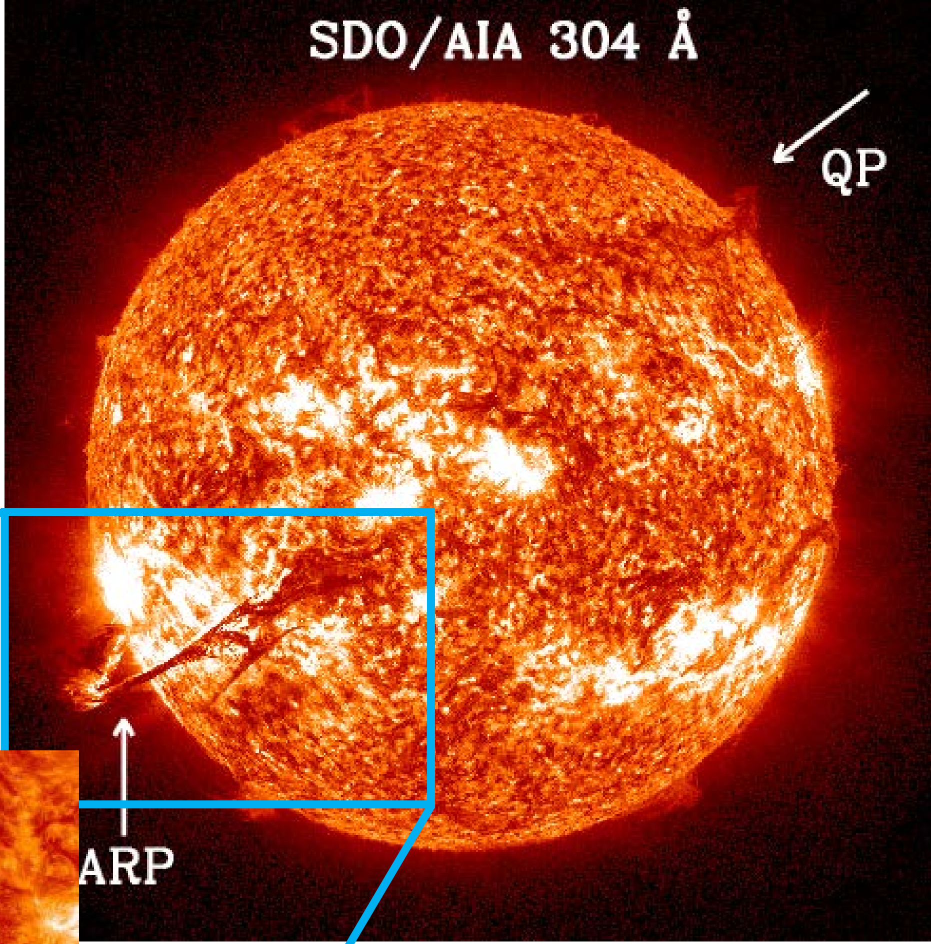
NASA POSTDOCTORAL PROGRAM

Outline

- Background
- Triggering of Jet-Driving Minifilament Eruptions
- Formation of Pre-Jet Minifilaments
- Triggering of CME-producing Filament Eruptions
- Build-up and Triggering of Jetlets (and Spicules?)
- Summary

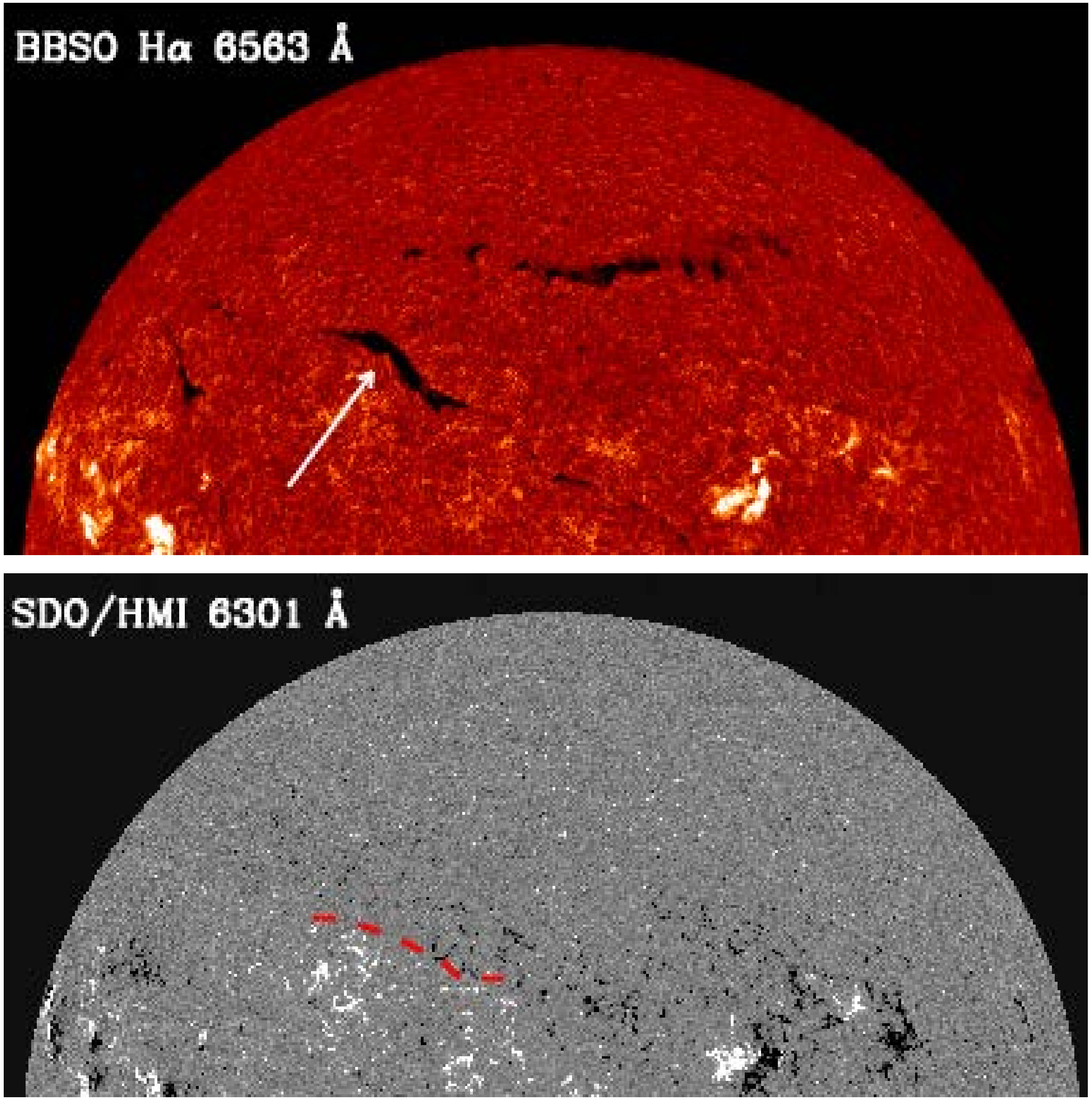
Background

Solar prominences consist of relatively cool (10^4 K) and dense plasma (10^{12} cm^{-3}), supported against gravity, embedded in the low-density hotter (10^6 K) corona at the height up to 100Mm.



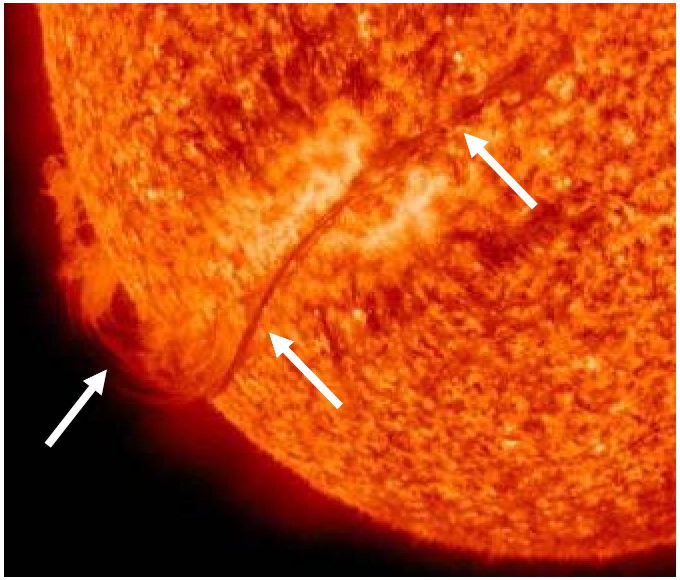
Coronal mass ejections (CMEs) consist of plasma and magnetic fields that are expelled from the Sun into the heliosphere. They often accompanied by solar flares and (with/without) prominence eruptions.

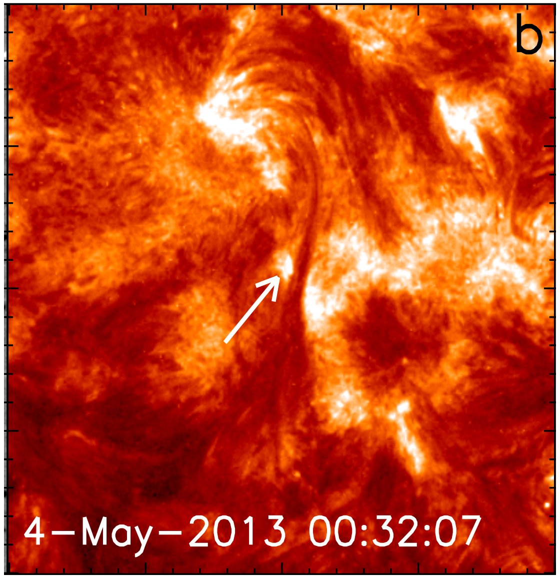
Polarity inversion line

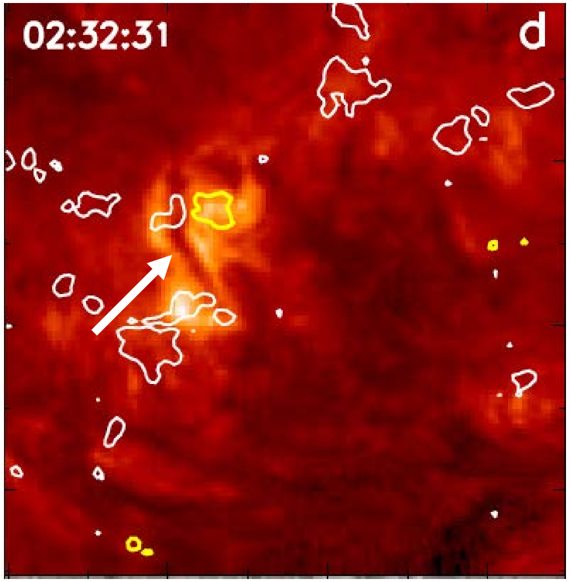


Examples of prominences/filaments and minifilament

SDO/AIA He II 304 Å





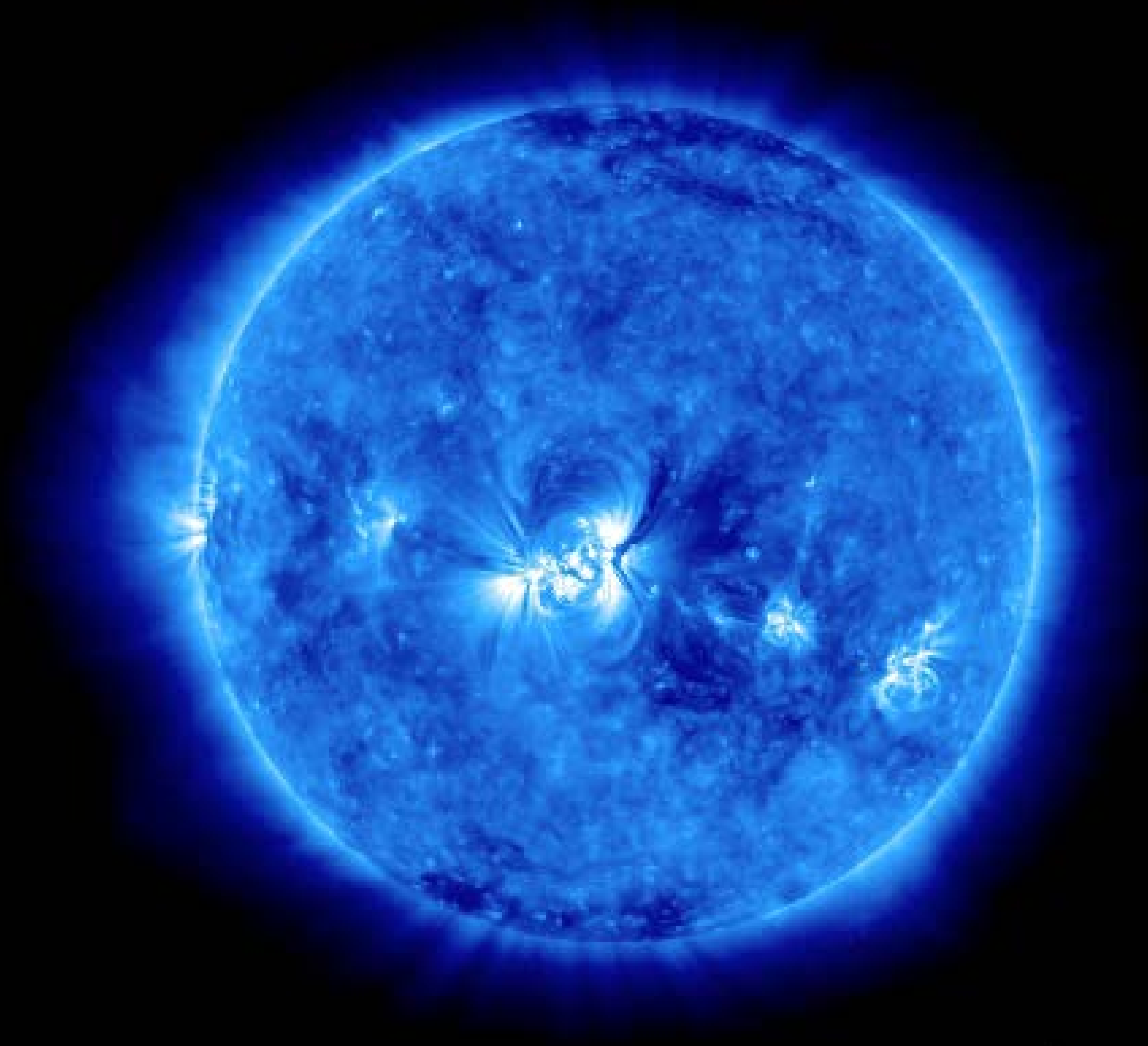


Typical length of solar filament is between 6 × 10$^{4-5}$ km (*Tandberg-Hanssen 1995*).

Average length of minifilament is 8 - 16 × 10^{3} km (*Sterling et al 2015, Panesar et al 2016b*).

Polar Coronal Hole Jet

Blue = 171 Å (0.7 MK)
Green = 195 Å (1.5 MK)
Red = 304 Å (0.040 MK)



https://sdo.gsfc.nasa.gov/gallery

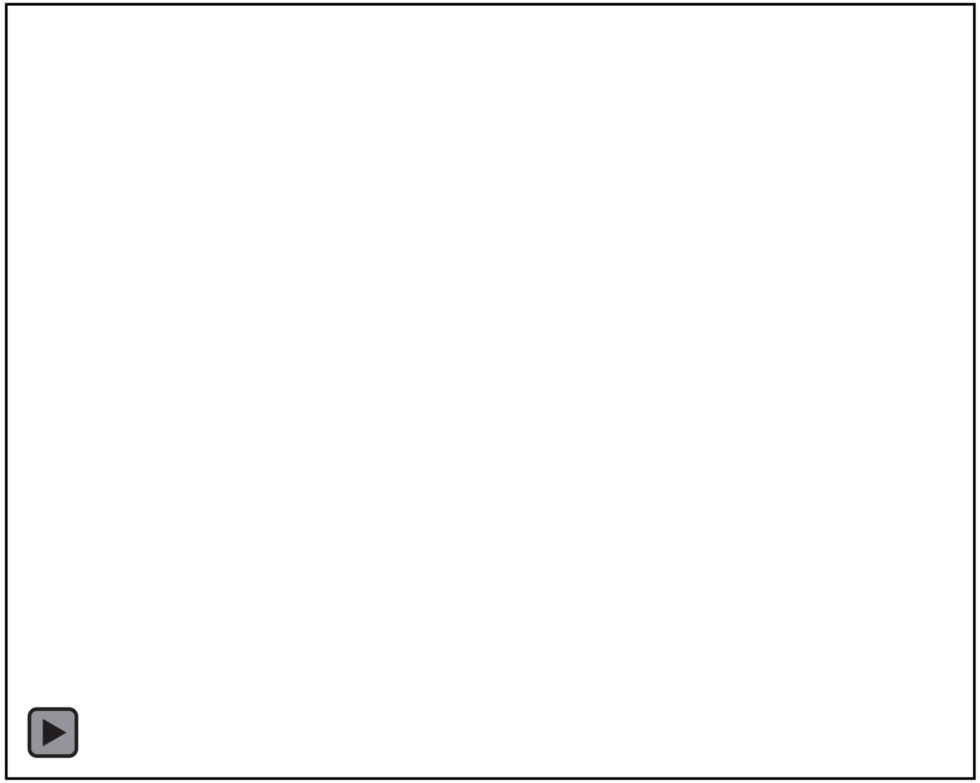
Why are these features important to study?

- Eruptive events of all sizes on the Sun – from the largest ones that make flares and CMEs (which make the most severe space weather) to the smallest ones that drive jets, jetlets and spicules that in aggregate are candidates for the continual powering of global coronal heating and the solar wind.

- Many researchers think that the main source of heating in quiet regions and coronal holes is small-scale eruptions (e.g. coronal jets, jetlets, spicules) that are triggered by magnetic activity.

Background

SDO/AIA 171Å



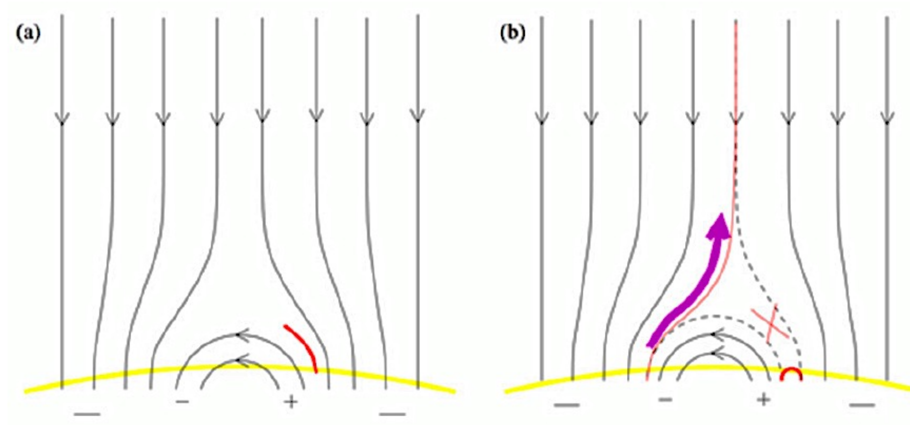
- Coronal jets are frequent magnetically channeled narrow eruptions. They occur in various solar environments: quiet regions, coronal holes and active regions.
- They are relatively short-lived features (of about 10 minutes; *Shimojo et al 1996, Savcheva et al 2007*) occur at a rate of ~60 per day in 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*).

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*.

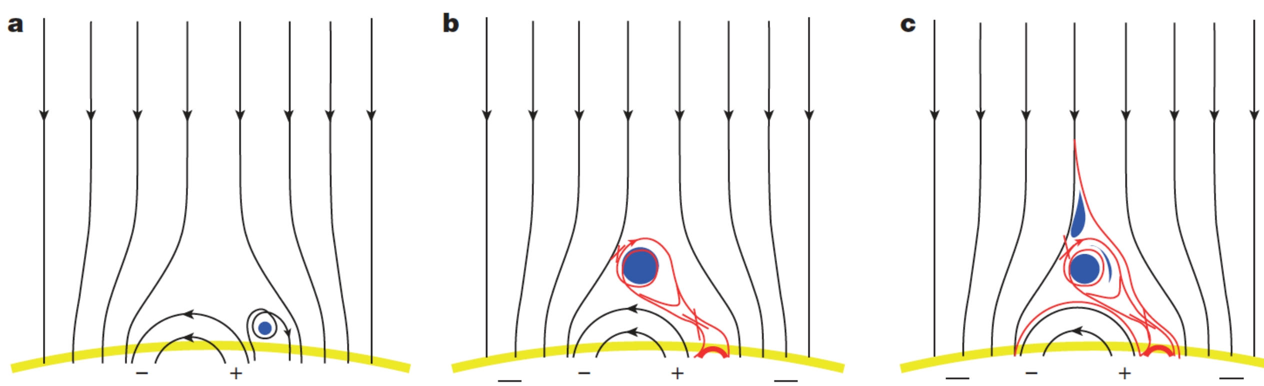
- **What leads to these minifilament eruptions?**
- **How and when are minifilaments formed?**

Emerging-flux jet model



Shibata et al 1992, 2007

Minifilament-eruption jet model



Sterling et al 2015

(I) Triggering of Pre-Jet Minifilament Eruptions

Quiet region jets

Coronal hole jets

Active region jets

Quiet region jets

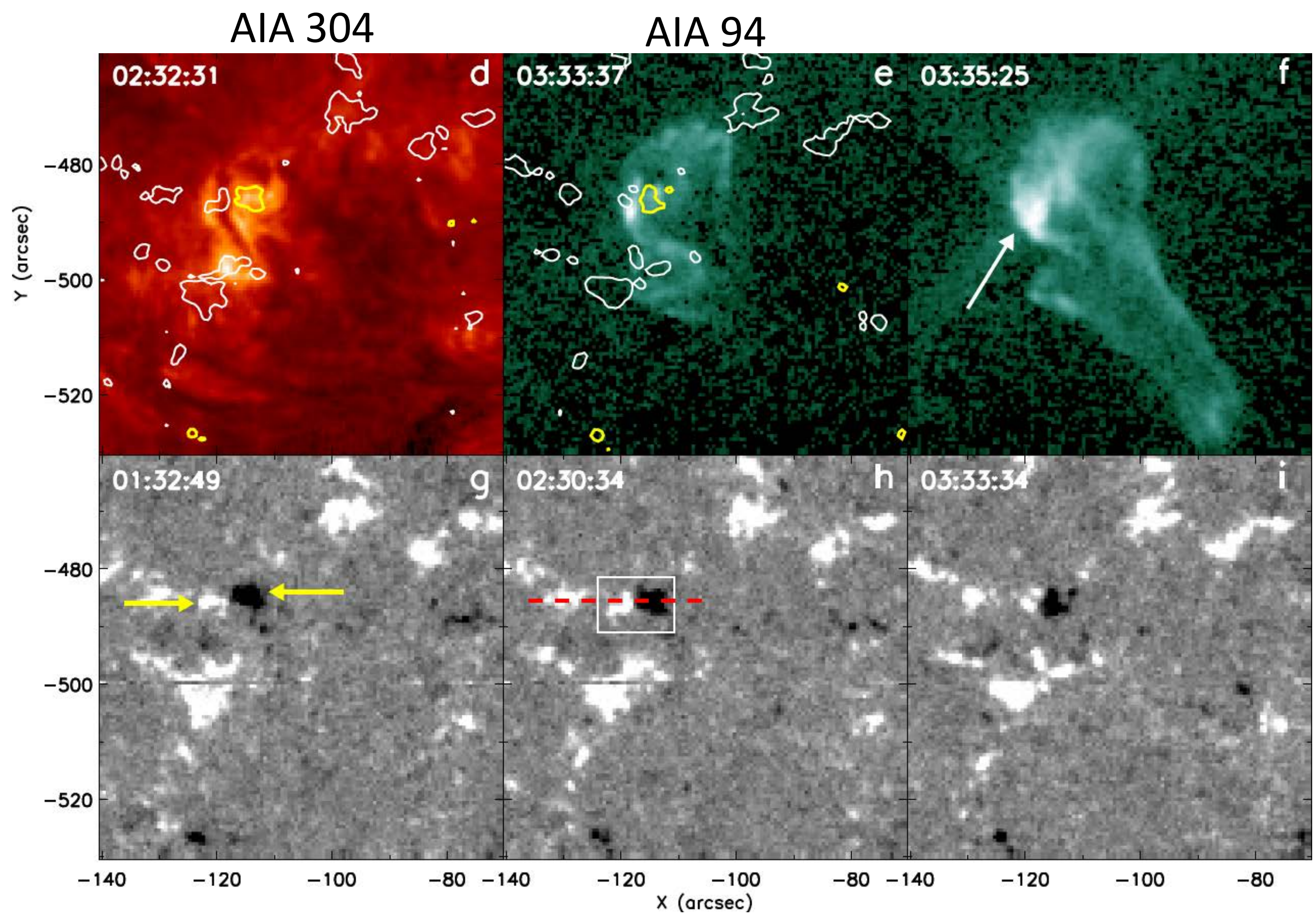
- We examined the magnetic cause of 10 random on-disk quiet region jet eruptions by using SDO/HMI magnetograms and SDO/AIA images.

Measured parameters for the observed quiet-region jets:

Event No.	Date	Time[a] (UT)	Location[b] x,y (arcsec)	Jet Speed[c] (km s^{-1})	Jet Dur.[d] min.	Jet-base[e] Width (km)	Minifil. length[f] (±1700 km)	Φ values[g] 10^{19} Mx	% of Φ[h] reduction
J1	2012 Mar 22	04:46	-470,-100	100±30	15±5	10500±500	9800	1.6	52 ± 5.8
J2	2012 Jul 01	08:32	-44, 285	100±10	10±2	27000±500	25000	4.0	18 ± 6.8
J3	2012 Jul 07	21:31	-192,-180	120±15	14±3	16500±400	10500	–[i]	–
J4	2012 Aug 05[j]	02:20	-485, 190	140±35	10±3	22000±1000	31000	1.5	21 ± 6.0
J5	2012 Aug 10	23:03	-168,-443	125±15	15±2	16000±400	10000	0.9	57 ± 5.4
J6	2012 Sept 20	22:56	-158,-486	35±5	9±2	20000±500	36000	2.0	23 ± 4.6
J7	2012 Sept 21	03:33	-115, -485	135±30	12±1	17500±500	15000	1.0	36 ± 7.2
J8	2012 Sept 22	01:25	-338, 103	110±45	11±1	13000±600	5700	0.9	50 ± 5.1
J9	2012 Nov 13	04:21	-28,-307	55±5	9±3	18000±1000	25000	1.7	34 ± 3.2
J10	2012 Dec 13	10:36	26, 50	65±20	10±2	9500±500	12500	1.2	38 ± 5.0

Panesar, Sterling, Moore, Chakrapani, 2016b, ApJ Letters, 832, L7

Quiet region jet (J7)

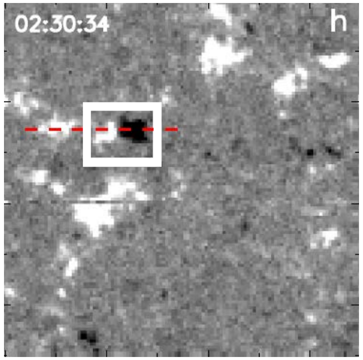


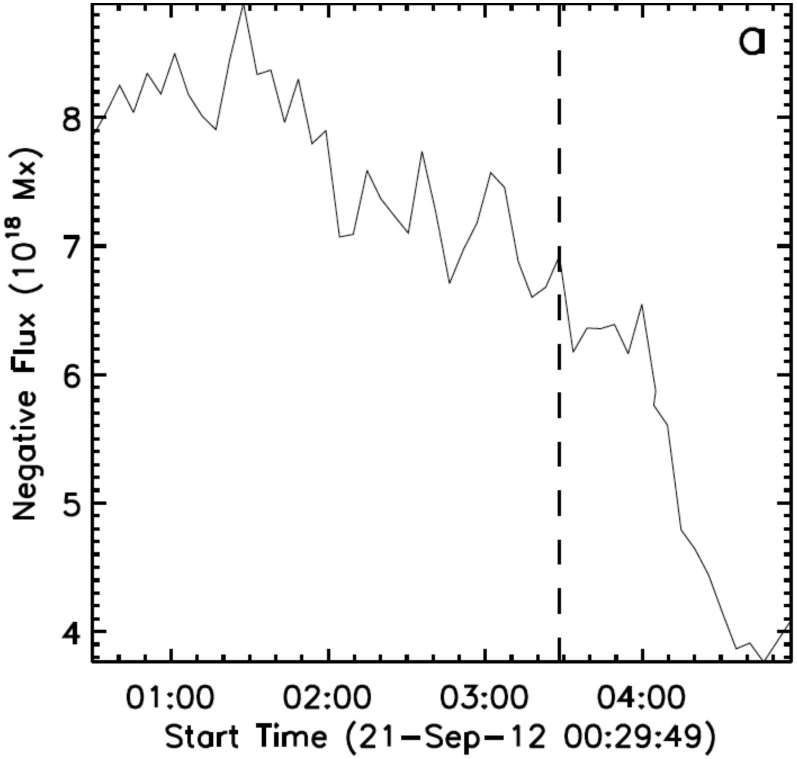
- A minifilament (length ~15000 km) is present in the jet-base region prior to jet eruption.
- It resides over the neutral line between the opposite-polarity flux patches.
- The JBP occurs at the pre-eruption location of the minifilament.
- The jet spire extends upward with an average speed of 135±30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

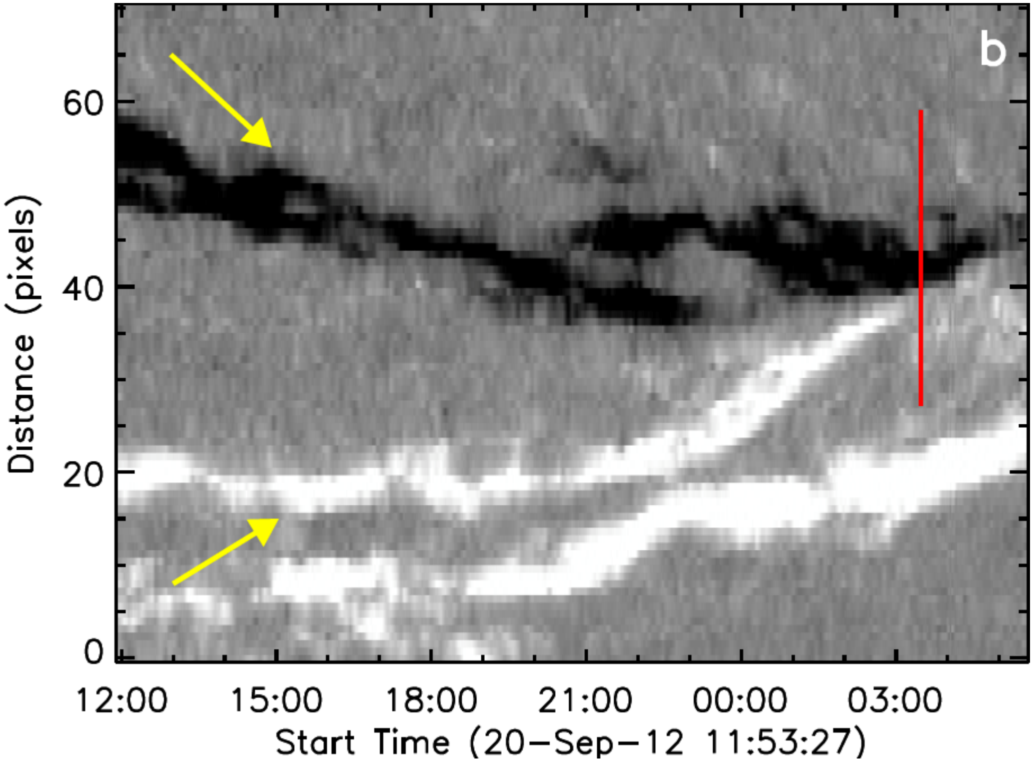
Quiet region jet (J7)

- The minifilament was present at the neutral line for 34 hours before the jet eruption.
- The jet-producing eruptions and JBPs 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.

Quiet region jet (J9)

- The minifilaments show a slow-rise, followed by a fast-rise as they erupt, analogous to larger-scale filament eruptions.
- The average flux cancelation rate is ~1.5×10^{18} Mx hr^{-1}.

(I) Triggering of Pre-Jet Minifilament Eruptions

Quiet region jets

Coronal hole jets

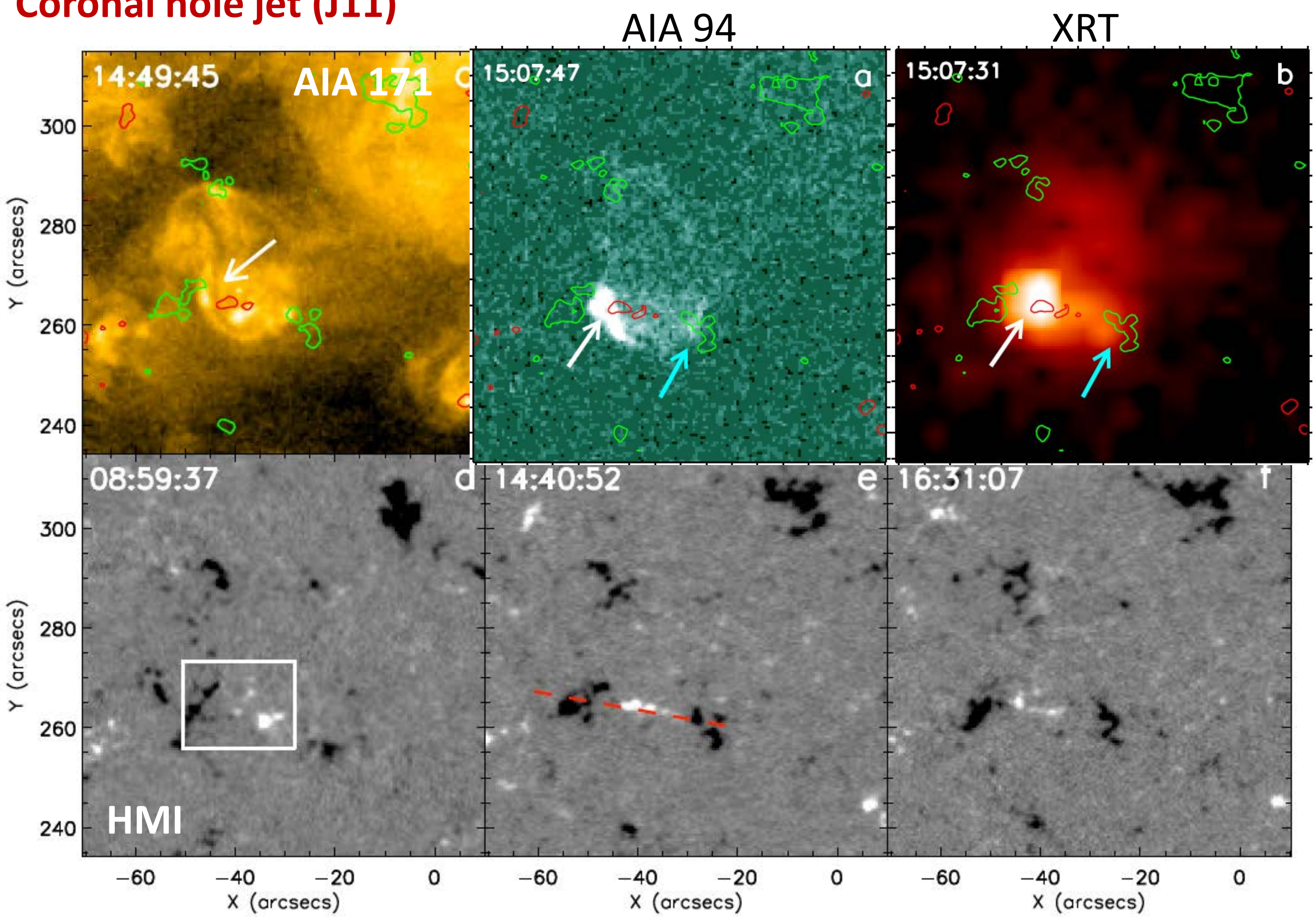
Active region jets

Coronal Hole Jets

Event No.	Date	Time[a] (UT)	Location[b] Helio. Cord.	Jet Speed[c] (km s^{-1})	Jet Dur.[d] (minutes)	Jet-Base[e] Width (km)	XRT[f] Coverage	Φ values[g] 10^{19} Mx	% of Φ[h] Reduction
J1	2012 Jul 02	02:11	N21, W07	65±1.5	10±2	22500±1500	No	1.5	33±4.5
J2	2015 Aug 18	13:07	N27, E02	40±20	12±3	9700±1000	Yes	0.9	31±10
J3	2015 Dec 28	09:54	N36, E19	110±40	7±1	13000±900	No	0.9	48 ±9.0
J4	2015 Dec 28	16:02	N37, E03	35±7	11±1	12000±2500	No	1.2	52±5.0
J5	2015 Dec 30	15:14	N36, W23	70±30	7±1	6700±1000	No	0.7	43 ±10
J6	2015 Dec 31	19:04	N43, W34	27±4	6±1	6600±500	No	0.6	41 ±8.5
J7	2016 Jan 01	11:45	N08, E30	30±5	8±1	18500±3500	No	0.7	52 ±6.5
J8	2016 Jan 01	18:11	N41, E39	204±70	4±1	1200±500	No	0.5	37 ±10
J9	2016 Apr 21	06:15	S01, E12	240±70	8±1[i]	10500±700	Yes	–[j]	–
J10	2016 Sep 15	23:36	S06, E00	–[k]	6±1[l]	19000±2000	Yes	–[m]	–
J11	2017 Jan 03	14:59	N20, E02	105±30	6±1	18700±6000	Yes	1.6	33±5.5
J12	2017 Jan 04	09:26	N24, W03	92±30	15±3	9500±1000	Yes	2.0	73 ±5.0
J13	2017 Jan 04	17:08	N19, W10	103±30	4±1	7000±500	Yes	0.9	21±8.0

Panesar, Sterling, Moore, 2018a, ApJ, 853,189

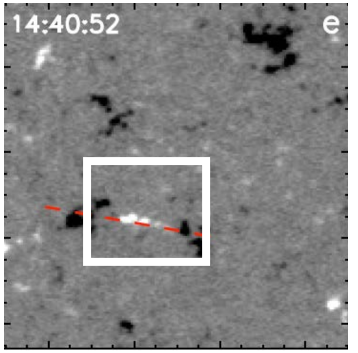
Coronal hole jet (J11)

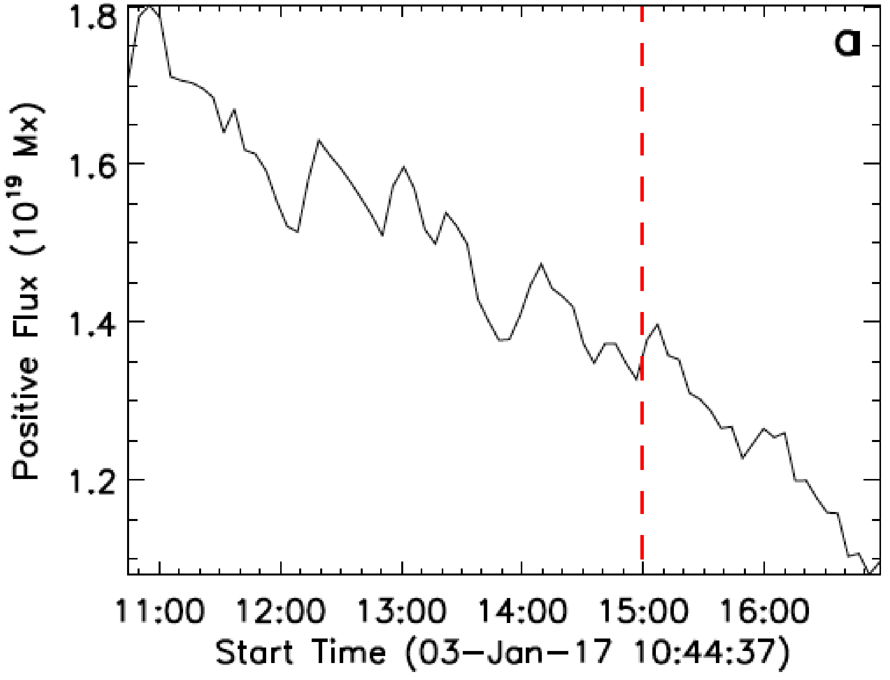


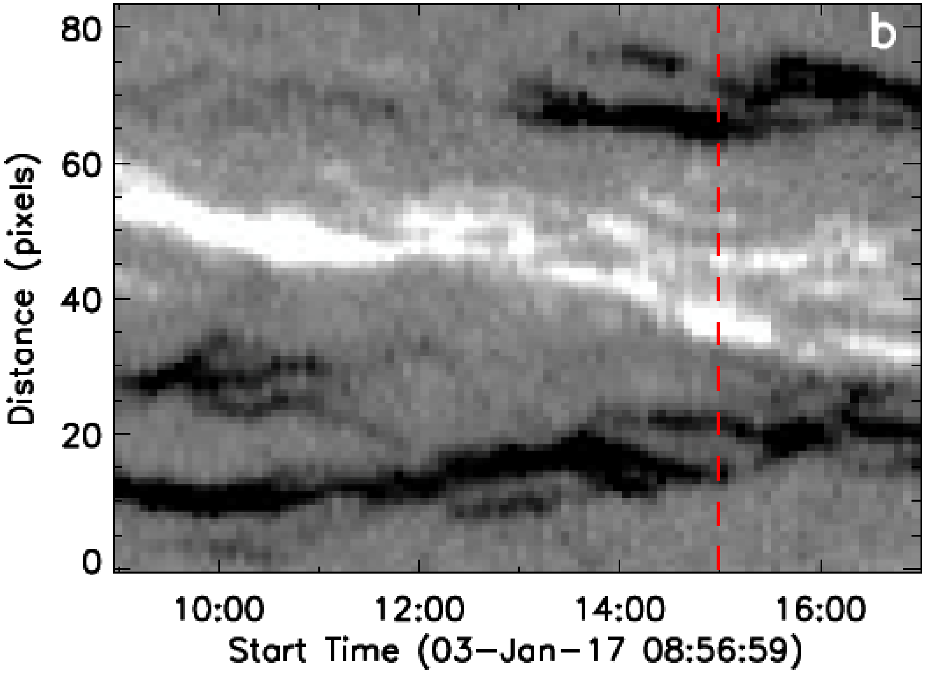
- A minifilament resides (1 hour before the eruption) over the neutral line between the opposite-polarity flux patches.
- The JBP occurs at the pre-eruption location of the minifilament.
- The jet spire extends upward with an average speed of 105±30 kms^{-1}.

Coronal hole jet (J11)

Flux cancelation leading to minifilament eruption

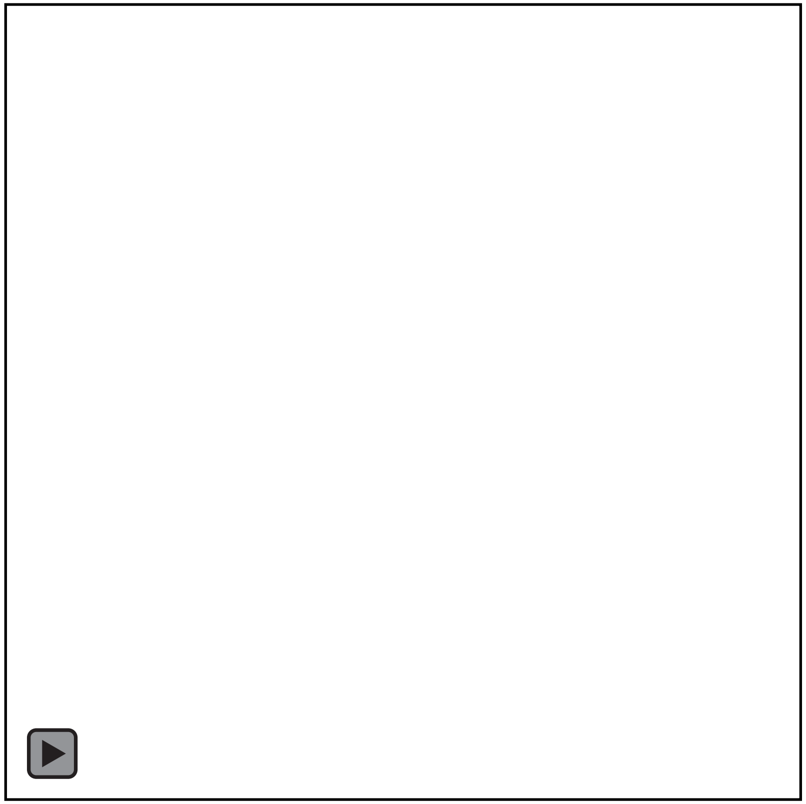


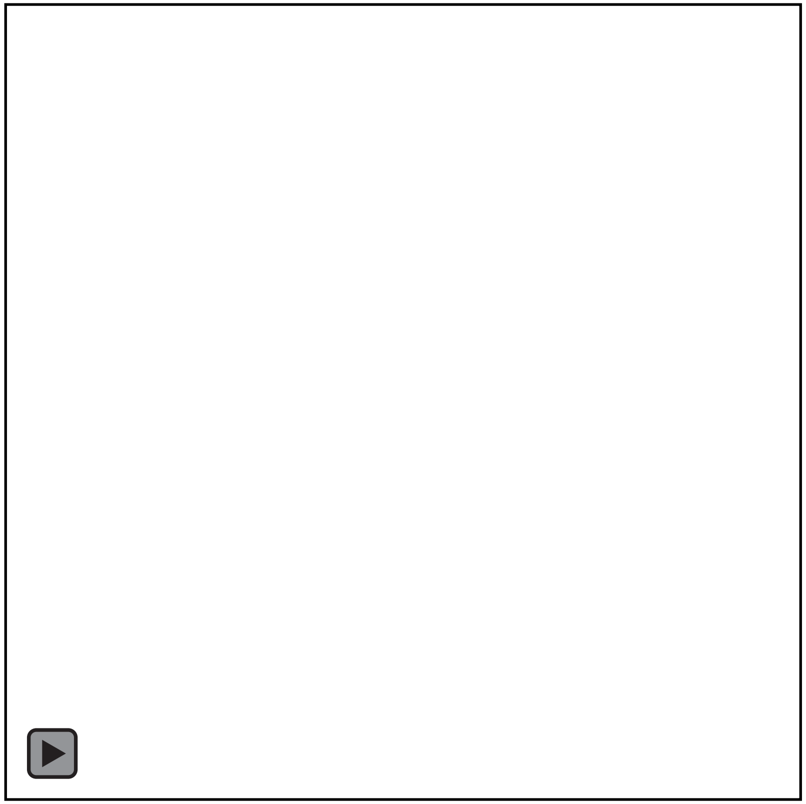




- The positive flux continuously decreases with time, which is clear evidence of flux cancelation at the neutral line of the minifilament.
- HMI time-distance map shows the convergence and cancelation of the jet-base polarities.
- We find in each of the 13 jets that opposite polarity magnetic flux patches converge and cancel, with a flux reduction of 20-75% until jet erupts.

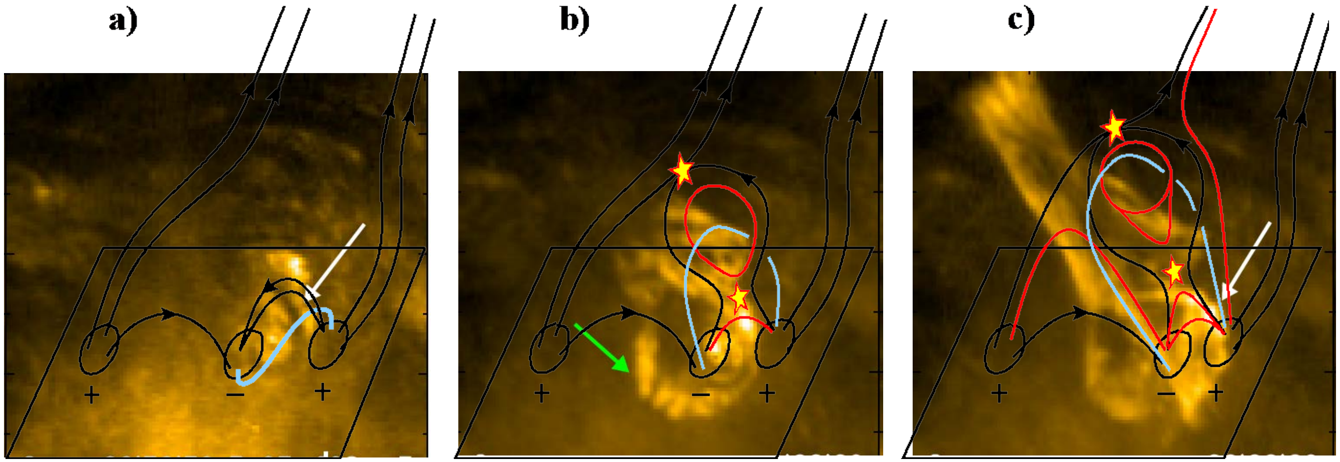
Coronal hole jet (J1)





- The average flux cancelation rate is 0.6×10^{18} Mx hr^{-1}.

Schematic Illustration of Observations



- 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.
- Recently (*McGlasson et al 2019, ApJ, under review*), we found similar results in the study 60 coronal hole and quiet region coronal jets.

Panesar, Sterling, Moore, Chakrapani, 2016b, ApJ, 832, L7

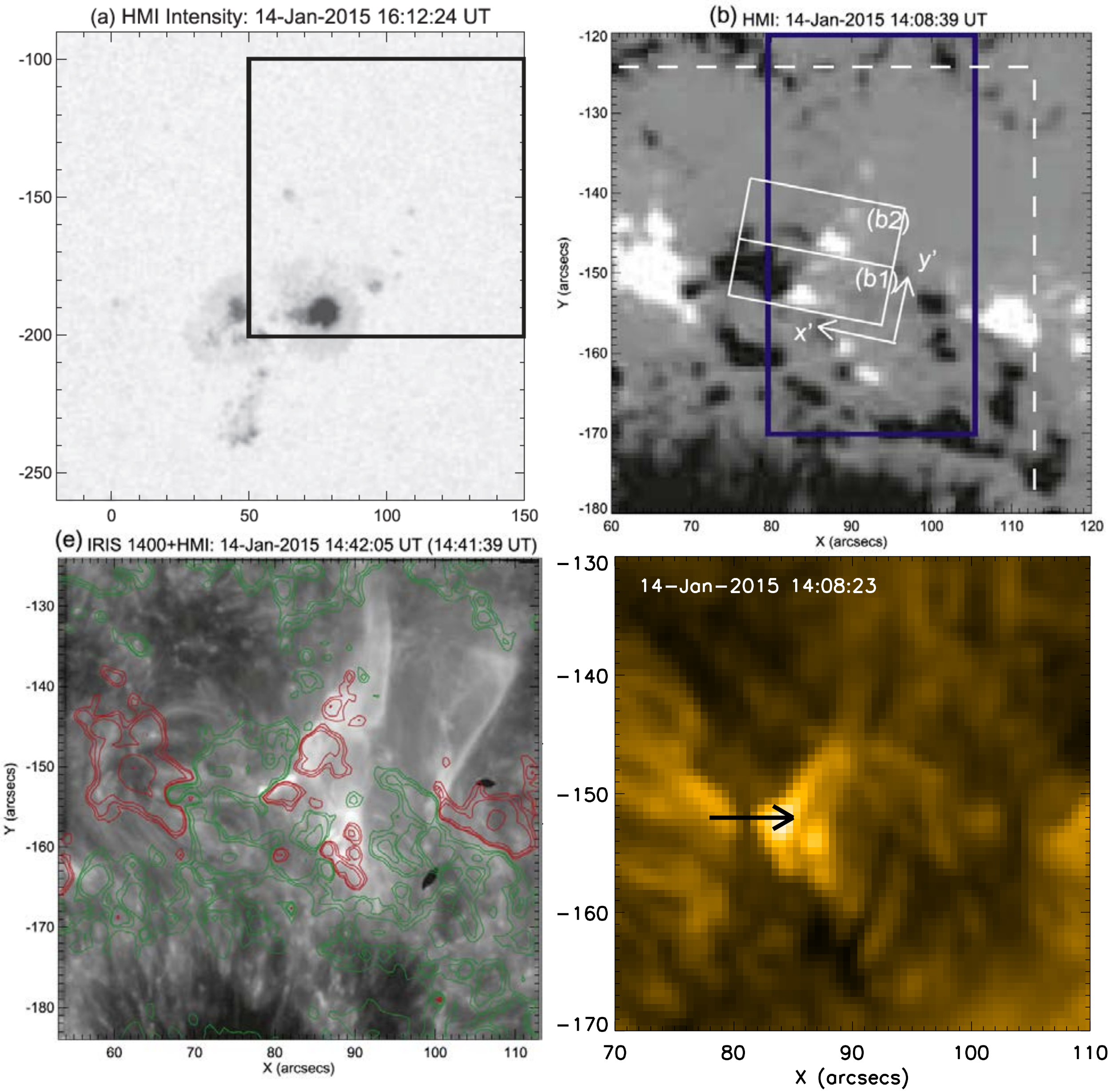
(I) Triggering of Pre-Jet Minifilament Eruptions

Quiet region jets

Coronal hole jets

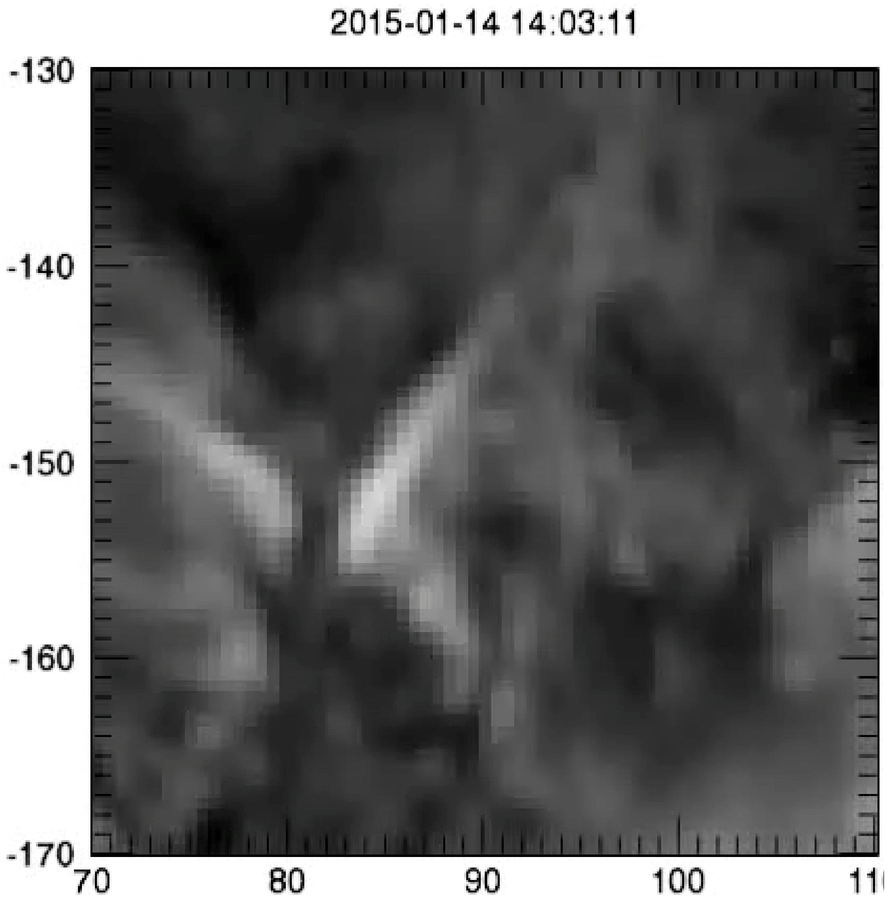
Active region jets

Active Region Jets

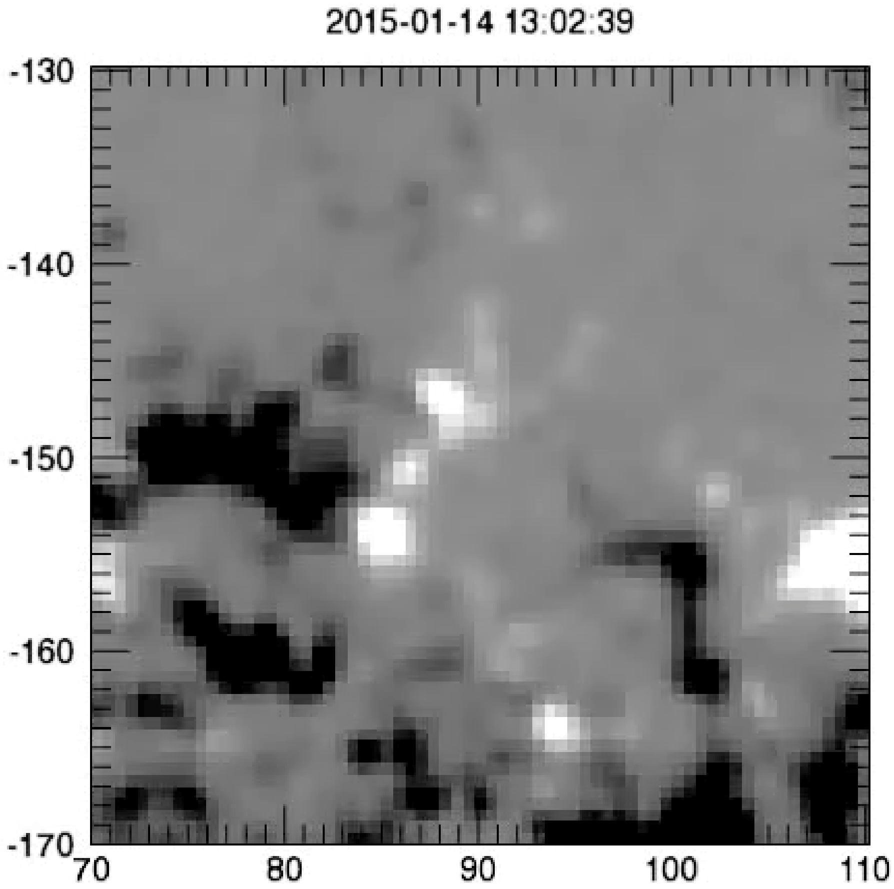


Sterling, Moore, Falconer, Panesar, Martinez, 2017, ApJ, 844, 28

Active Region Jet



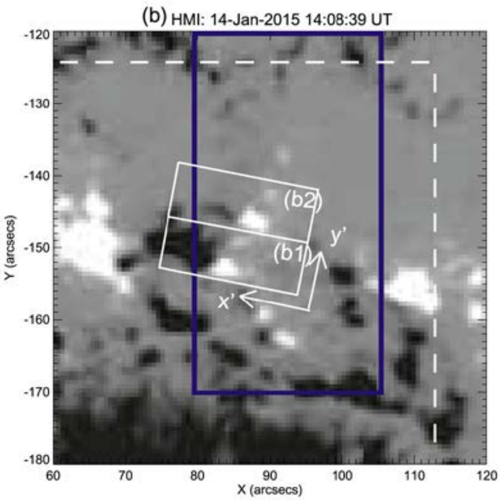
AIA 171 movie

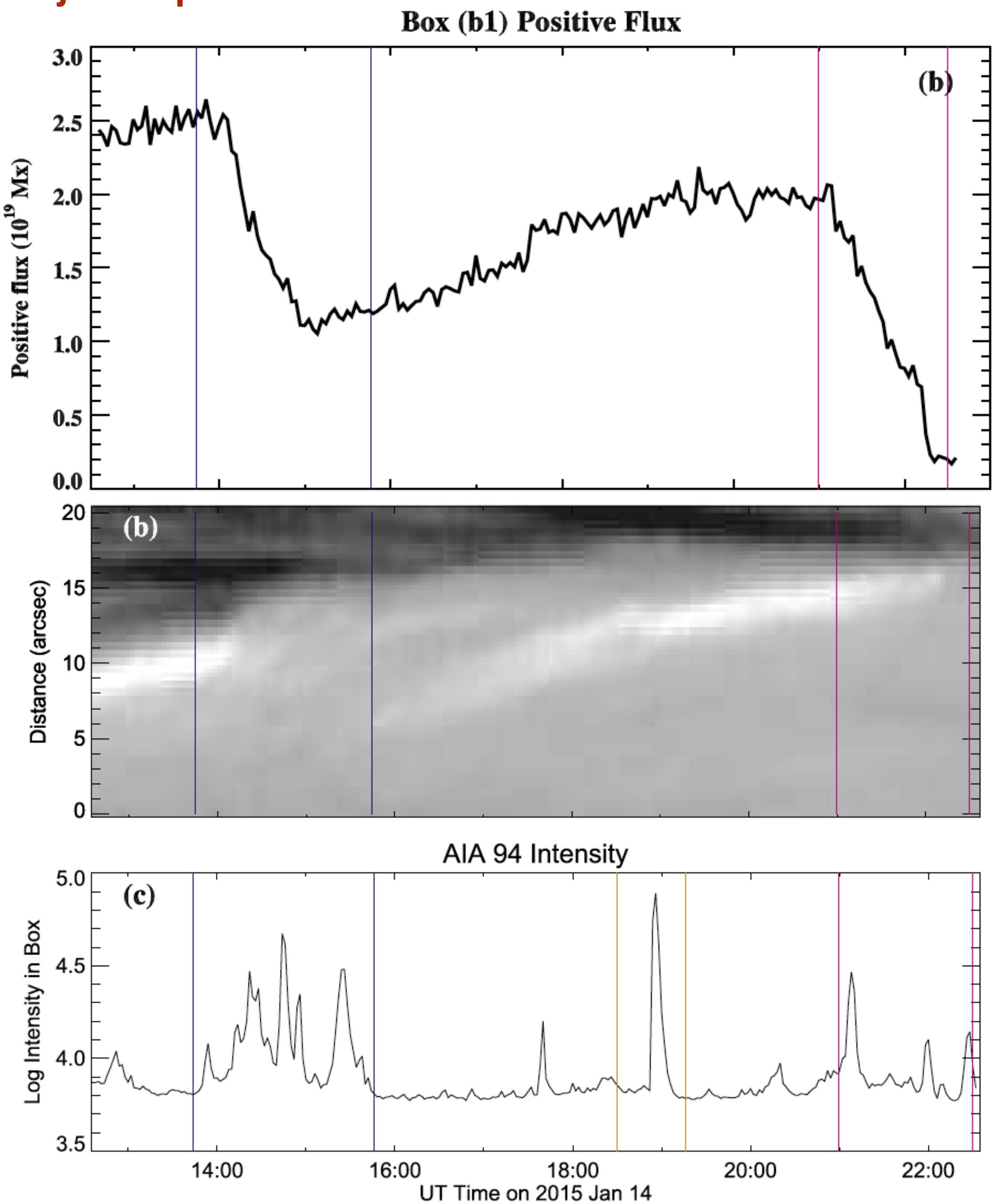


HMI movie

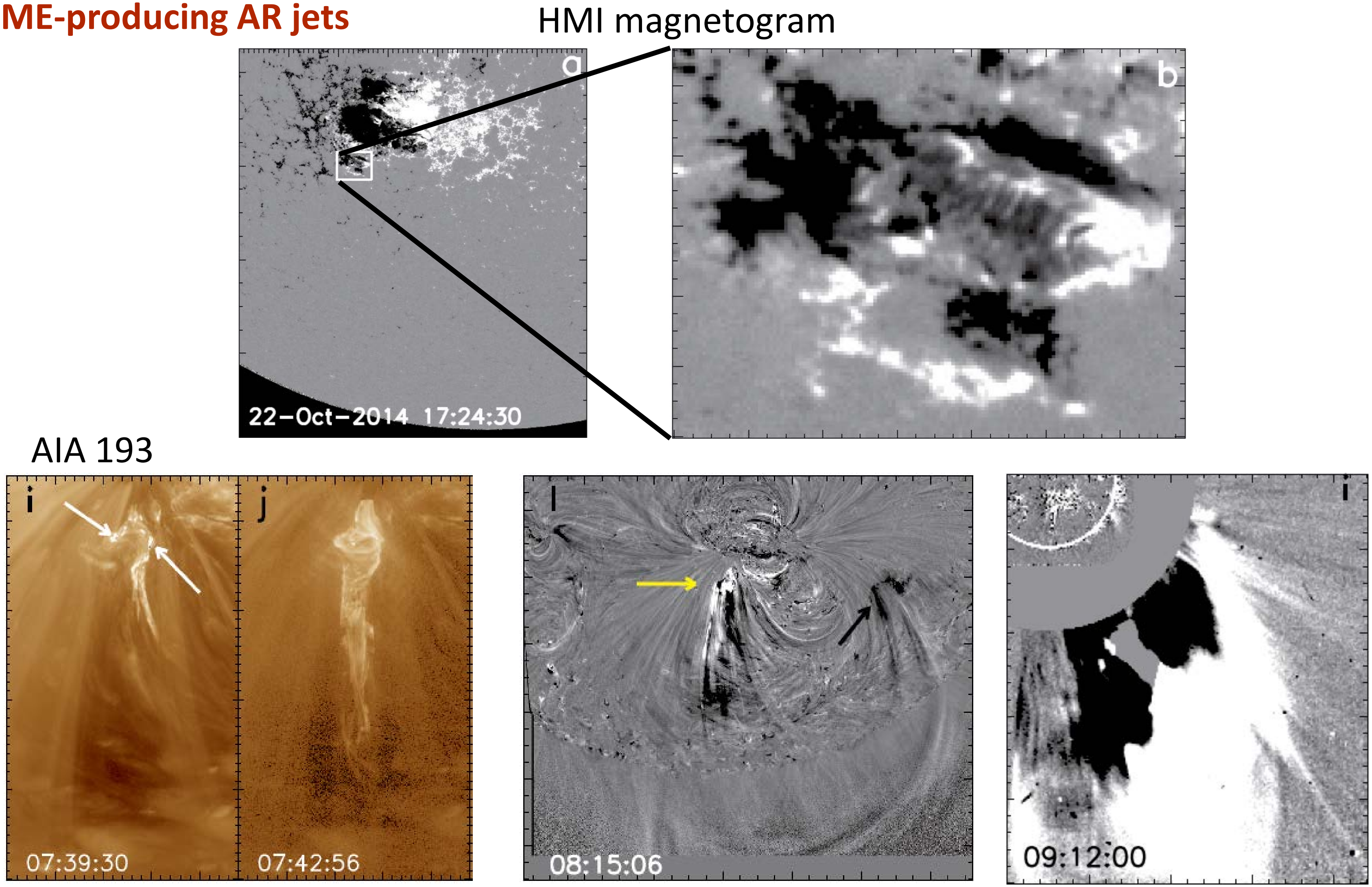
- The average flux cancelation rate is ~1.5×10^{18} Mx hr^{-1}.

Flux cancelation leading to the jet eruption





CME-producing AR jets



These jet eruptions occur at the foot of only one loop of the streamer arcade.

Panesar, Sterling, Moore, 2016a, ApJ Letters, 882, 23

(II) Minifilament Formation

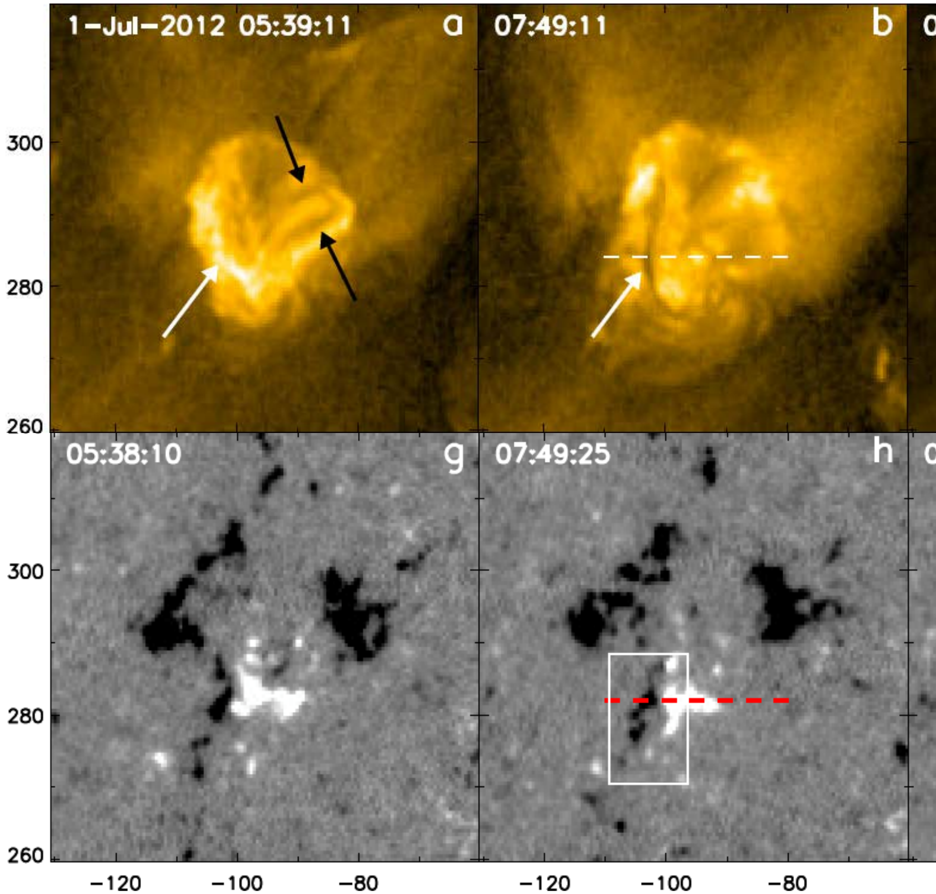
Quiet Region Minifilament Formation

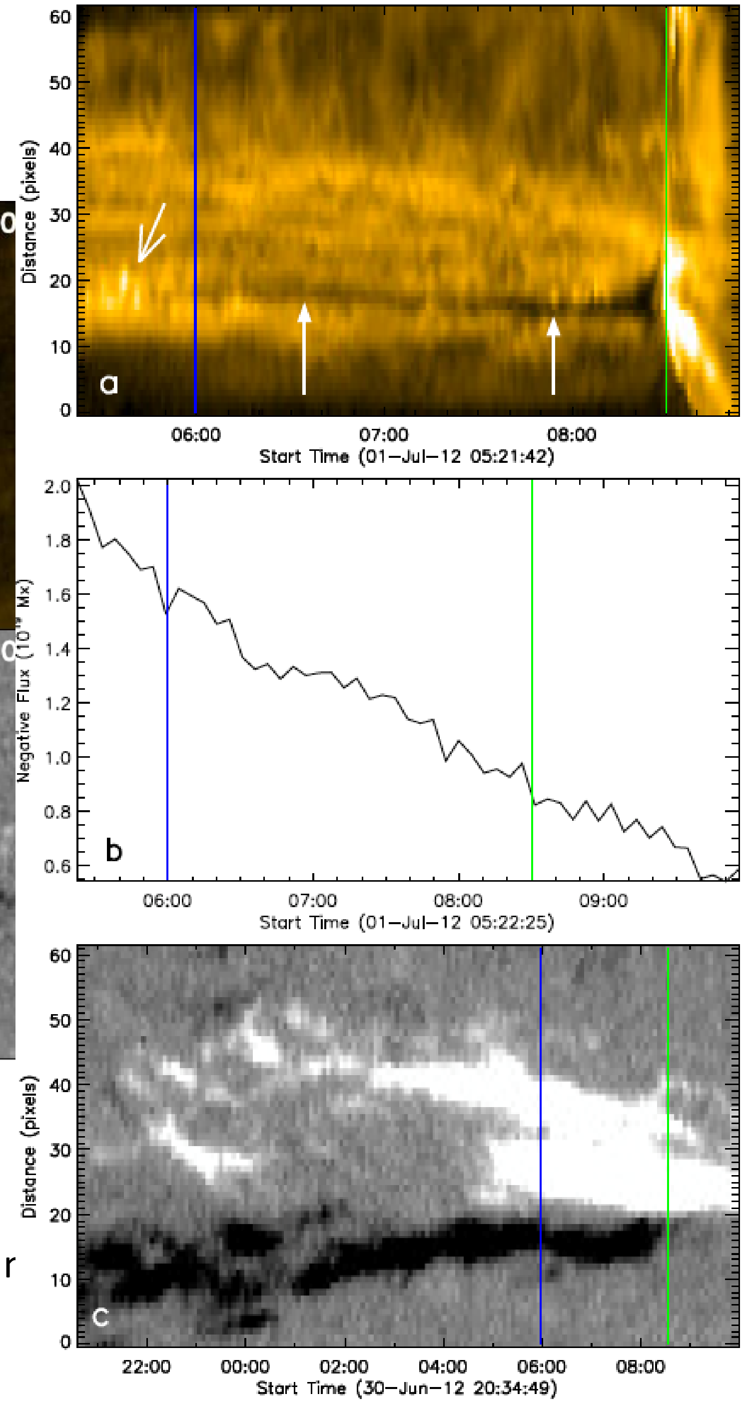
Event No.	Minifil. formation[a] time (UT)	Minifil. eruption[b] time (UT)	Location[c] helio. cord.	Duration of [c] minifil. (hrs)	Width of[d] minifil. (km)	No. of[e] Jets	Φ values[f] 10^{19} Mx	% of Φ[g] reduction
J1	2012 Mar 21 22:46	2012 Mar 22 04:46	S09, E29	6	2000±500	1	1.6	20 ± 6.8
J2	2012 Jul 01 05:58	2012 Jul 01 08:29	N12, E02	2.5	1500±200	1	1.9[h]	20 ± 7.3
J3	2012 Jul 07 —[i]	2012 Jul 07 21:31	S15, E12	–	2200±200	1	–	–
J4	2012 Aug 04 05:14	*2012 Aug 05 01:58*[j], 2012 Aug 05 02:20	N07, E30	21	2500±500	2	5.8	14 ± 4.6
J5	2012 Aug 10 19:43	2012 Aug 10 23:03	S31, E11	3.2	1500±200	1	0.9	27 ± 6.1
J6	2012 Sept 19 17:15	2012 Sept 20 22:52	S34, E11	34	2500±500	2	3.0	9 ± 5.3
J7	2012 Sept 21 00:51	2012 Sept 21 03:33	S34, E08	3.5	2500±500	1	1.7	38 ± 2.6
J8	2012 Sept 21 23:55	2012 Sept 22 01:25	N01, E20	1.5	1500±500	1	0.9	38 ± 5.5
J9	2012 Nov 11 02:56	*2012 Nov 11 13:08*, *2012 Nov 12 17:06*, *2012 Nov 12 21:34*, 2012 Nov 13 04:20	S23, E01	49.5	2500±500	4	–[k]	–
J10	2012 Dec 13 08:06	*2012 Dec 13 10:11*, 2012 Dec 13 10:36	S01, W01	2.5	1600±200	2	1.2	7.0 ± 8.3

Panesar, Sterling, Moore, 2017, ApJ, 833, 131

Minifilament Formation (J2)

Minifilament Formation (J2)





- Duration of minifilament ~ 2.5 hours.
- Brightenings appear at the location where the minifilar

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.

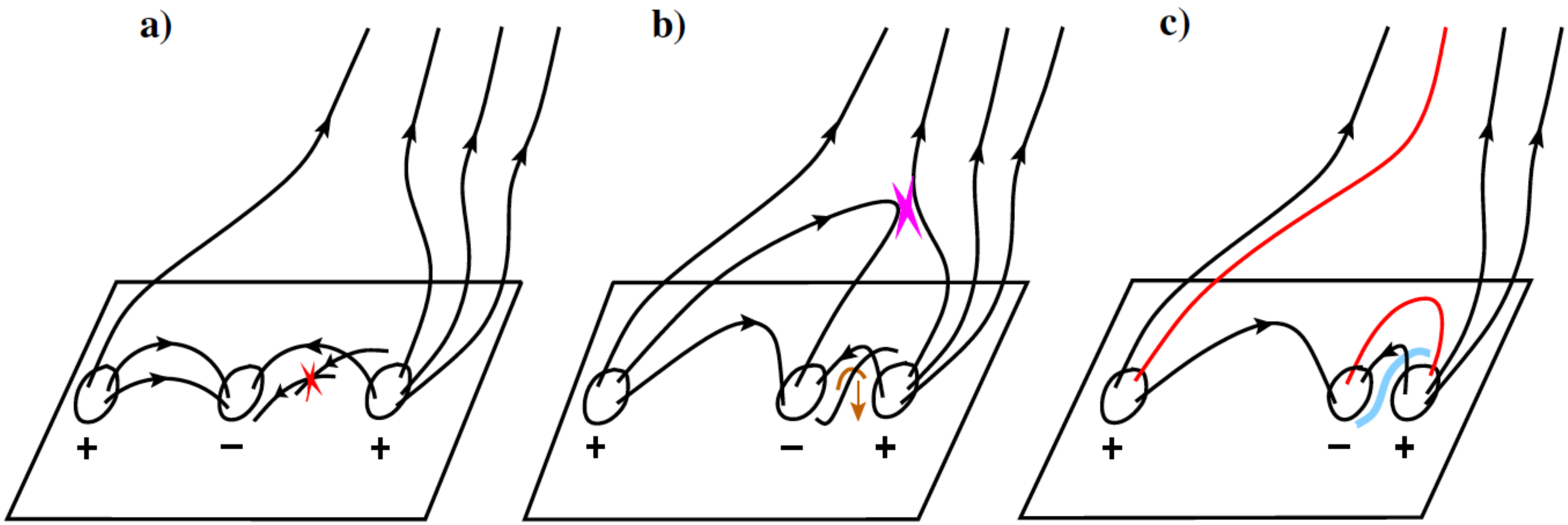
- This process occurs as flux cancelation is ongoing and continues until all the minority-polarity flux vanishes. Eventually, the neutral line disappears, no more minifilaments and homologous jets are produced.

Origin of Minority-Polarity Flux Patch

We found 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 rotated onto the Earthward side of the Sun 2-3 days before our observations began.

Schematic Illustration of Observations

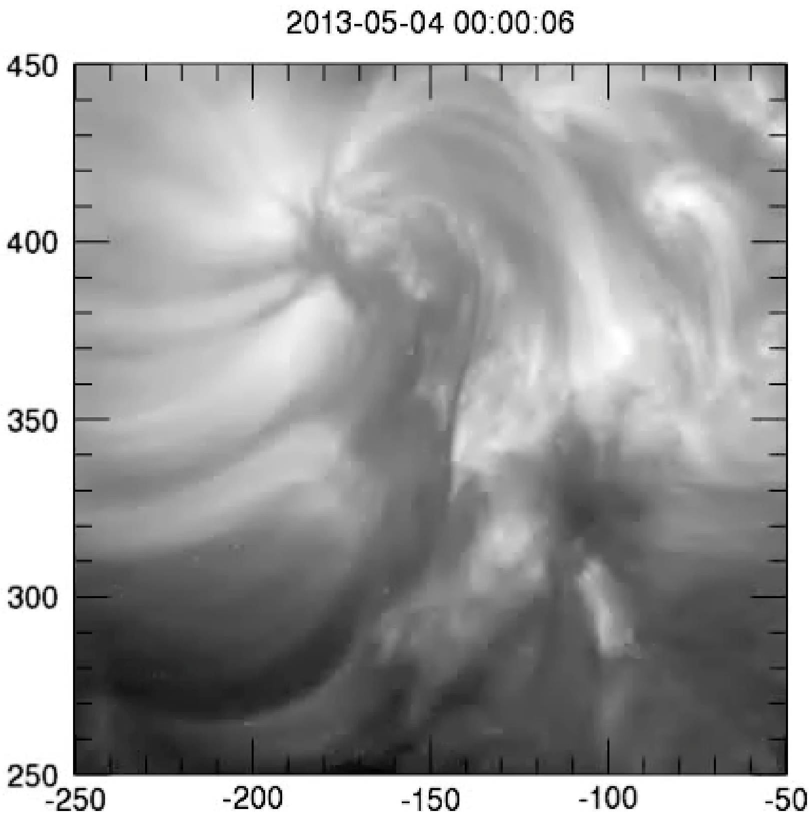


- Continuous flux cancelation between a minority-polarity flux clump and a majority-polarity flux clump builds a highly sheared minifilament field, leading to the formation of a minifilament.
- These results are consistent with the models for the formation of the field of typical solar filaments (*van Ballegooijen & Martens 1989; Martens & Zwaan 2001*).

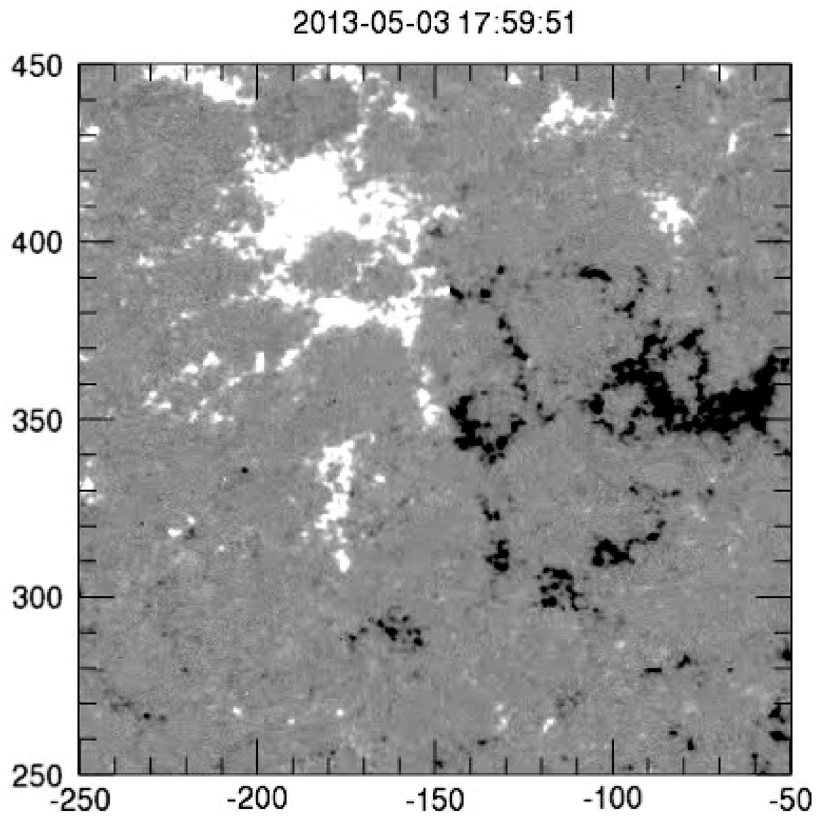
Panesar, Sterling, Moore, 2017, ApJ, 833, 131

(III) CME-producing Filament Eruptions

CME-producing Filament Eruption

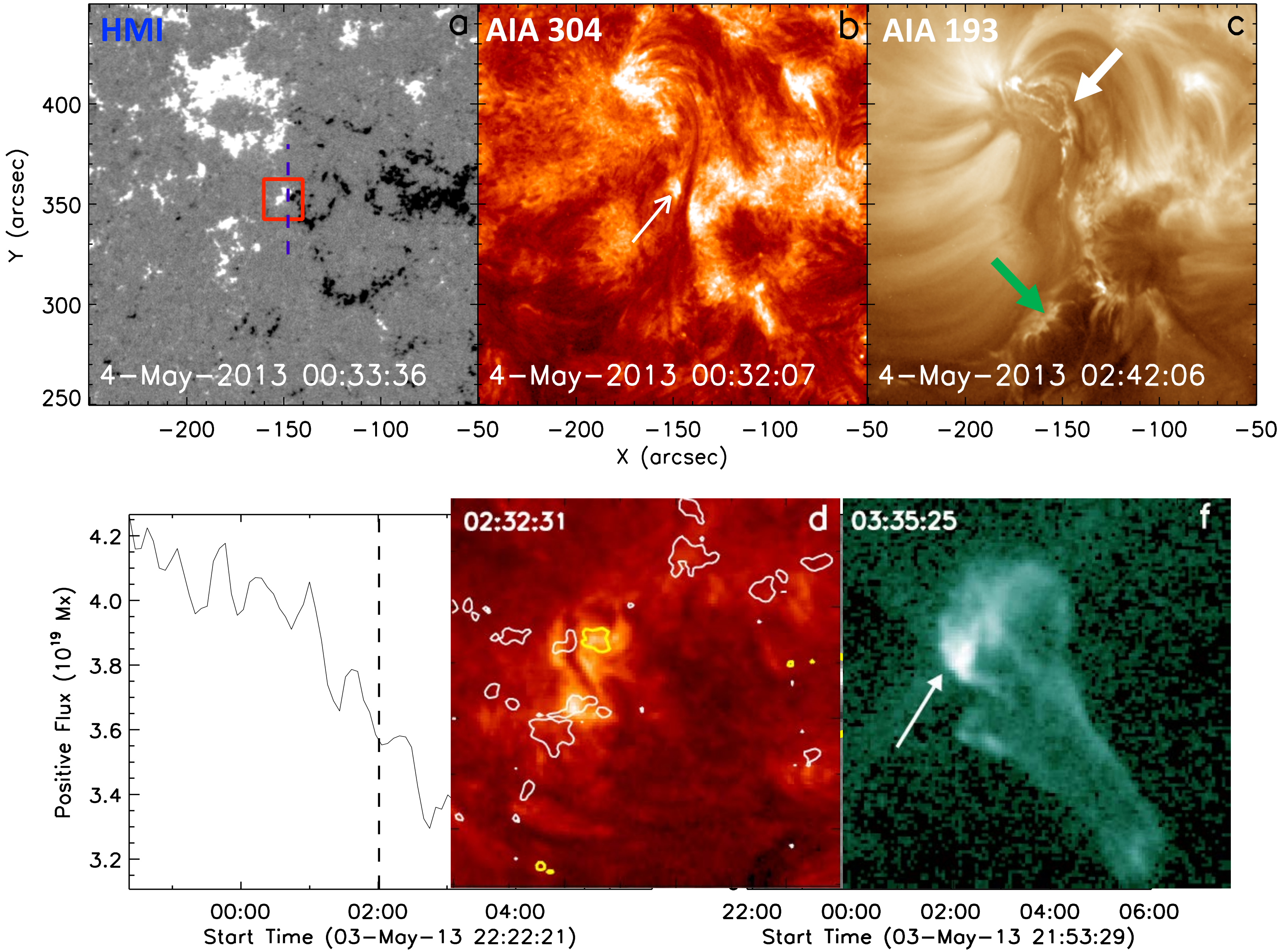


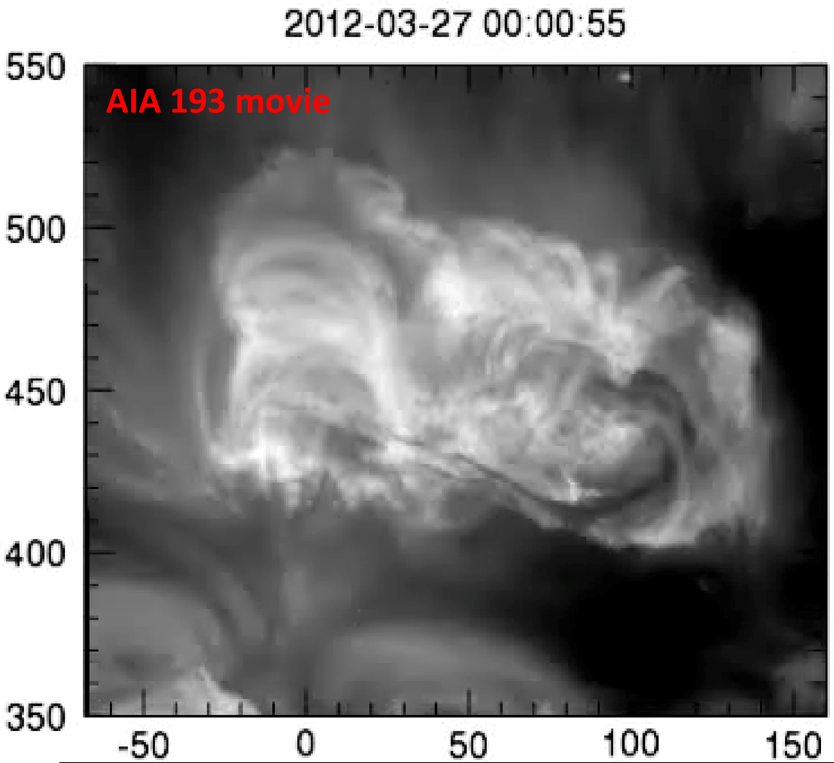
AIA 193 movie

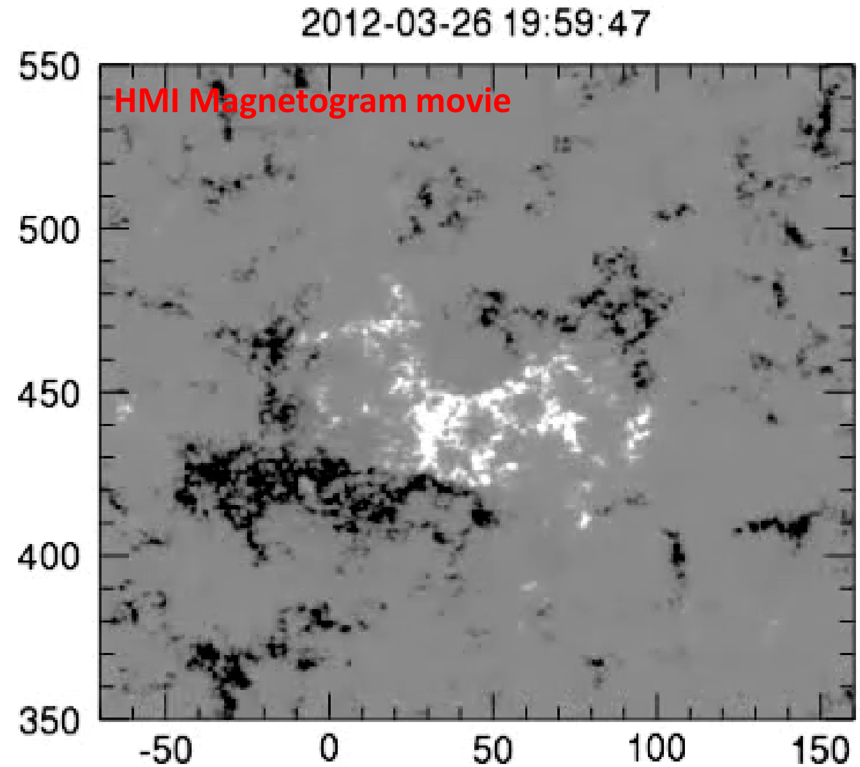


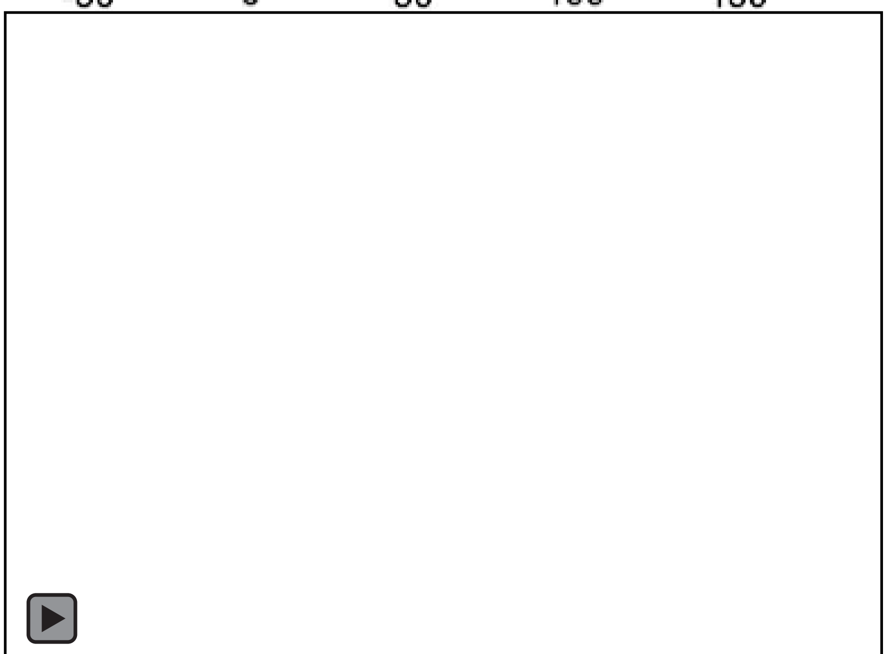
HMI Magnetogram movie

Flux Cancelation at the Neutral line





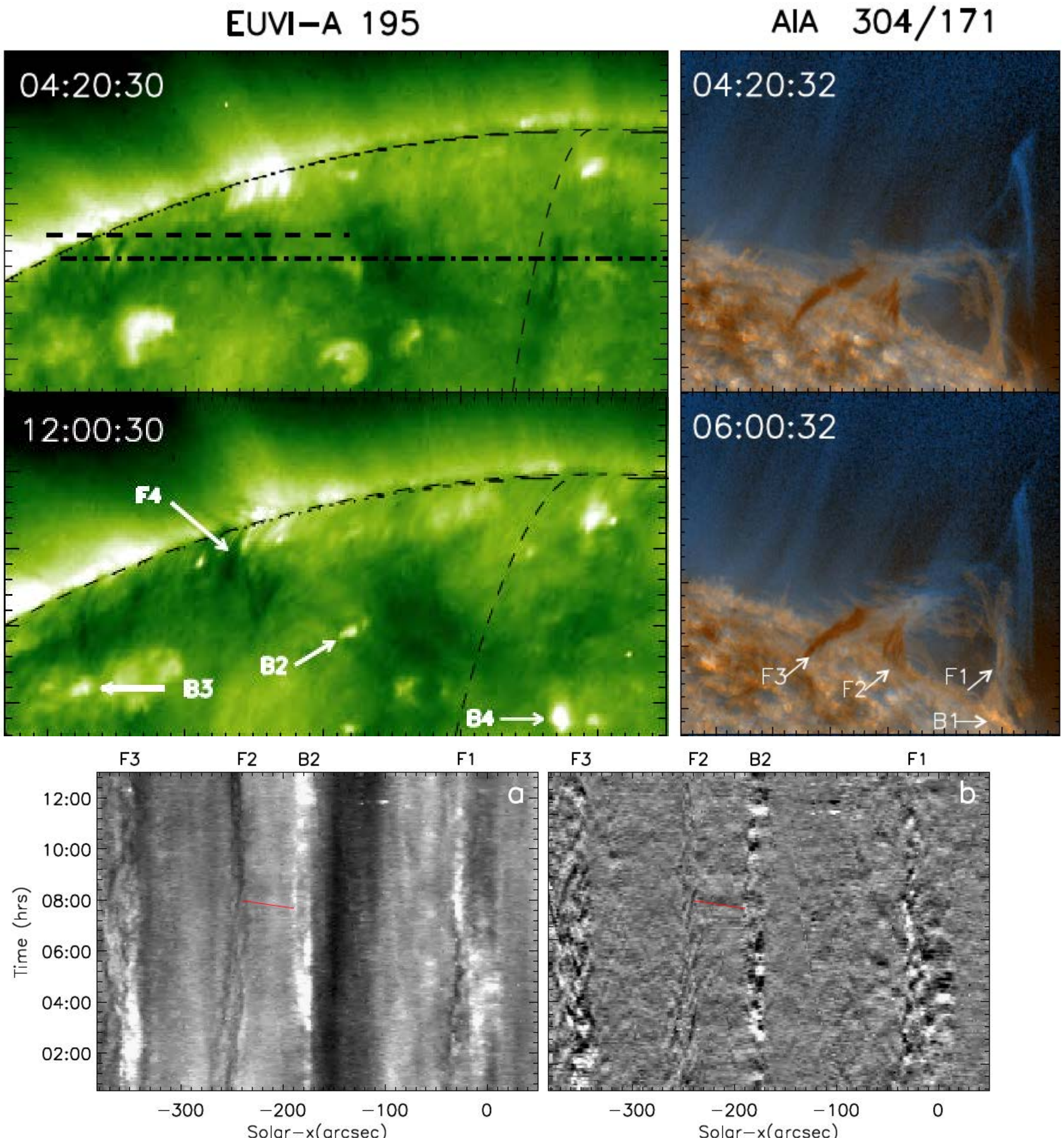




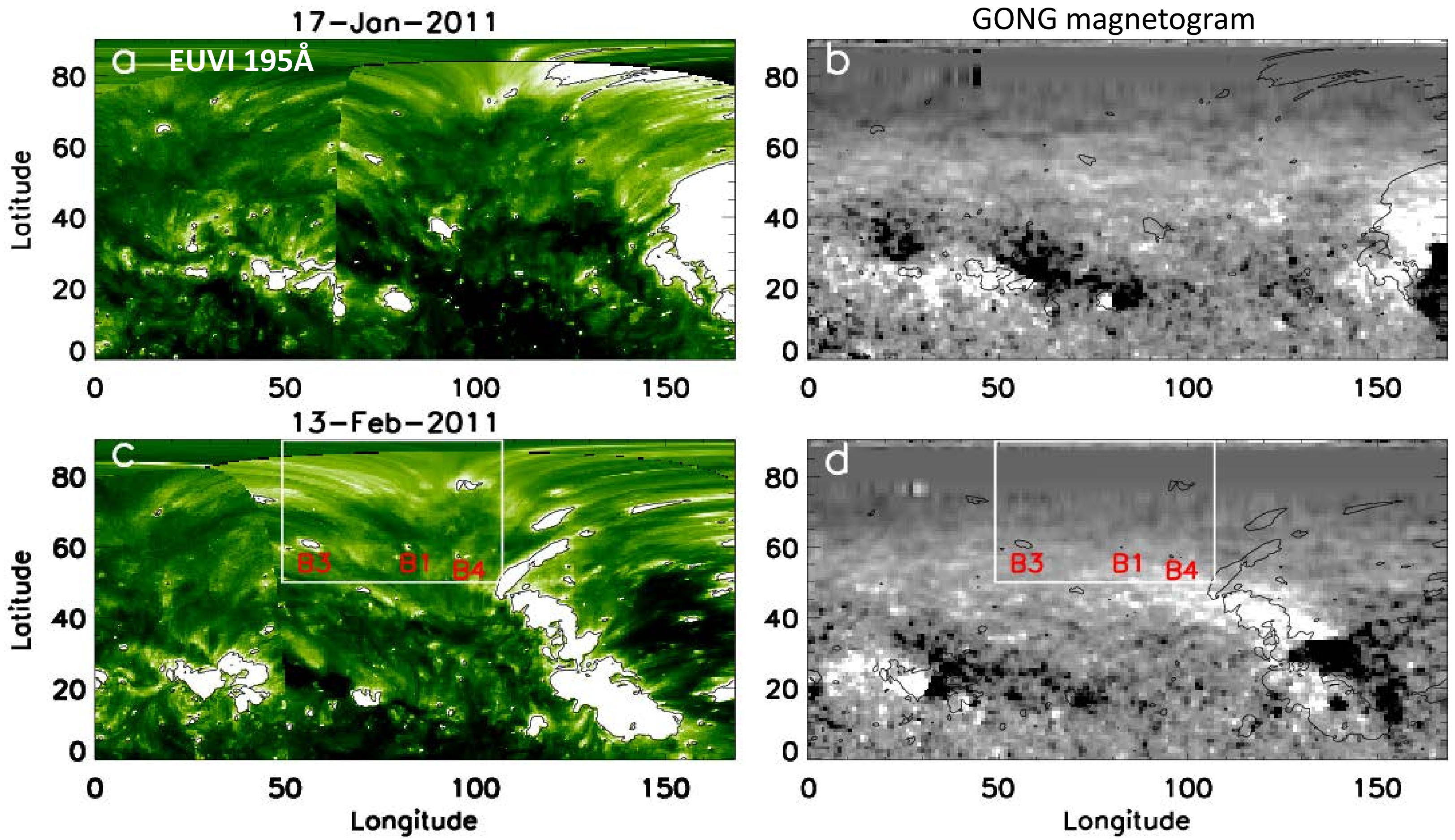
- Continuous flux cancelation at the neutral line of the filaments often triggers their eruptions. This corresponds to the finding that persistent flux cancelation at the neutral is the cause of jet-producing minifilament eruptions.

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

Polar Crown Prominence Observed on 13 Feb 2011



Magnetic Field Structure



Panesar, Innes, Schmit, Tiwari, 2014, Solar Phy, 289, 2971

Prominence Tornado

- After the flare, active region field loses its free energy which results in the decrease of the magnetic pressure.

- Prominence cavity started to expand, to fill the surrounding corona.

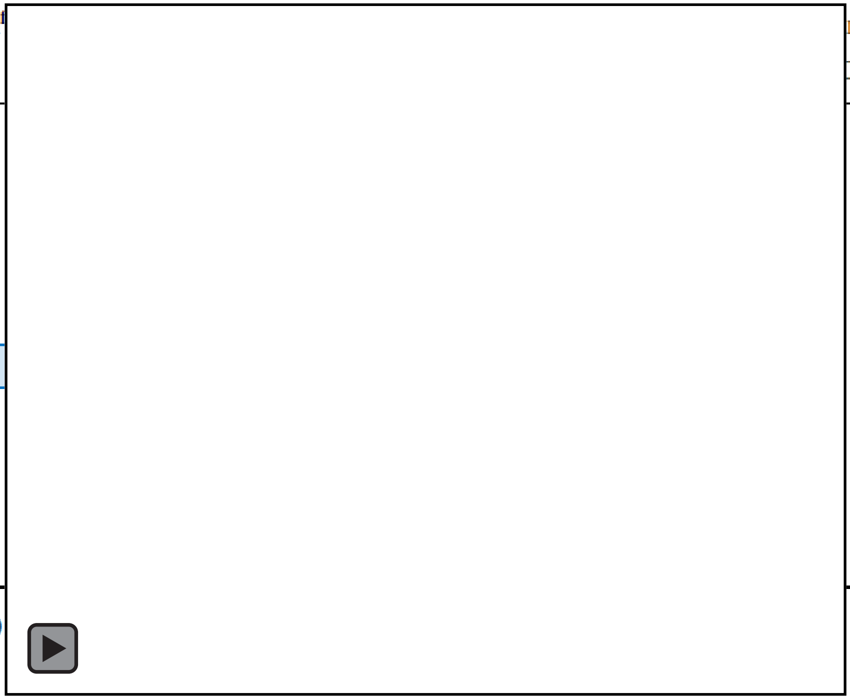
- The expansion of the cavity is clearly associated with the rise of the prominence and the appearance of the tornado.

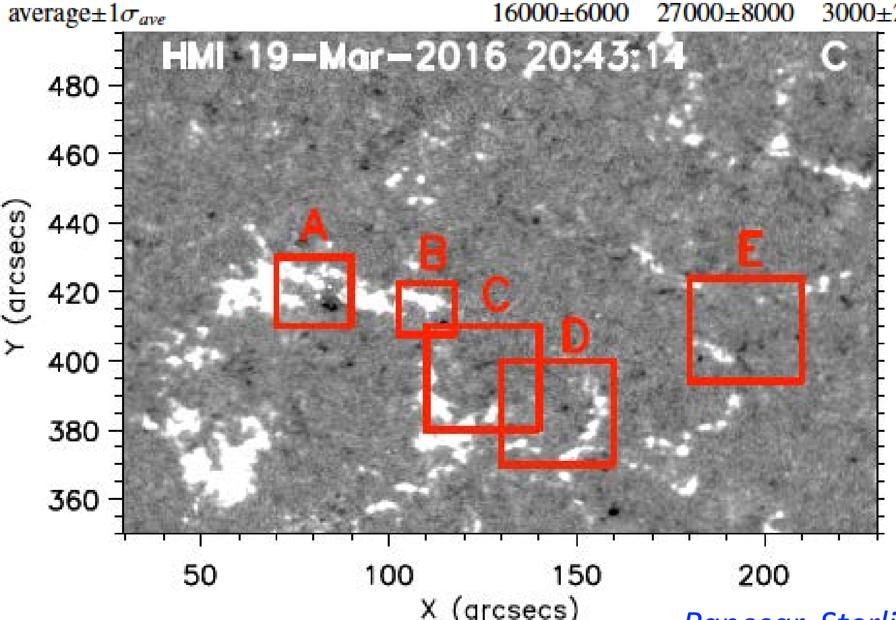
Panesar, Innes, Tiwari & Low, 2013, A&A, 549, 105

(IV) Jetlets

IRIS Jetlets: We find 10 jetlets in a network region, at five different locations.

Jetlet[a] Location	No. of[b] Jetlets	Time[c] (UT)	IRIS Coverage	Spire Length[d] IRIS (km)	Spire Length[e] AIA (km)	Spire Width[f] IRIS (km)	ncelation[l] 10^{18} Mx hr^{-1}
A	1 (A1)	22:07	No	-	11000±500	-	1.0
B	2 (B1)	13:57,	No	-	-[m]	-	-[m]
	(B2)	19:04[n]	Yes	6900±800	-	800±70	-
C	3 (C1)	16:40,	No	-	25000±2500	-	1.7
	(C2)	18:33,	Yes	19000±1000	-[o]	1300±300	
	(C3)	19:15	Yes	23000±1000	33000±1800	2100±200	
D	1 (D1)	19:15	Yes	11000±800	18000±1500	4000±300	2.6
E	3 (E1)	21:16,	Yes	16500±300	33000±3500	7000±100	0.6
	(E2)	22:37,	No	-	32000±2000	-	
	(E3)	23:14	No	-	33600±1200	-	
average±1σ_{ave}				16000±6000	27000±8000	3000±2500	1.5

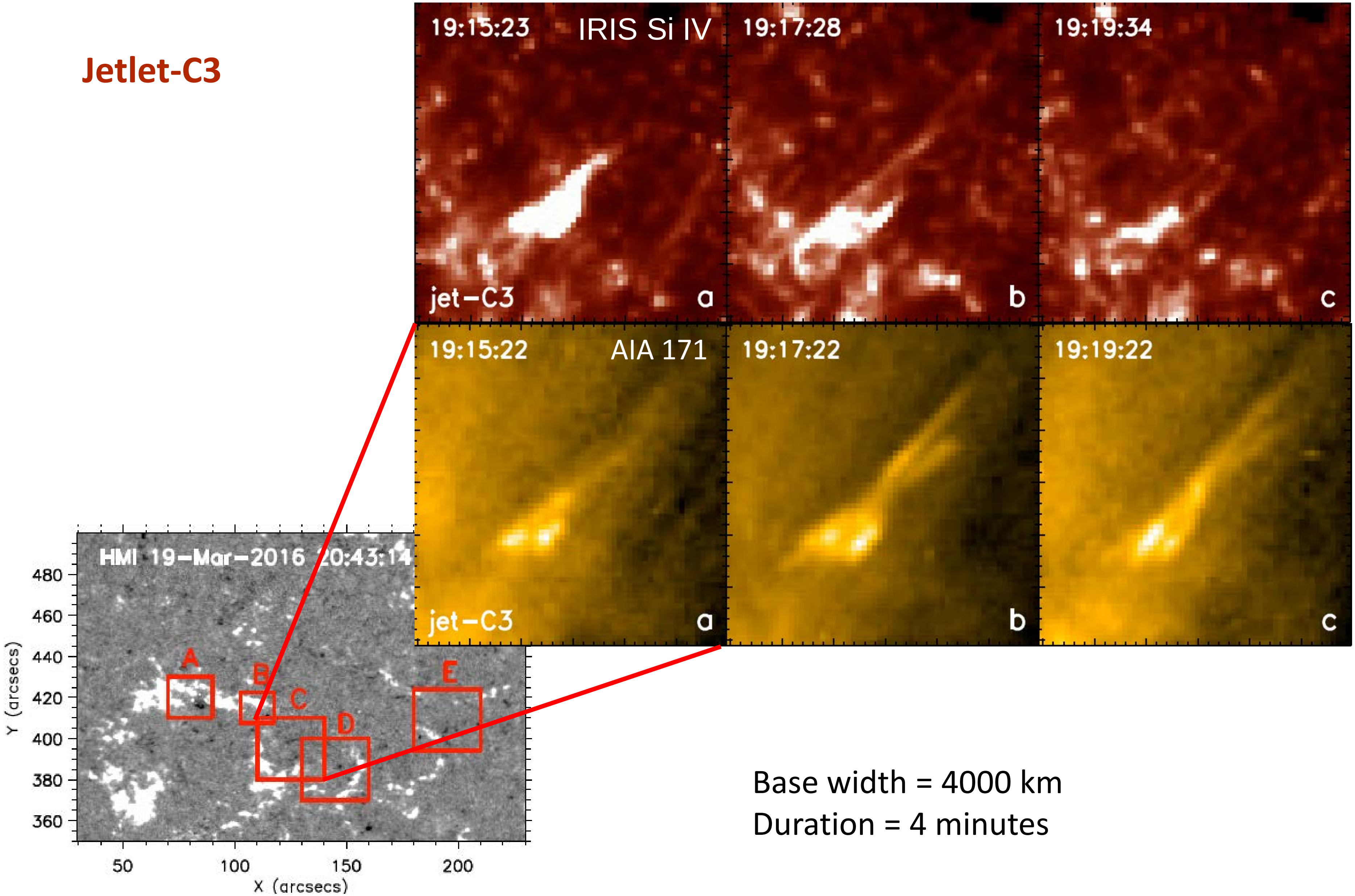




Jetlets are small-scale jets that occur at flux cancelation sites at the bases of plumes *(Raouafi & Stenborg 2014)*.

Panesar, Sterling, Moore, Tiwari, De Pontieu, Norton, 2018b, ApJ Letters, 868, 27

Jetlet-C3



Base width = 4000 km
Duration = 4 minutes

Panesar, Sterling, Moore, Tiwari, De Pontieu, Norton, 2018b, ApJ Letters, 868, 27

Jetlet-C3

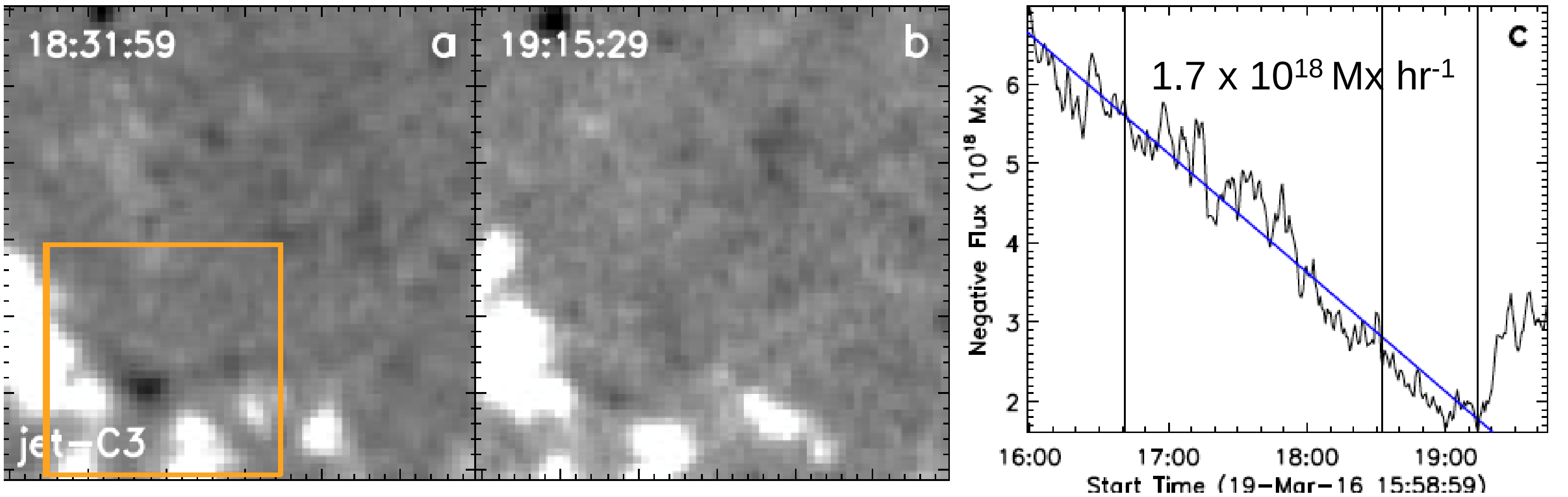
IRIS Si IV

AIA 171

HMI

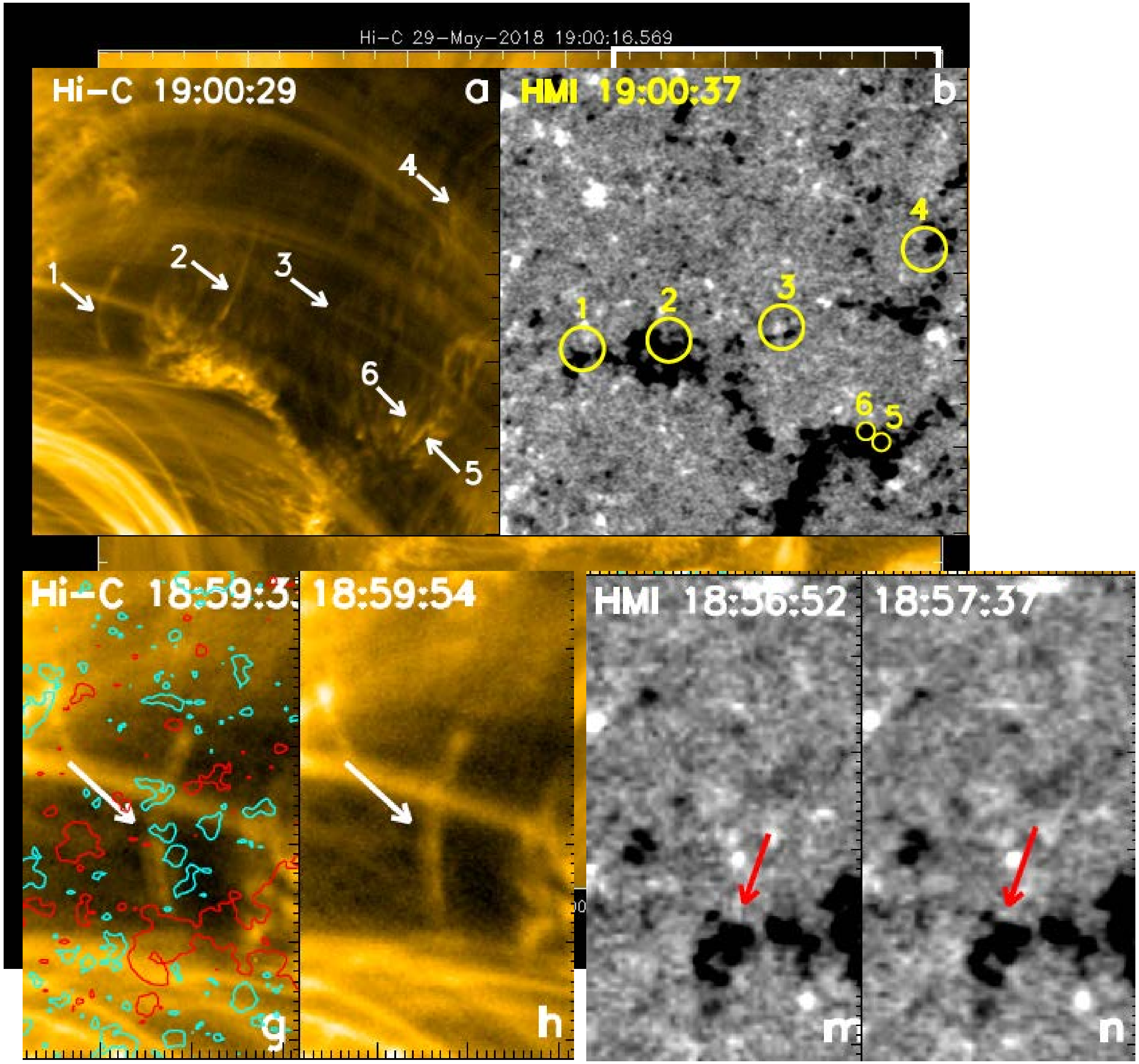
- We find three jetlet eruptions from the same neutral line due to continuous flux cancelation. Minifilaments in homologous coronal jets have also been observed to erupt and reform at the same neutral line due to flux cancelation (*Panesar et al. 2017*).

Flux cancelation leading to Jetlets



- We find that jetlets occur at many locations along the edges of network lanes (not limited to the base of plumes).
- The average jetlet-base width (4000 km) three to four times smaller than for coronal jets in quiet regions and corona holes.
- The average flux cancelation rate is 1.5×10^{18} Mx hr^{-1}.

Hi-C Jetlets



The Hi-C jetlets, on average, are at least six times smaller in spire length and three times smaller in spire width than the spire length (27,000 ± 8000 km) and spire width (3200 ± 200 km) of the IRIS jetlets.

The observed spicule widths are similar to spicule widths (≤400 km) of *Sterling 2000, De Pontieu et al 2007 and Tian et al 2014.*

Panesar et al 2019, ApJ, in prep

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 and jetlets.

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

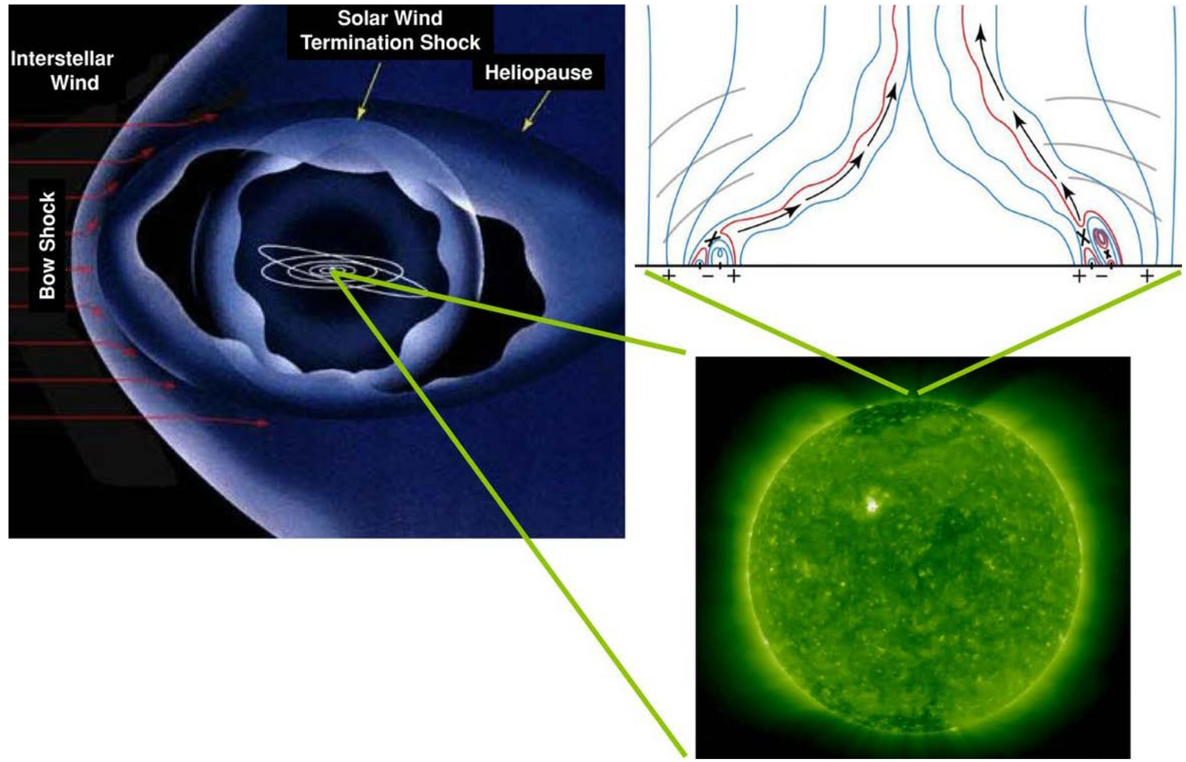
- All the jet-producing eruptions are similar to typical solar flare eruptions, where a solar flare arcade forms during the filament eruption along the neutral line along which the filament resided prior to its eruption.

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

- Solar wind escapes along the open coronal magnetic field lines, mainly from coronal holes (e.g. *Zirker 1977*).

- Many researchers think that the main source of heating in quiet regions and coronal holes is small-scale eruptions (e.g. coronal jets, jetlets, spicules) that are triggered by magnetic activity.

- All of these jets in aggregate might have enough power to drive the coronal heating and the solar wind.



Moore et. al 2011, ApJ, 731, L18

Teaching Interests

I did teaching for Bachelor students (BSc) at Gottingen University in Winter semester 2012-13: '**Thermodynamics and Statistical Physics**'.

In summer semester 2013, I gave a course on '**Morphology of Galaxies**' to Master students in Gottingen University.

I have mentored 6 REU students and 2- high school summer students, at UAH/MSFC, on different research projects, which have resulted in to 3 research publications.

I have given a number of guest lectures to master and graduate students as part of their courses at the CSPAR, UAH and also to the students of REU program, Space Weather Camp and Space Science Course at CSPAR, UAH.

I will give/contribute to the following two graduate level courses:

(i) **Introduction to the Sun**; that includes lectures on the different layers of the Sun and solar features and their dynamics.

(ii) Space weather course; it will include the formation and eruption mechanisms of CME-producing eruptions that drives space weather, and the basics of the solar wind. I am also happy to collaborate to give joint courses (e.g. on space weather, heliopshere) with the faculty members of the Department of Space Science at UAH.

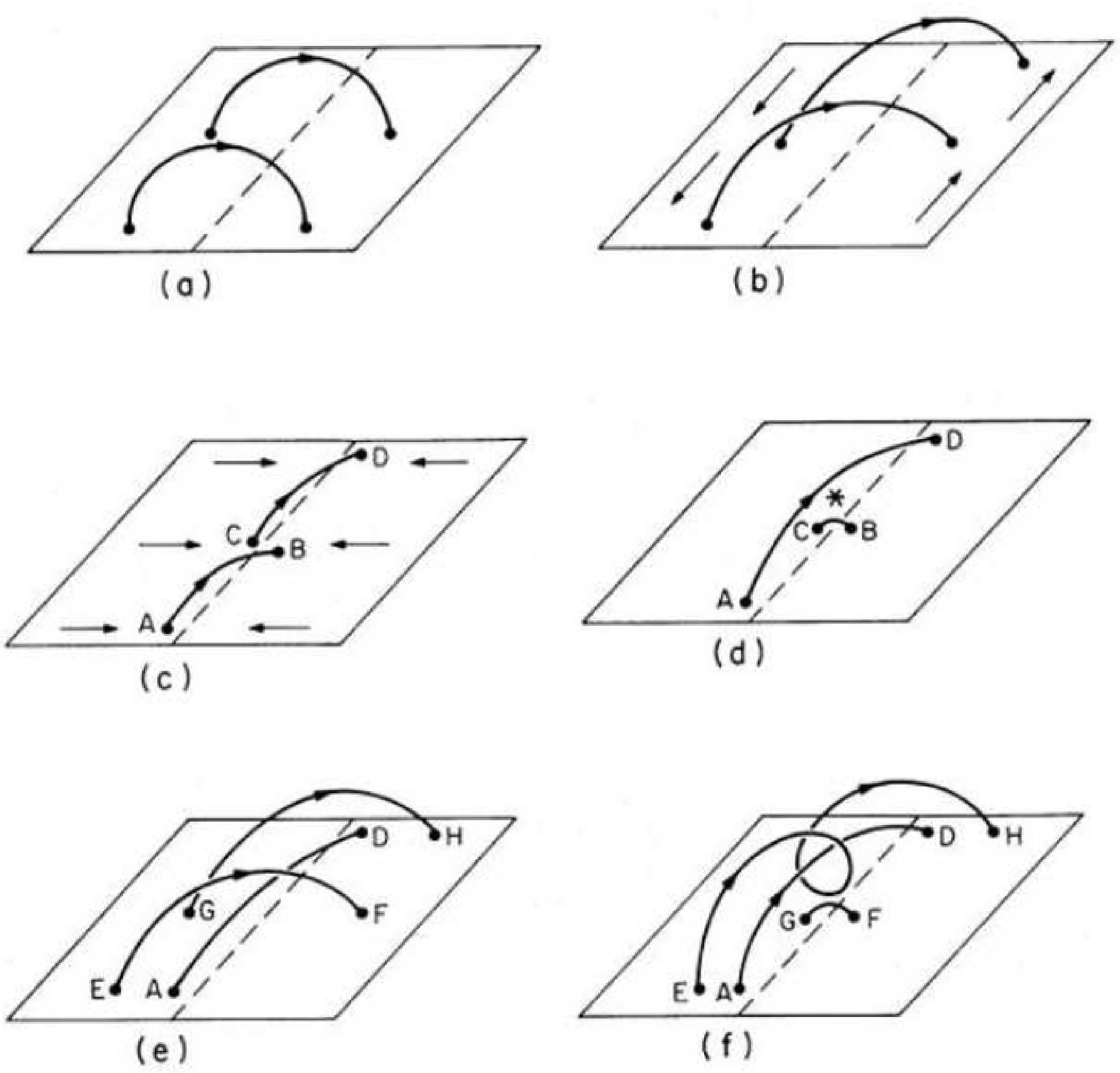
Magnetic properties of coronal jets and CME-producing active regions

Objects	Study	Cancel Rate (10^{18} Mx hr^{-1})	Canceled amount[a] (10^{18} Mx)	Percentage	Energy (erg)
CH Jets	Pucci et al. (2013)	…[b]	…[b]	…[b]	10^{26}–10^{27}
CH Jets	Panesar et al. (2018)	0.6	0.5–2.0	45 ± 16[c]	…[b]
QS Jets	Panesar et al. (2016a)	1.5[d]	0.9–4.0	37 ± 13[e]	…[b]
QS and AR Jets[f]	Shimojo & Shibata (2000)	…[b]	…[b]	…[b]	10^{27}–10^{29}
AR Jets	Sterling et al. (2017)	15	5	—	10^{28}–10^{29}
2013 Oct 20	This paper, Section 4	13	390	29 ± 3[g]	$\sim10^{30}$–10^{31}
2010 Jul 16	This paper, Section 5	4	420	51 ± 3[g]	$\sim10^{30}$–10^{31}

Sterling, Moore, Panesar, 2018, ApJ, 864, 68

Flux rope model

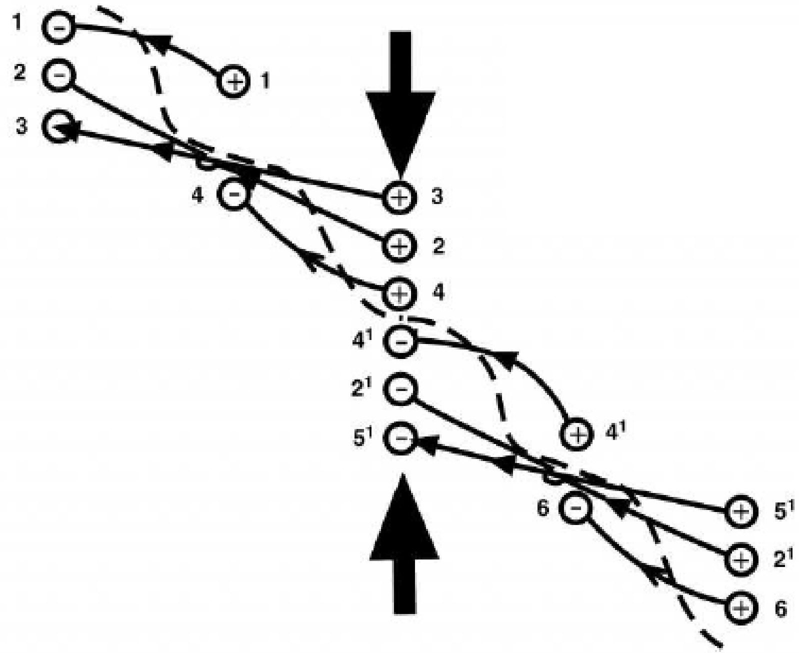
- Footpoints get displaced along the PIL due to the differential rotation of the Sun.
- Footpints come closer, due to the flux convergence at the PIL.
- Reconnection at the footpoints lead to the formation of longer helical field lines which carried the prominence plasma.

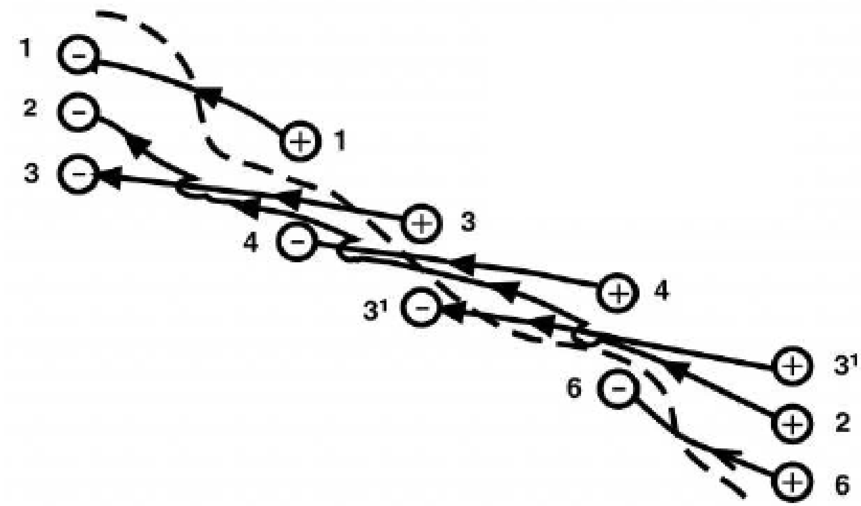


van Ballegooijen and Martens (1989)

Jet No	Date (UT)	Time[a]	Flare class	CME Speed[b,c] (km s^{-1})	CME Angular width (°)	Jet Speed[d] (km s^{-1})	Jet Rise Dur. (± 5 min)	Jet Width[e] (± 1500 km)	Remote Bri.& Dim.
a) CME-producing Jets:									
J1	20-Oct-14	18:43	C6.2	187	40	190 ± 10	20	34000	Yes
J2	22-Oct-14	16:52	C5.8	281	20	310 ± 20	30	38000	Yes
J3	23-Oct-14	19:11	C3.3	239	35	330 ± 20	50	26000	No
J4	24-Oct-14	03:56	C3.6	250	30	300 ± 20	45	34000	Yes
J5	24-Oct-14	07:37	M4.0	677	50	400 ± 40	35	86000	Yes
J6	27-Oct-14	17:33	M1.4	186	25	ambiguous[f]	-	-	-[g]
b) Non-CME-producing Jets:									
J8	22-Oct-14	02:31	-	-	-	75 ± 10	35	19000	-
J9	22-Oct-14	05:51	-	-	-	120 ± 20	10	15000	-
J10	22-Oct-14	10:46	C1.9	-	-	140 ± 20	15	11000	-
J11	22-Oct-14	12:56	-	-	-	50 ± 10	20	16500	-
J12	22-Oct-14	17:30	C3.0	-	-	ambiguous[h]	10	13000	-
J13	22-Oct-14	20:11	C3.0	-	-	150 ± 20	10	16000	-
J14	22-Oct-14	23:15	C1.1	-	-	110 ± 10	25	13000	-

Flux Linkage Model





- 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)