

What Are the Outstanding Issues with Coronal Jets?

Alphonse C. Sterling

Main Additional Contributions:

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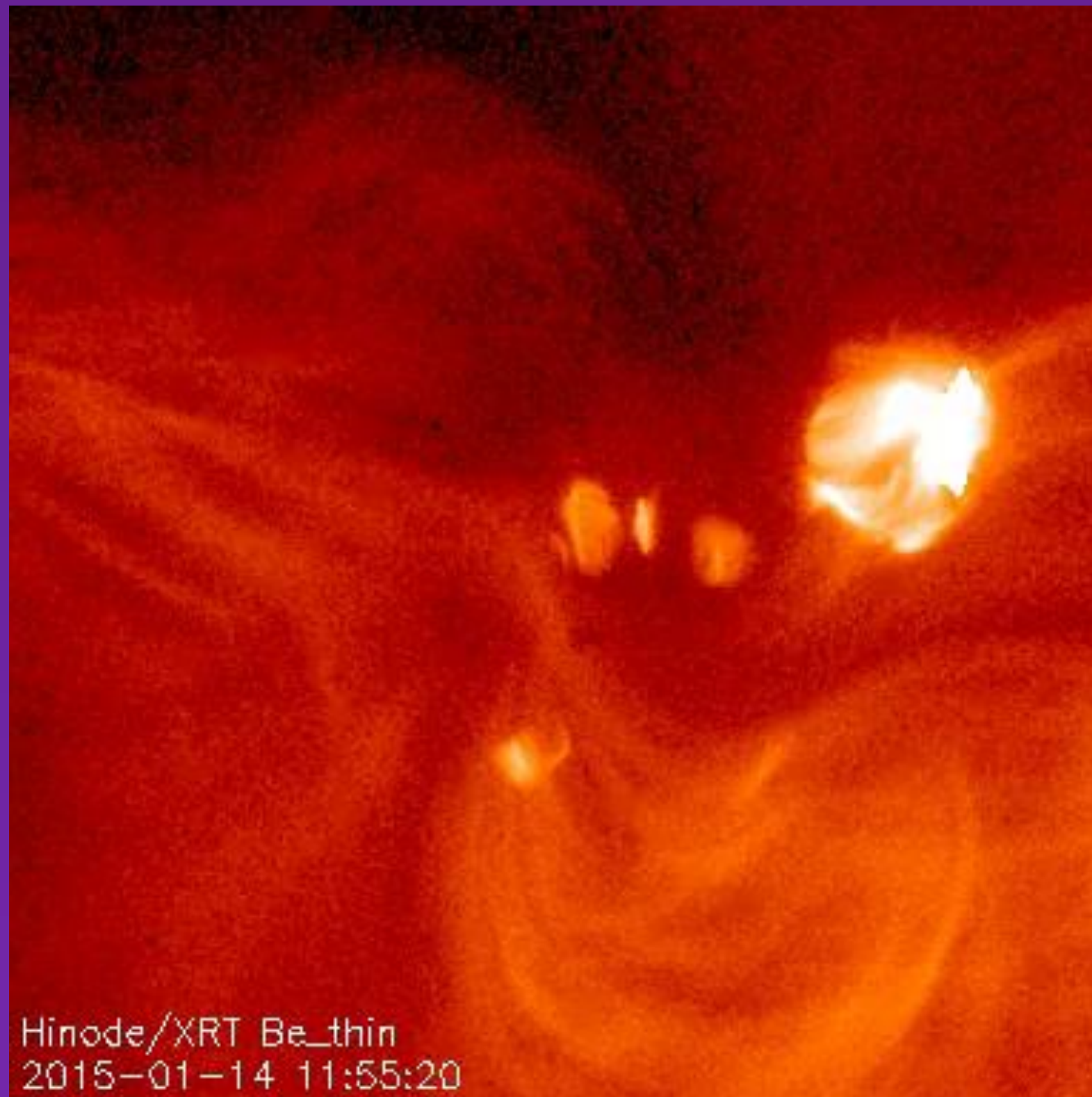
Supported by NASA's HGI program, NASA NPP
program, and the MSFC/Hinode project.)

Wed Jan 10 16:13:36 2007



SAO /NASA/JAXA/NAOJ

Cirtain et al. (2007)



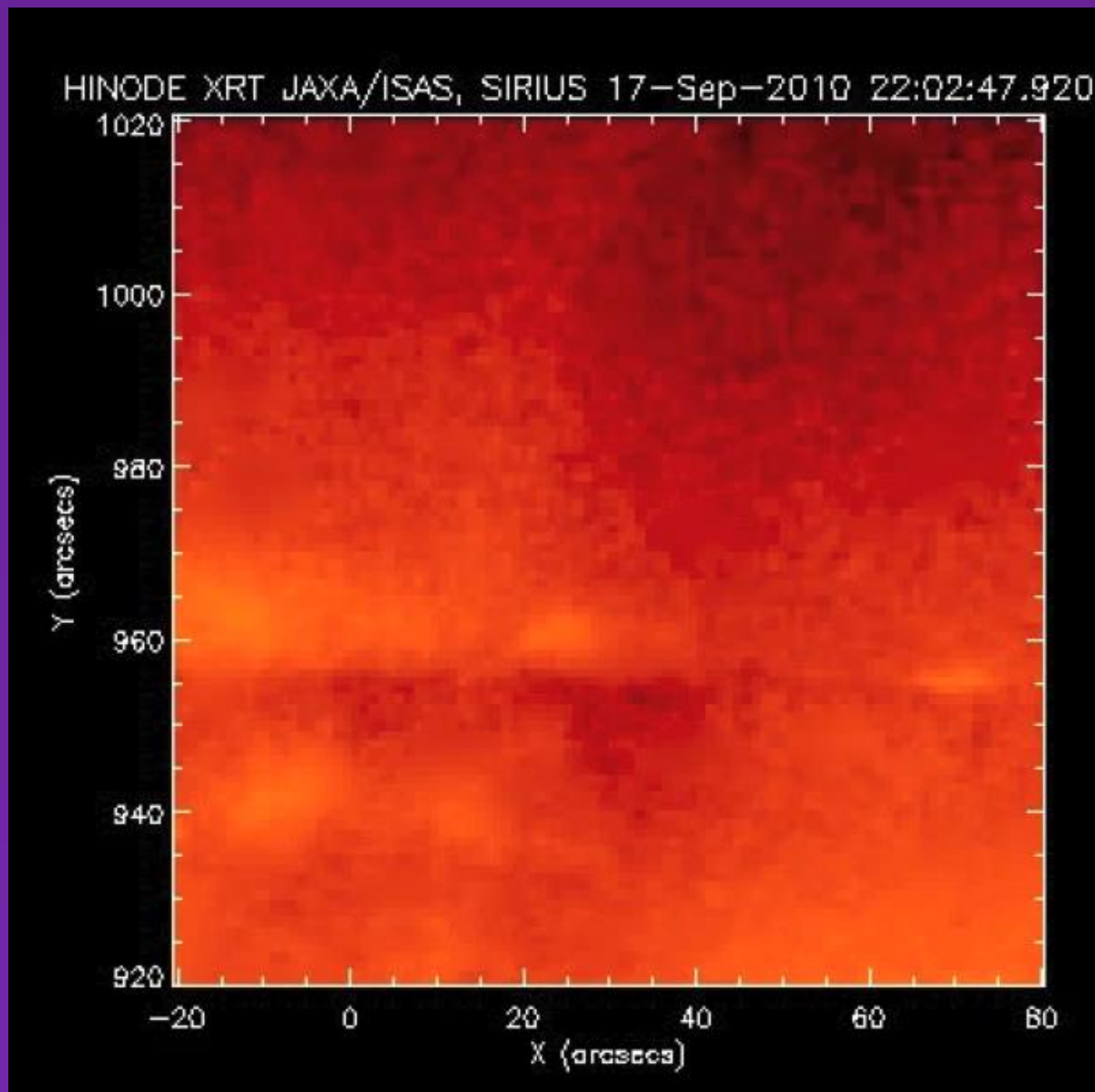
Sterling et al. (2017)

Introduction: Solar X-Ray Jets

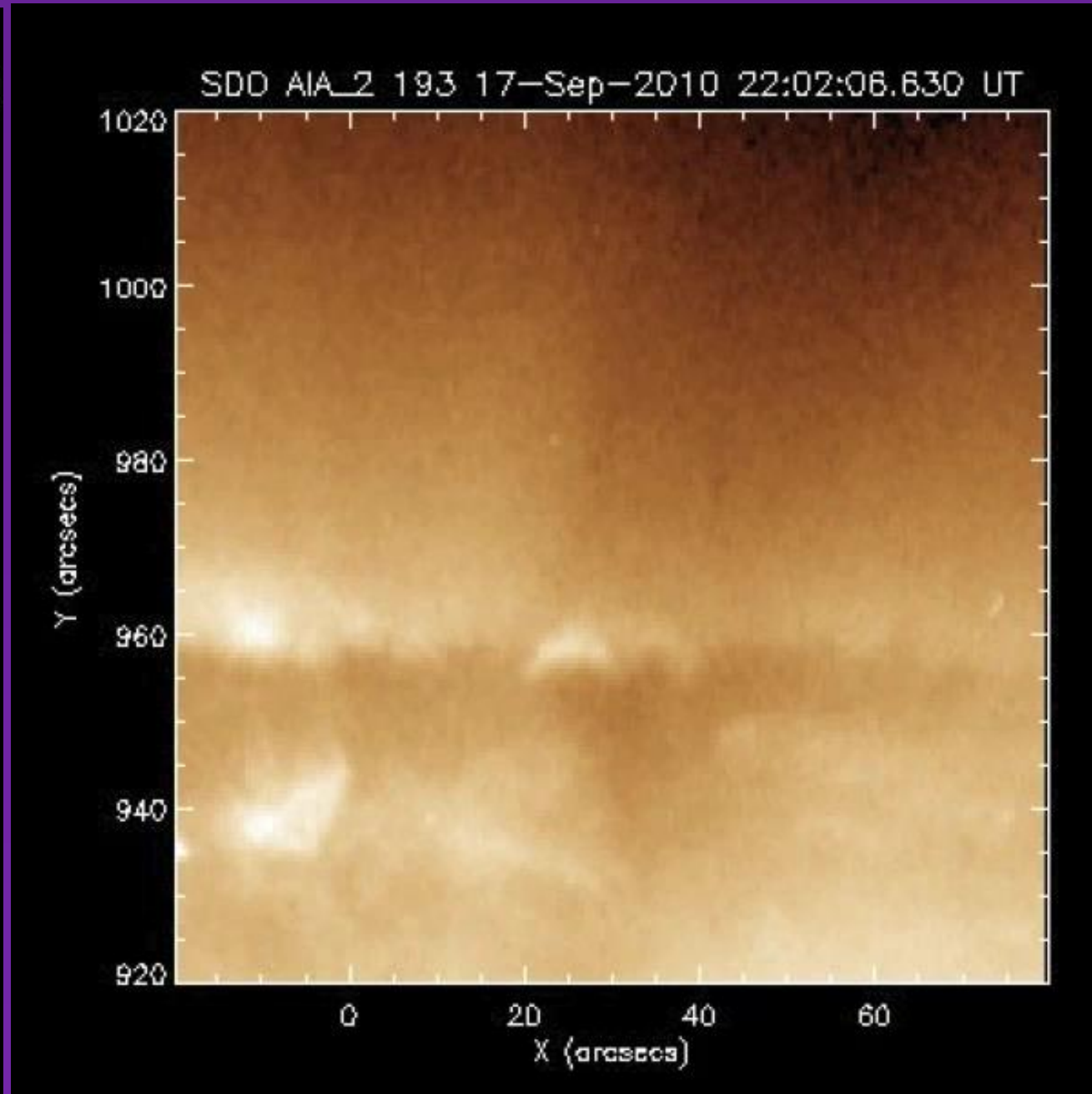
- ♦ Observed since the Yohkoh days (Shibata et al. 1992; also Shimojo et al. 1996, etc. Reviewed by Raouafi et al. 2016.)
- ♦ Yohkoh (SXT) saw them mainly in active regions.
- ♦ Hinode/XRT found them to be plentiful in polar coronal holes (Cirtain et al. 2007; also Savcheva et al. 2007, etc.)
- ♦ In polar coronal holes: size $\sim 50,000$ km x 8000 km; rate ~ 60 /day (Savcheva et al. 2007).
- ♦ Often have a “hot loop” at the jet’s base.
- ♦ Previously often-discussed mechanism is based on emerging flux (“emerging-flux model”). (Shibata et al. 1992; see also Moore et al. 2010.)
- ♦ Many of the above ideas deduced from SXR, and pre-SDO AIA observations.

Coronal Hole Jets: “Minifilament eruptions”

XRT



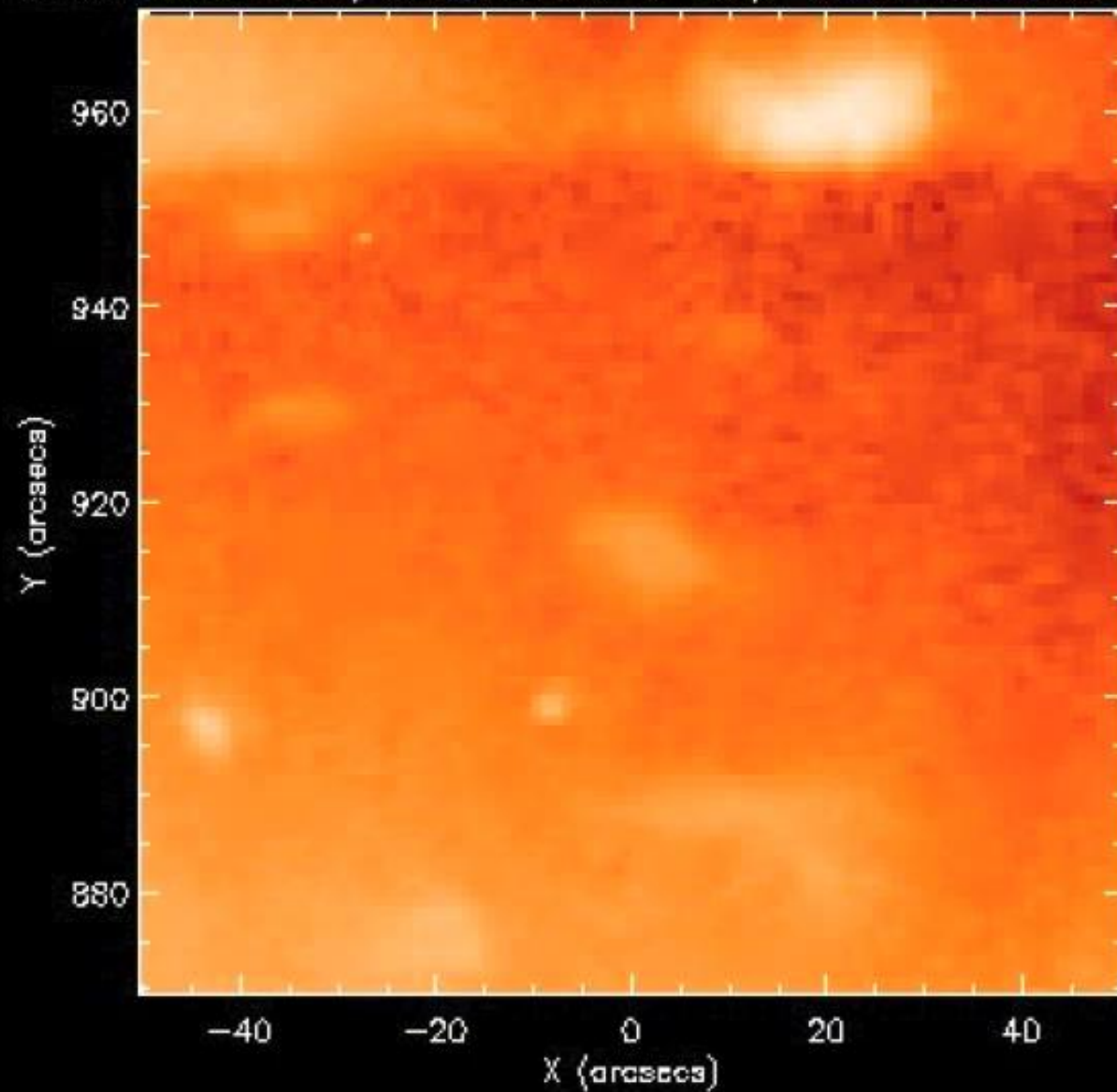
AIA 193



Sterling et al. (Nature, 2015): 20 Polar CH jets.

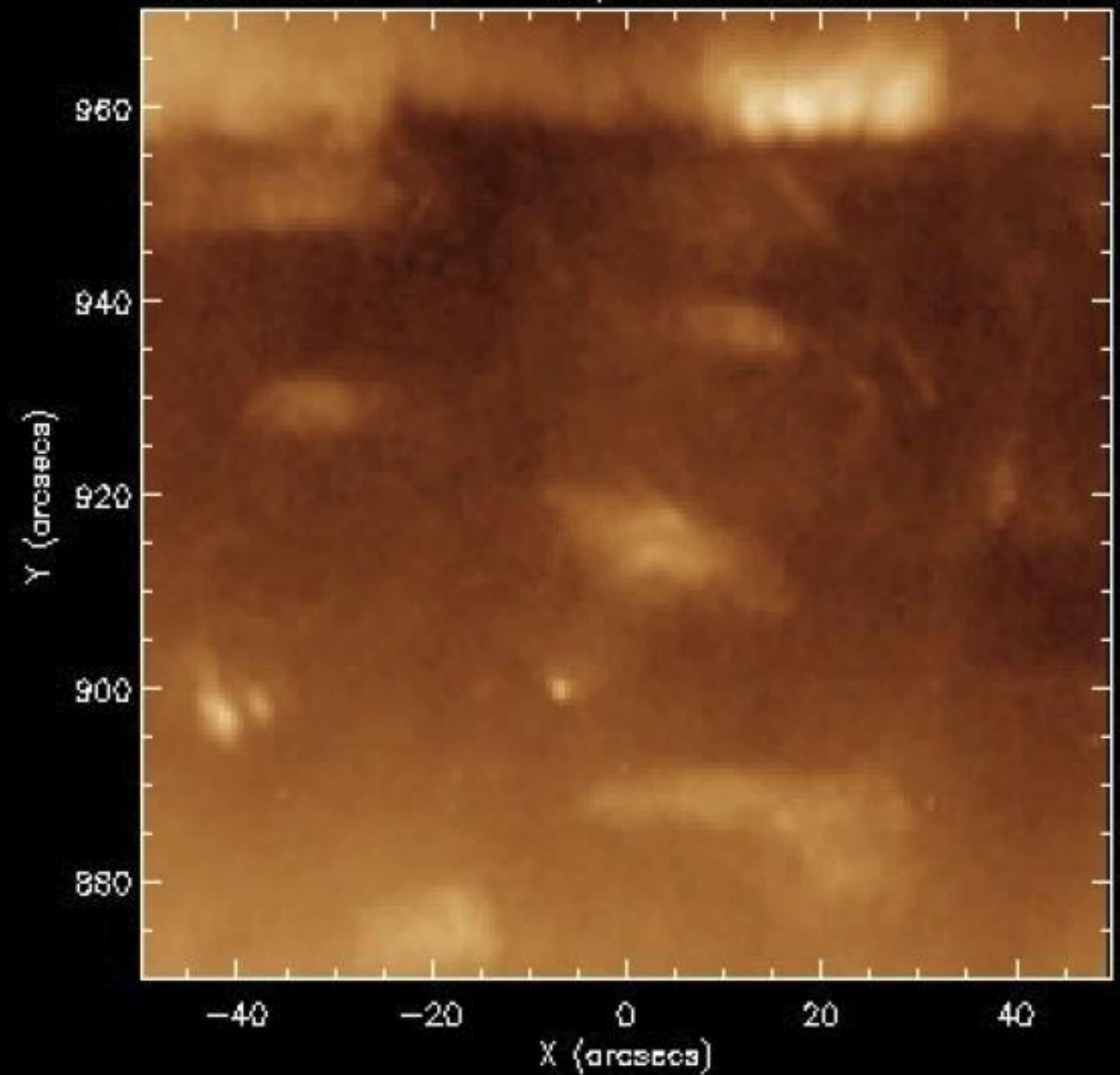
XRT

HINODE XRT JAXA/ISAS, SIRIUS 9-Sep-2010 21:50:23.471



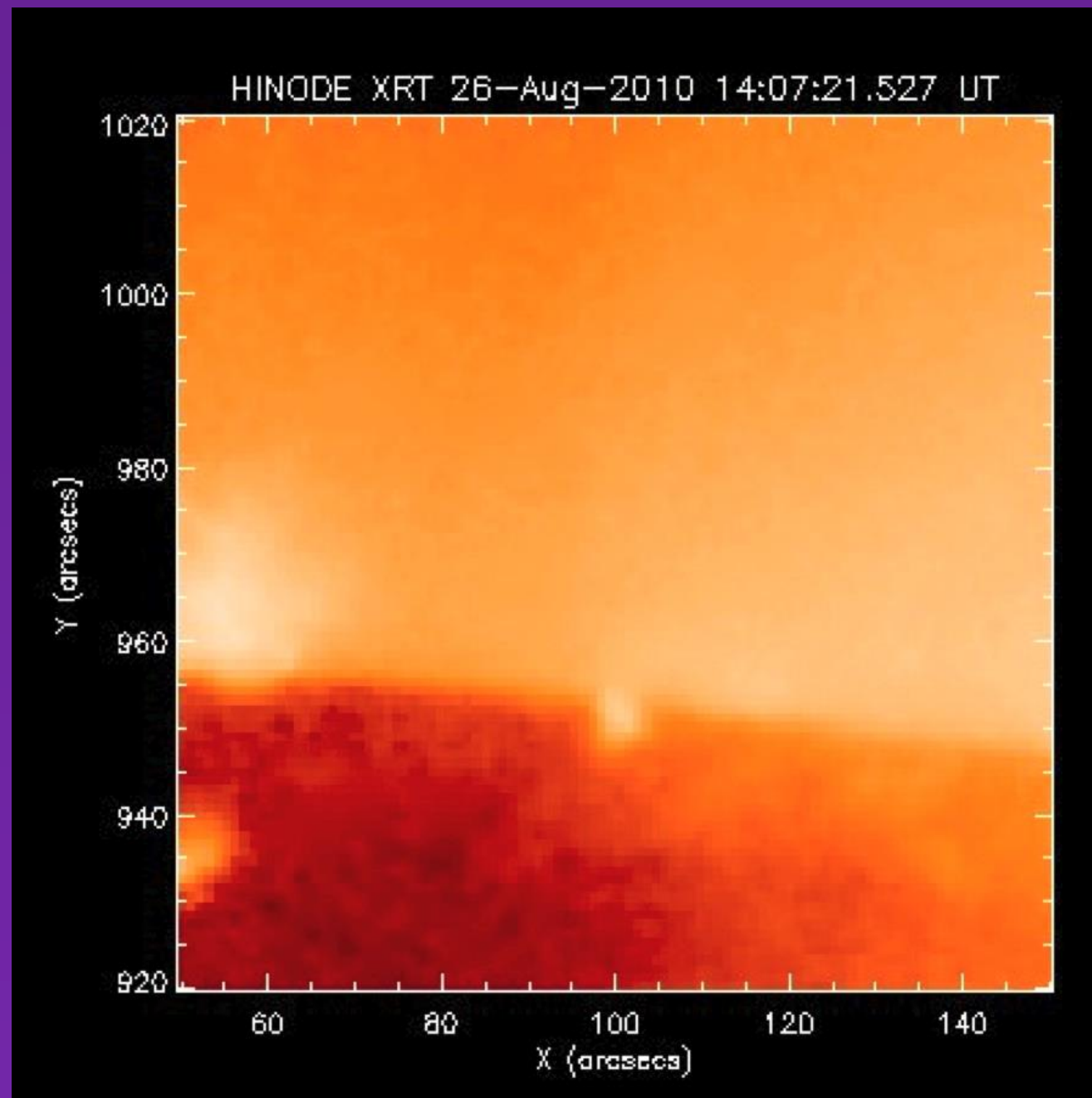
AIA 193

SDO AIA_2 193 9-Sep-2010 21:50:06.630 UT

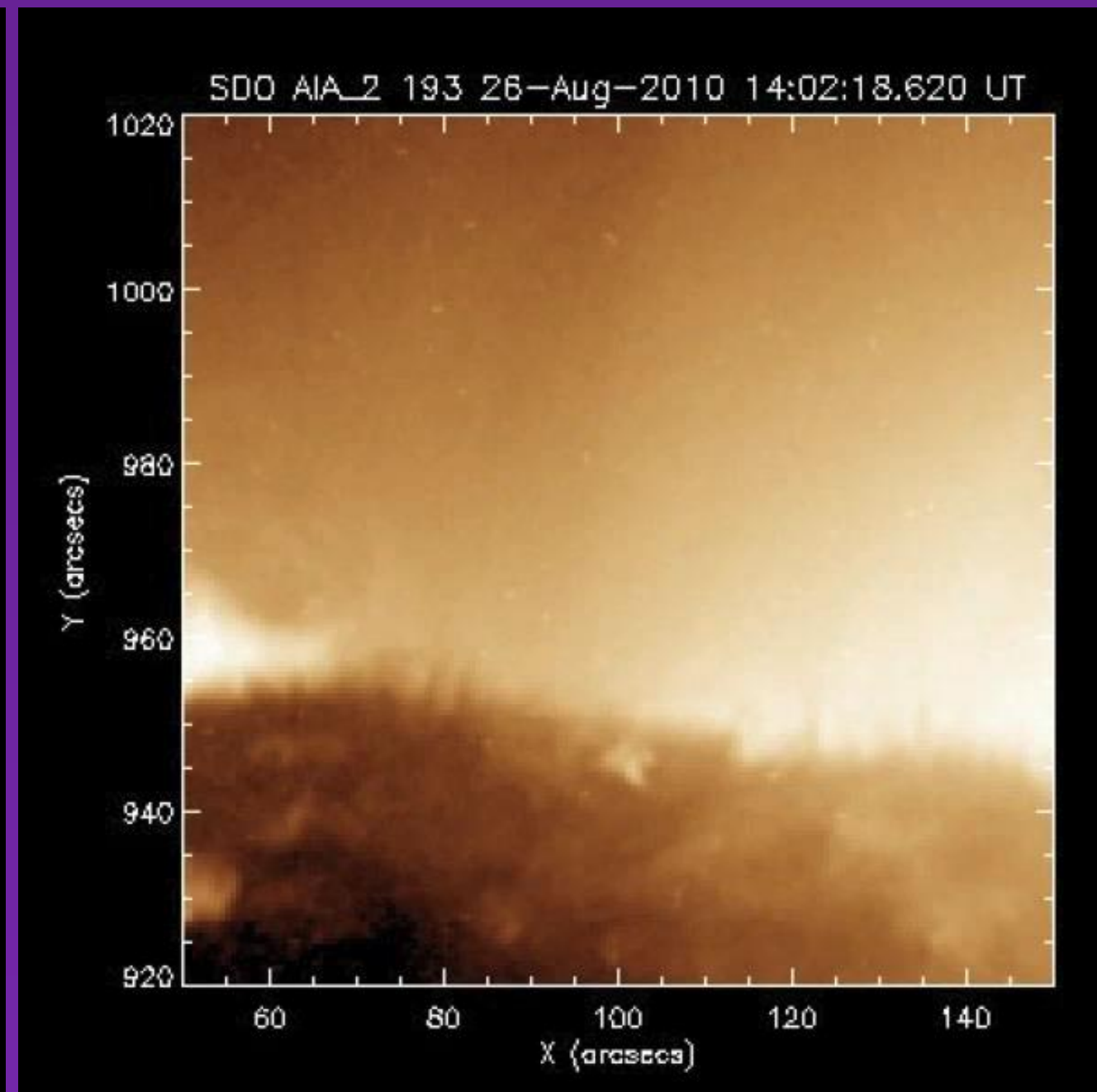


Event 12

XRT



AIA 193

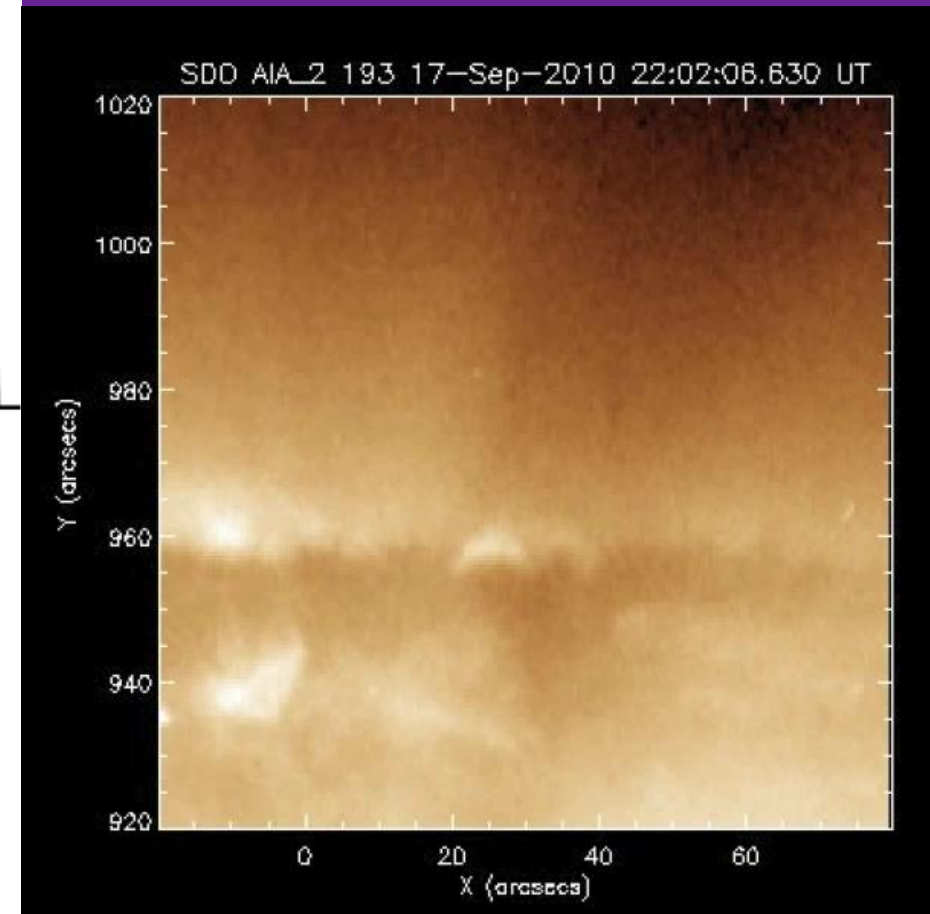
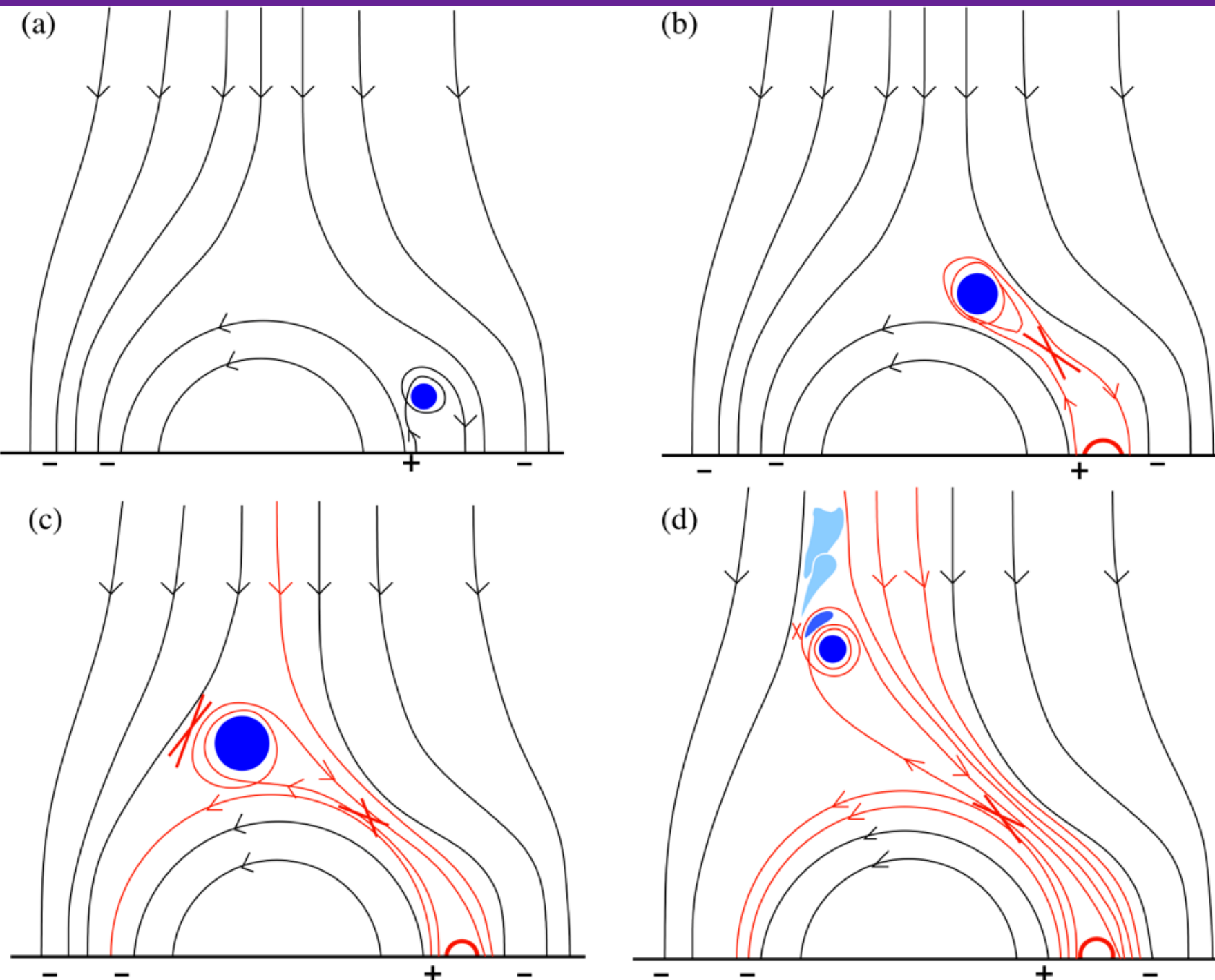


Event 3

“Normal” Filament Eruption (TRACE)



Minifilament-Eruption Model for (X-Ray) Jets



Sterling et al. (2015, 2016, 2017)

Quiet Sun jets work the same way (Panesar et al. 2016b)

Recently modeled by Wyper et al. 2017, 2018)

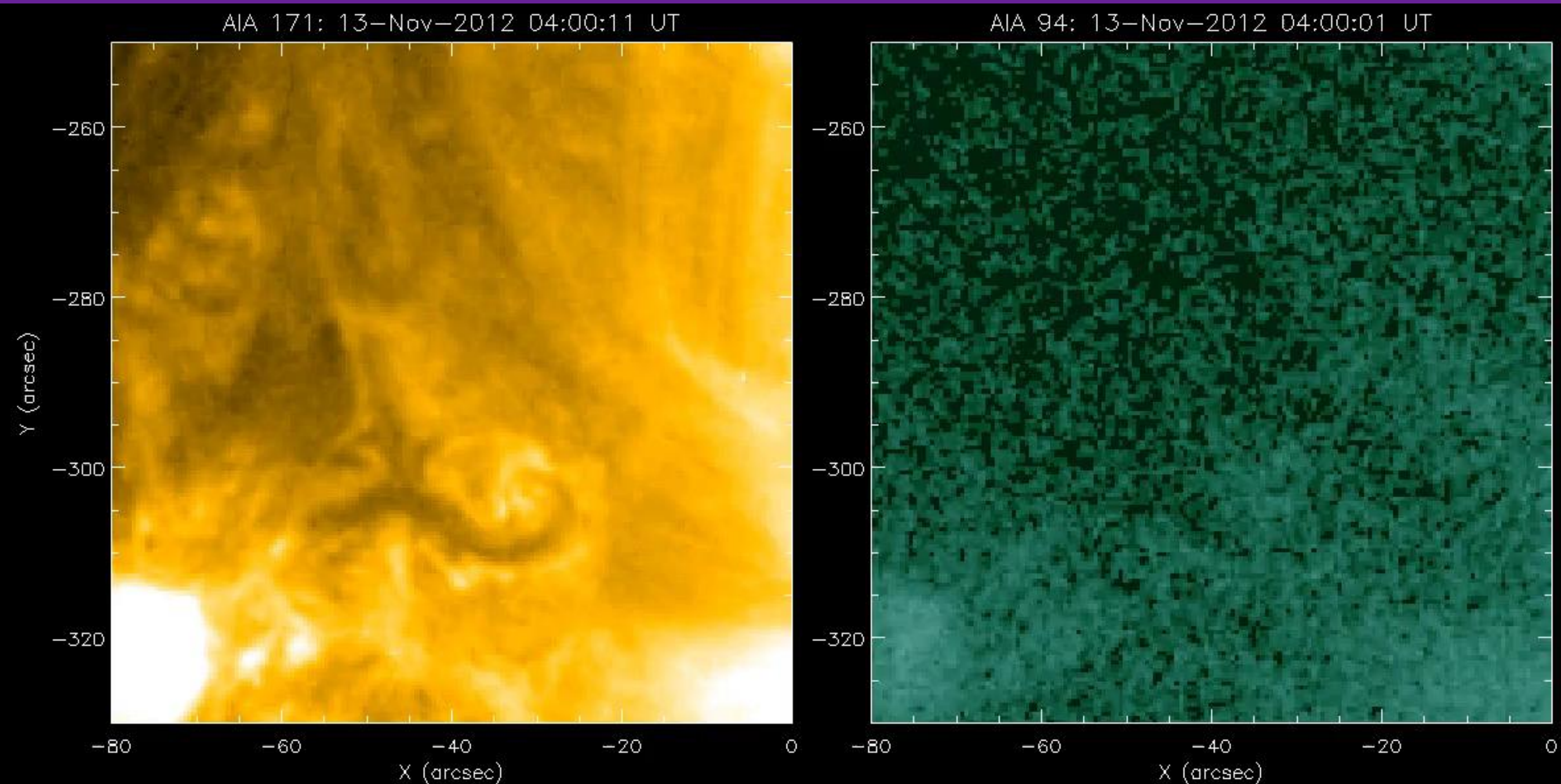
What Causes Miniature-Filament Eruptions?

- ♦ Did not look on-disk in this study, due to polar view. But....
- ♦ Adams et al. (2014) found no emerging flux in the jet region. Filament erupted from location where flux canceled.
- ♦ Several other found cancelation leading to jets (e.g., Hong et al. 2011; Huang et al. 2012; Young & Muglach 2014a,b).
- ♦ Some others found jets from location of emerging flux+flux cancelation (e.g., Liu et al. 2011, Shen et al. 2012, Hong et al. 2012, Li et al. 2015).

Quiet Sun Jets — Similar to PCH jets

AIA 171

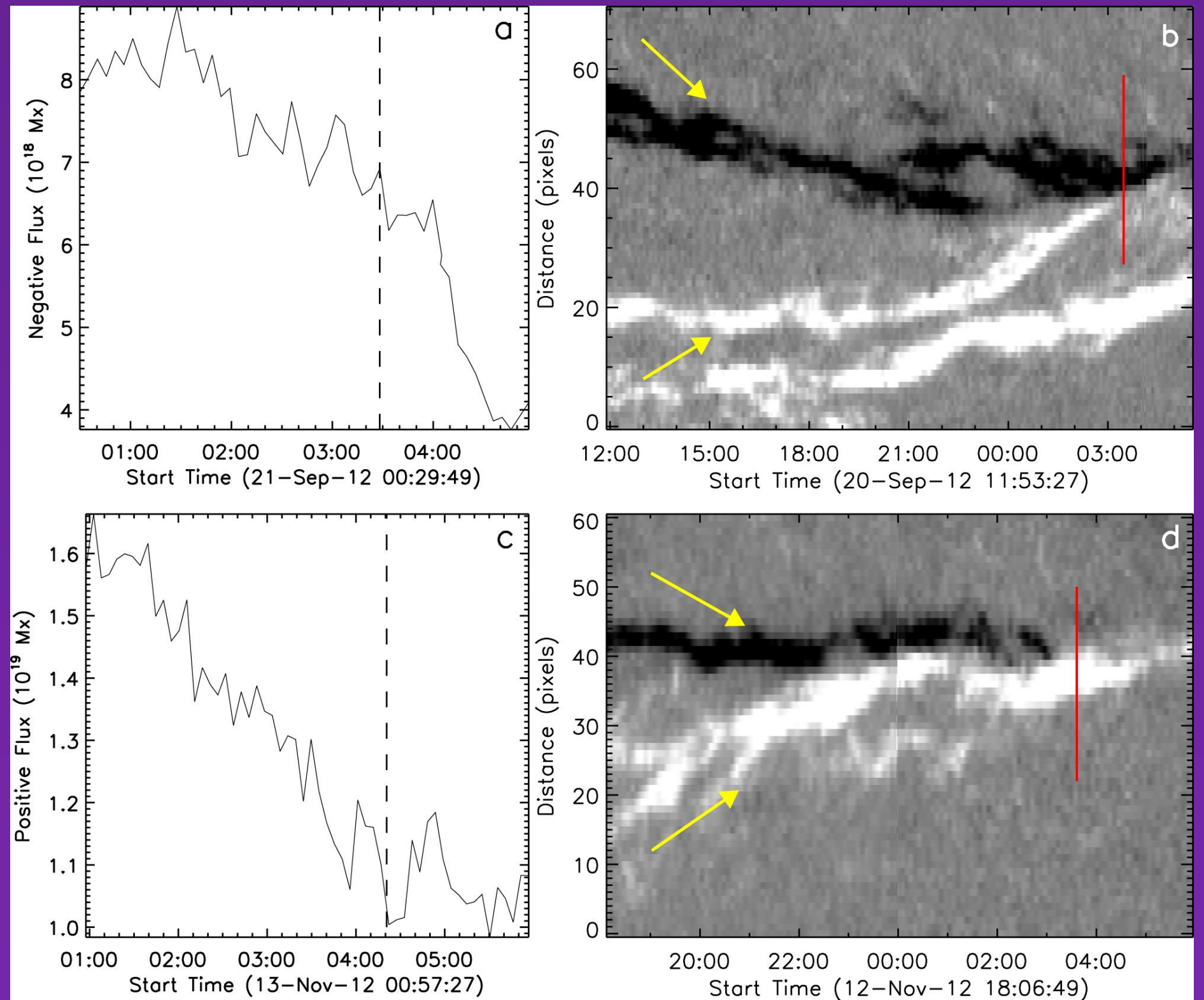
AIA 94



(Panesar et al. 2016b)

Same for QS jets: Occur at cancelation sites.

Ave. Cancelation
rate: $\sim 10^{18}$ Mx/hr.



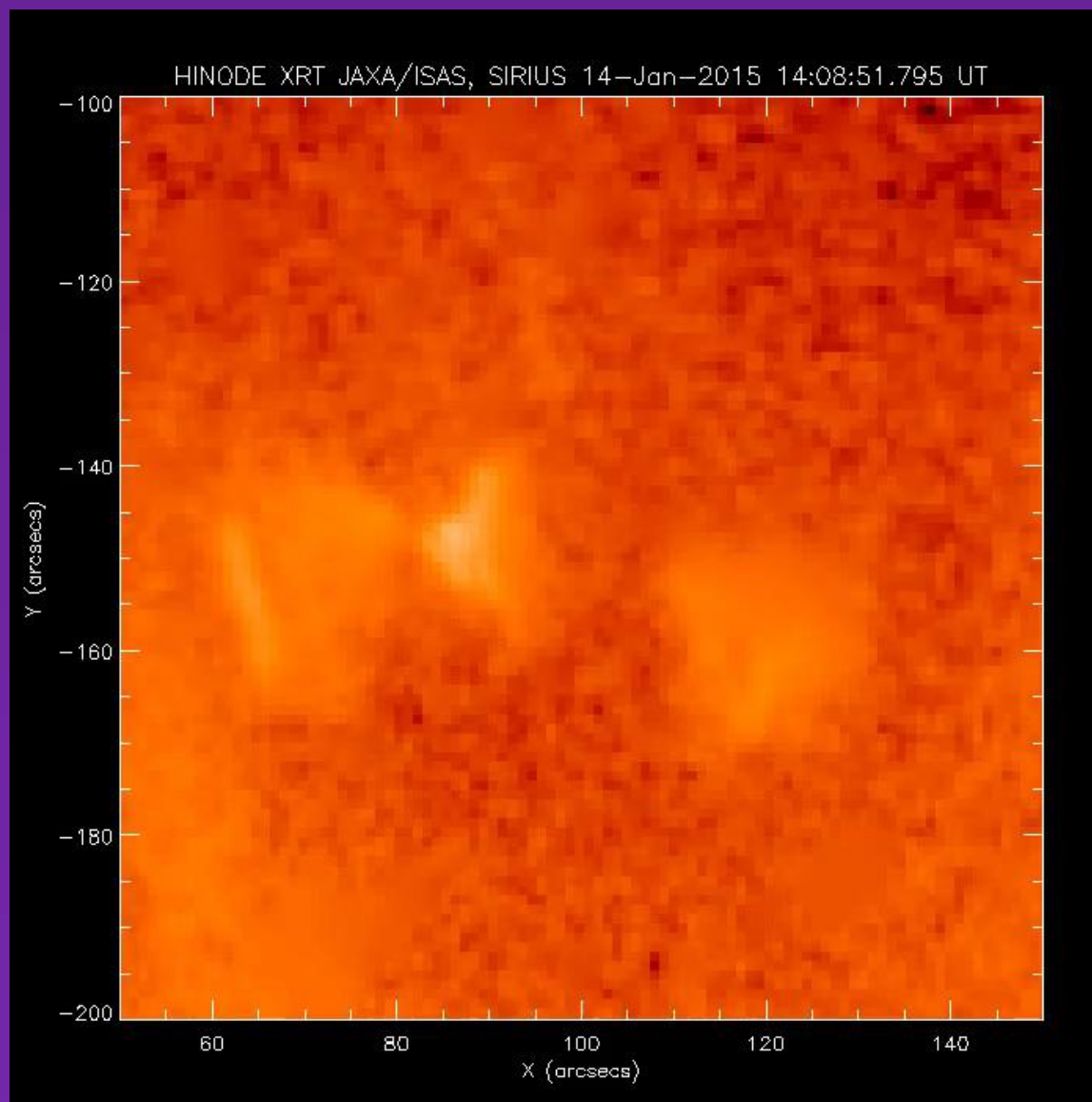
Panesar, Sterling, & Moore (2016b) — 10 jets.

Active Region Coronal Jets

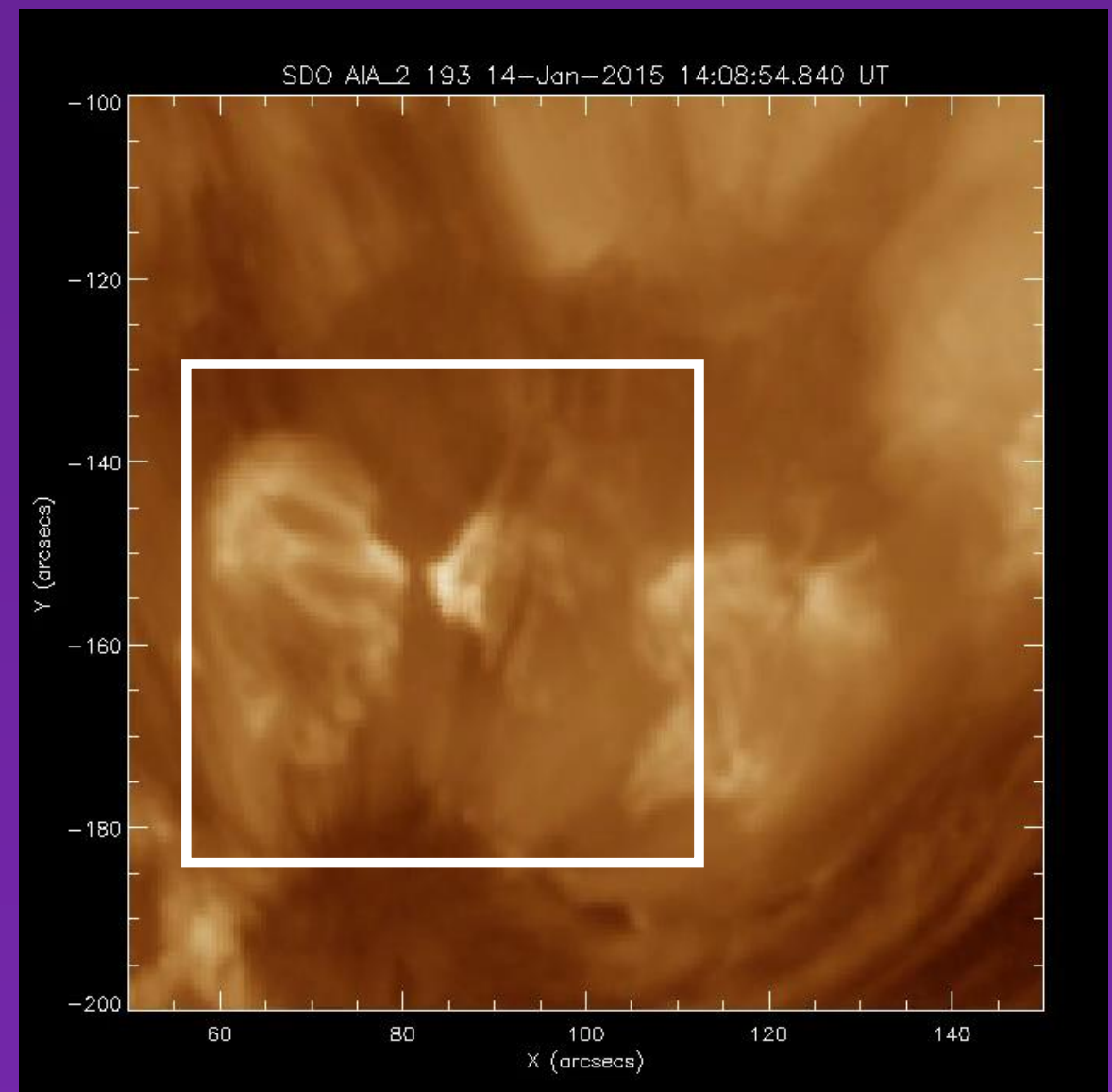
- Yohkoh studies (Shibata et al., Shimojo et al., many others).
- Raouafi et al. (2016).
- Panesar et al. (2016a).
- Sterling et al. (2016, 2017).

An Example: AR Jets

- 14 Jan 2015 (NOAA AR 12259), AIA, HMI, Hinode, IRIS.
- Sterling et al. (2017)



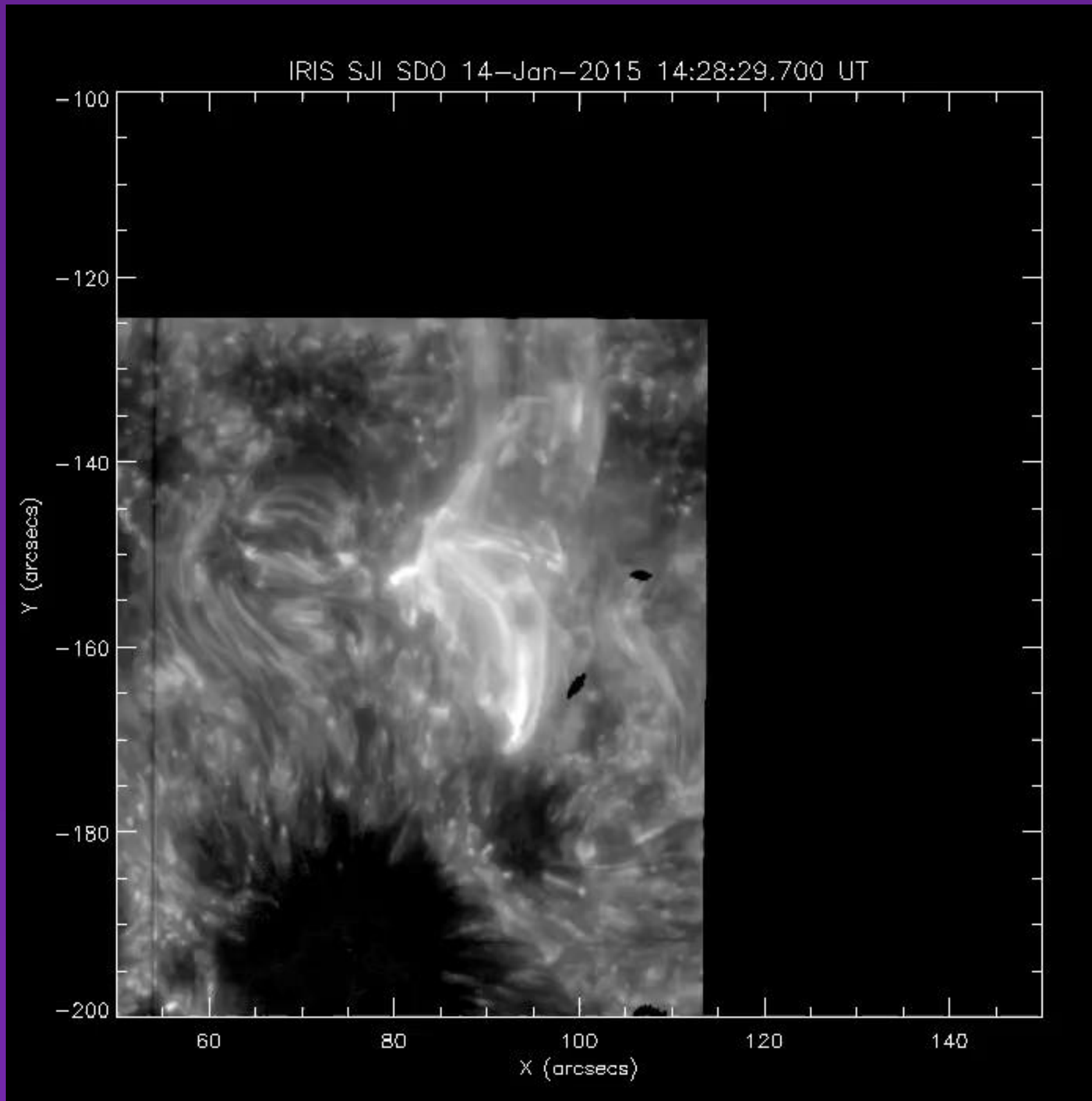
Hinode/XRT



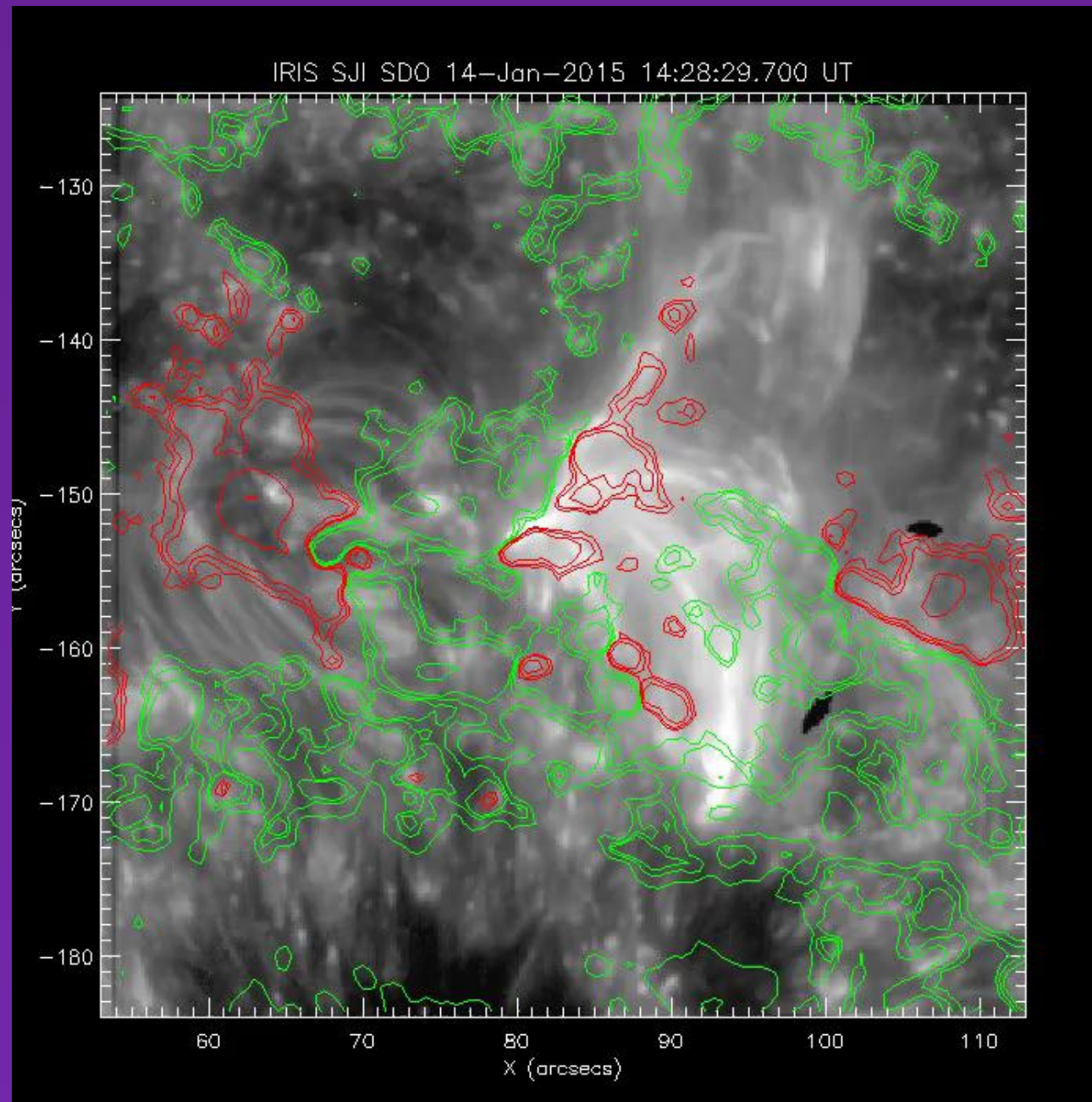
AIA 193

Minifilament hard to see (absent?). Work the same way??

IRIS 1400

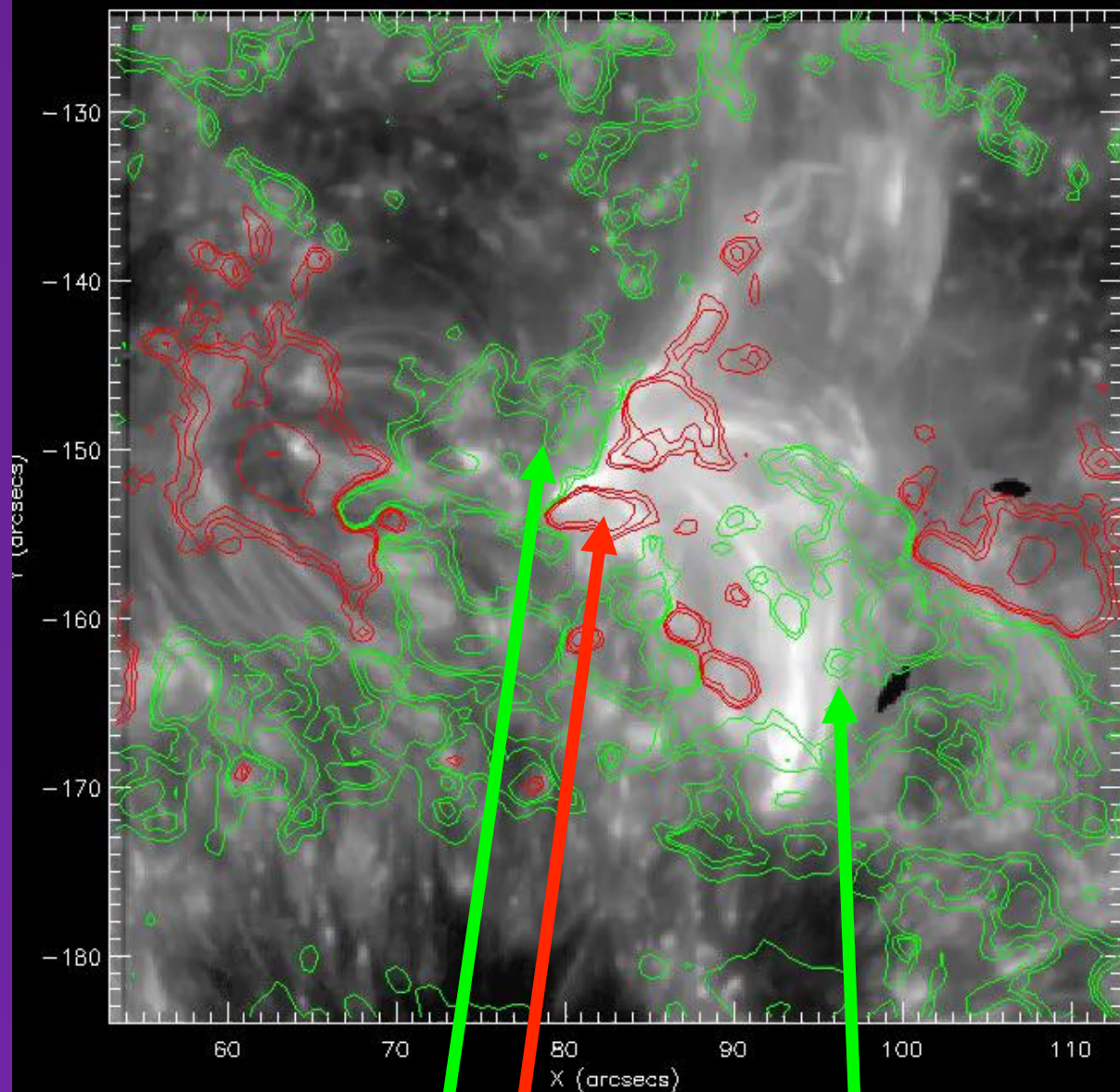


Coronal Jets in Active Regions

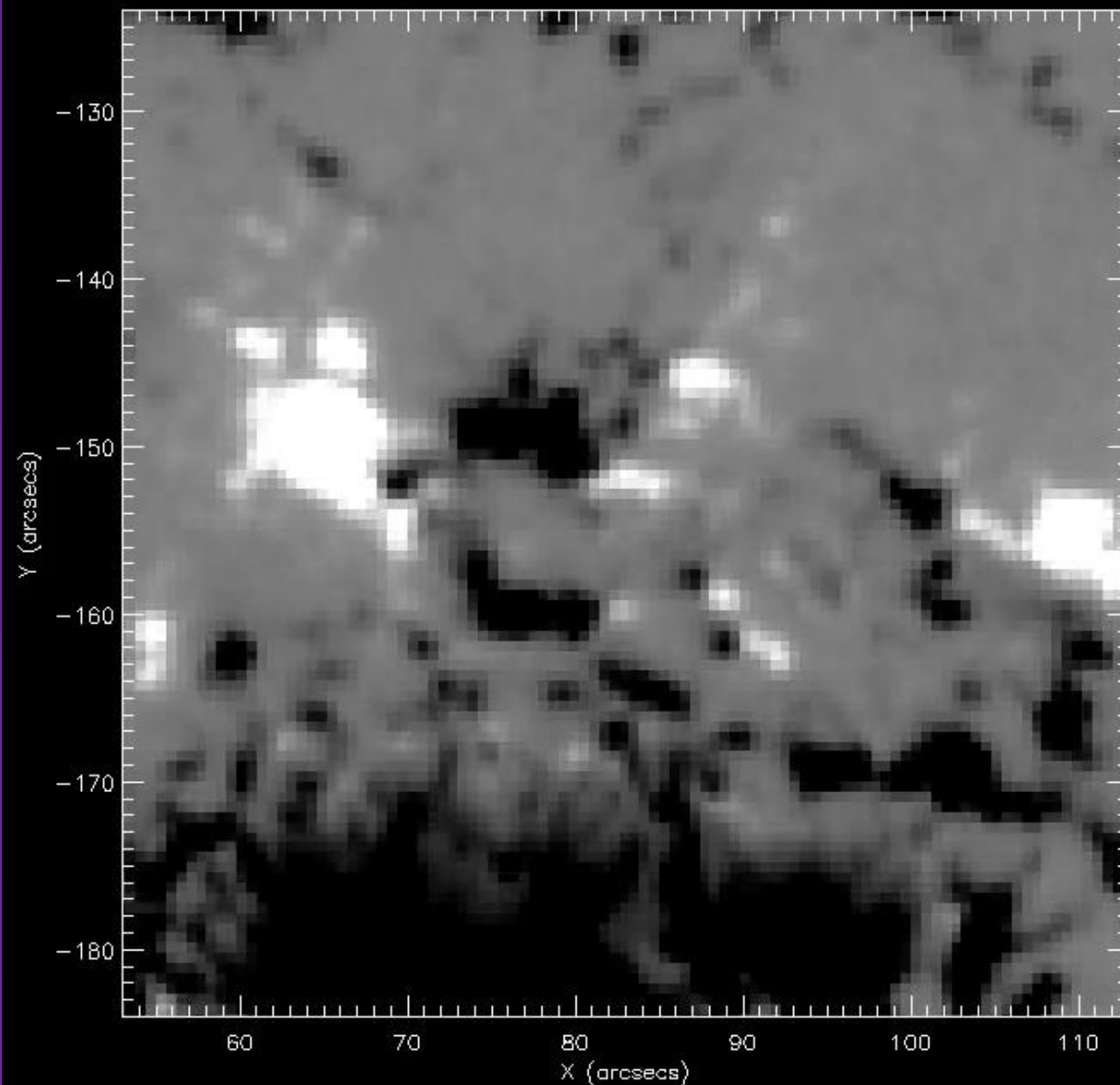


Sterling et al. (2017)

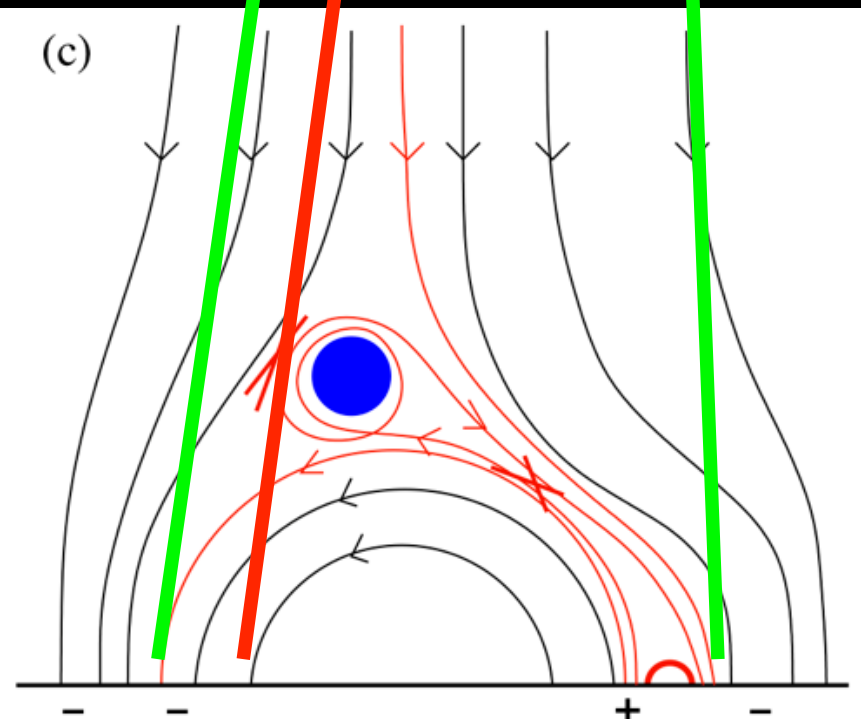
IRIS SJI SDO 14-Jan-2015 14:28:29.700 UT



SDO HMLFRONT2 6173 14-Jan-2015 14:29:39.300 UT

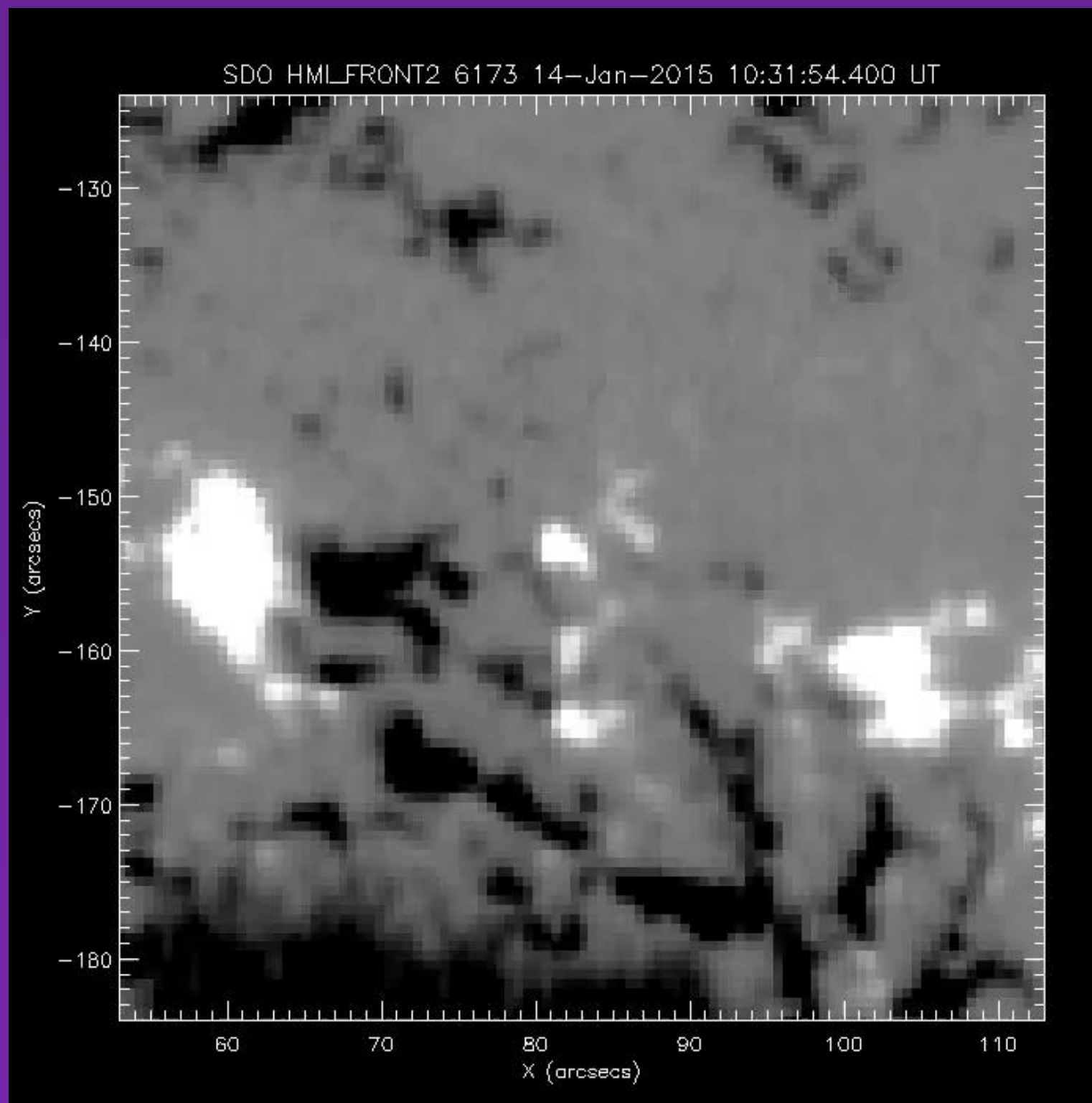


(c)



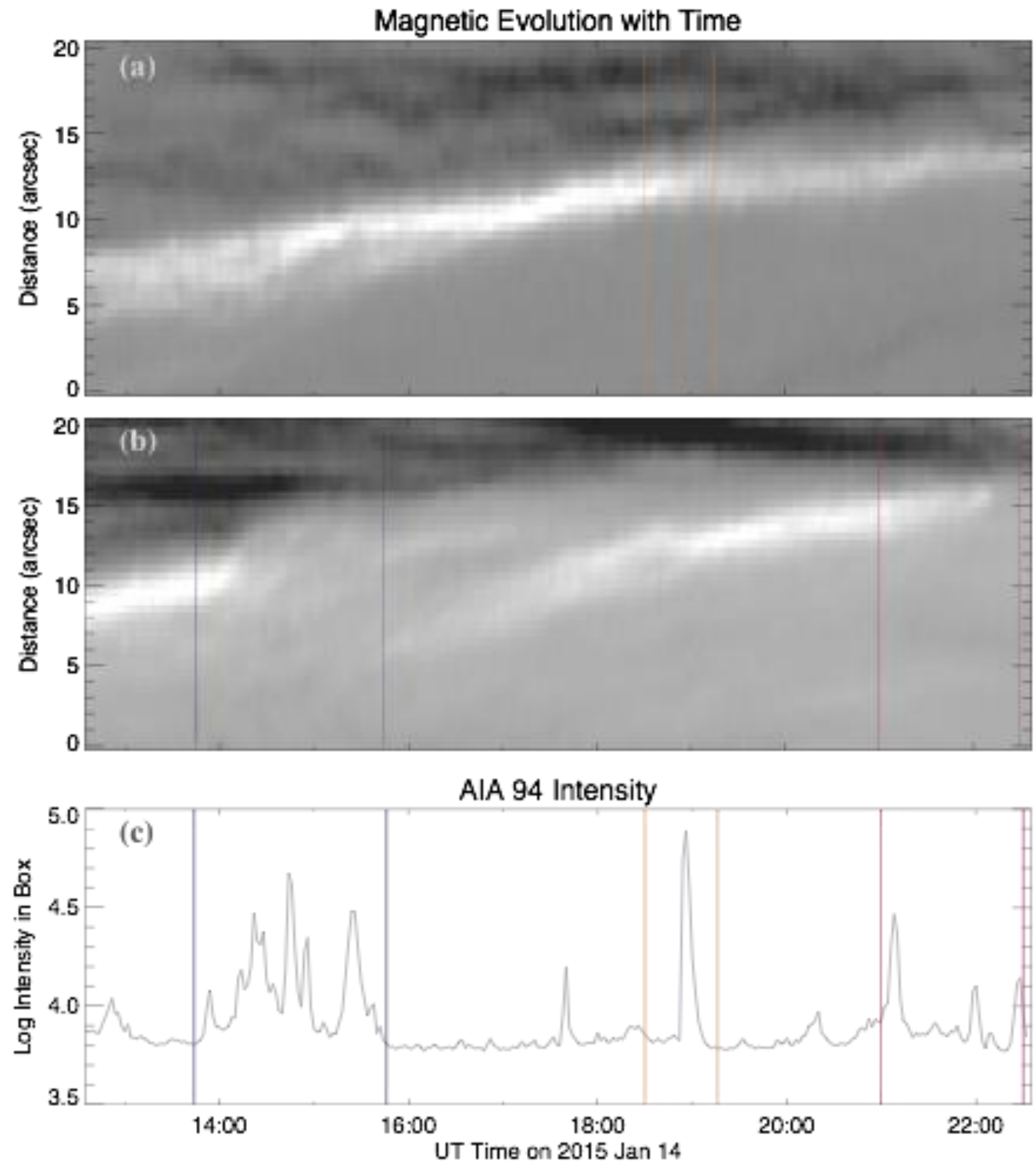
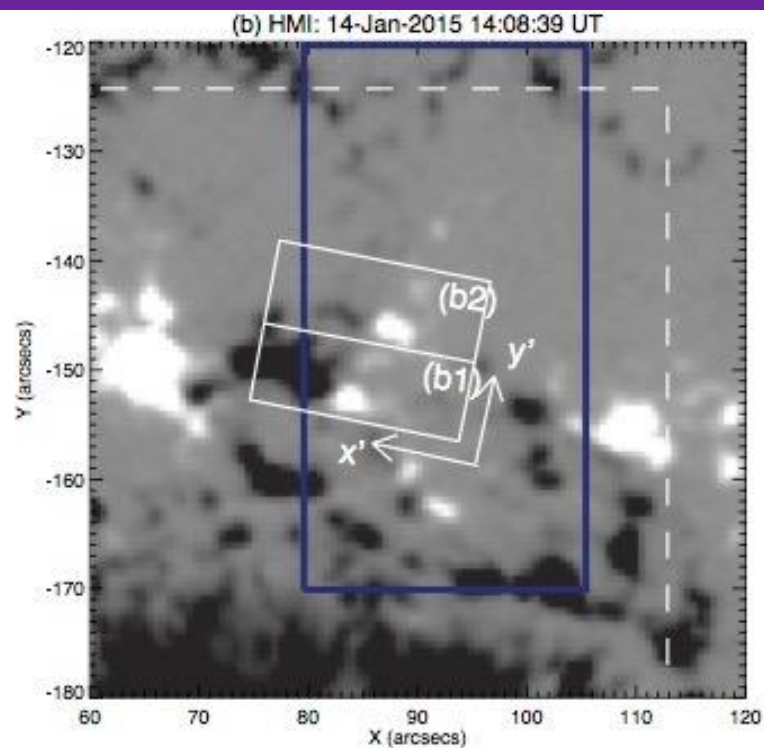
Sterling et al. (2017)

HMI of jetting region

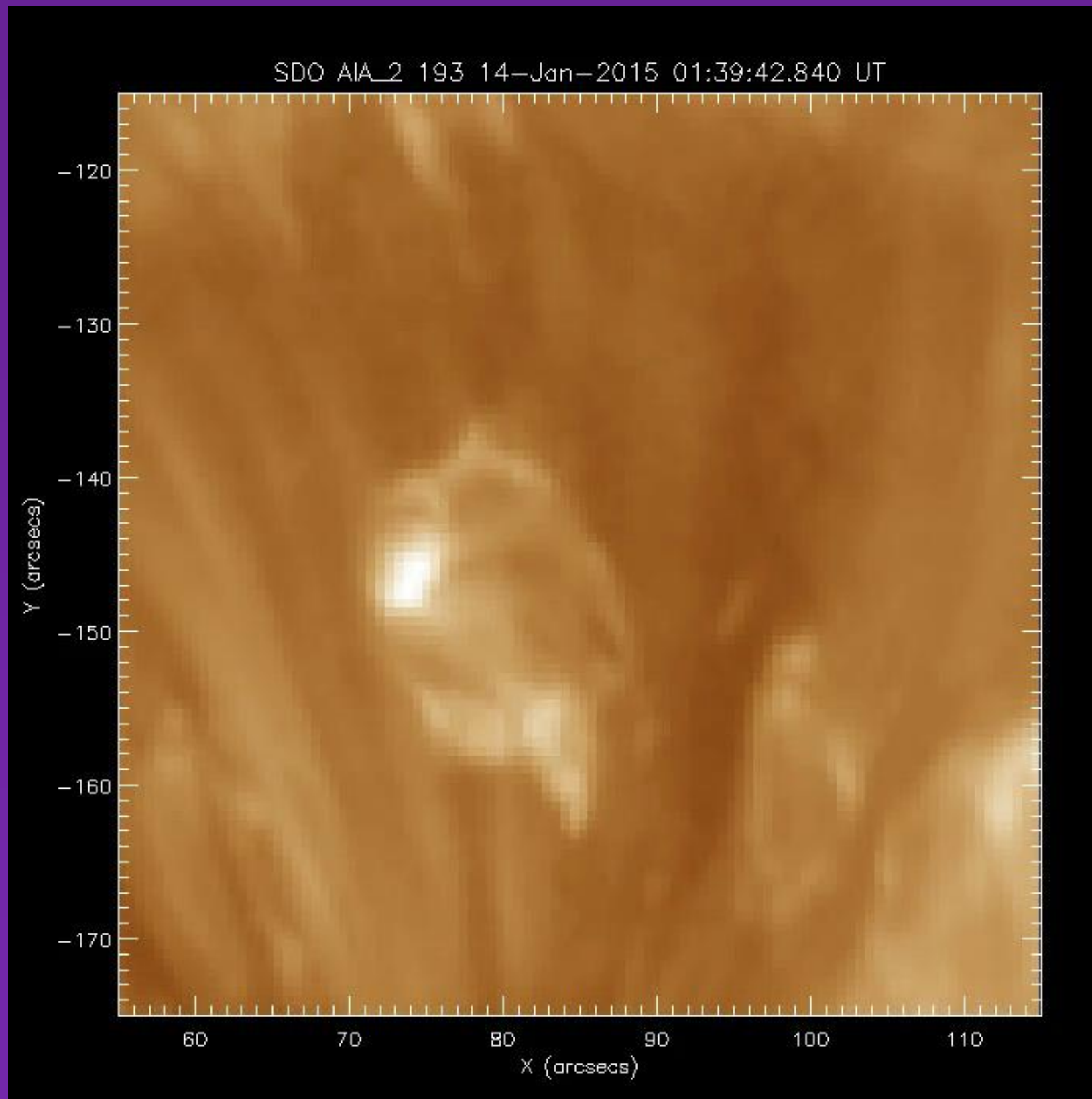


Jets occur at *flux cancellation* locations!

AR jets (Sterling et al. 2017)



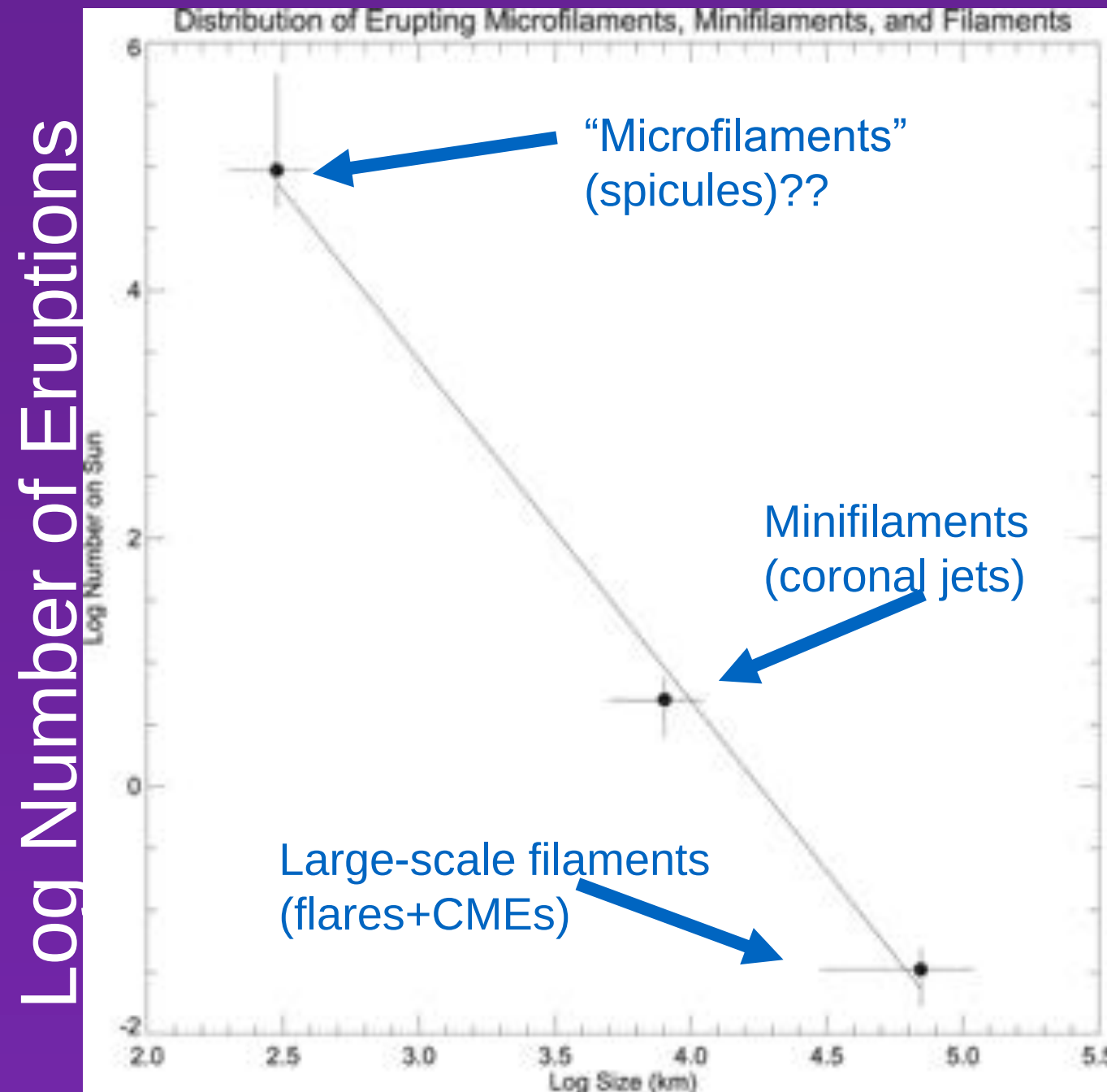
Minifilament “strand” visible from neighboring region, slightly different time.



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Do Jets Exist on Smaller Size Scales?

Filament-Like Feature Eruptions on Smaller Scales??



Log “Filament” Size
Sterling & Moore (2016)

“Jetlets” in plumes (Raouafi & Stenborg 2014)?
 (“Jetlets” in more general network?? Panesar talk).

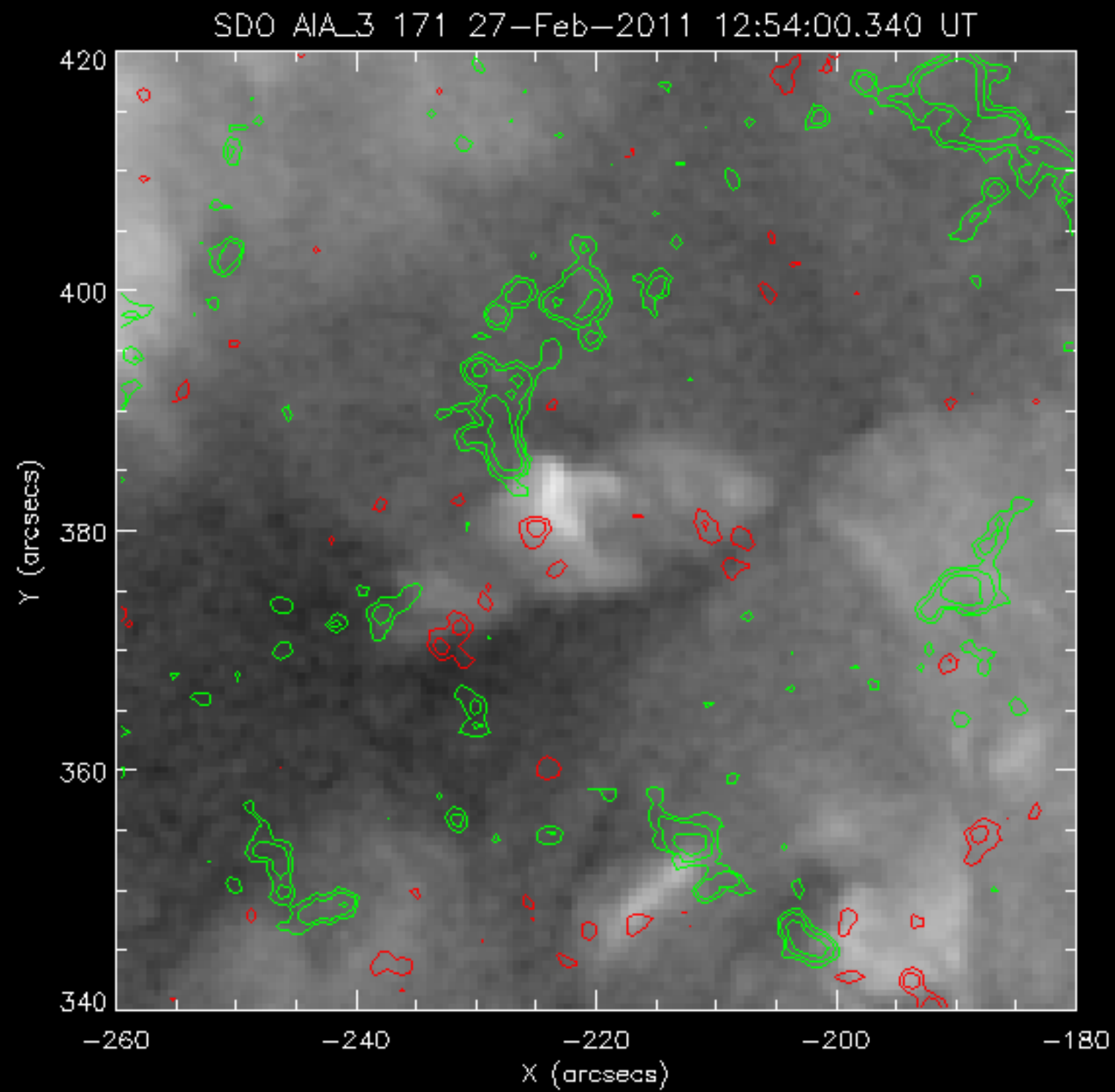
Some Outstanding Questions

- What causes jets? Strong evidence that it is flux cancelation in quiet Sun and CHs (20+ events; Panesar talk). Still must study more! (Shear only?? Kumar et al. 2018.)
- AR jets: Minifilaments sometimes less obvious (absent?). Also, “brightest” bright points sometimes in unexpected locations. (Result of complex field, multiple eruptions? Sterling et al. 2016, 2017.) Frequently see cancelation+emergence.
- How do jets scale to smaller structures (contribute to coronal heating? (Moore et al. 2015)).
- If most jets result from flux cancelation, what about larger eruptions? (Field complexities might disguise the key processes.)

Summary

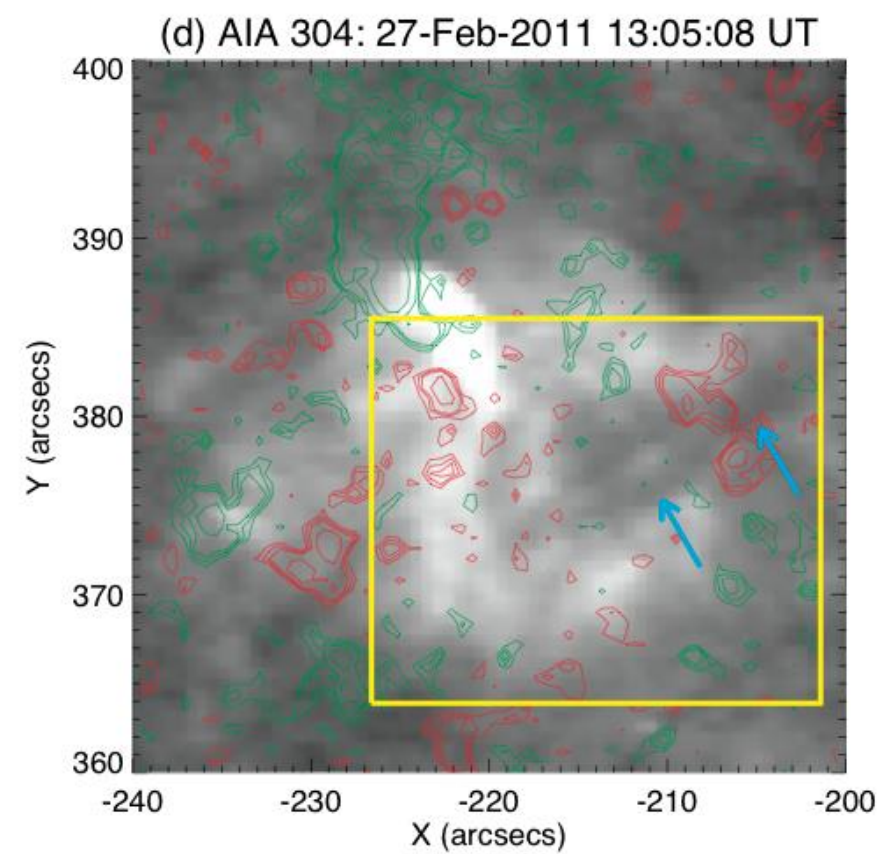
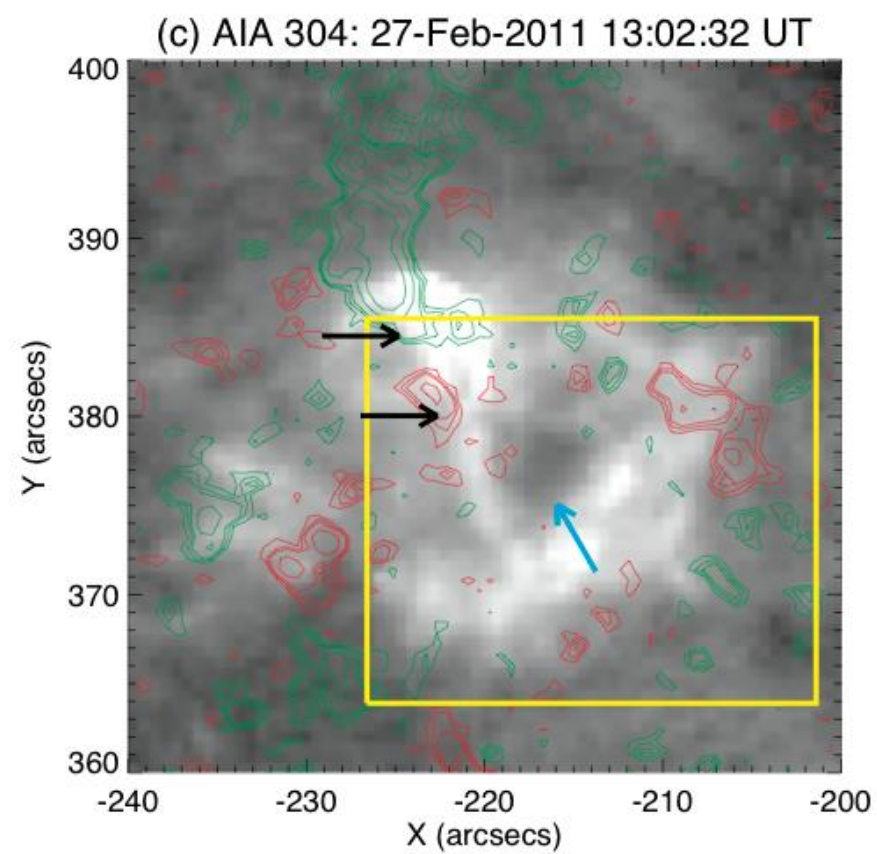
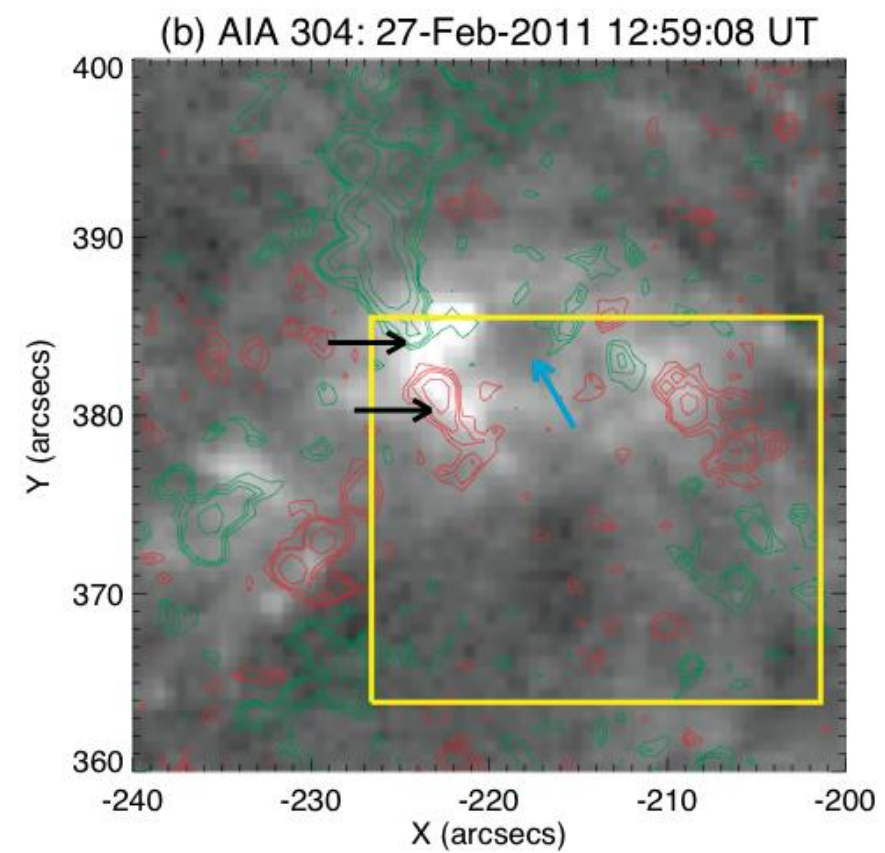
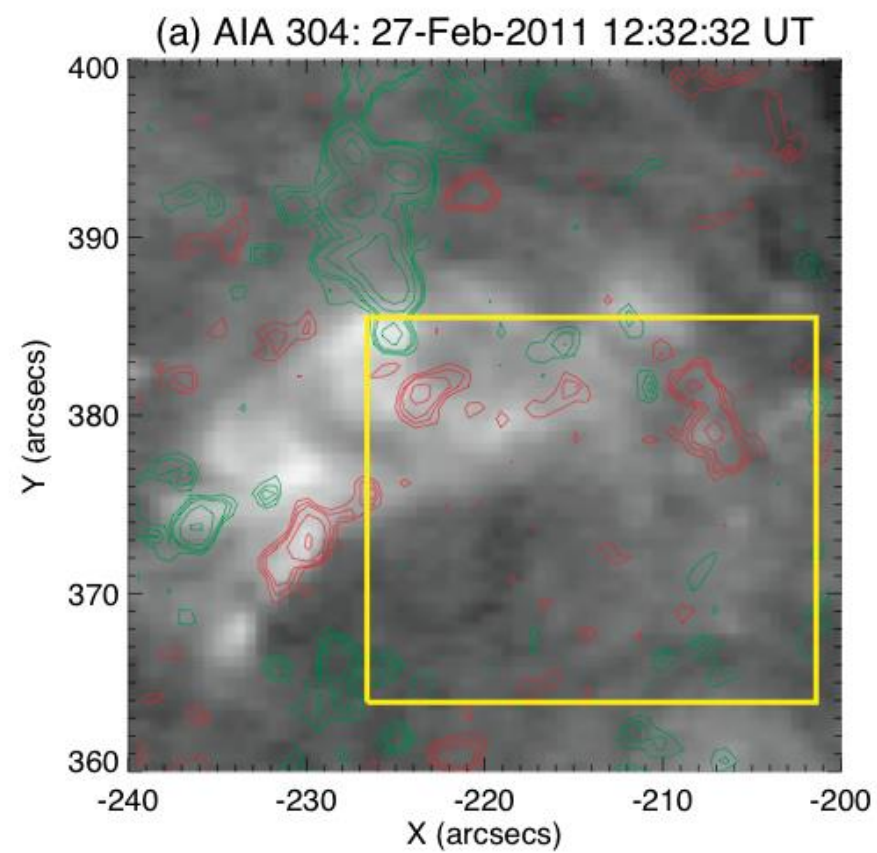
- Approaching a good understand of jets, especially in QS and CHs: At least many jets are miniature filament eruptions triggered by flux cancelation.
- AR jets are similar, but they can be more complicated. (Due to complex dynamic field?)
- More observations needed: Factors besides flux cancelation? Can field complexities explain uncertain aspects of AR jets?
- How does jet physics scale to different sizes? (Large eruptions? ``Jetlets"? Spicules??)
- Needed: Jet simulations based on minifilament eruptions (e.g. Wyper et al), and *flux cancelation*!

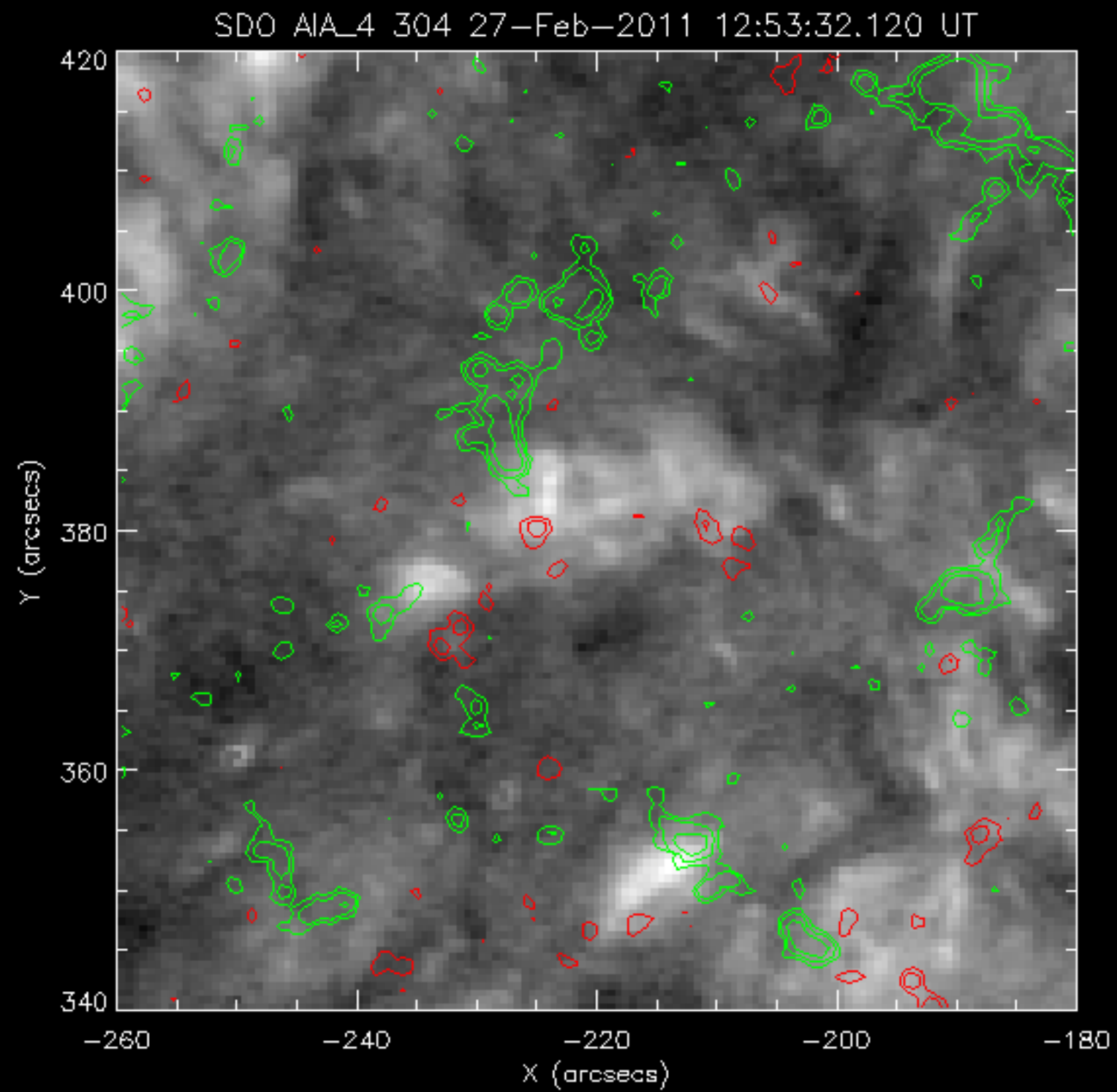
Image:
Alphonse Sterling
21 August 2017,
Lewisville, Idaho



A. Sterling,

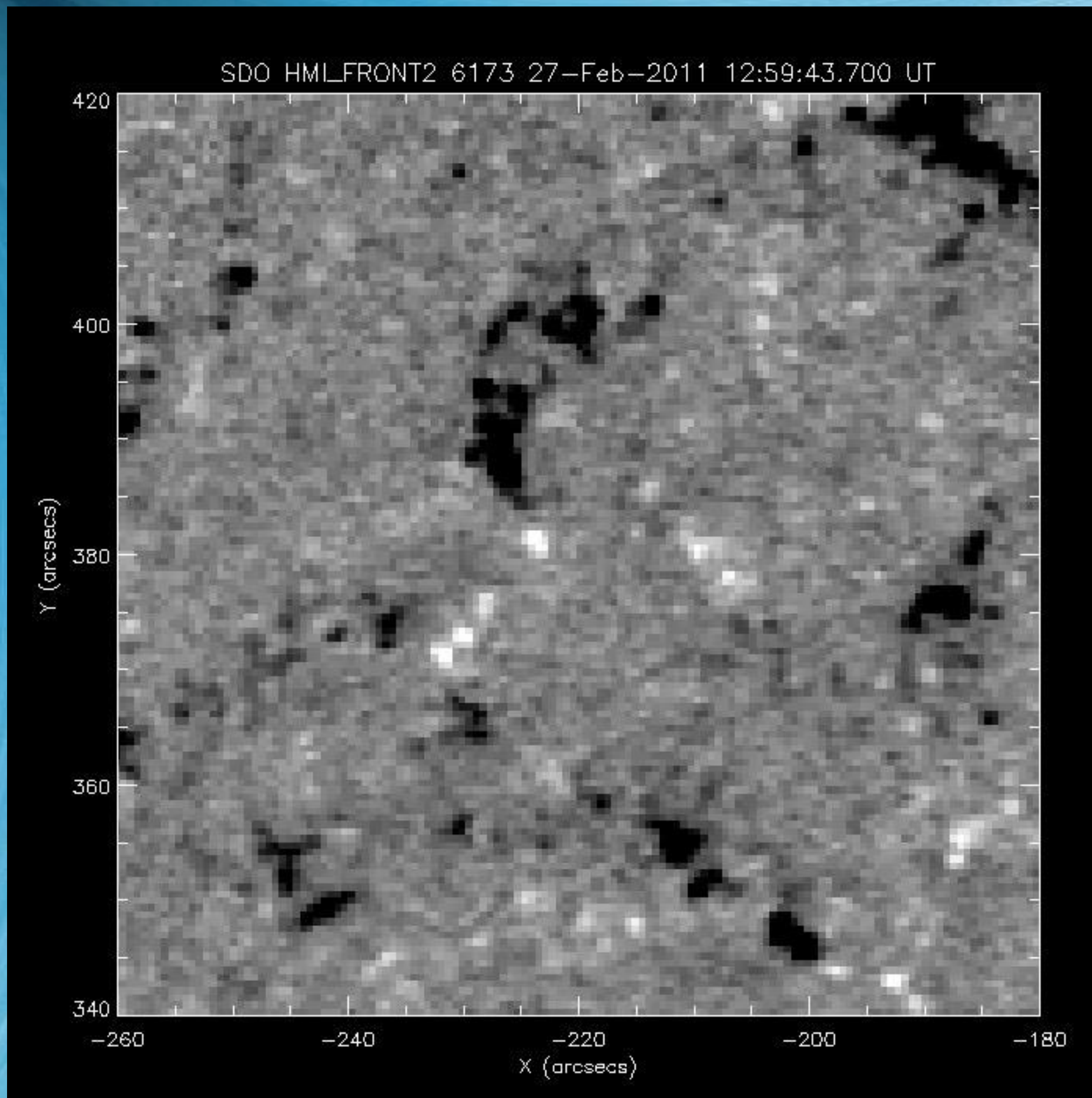
Adams et al. (2014)

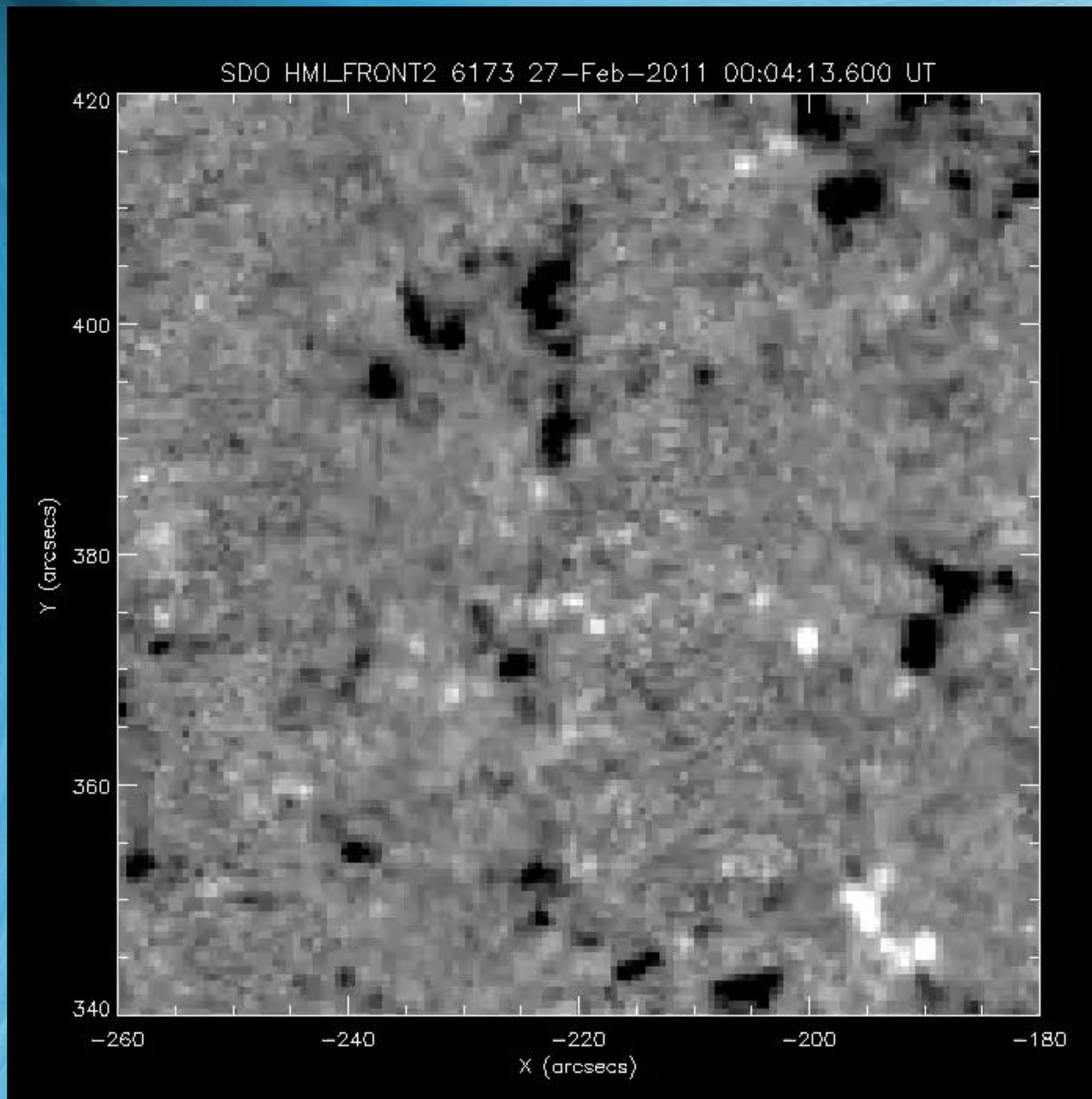




A. Sterling,

Adams et al. (2014)





Jets and CMEs: History (sampling)

- ♦ Wang et al. (1998) - EIT and LASCO white-light jets.
 - ♦ Gilbert et al. (2001), Dobrzycka et al. (2003); “narrow CMEs” (angular width $\lesssim 15^\circ$).
- ♦ Nisticò et al. (2009) - STEREO; 5/79 “micro-CMEs”/jets.
- ♦ Several single-event studies:
 - ♦ Hong et al. (2011) - Single-event study of a micro-CME originating from a blowout jet triggered by flux cancelation.
 - ♦ Shen et al. (2012) - Bubble-like CME from a blowout jet (SDO, STEREO, $H\alpha$).
- ♦ See Raouafi et al. (2016) review for more.

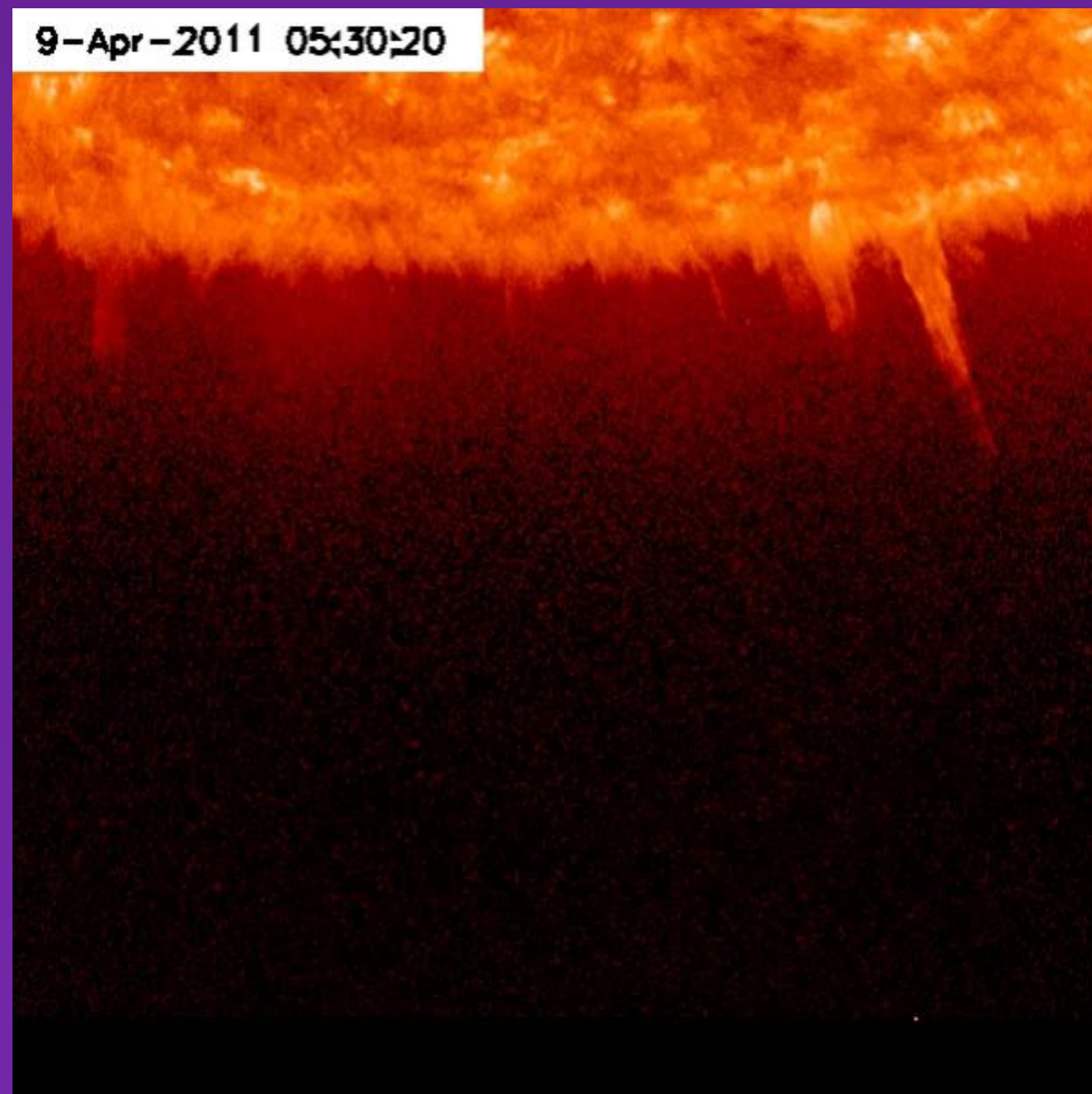
Jets and CMEs: Some recent investigations

- Moore et al. (2015): Polar coronal hole jets that extend into outer corona.
- Sterling et al. (2016): “CMEs” from AR jets.
- Panesar et al. (2016a): A “different type” of CME from AR jets. (Bemporad et al. 2005.)
- (Narrow CMEs = white-light jets.)

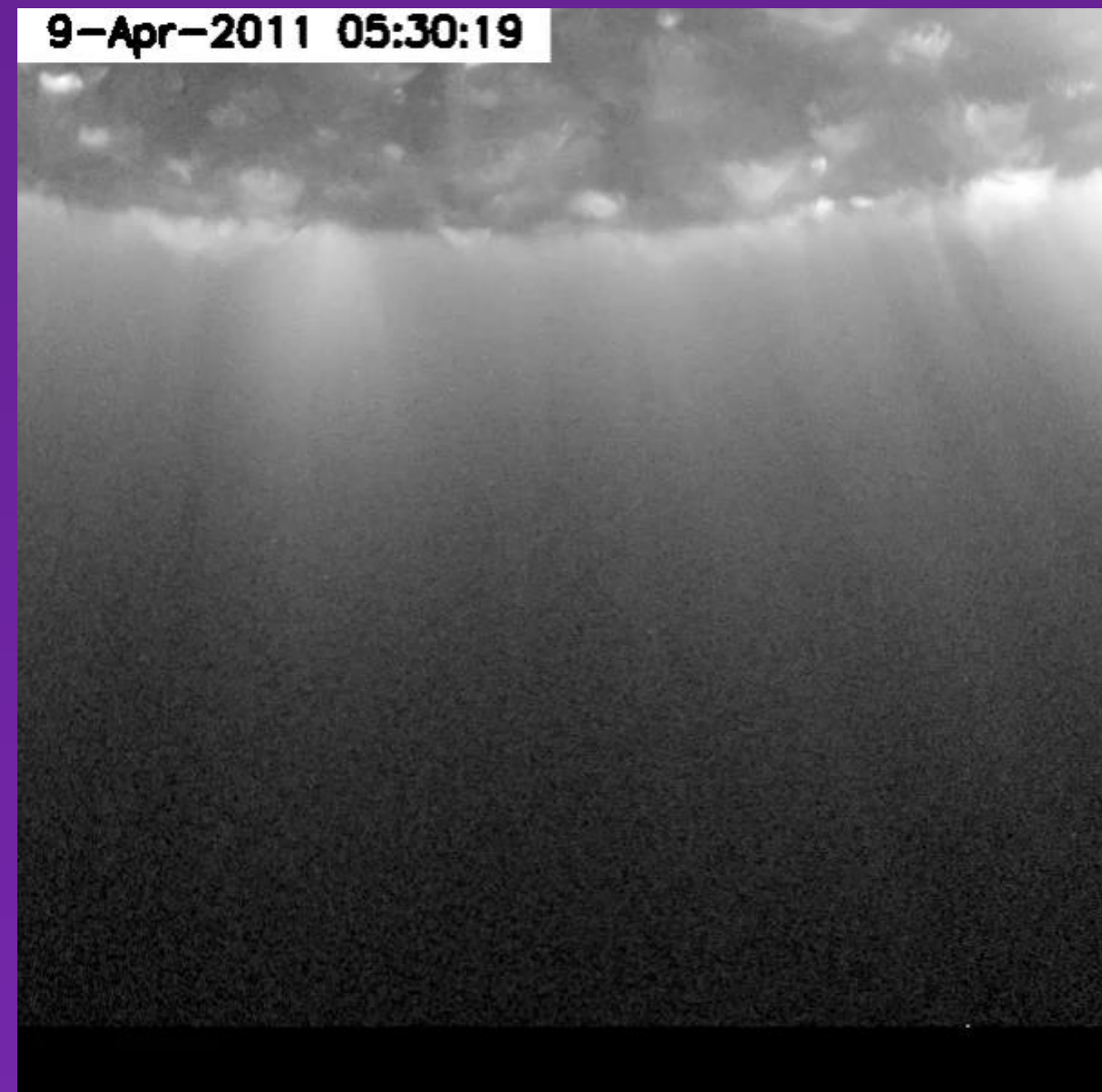
Moore et al. (2015)

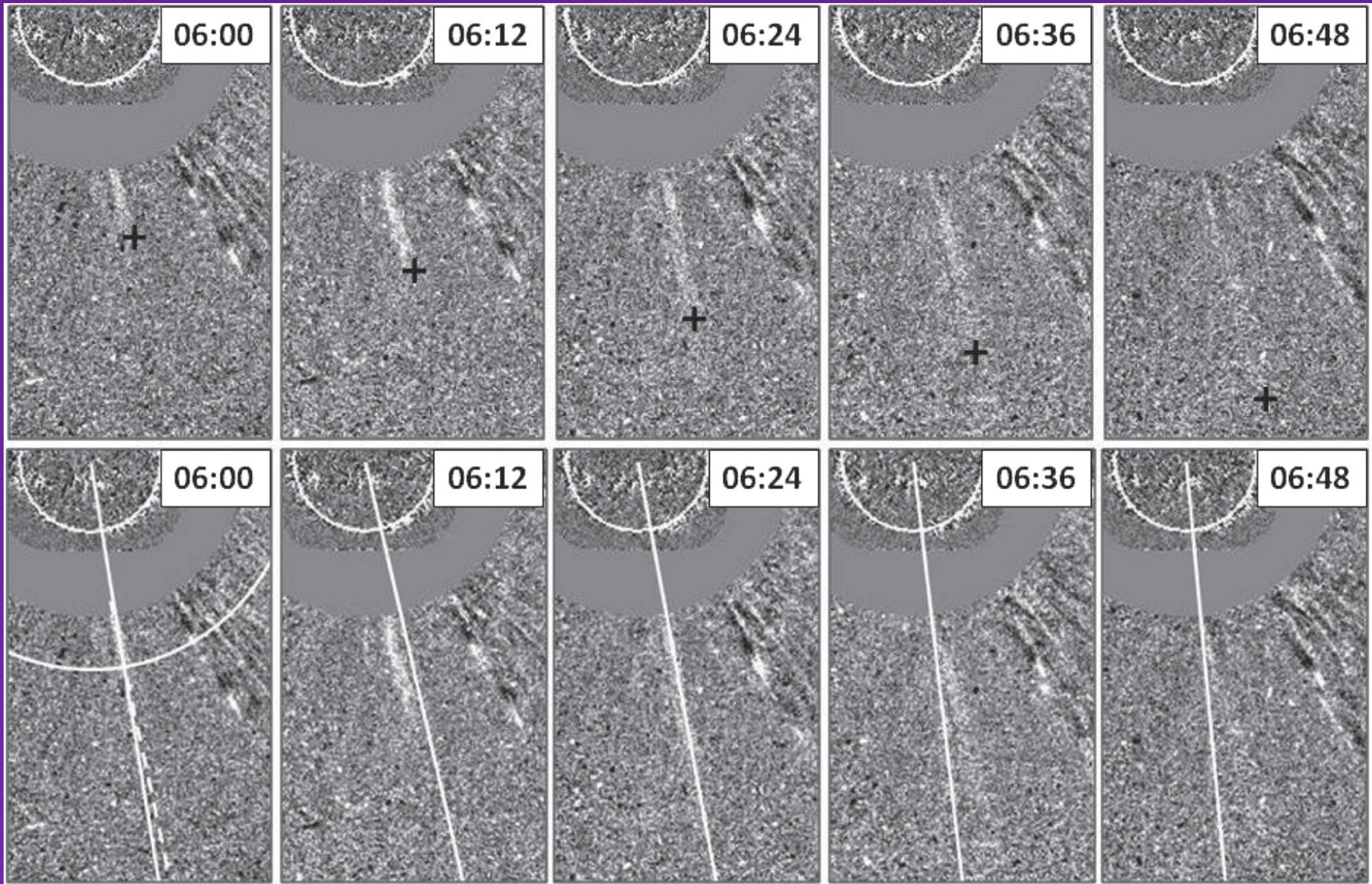
- Selected 14 polar CH jets, that extended into LASCO/C2 FOV.
- Looked for narrow (width $\lesssim 10^\circ$) LASCO features.
- AIA/EUV jet.
- Found that narrow-CME-producing jets tended to have large twist.

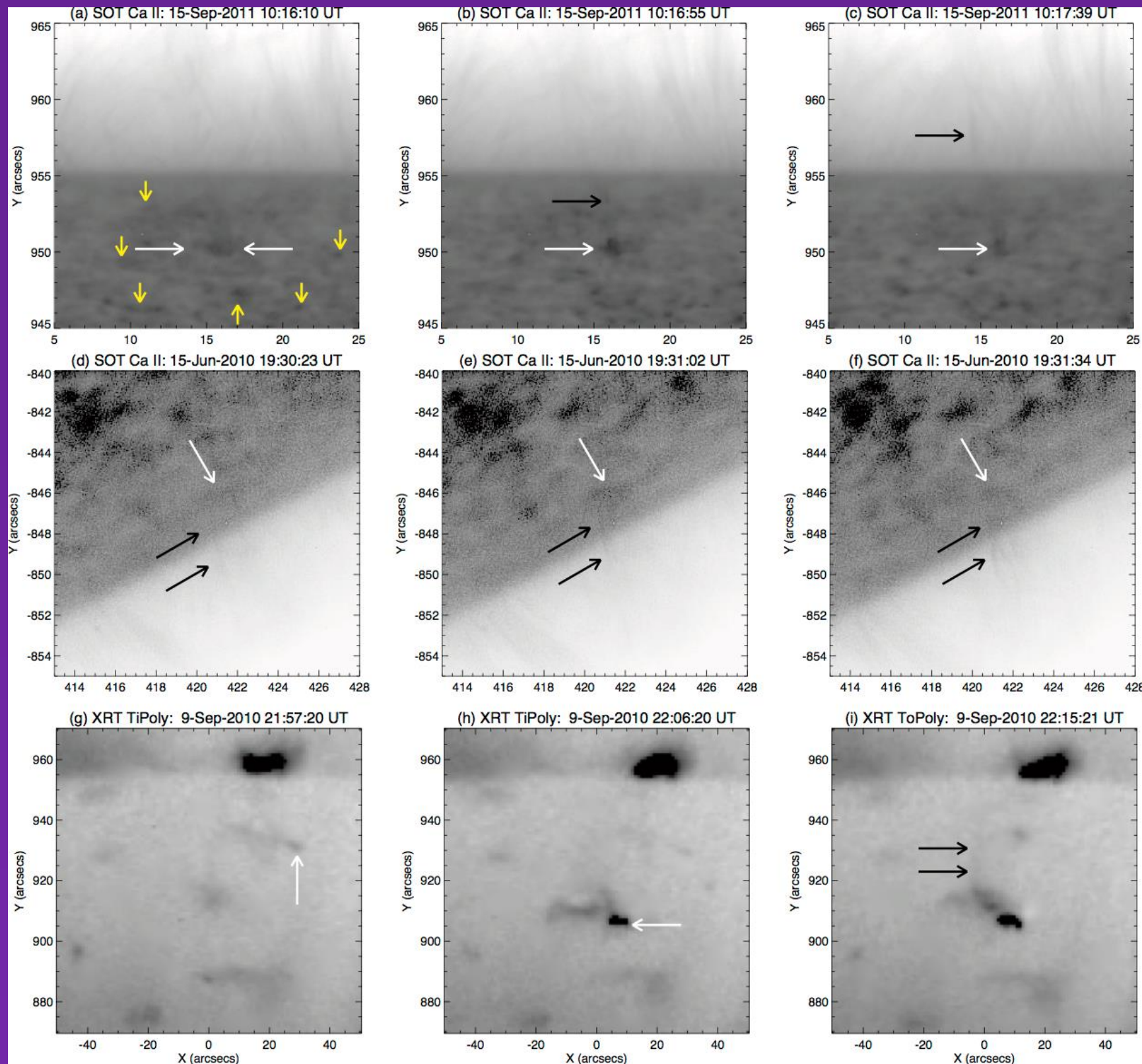
AIA 304



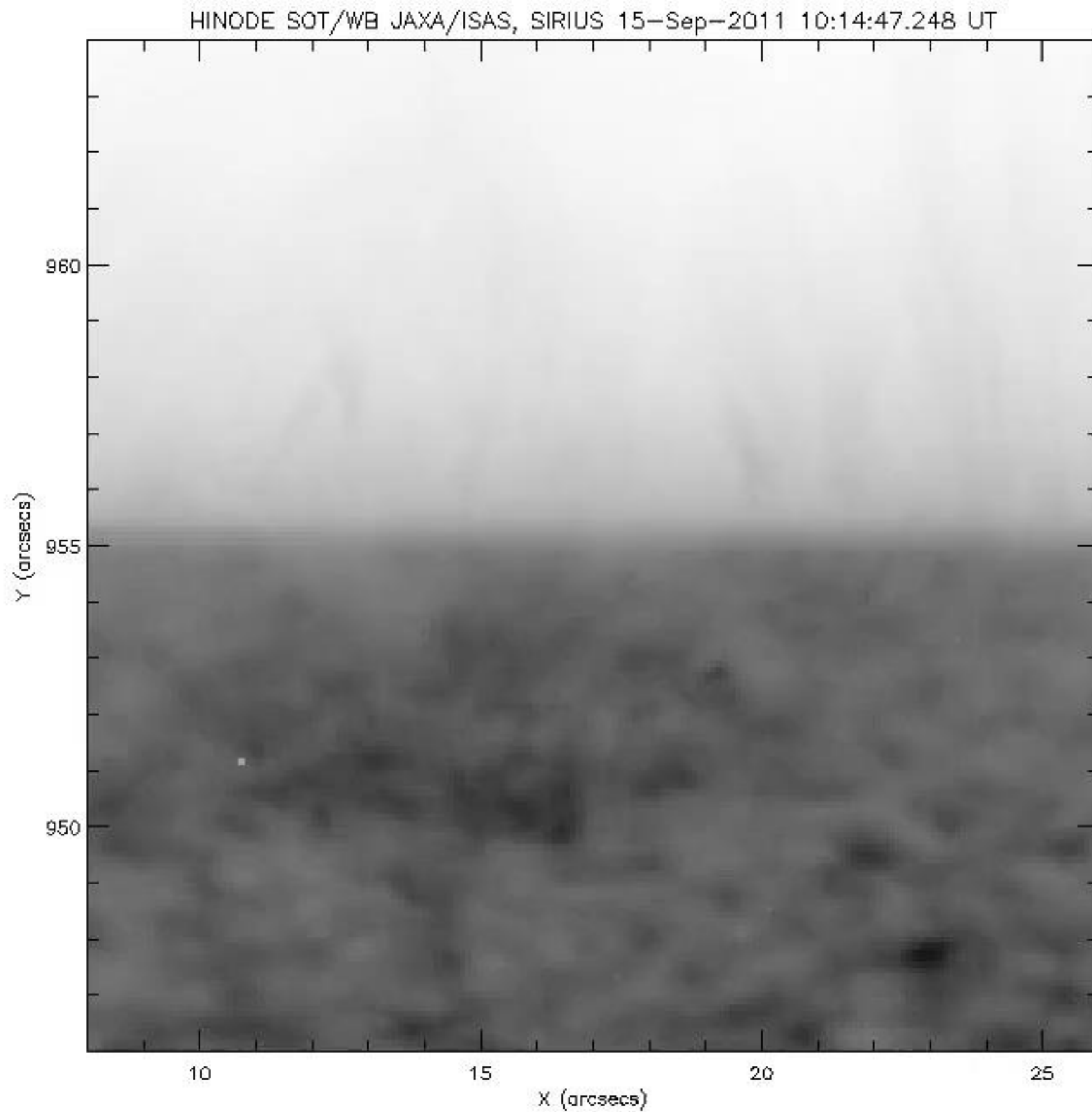
AIA 193



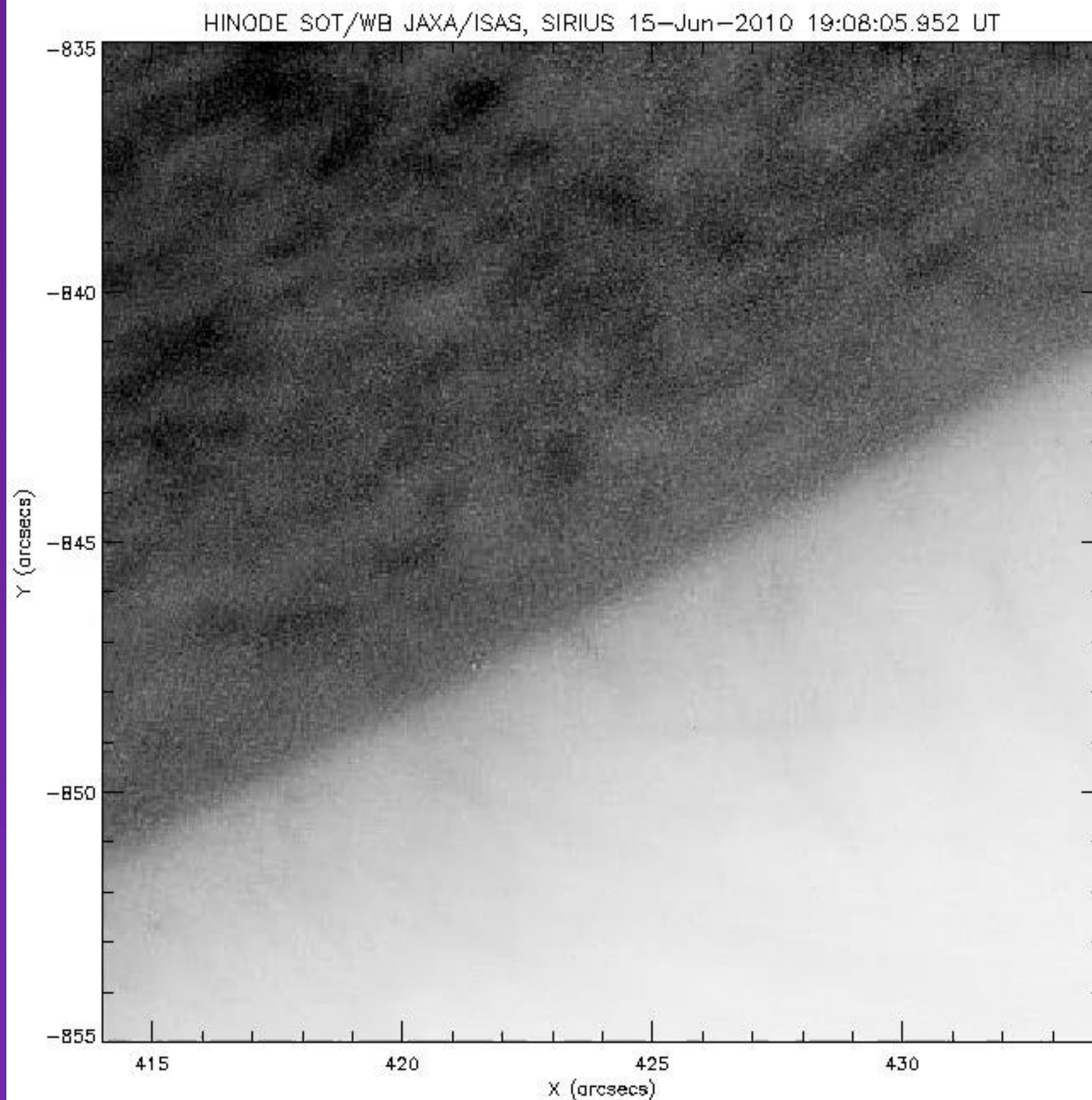




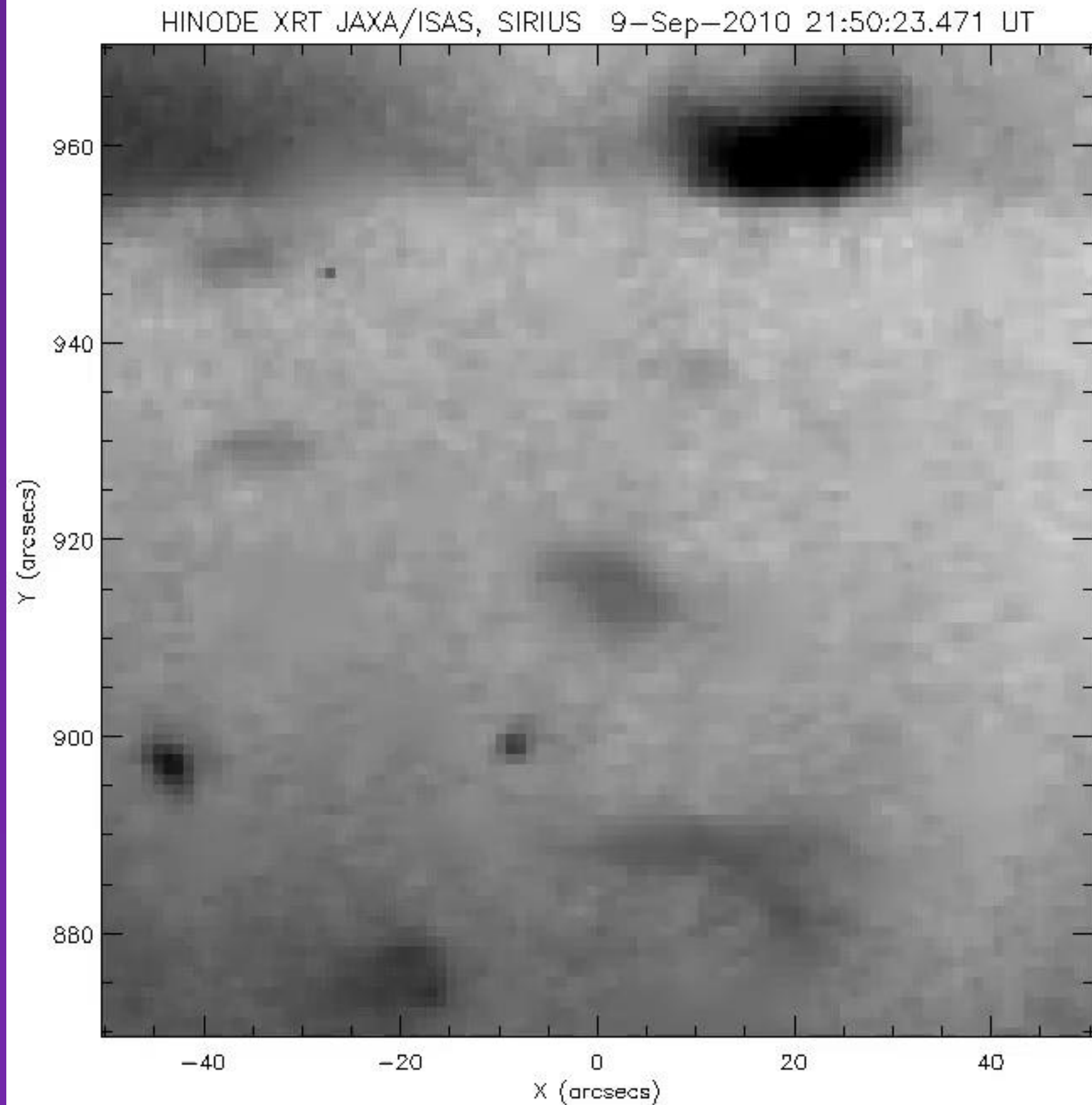
Sterling & Moore (2016)



Sterling & Moore (2016)



Sterling & Moore (2016)



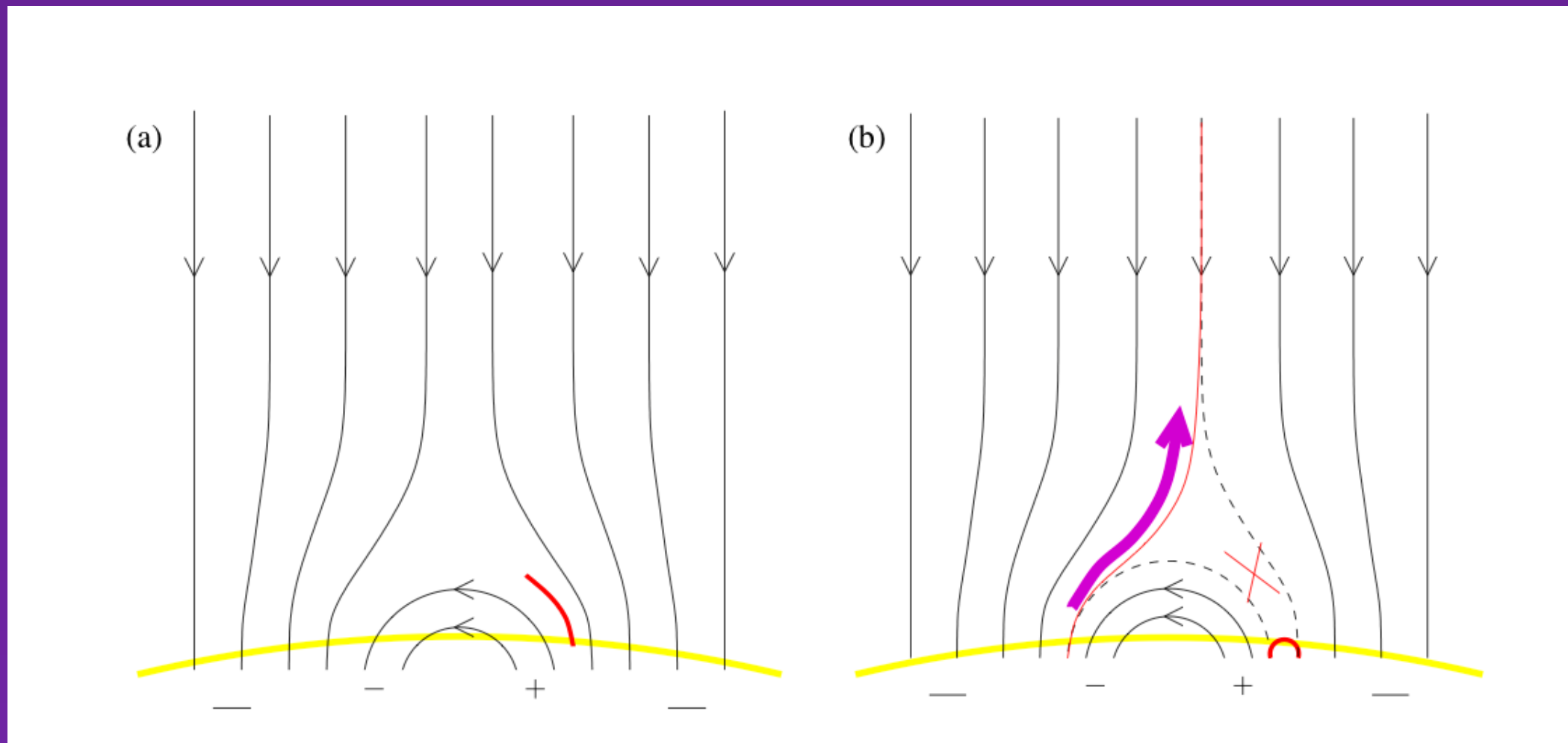
Sterling & Moore (2016)

Summary

- Jets are common, and occur all over the Sun (CHs, QS, and ARs).
- At least many, if not all, jets result from minifilament eruptions; smaller-scale version of large eruptions.
- Many (virtually all?) minifilament eruptions triggered by flux cancelation.
- At least two types of CMEs from jets:
 - ♦ Extensions of jets (narrow CMEs/white light jets).
 - ♦ Broader CMEs can be triggered by jets (streamer puff CMEs).
- Smallest-scale jets might make up some percentage of the spicule population.

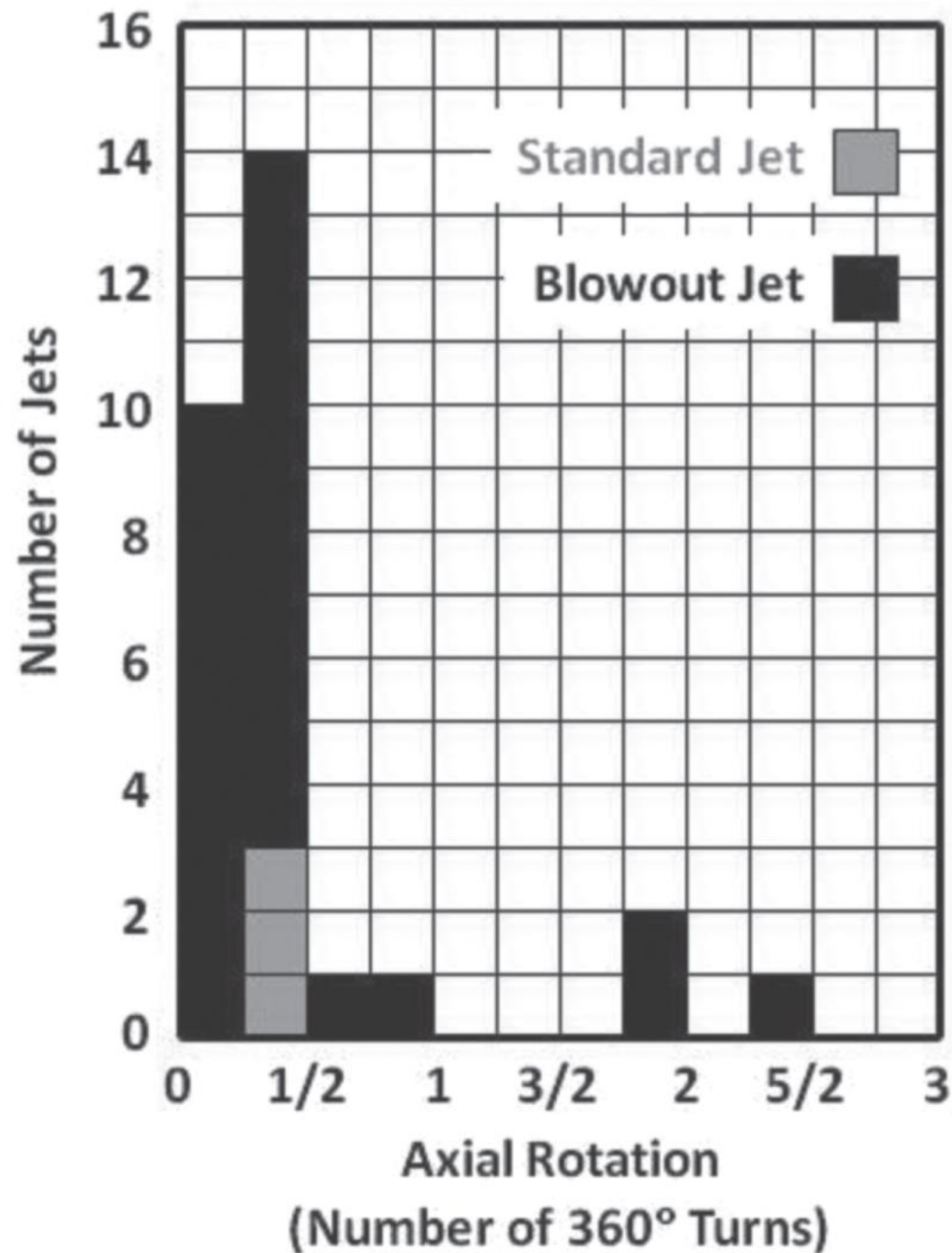
Image:
Alphonse Sterling
21 August 2017,
Lewisville, Idaho

Emerging-Flux Model for (X-Ray) Jets

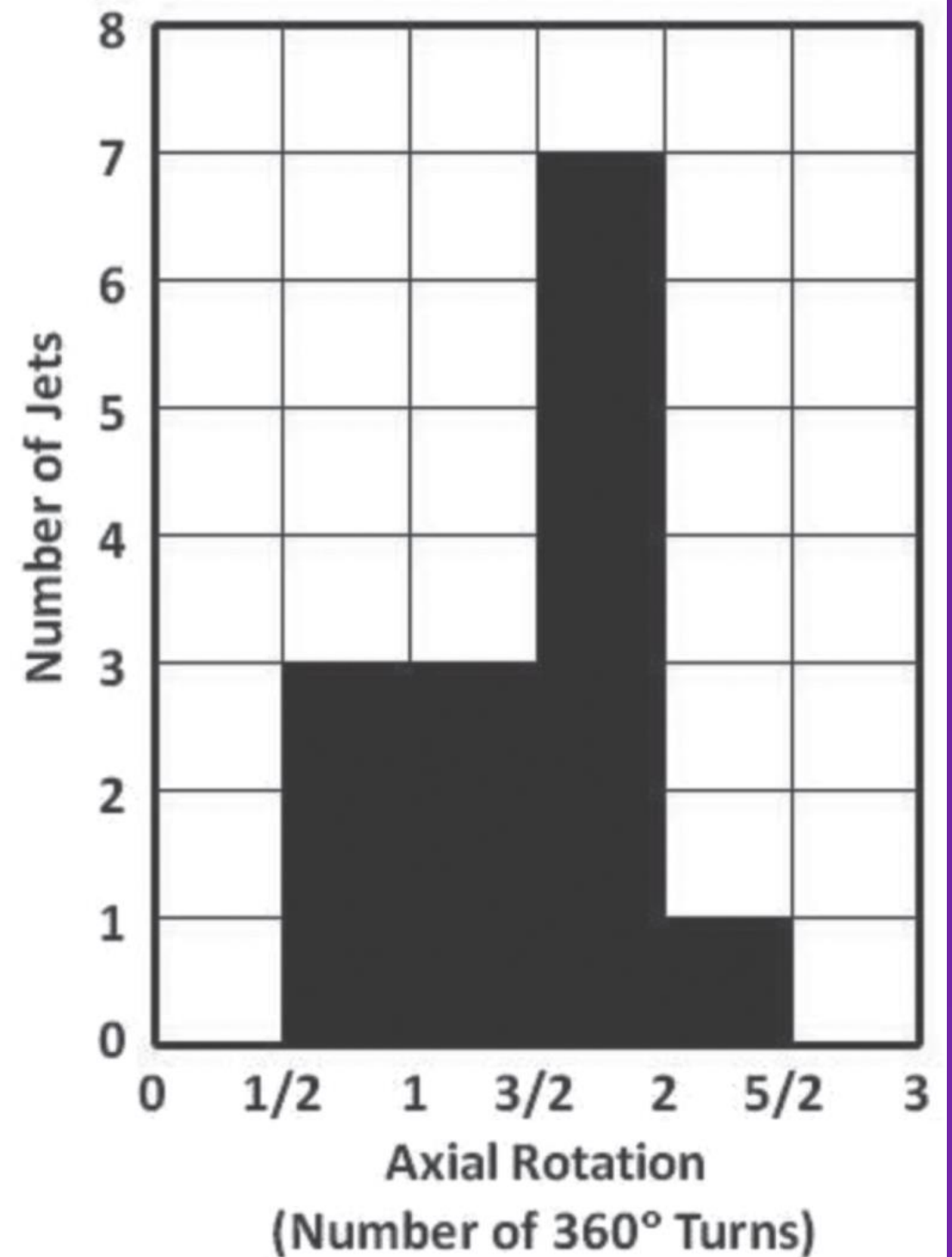


Supported by numerical simulations: Yokoyama & Shibata (1995), Nishizuka et al. (2008), Archontis et al. (2013), Moreno-Insertis et al. (2013), Fang et al. (2014), etc. (Cf. Heyvaerts, Priest, & Rust 1977.)

Twist in Jets

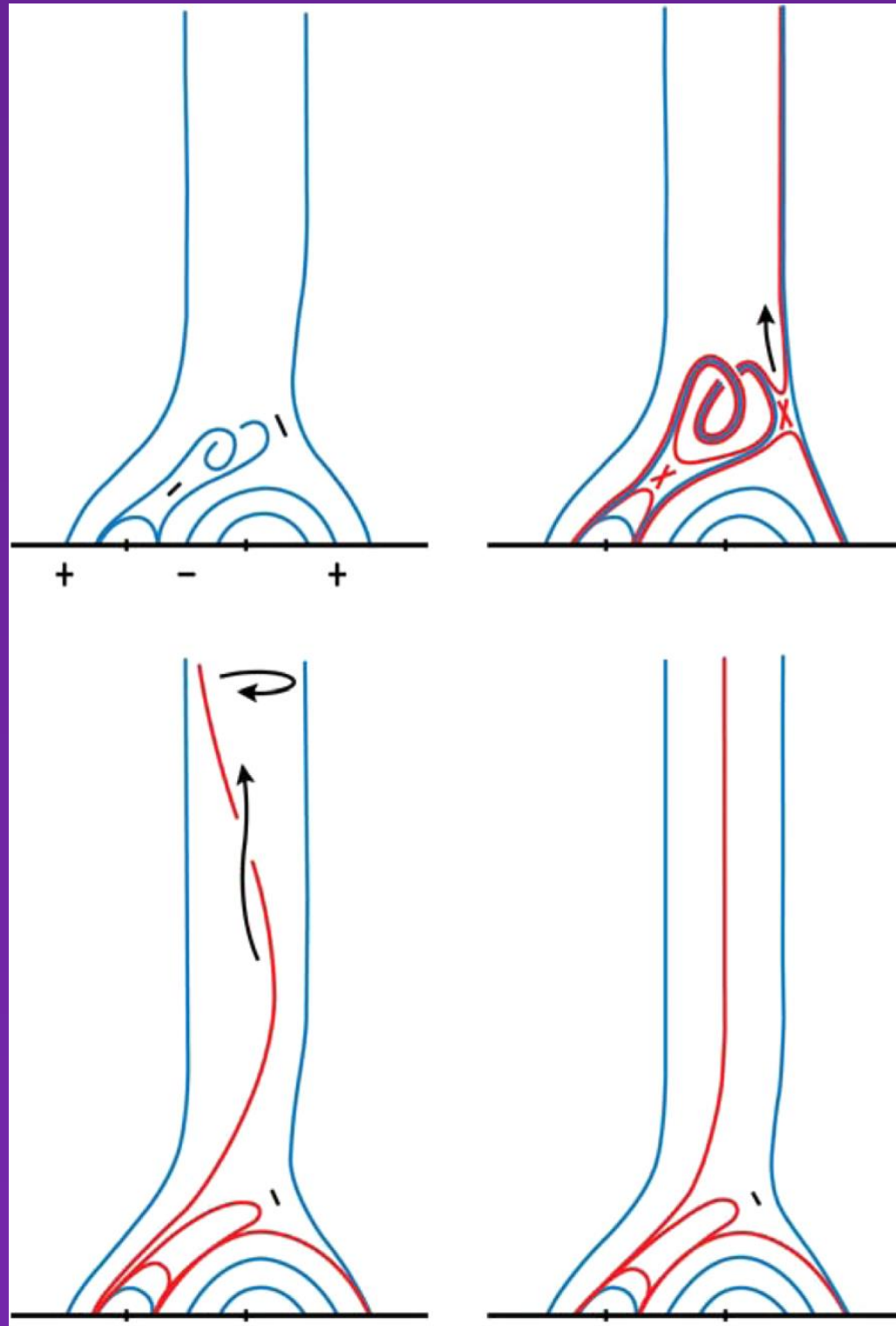


Random twisting PCH jets with cool component: Moore et al. (2013)



Narrow-CME-Producing Jets: (Moore et al. 2015)

This suggests that: “polar jets having more axial rotation usually extend to greater heights than polar jets having less axial rotation.”

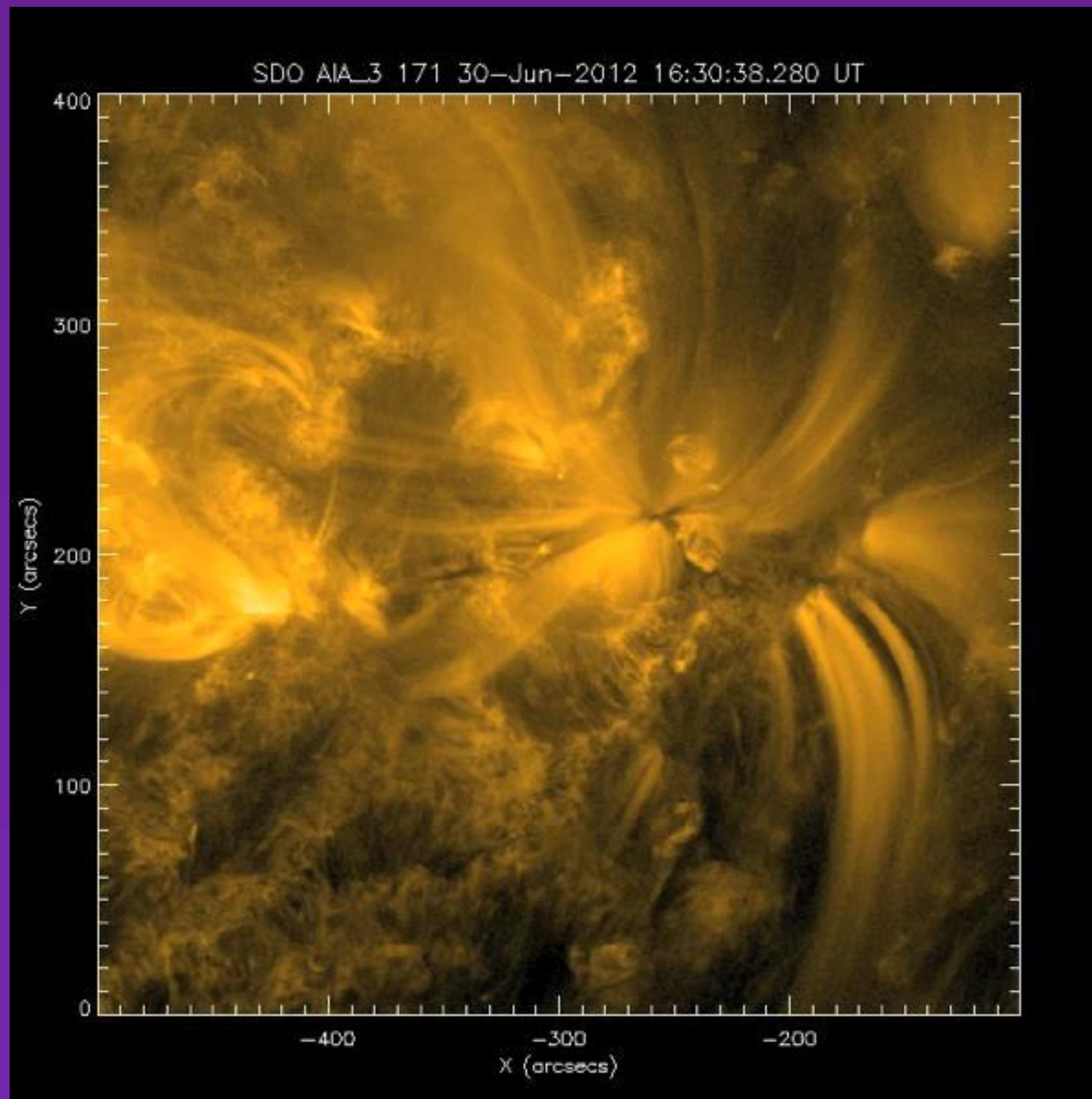


Moore et al. (2015). (Shibata & Uchida 1986-type mechanism; Patsouraos et al. 2008; Pike & Mason 1998.)

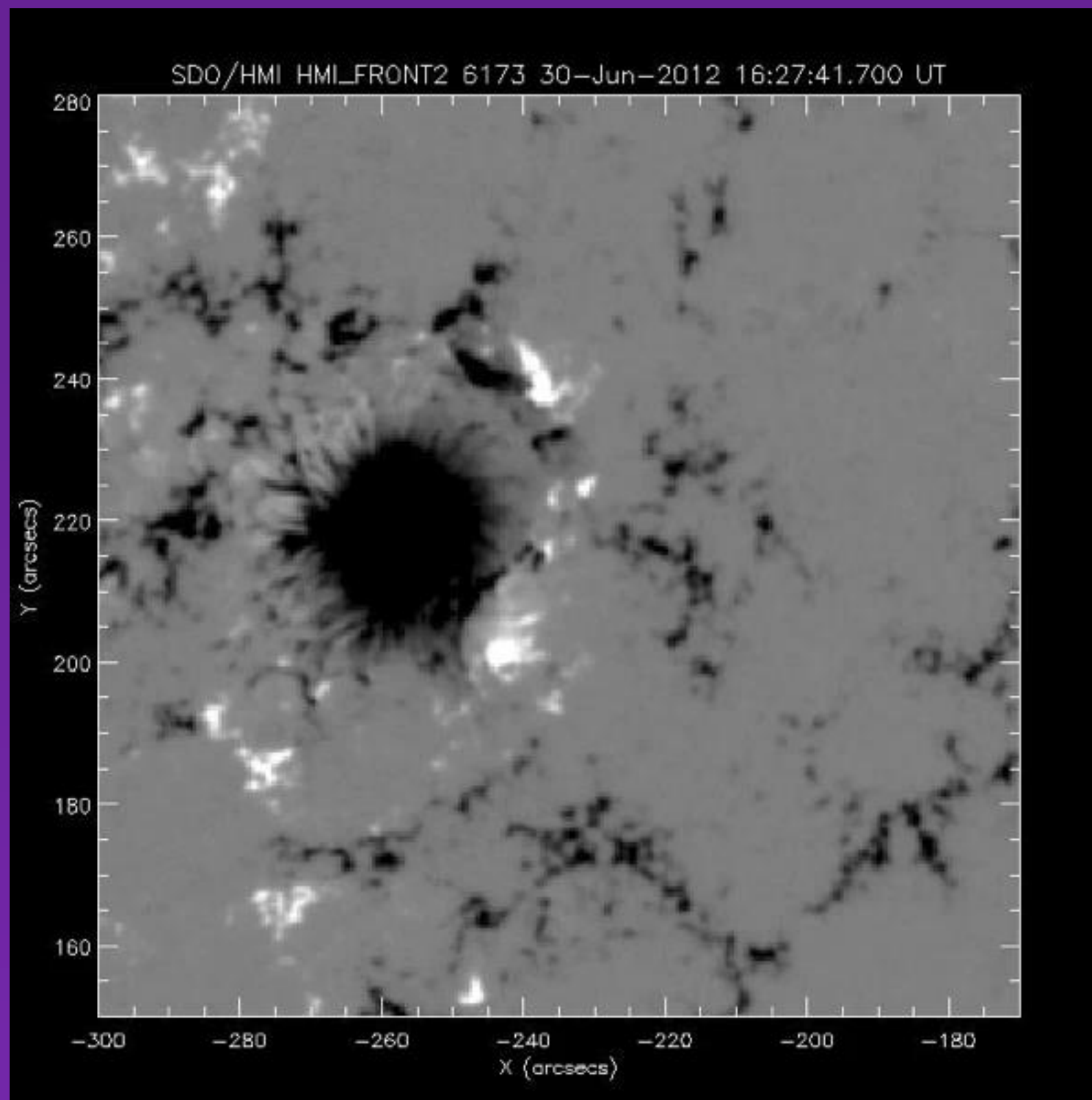
CMEs from AR Jets:

Sterling et al. (2016)

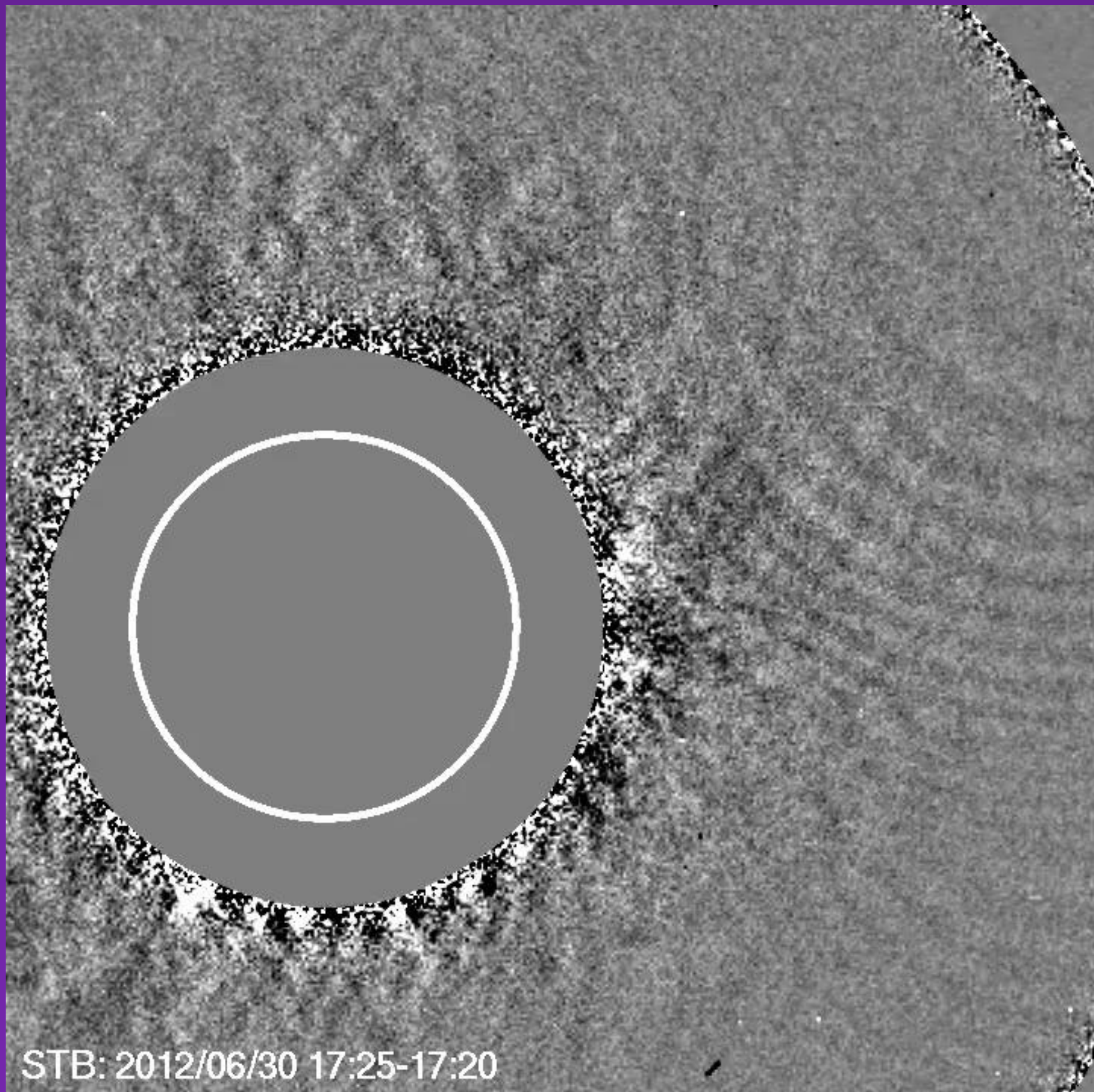
AIA 171



Sterling et al. (2016, ApJ)



Minifilament eruptions (jets) often occur at flux-cancellation sites. Flux emergence may play a role in triggering eruptions. (Also, e.g., Kano et al. 2010; Hong et al. 2010; Shen et al. 2012; Young & Muglach 2014a, b; Chandrashekar et al. 2014, Adams et al. 2014.)



STB: 2012/06/30 17:25-17:20

Table 1
GOES List for Events of Figure 4, and CME Properties

Jet/Event	Time (UT) ^a	Flare	Region ^b	CME? ^c	CME Time (UT) ^c	Width (deg) ^c	Velocity (km s ⁻¹) ^c
1	17:28	B6.0	C	Probably	17:35	4.0 ± 0.6	458 ± 66
2	17:47	B7.0	A	No	...	...	...
3	18:12	C1.6	B	Yes	18:10	62.8 ± 1.4	300 ± 9
4	18:33	M1.6	D	Probably	18:40	26.7 ± 3.6	482 ± 102
5	19:32	B7.0	C	Yes	19:40	7.7 ± 1.6	368 ± 44
6	20:19	B8.0	C	Probably	20:20	4.3 ± 0.6	479 ± 17
7	20:28	B9.0	A	Probably	20:35	3.3 ± 0.6	521 ± 32
8	21:26	C1.6	C	Yes	21:30	7.2 ± 2.5	841 ± 10
9	22:37	C1.1 ^d	C	Maybe	22:45	2.6 ± 0.9	356 ± 61
10	23:54	C1.0	D	Maybe	23:50	8.0 ± 2.8	515 ± 39
11	00:09	B6.0	A and C	No	...	...	...

Notes.

^a Time of peak brightening (within $\lesssim 1$ minute) in *GOES* 1–8 Å X-ray flux on 2012 June 30 (July 1 for event 11); event 3 is a filament eruption, while other events are jets. In some cases the CME appears prior to the peak in X-ray flux, but this is consistent with other observations (e.g., Harrison 1986).

^b Region in Figure 3(a) where the source of the event is located.

^c Indicates whether a CME was detected from the event in *STEREO-B/Cor1* images. If not “no,” then entries in column 5 reflect the level of confidence that the observed CME originates from the event. Subsequent columns give the time of the CME’s first appearance in *STEREO-B Cor1* images, and the angular width and plane-of-sky velocity of the CME. Widths and velocities are averages of four measurements, and uncertainties are 1σ standard deviations.

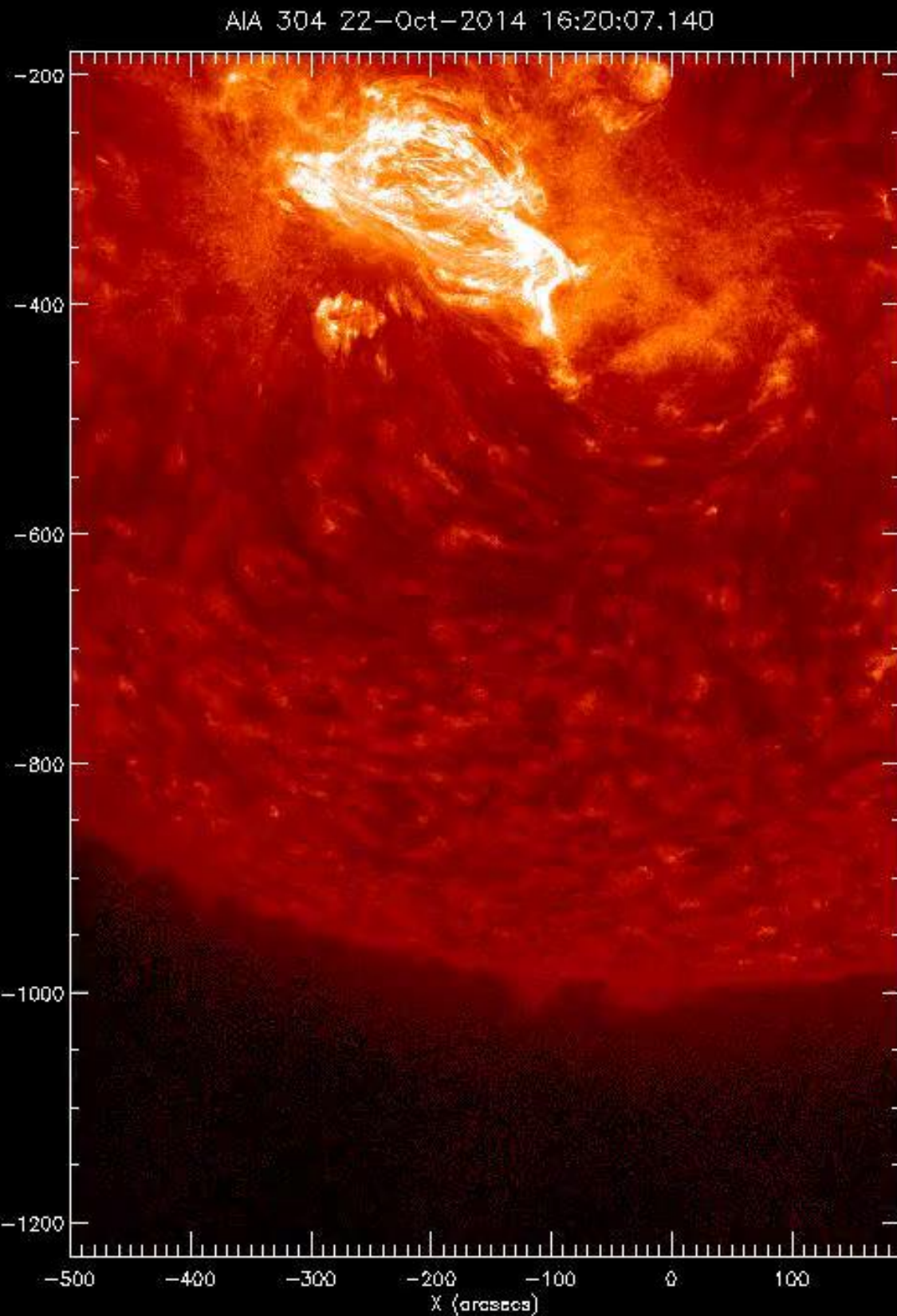
^d Much or most of this emission is from a different active region, AR 11514 (S17E18).

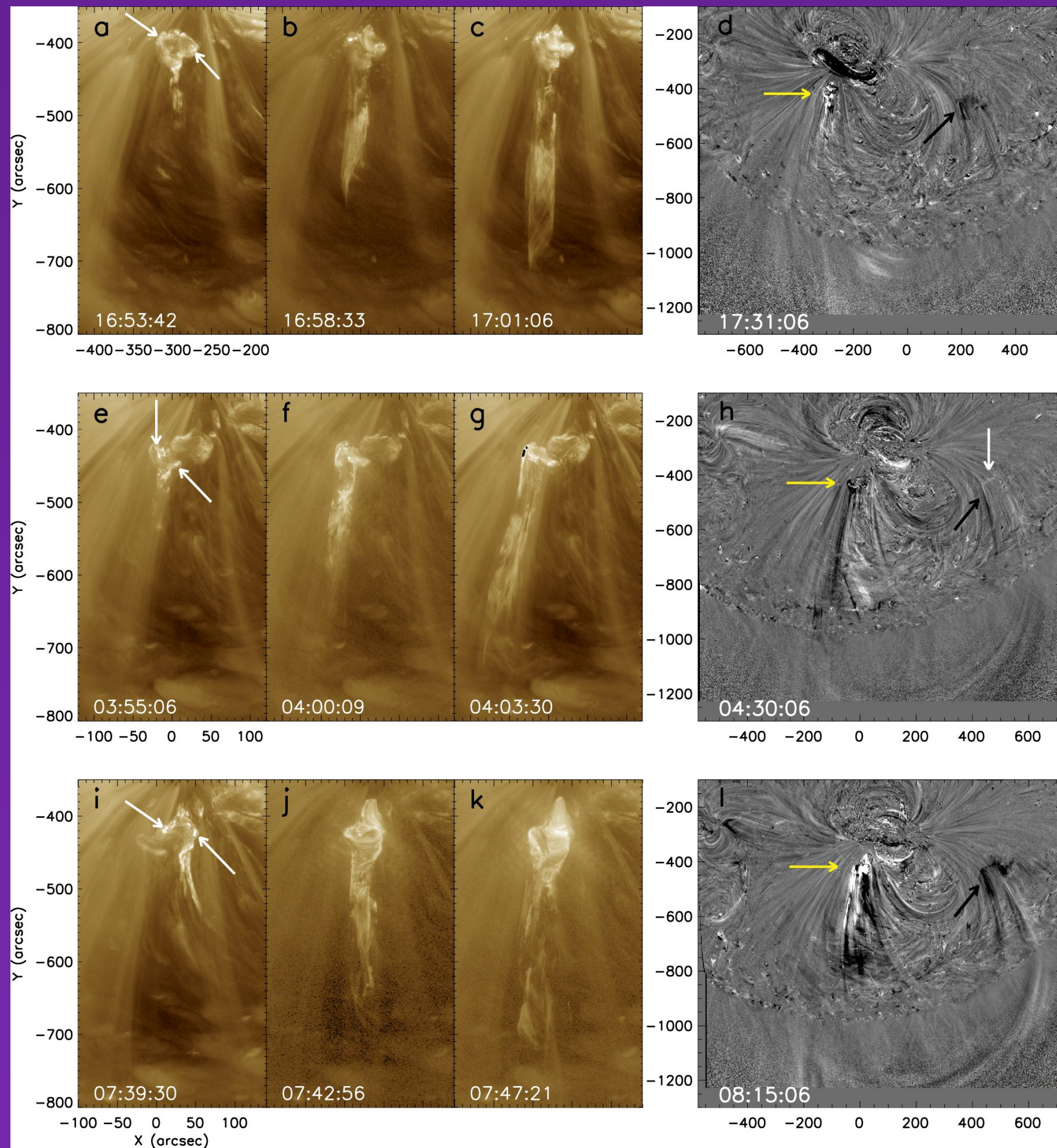
Most of AR jets made/likely made narrow CMEs/WLJs (width $\lesssim 10^\circ$).
 (NB. Event 3 is a large-scale eruption; Event 4 is a surge/jet.)

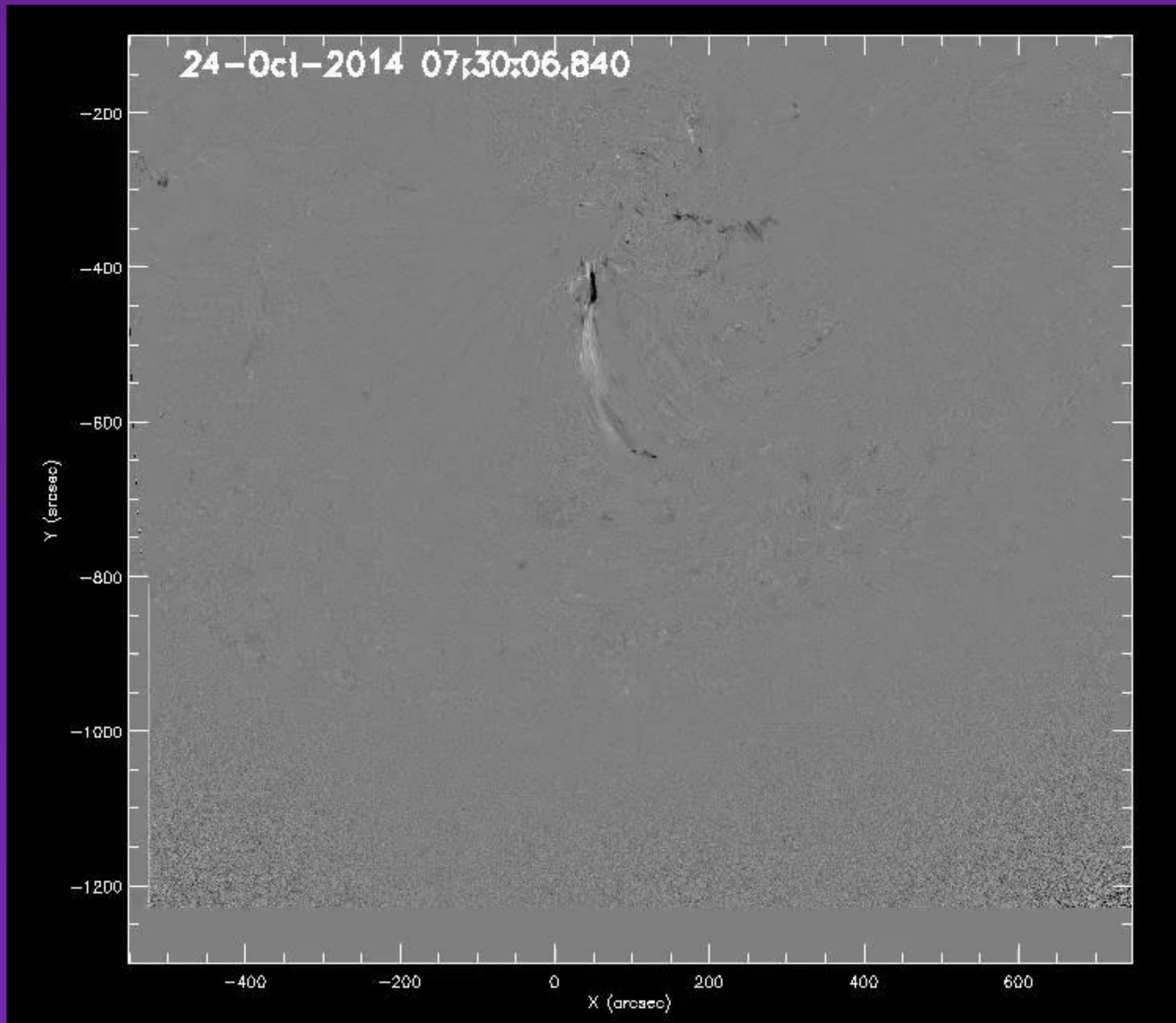
(Wide) CMEs from AR Jets

Panesar et al. (2016a)

“Weak” CMEs from AR 12192







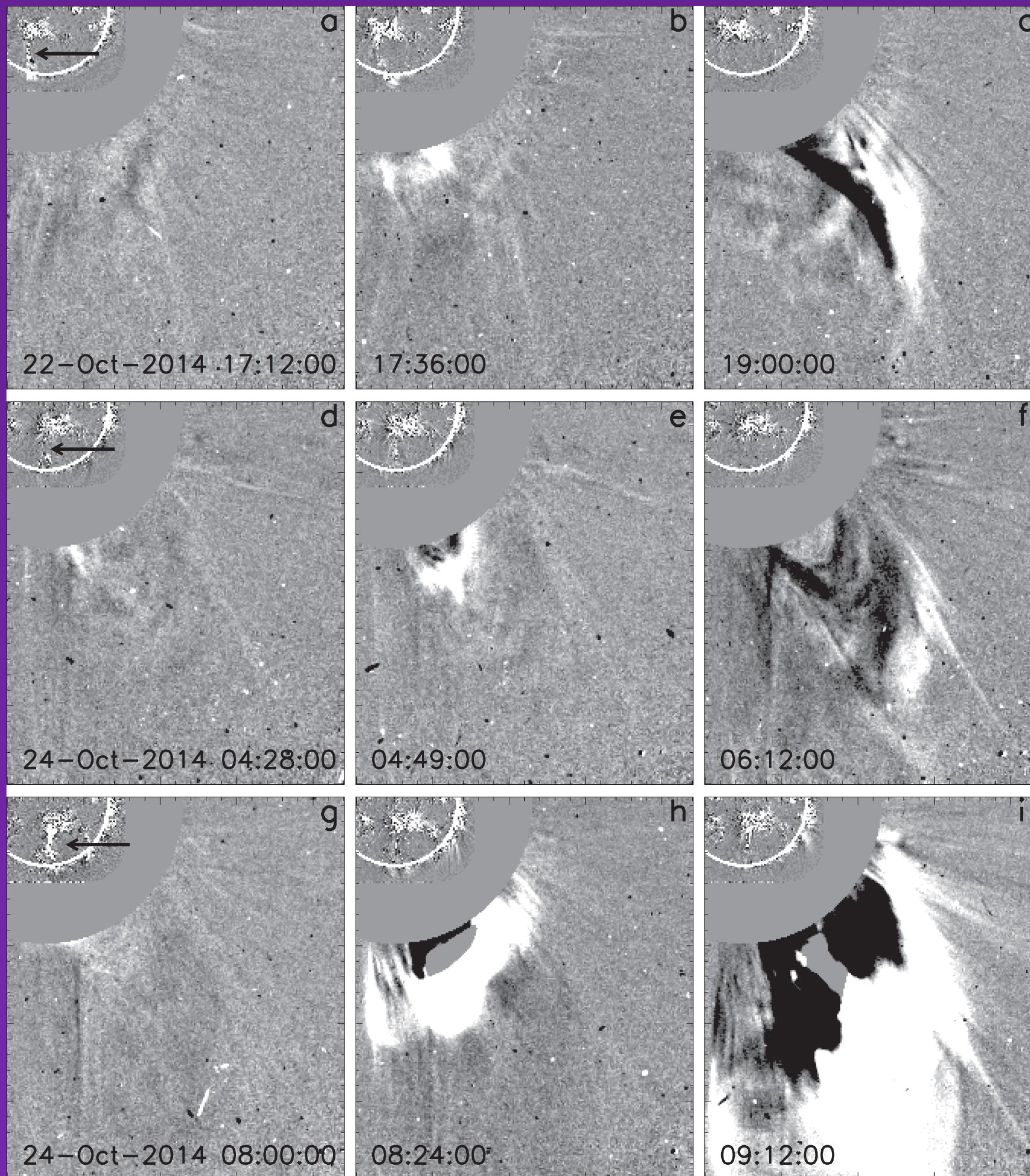


Table 1
Date and Time for the Observed Jets and Their Measured Parameters

(a) CME-producing Jets									
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 minute)	Jet Width ^e (±1500 km)	Remote Bri. and Dim.
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	...

Notes.

^a <ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/2014/>

^b http://cdaw.gsfc.nasa.gov/CME_list

^c Uncertainty in the CMEs speed measurement is less than 10% (Yashiro et al. 2004).

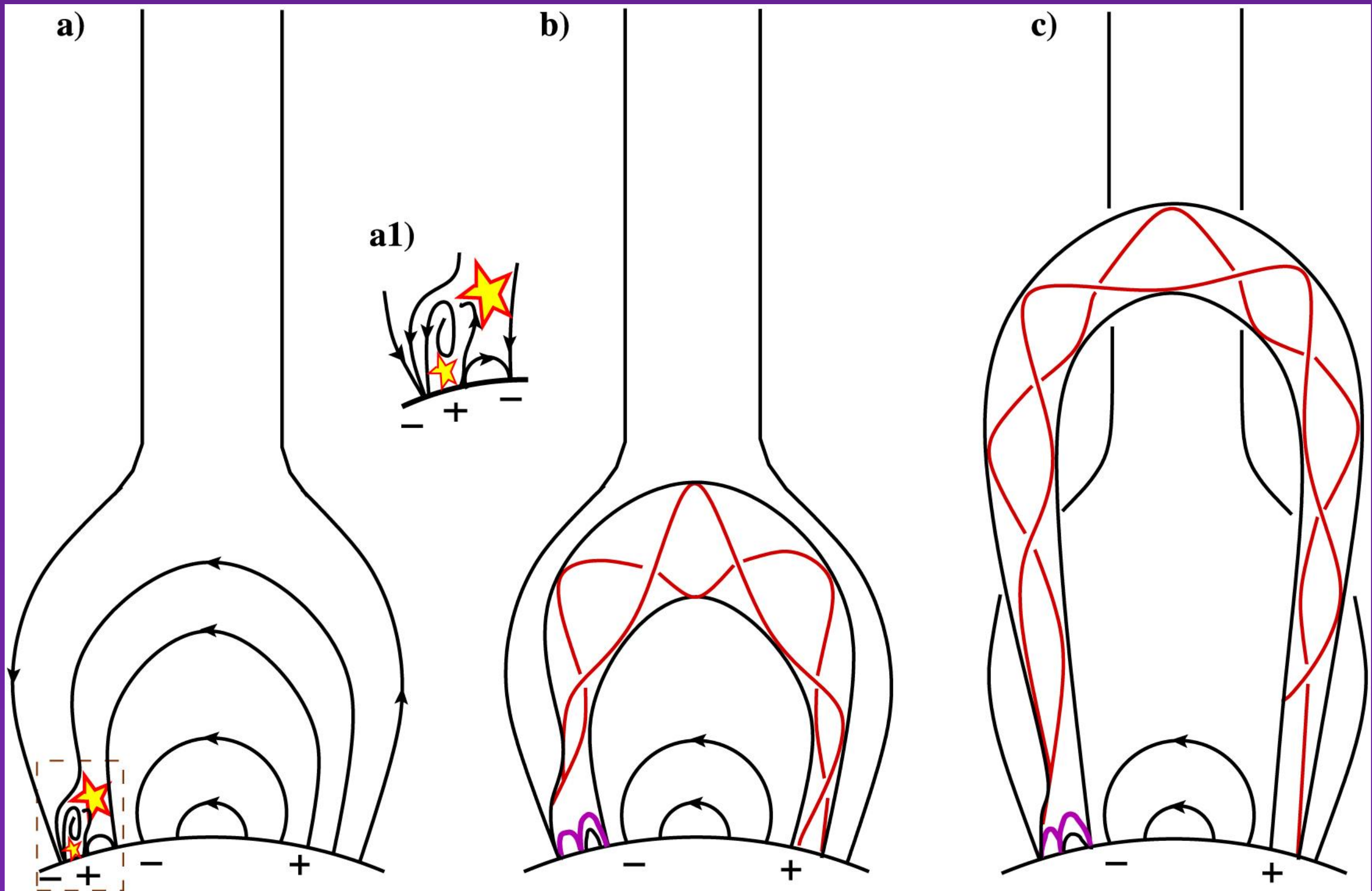
^d Uncertainties are estimated from the time–distance plots.

^e Measured at a projected height of ~72,000 km from jet base.

^f This jet shows up well in the AIA 94 Å images, but not in 304 Å images. Due to its poor visibility in 304 Å images, we were unable to follow the jet plasma well enough to measure its speed.

^g AR was close to the west limb, obscuring any remote brightening/dimming.

^h Slower velocity (250 km s⁻¹) in the beginning, but faster (>650 km s⁻¹) later when a plug of plasma separates.



(Update to Bemporad et al. 2005 picture of “streamer puff” CMEs.)