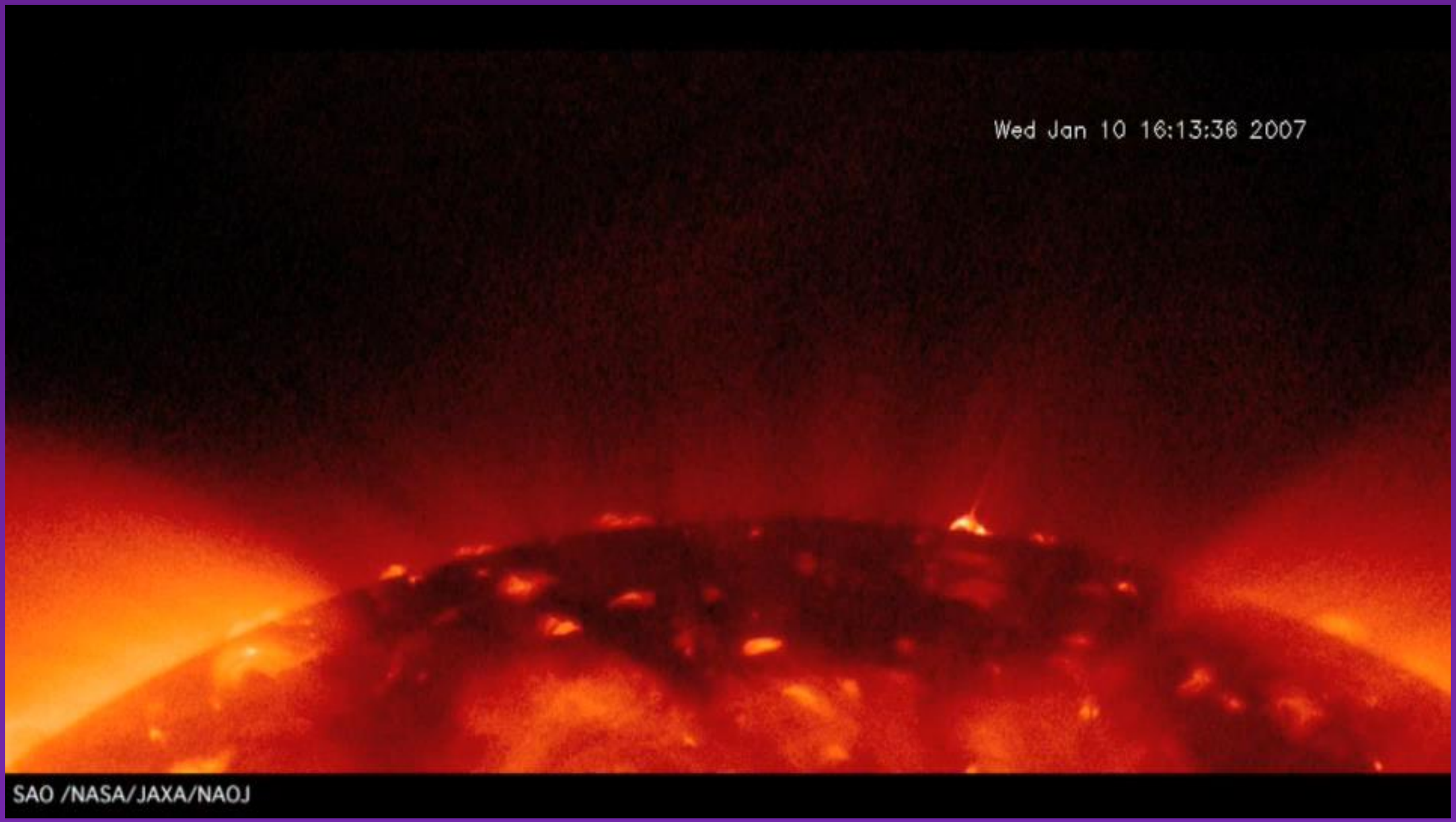
Solar Coronal Jets and Jet-like Features: Some Recent Investigations

Alphonse C. Sterling

Supported by NASA's HSR and HGR programs, and the MSFC/Hinode project.

Coronal Jets



Cirtain et al. (2007)

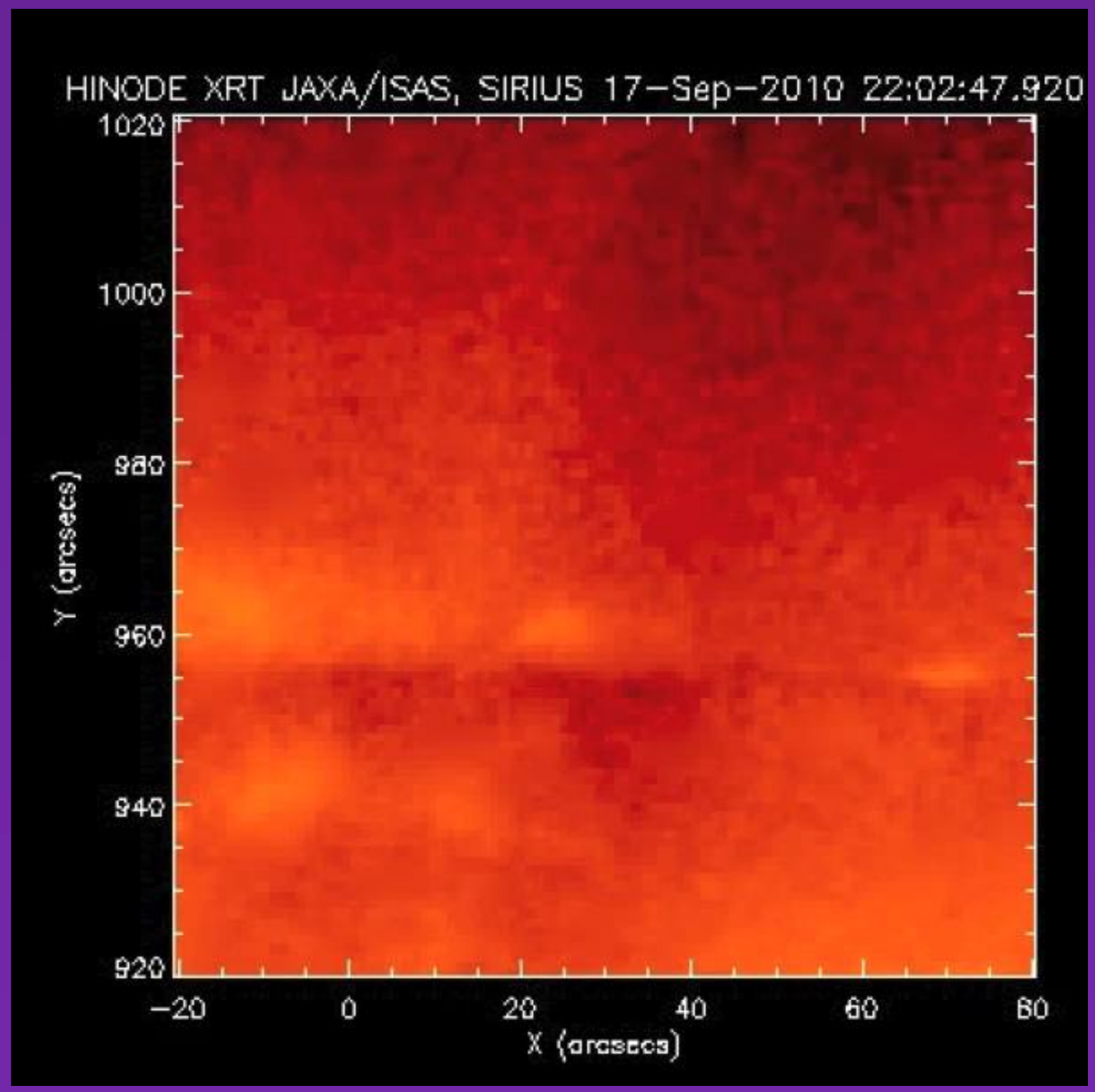
Introduction: Solar Coronal Jets

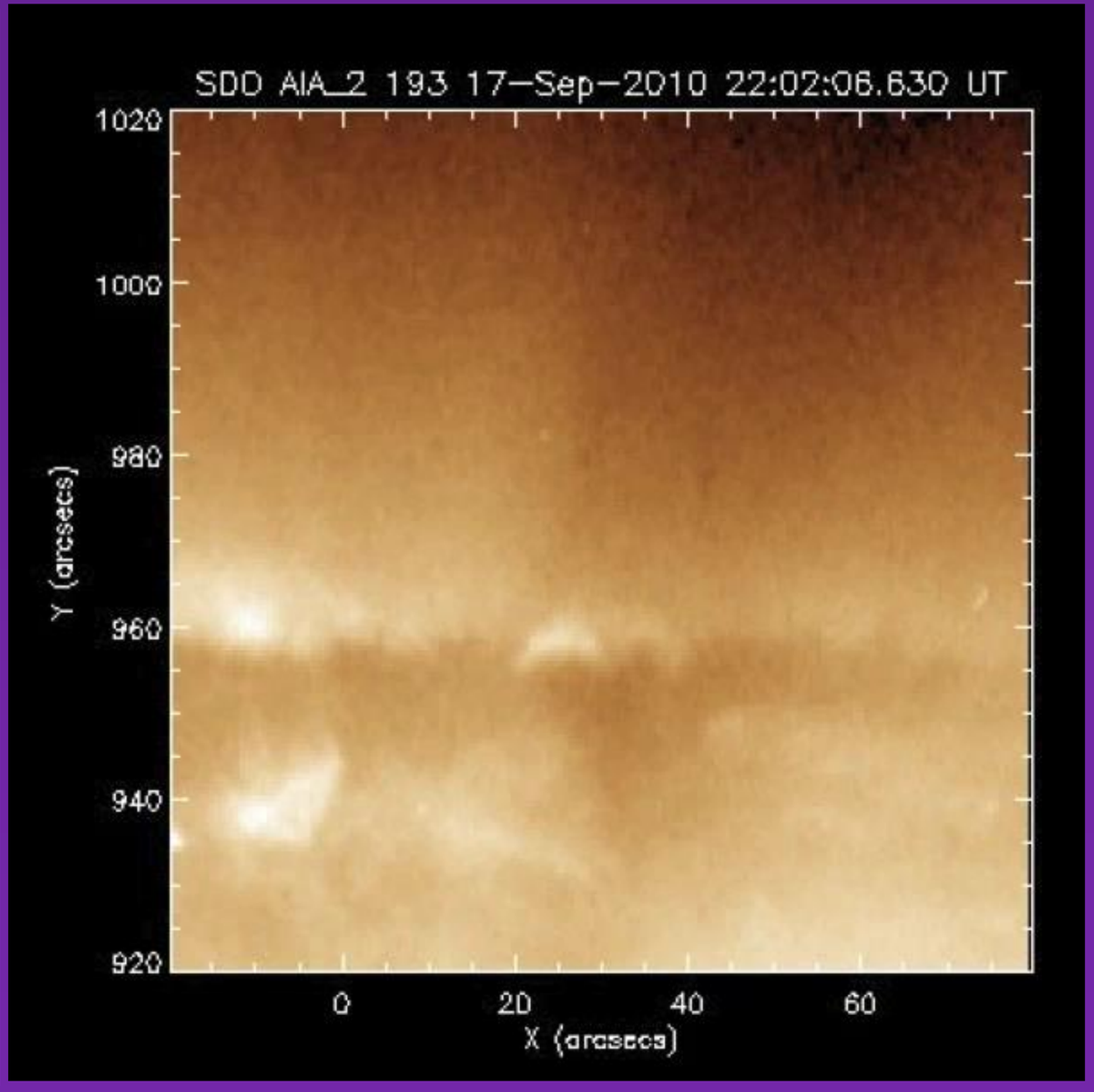
- Observed since the Yohkoh days (Shibata et al. 1992; also Shimojo et al. 1996, etc.) (Reviewed by Raouafi et al. 2016; Hinode Review (Sterling) 2019; Shen 2021.)
- Yohkoh (SXT) saw them mainly in active regions.
- Hinode/XRT found them to be plentiful in polar coronal holes (Cirtain et al. 2007; also Savcheva et al. 2007, etc.)
- Stereo EUVI+coronagraph (Nisticò et al. 2009, 2015).
- In polar coronal holes: size ~50,000 km x 8000 km; rate ~60/day (Savcheva et al. 2007).
- Often have a "hot loop" at the jet's base.
- Jets often display spinning (untwisting?) motions, both visually and spectroscopically (e.g., Pike & Mason 1998).

Coronal Hole Jets: "Minifilament eruptions"

XRT

AIA 193

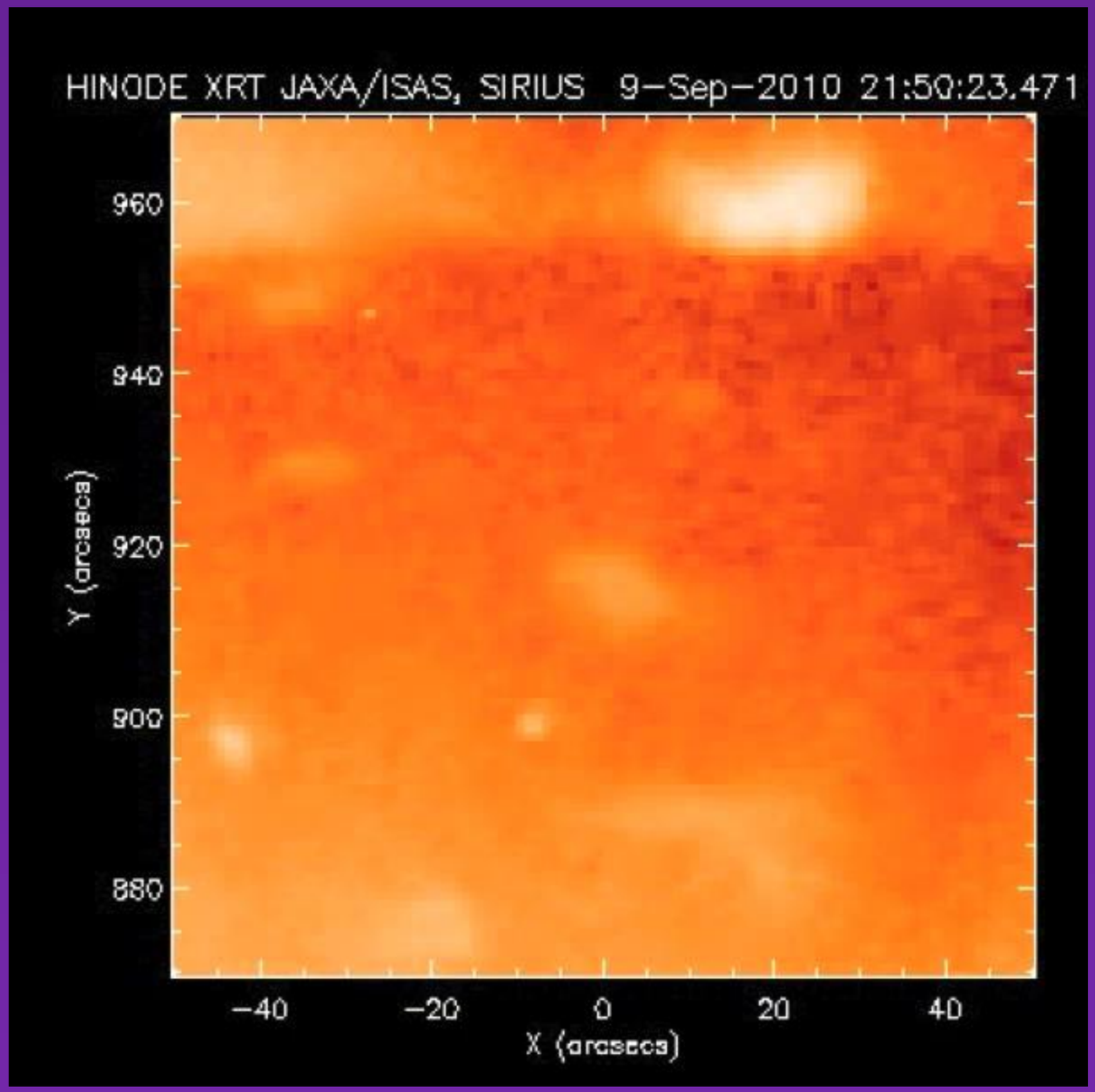


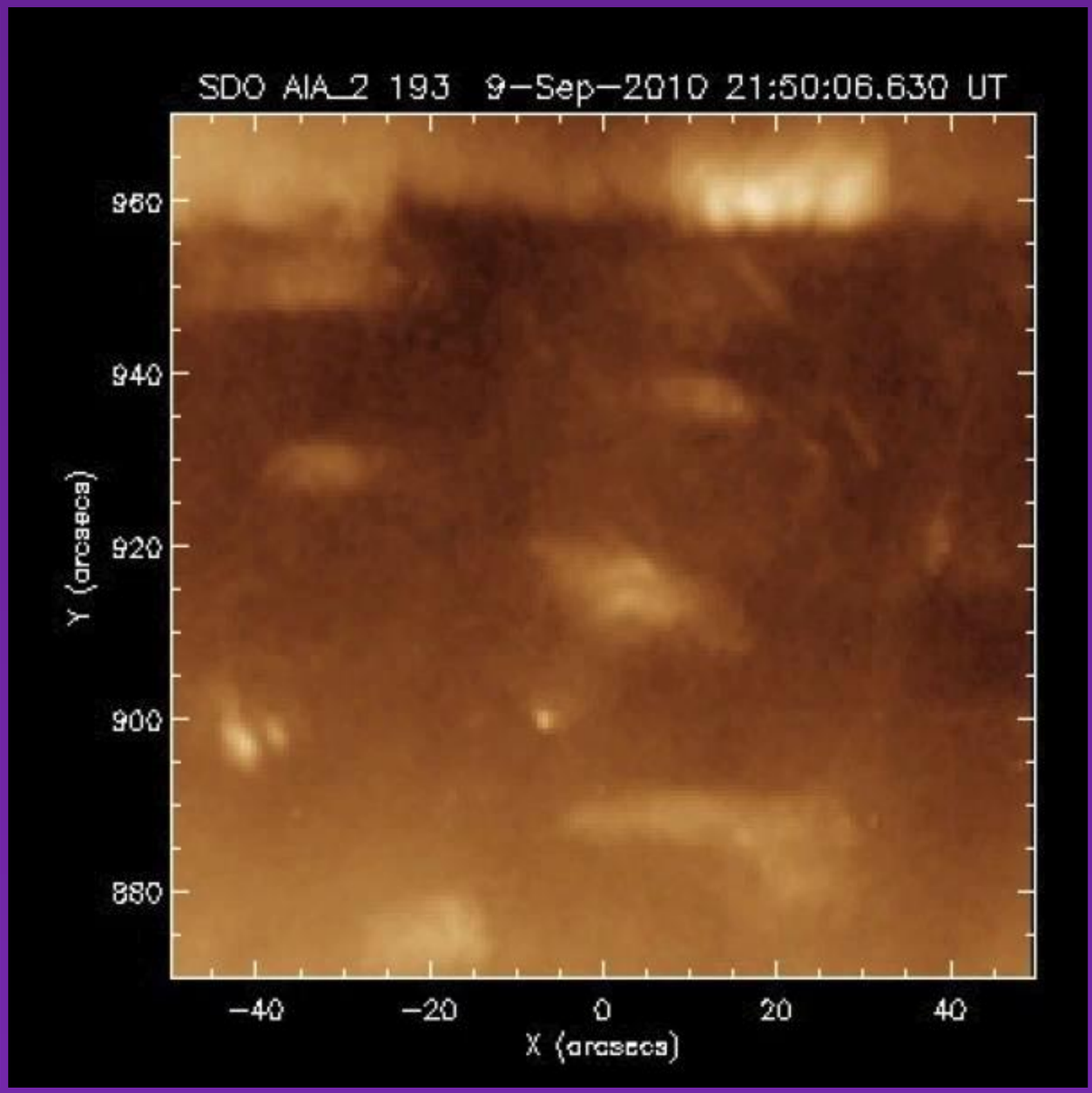


Sterling et al. (Nature, 2015): 20 Polar CH jets.

XRT

AIA 193

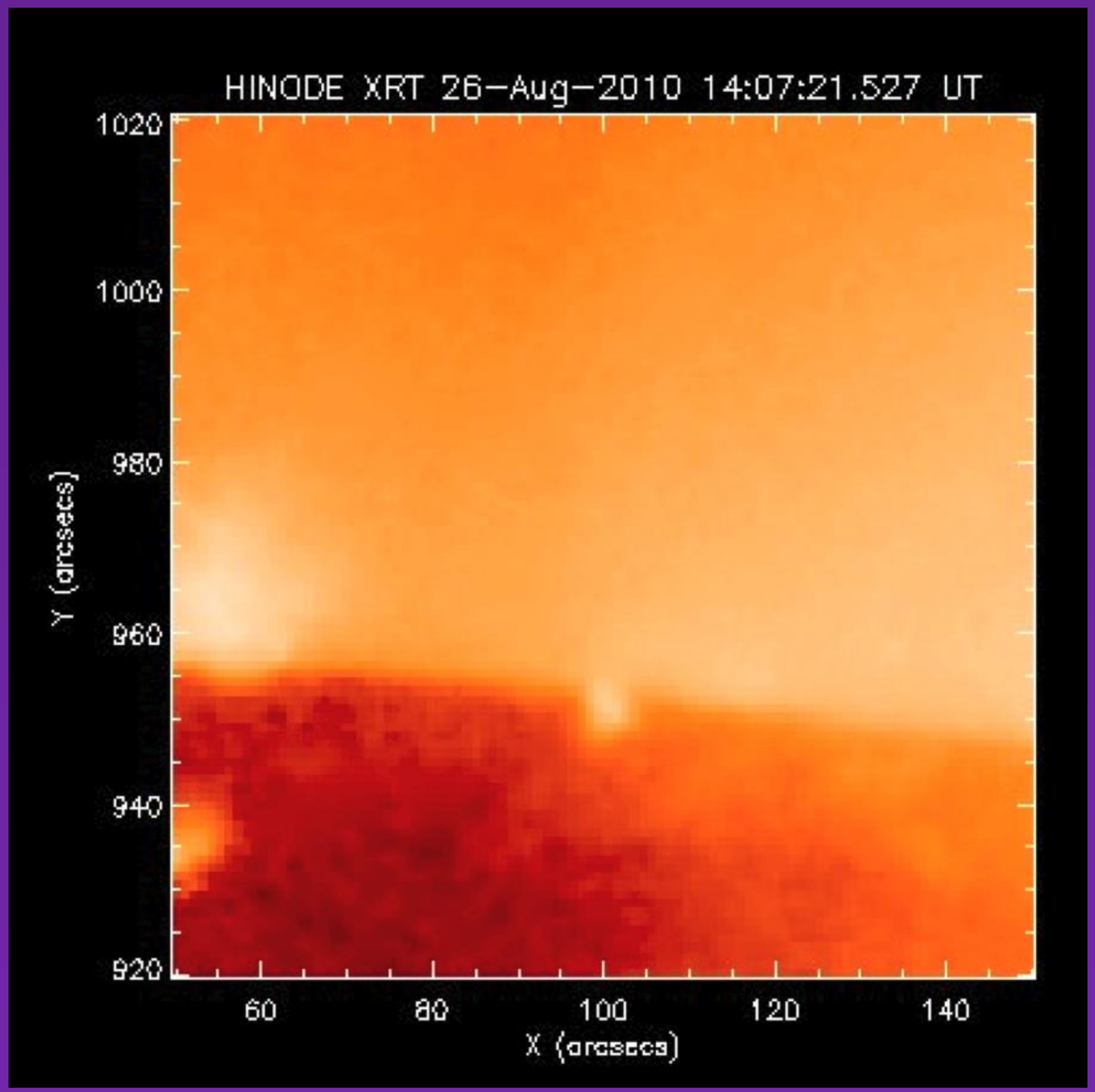


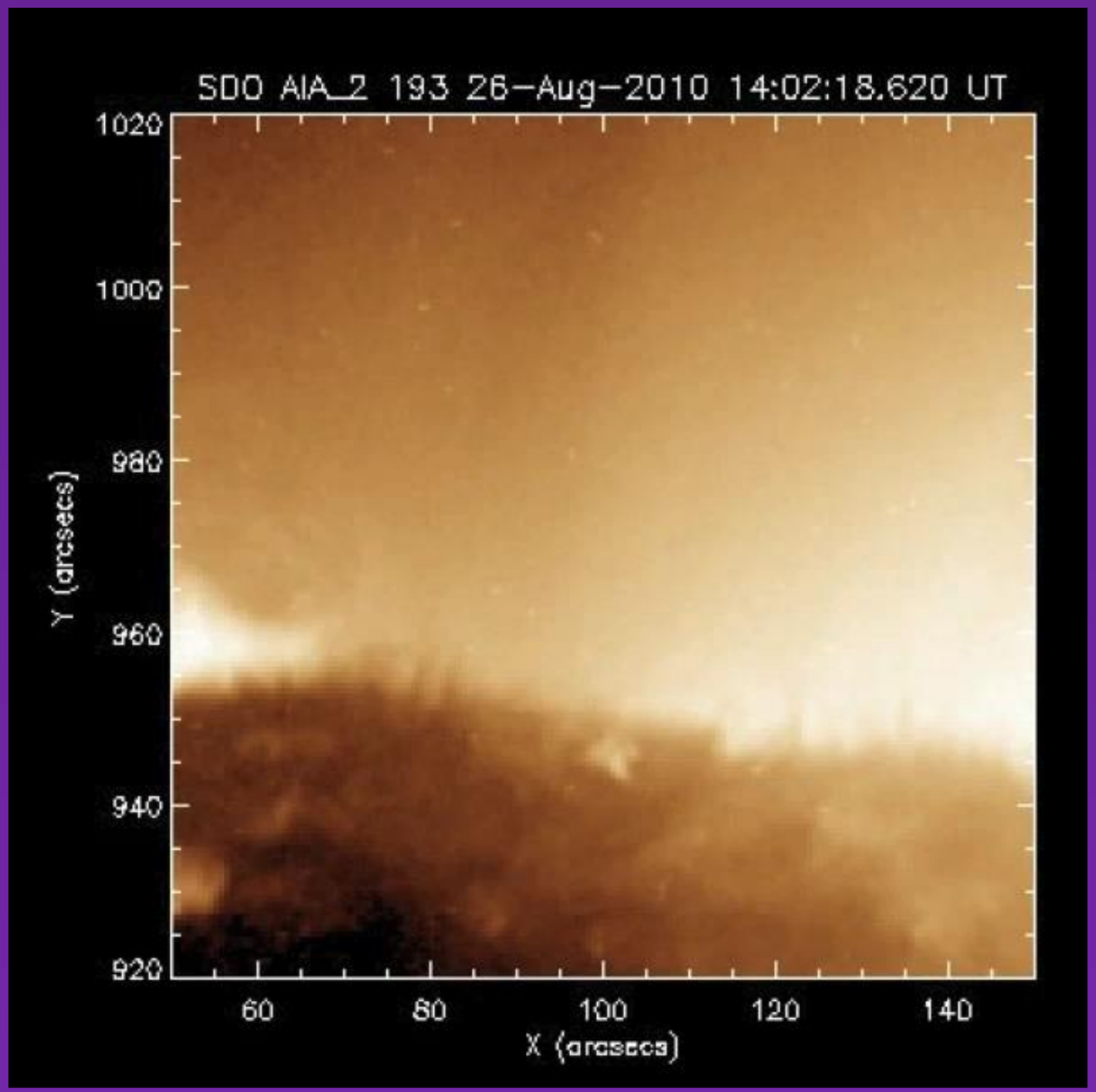


Event 12

XRT

AIA 193





Event 3

“Normal” Filament Eruption (TRACE)

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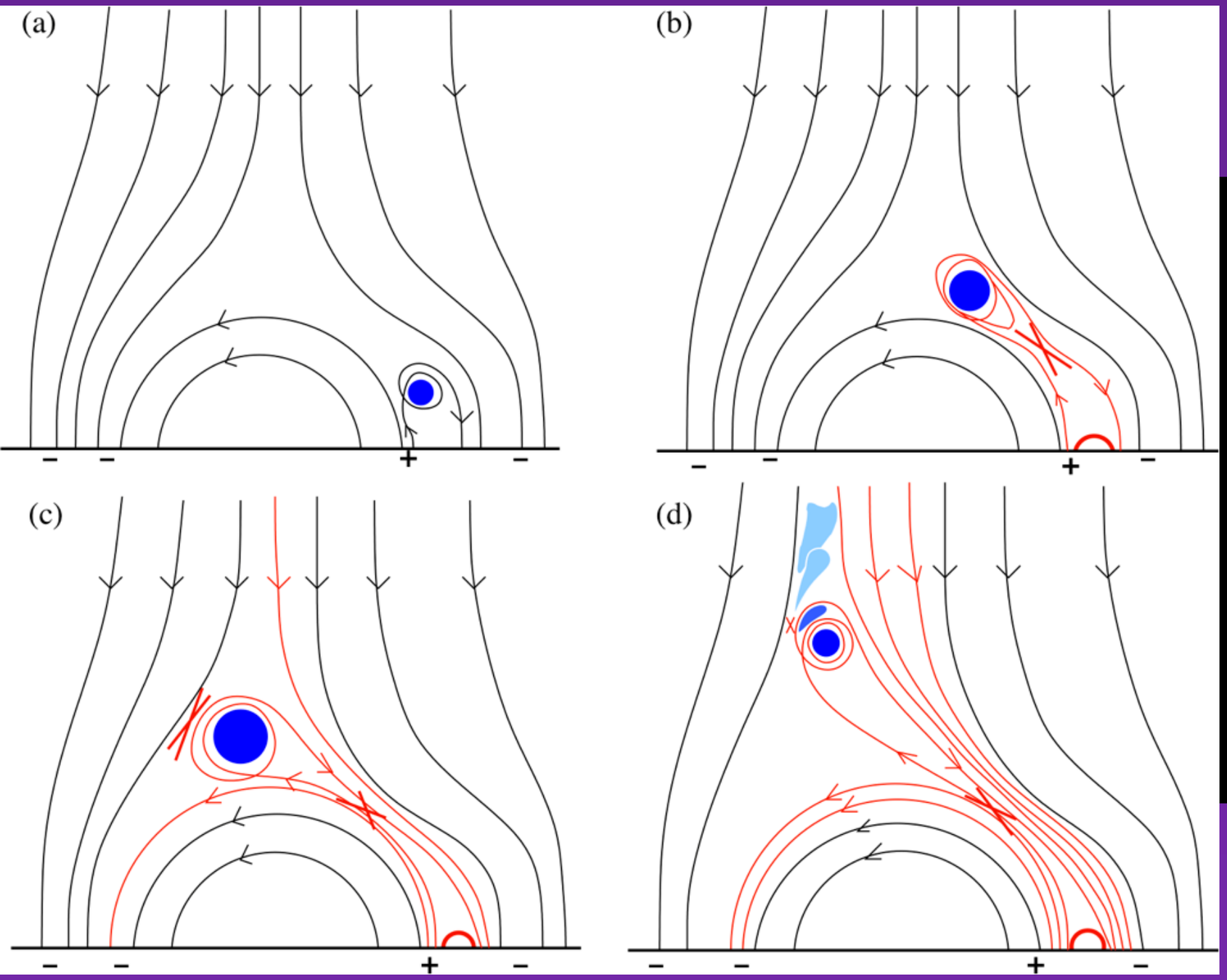
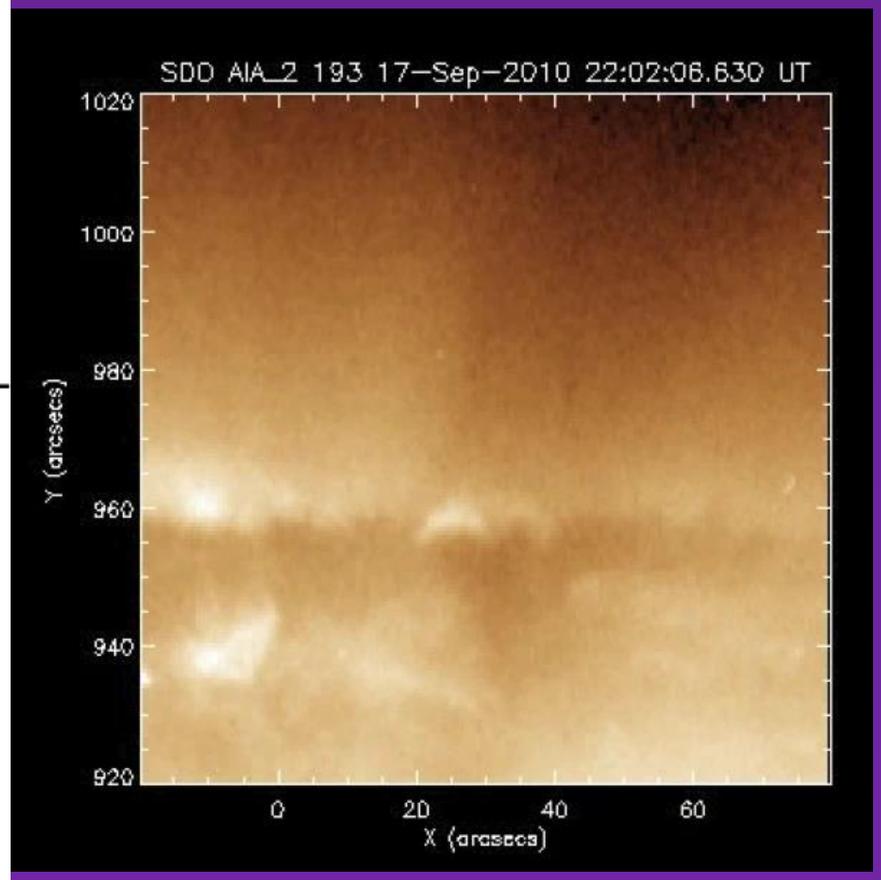
Minifilament-Eruption Model for (X-Ray) Jets





Sterling et al. (2015, 2016, 2017)

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

Modeled by Wyper et al. 2017, 2018)

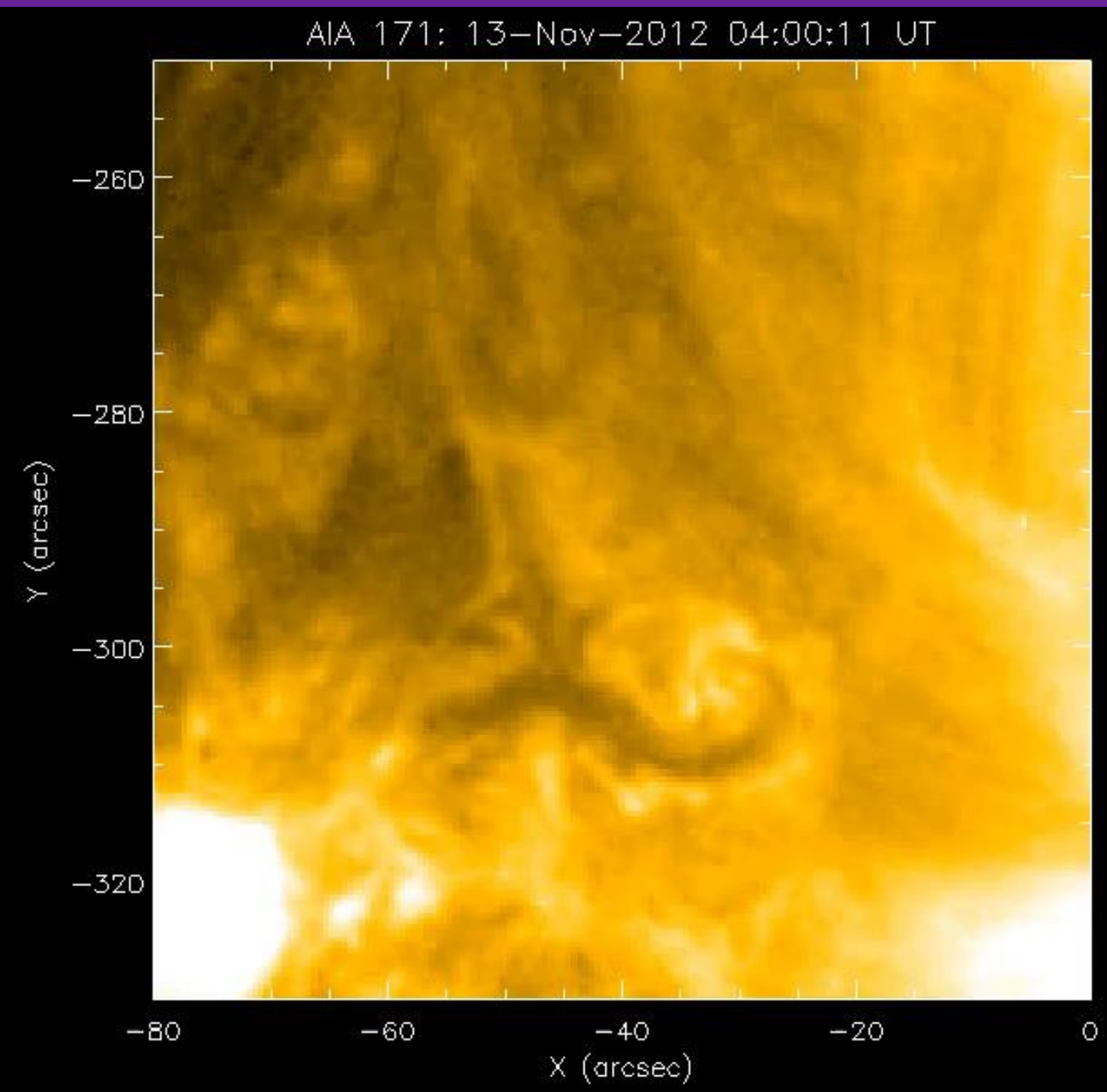
What Causes Miniature-Filament Eruptions?

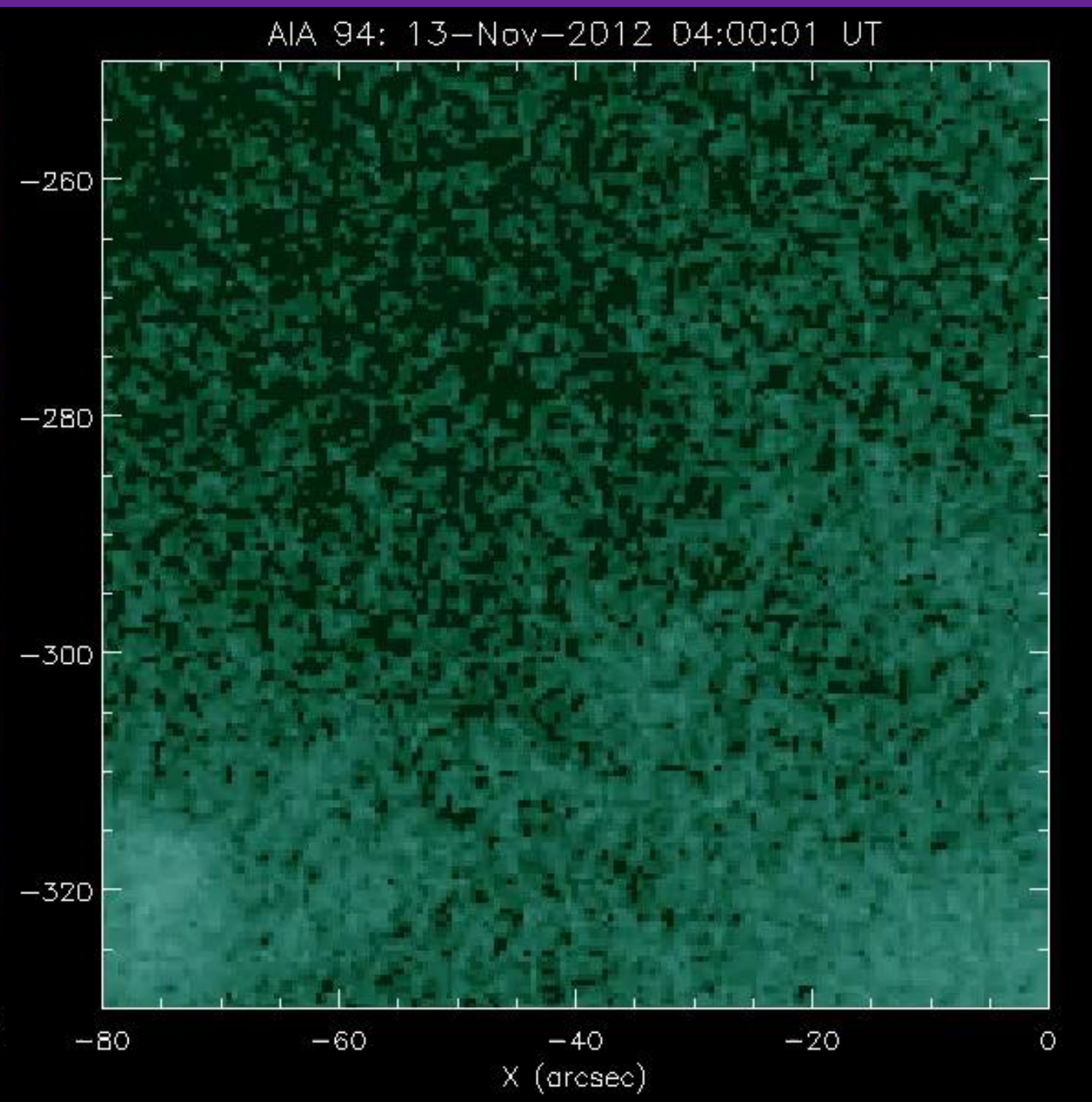
- Did not look on-disk in this study, due to polar view. But….
- Adams et al. (2014) found no emerging flux in the jet region. Filament erupted from location where flux canceled. (Also, Hong et al. 2014.)
- Several other found cancelation leading to jets (e.g., Hong et al. 2011; Huang et al. 2012; Young & Muglach 2014a,b).
- Some others found jets from location of emerging flux+flux cancelation (e.g., Liu et al. 2011; Shen et al. 2012, 2017; Hong et al. 2012; Li et al. 2015).

Quiet Sun Jets — Similar to PCH jets

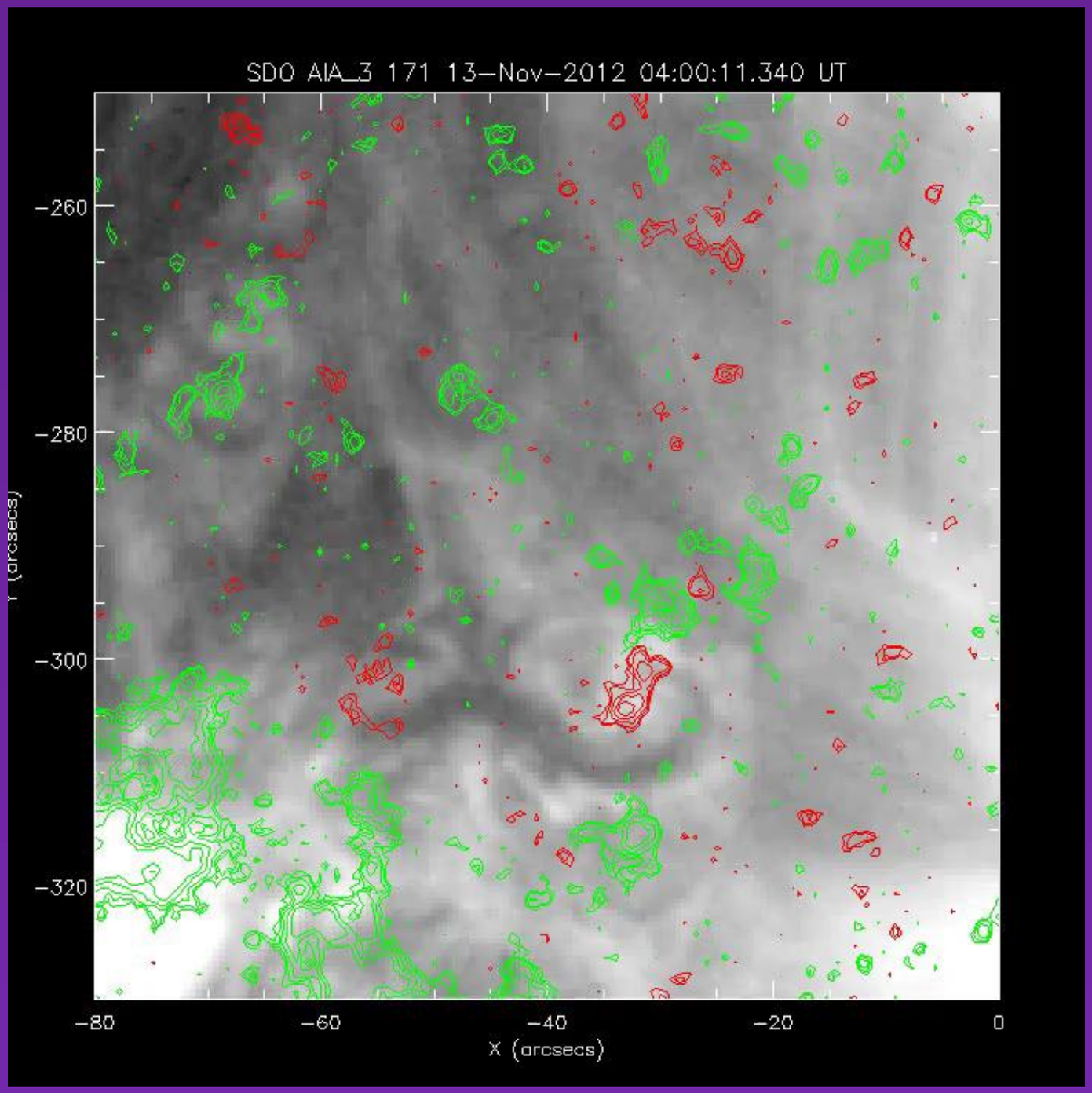
AIA 171

AIA 94





(Panesar et al. 2016b)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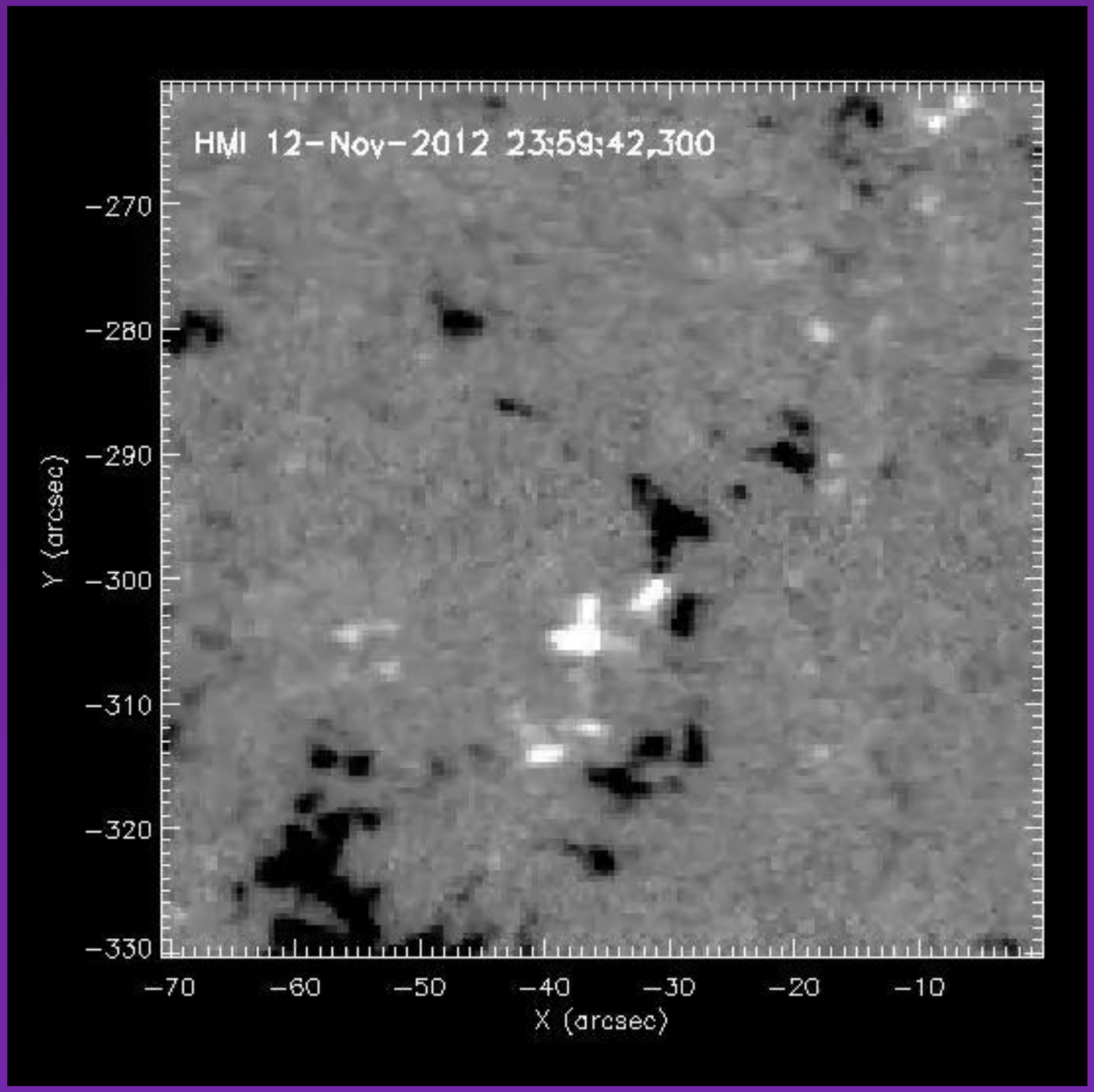
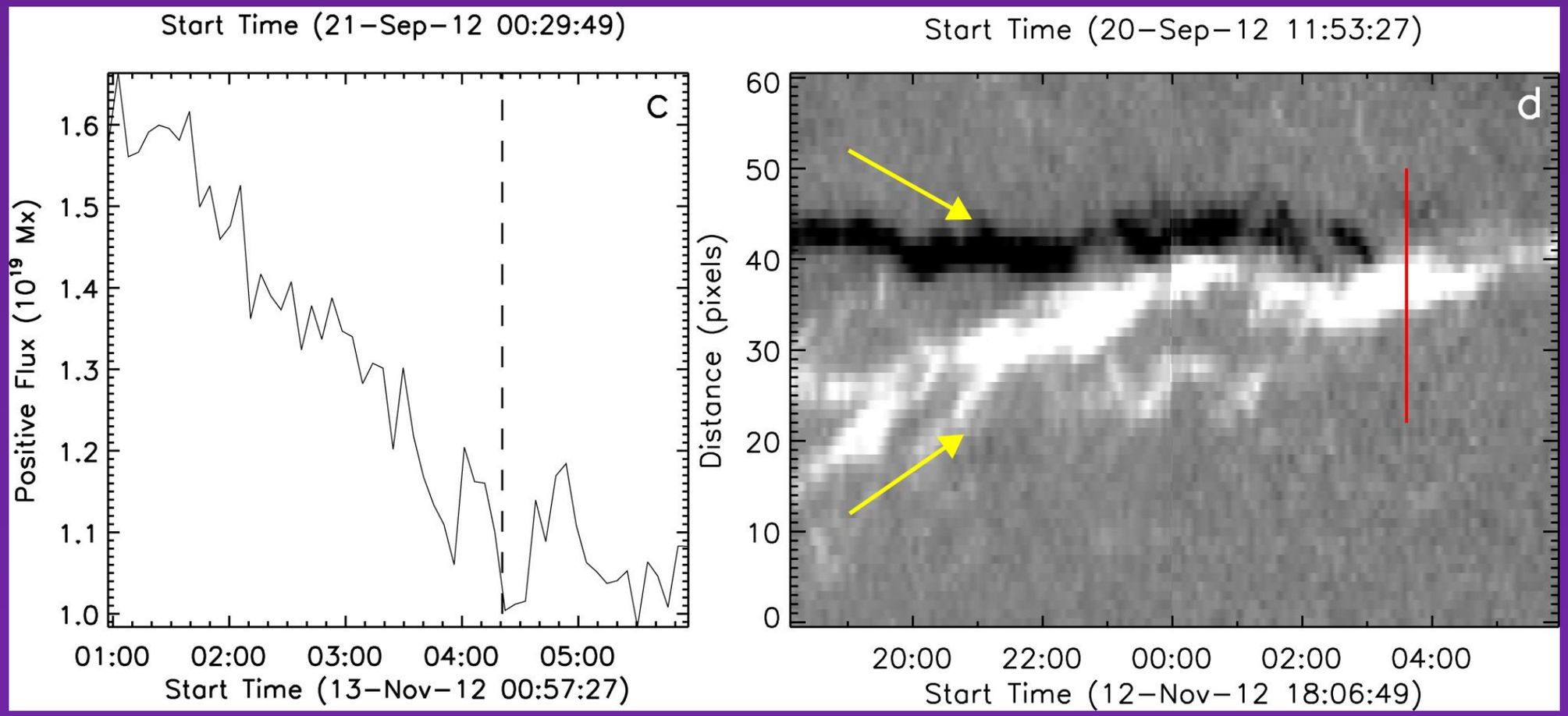
X (arcsecs)



Panesar et al. (2016)

Same for QS jets: Occur at cancelation sites.



(Ave. Cancelation rate: ~10^{18} Mx/hr.)

Panesar, Sterling, & Moore (2016b)

Large-ish Studies of Quiet Regions and Coronal Hole Jets:

- Sterling et al. (2015): 20 PCH jets - all have minifilament eruptions.

- Panesar, Sterling, & Moore (2016b): 10 QS jets
- Panesar, Sterling, & Moore (2018): 13 CH jets
  - All due to flux cancelation and minifilament eruptions (relatively large - easy-to-find jets).
- McGlasson et al. (2019) — 60 jets; 30 QS and 30 CHs. 85% consistent with flux cancelation and minifilament eruptions.

- Mulay et al. (2016). 20 AR jets - report 50% with flux cancelation.
- Kumar et al. (2019): 27 on-disk CH jets: 67% with minifilament eruptions, remainder filament-less eruptions; 22% with flux cancelation.

Active Region Coronal Jets

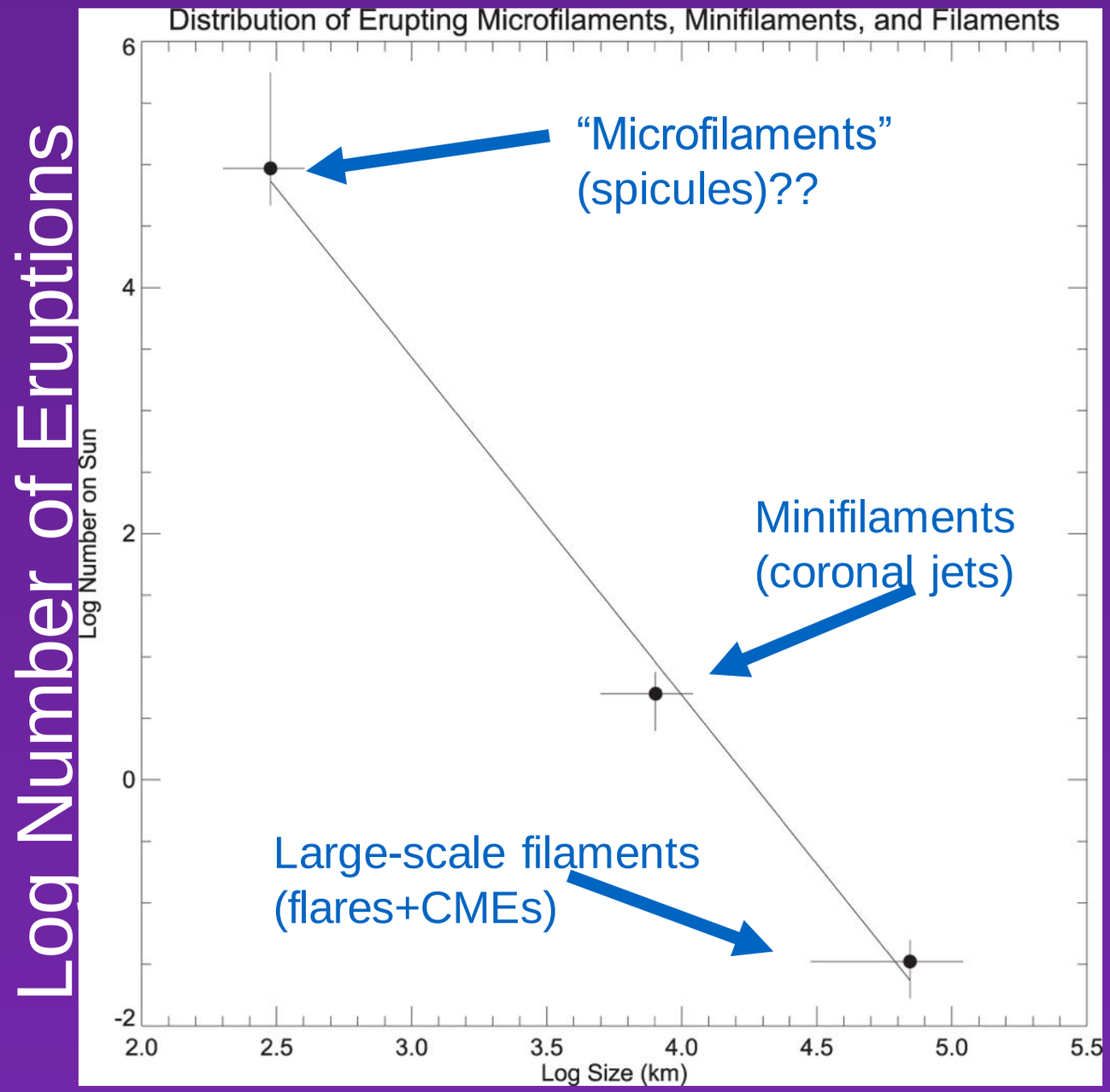
- Yohkoh studies (Shibata et al., Shimojo et al., many others).
- Raouafi et al. (2016).
- Mulay et al. (2016, 2017a, b, 2018) - AR-jet temps/emissions.
- Hong et al. (2017) — Minifil. eruption —> AR jet & Type III burst (also Shen et al. 2017, Moroccan et al. 2017).
- Panesar et al. (2016a); Sterling et al. (2016, 2017).

Current Views Regarding AR Jets

- Some can have different appearance from QS and CH jets.
- The ones we have studied follow the same basic picture: flux cancelation followed by a minifilament eruption that produces the jet.
- Different appearance likely due to complex magnetic environment and stronger fields.
- Some (many?) may have erupting minifilament flux rope, but little or no cool minifilament material.
- Still must study more!

Do Jets Exist on Smaller Size Scales?

Filament-Like Feature Eruptions on Smaller Scales??

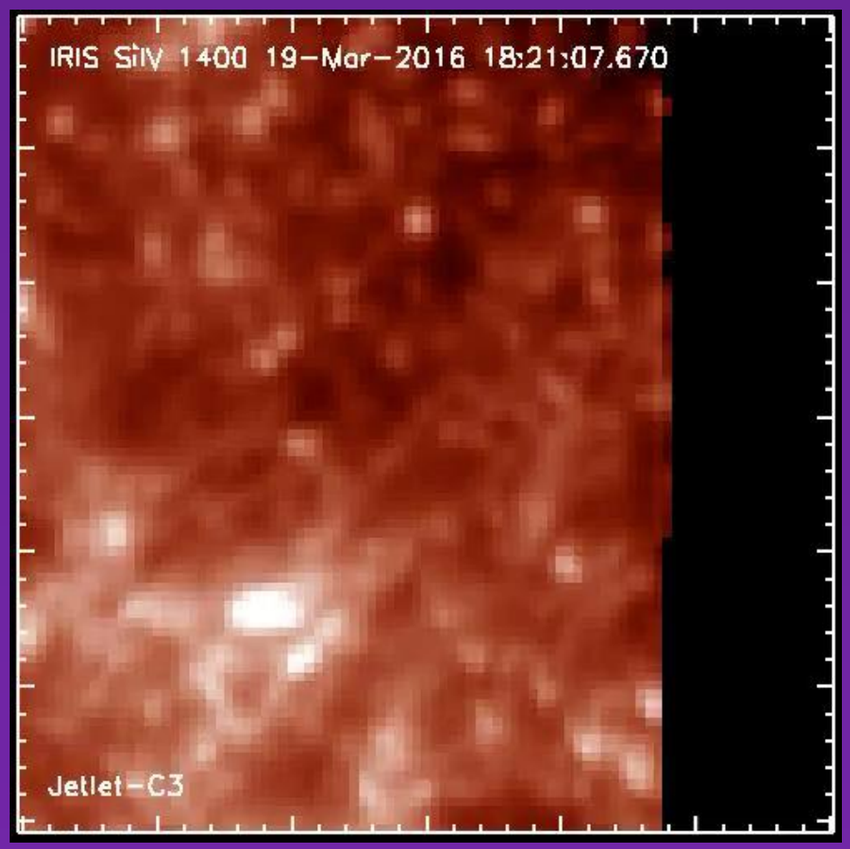


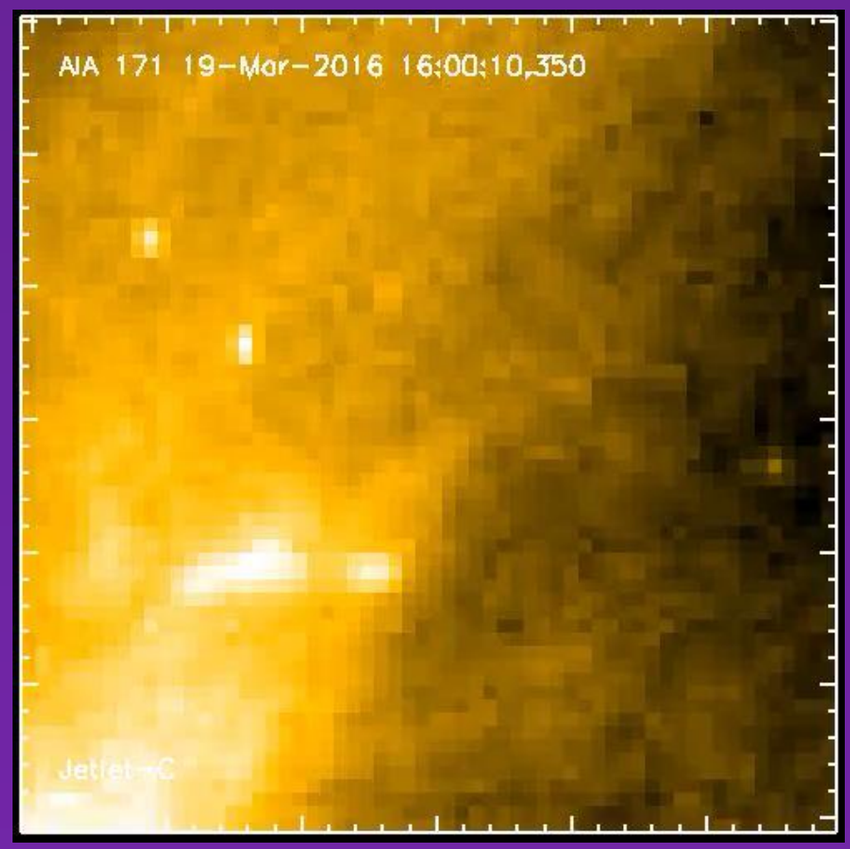
Log "Filament" Size

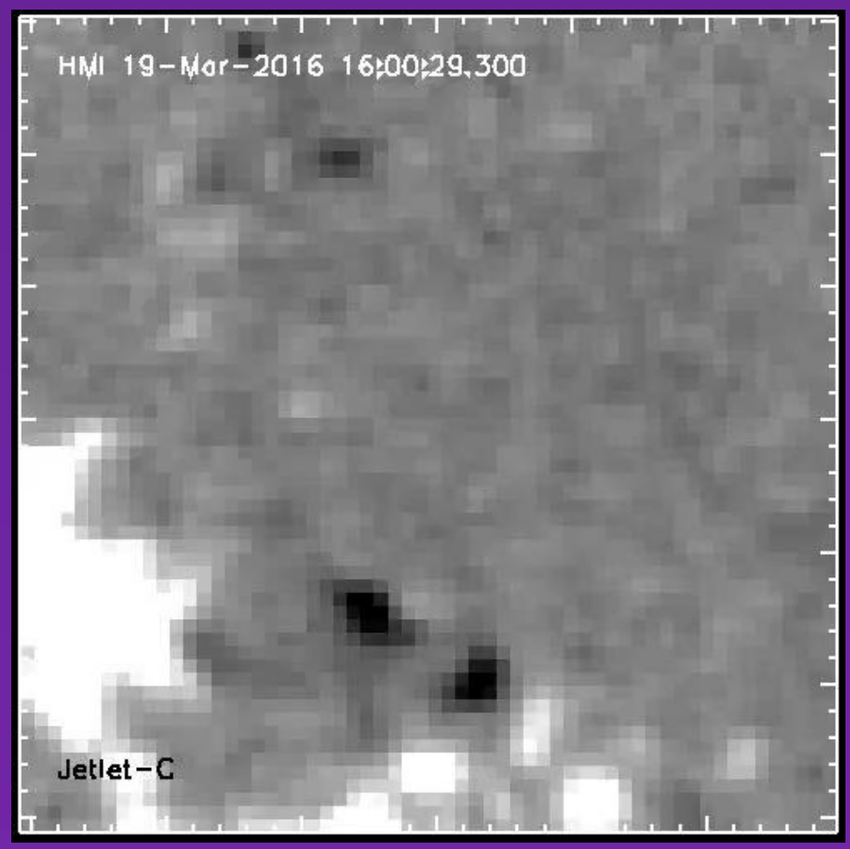
Sterling & Moore (2016)

Jetlets

- Smaller than jets, larger than spicules.
- Seen in EUV, and in UV (IRIS).
- First identified at plume bases (Raouafi & Stenborg 2014).
- Also occur in more general network locations (Panesar et al. 2018, 2019).

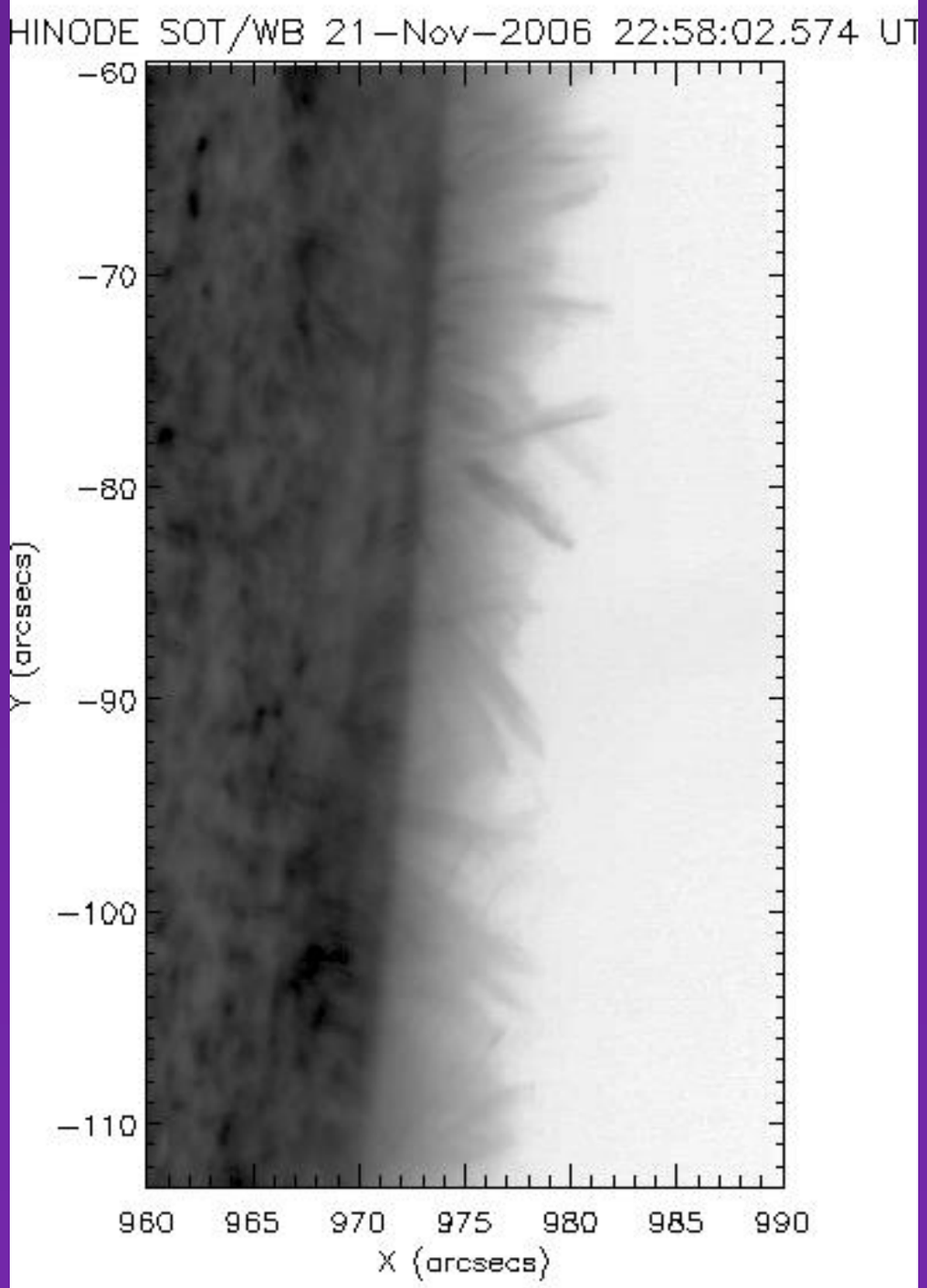




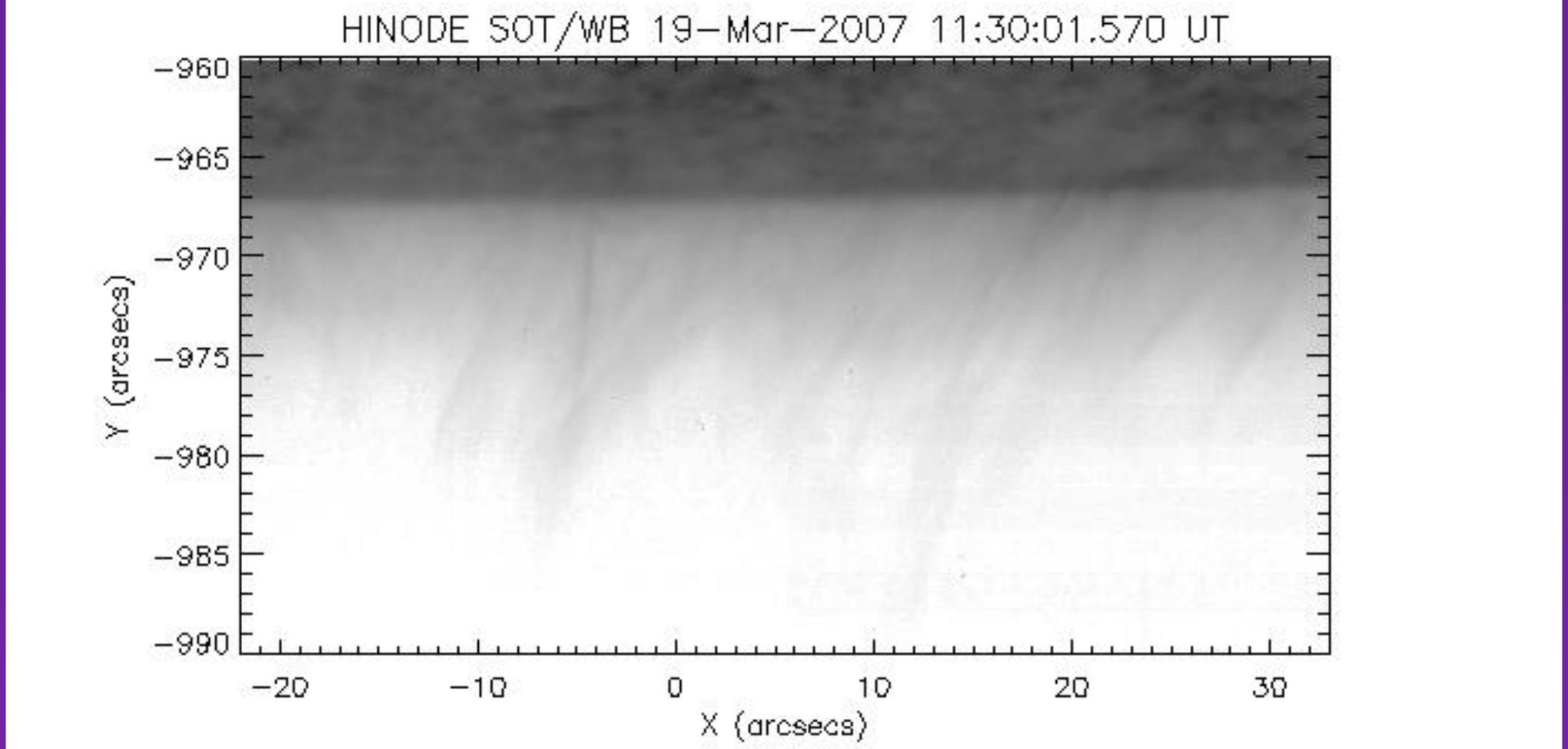


Panesar et al. (2018)

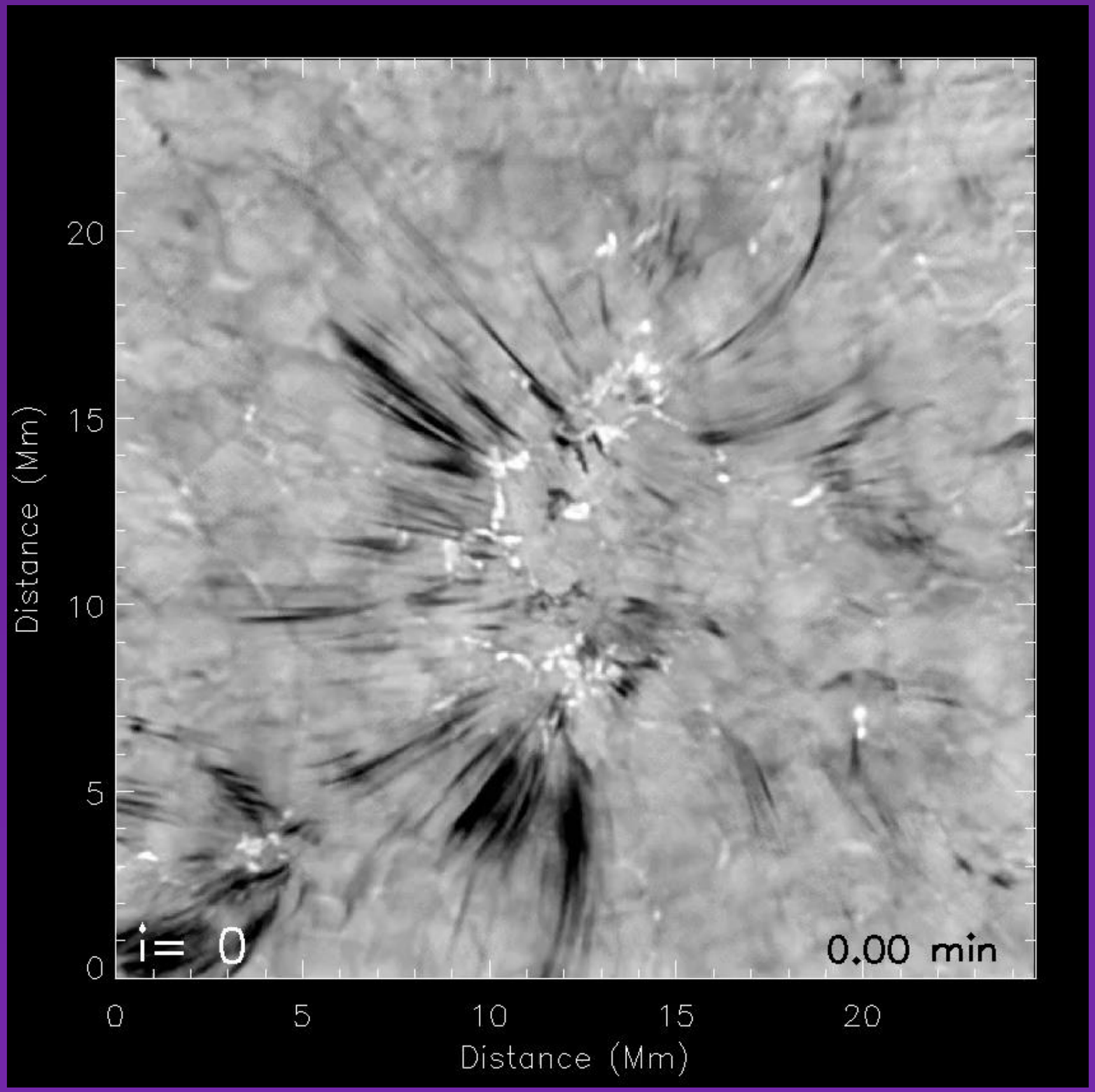
Spicules



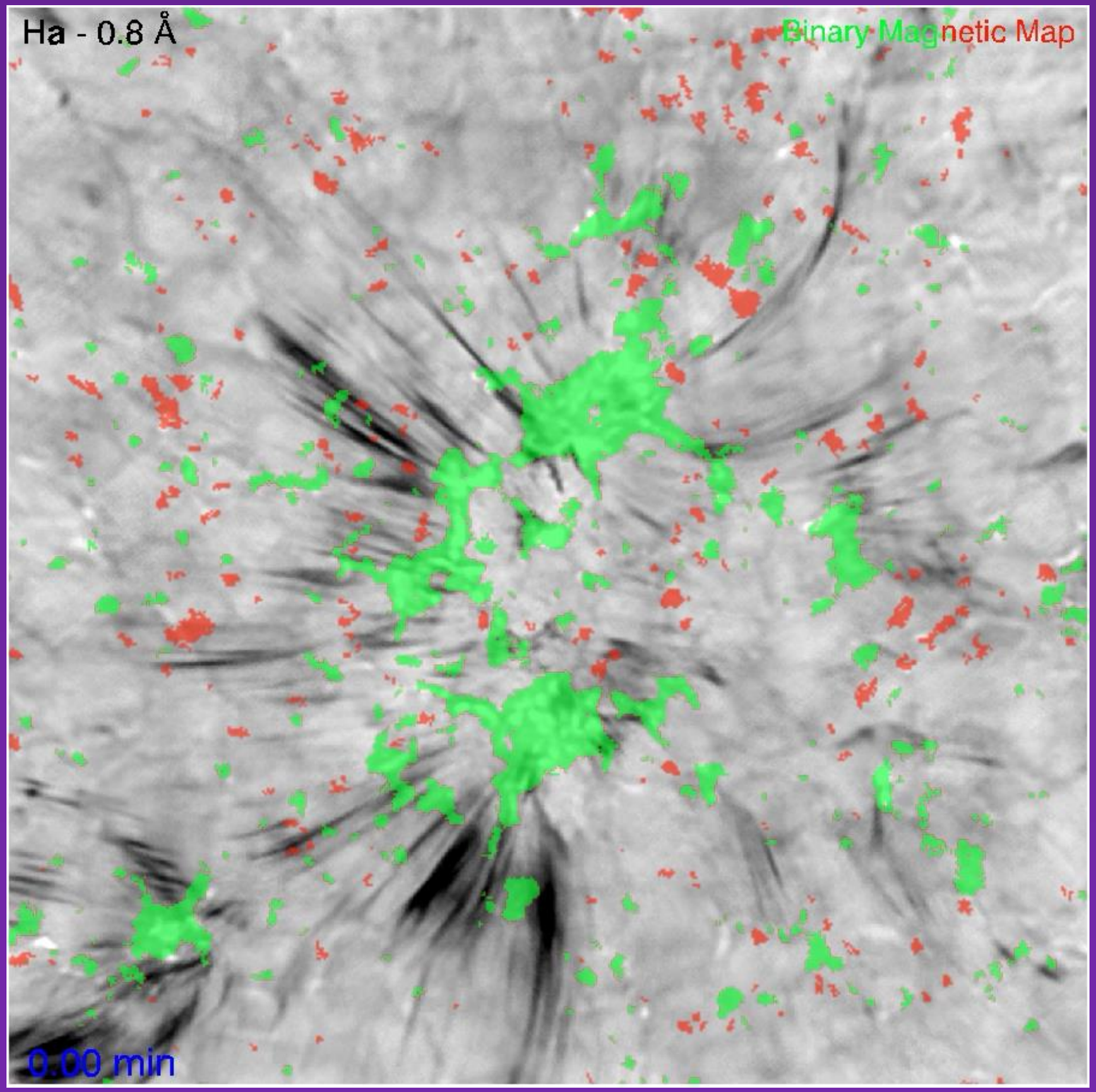
(Sterling 2021; Data set studied in Zhang et al. 2012)



(Data set studied in Pereira et al. 2012)



(Sterling et al. 2020 [Samanta et al 2019])



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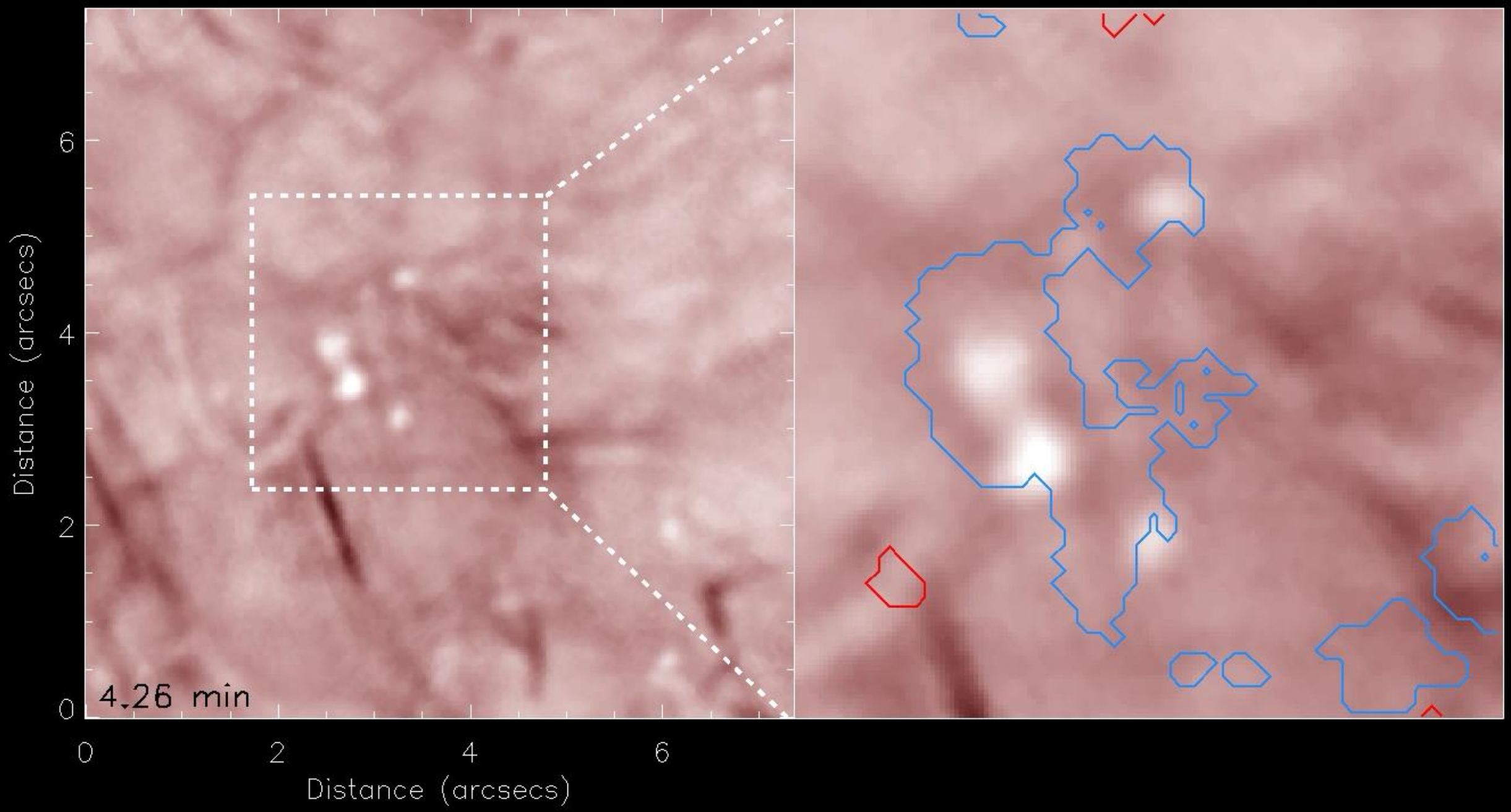
Samanta et al. (2019, Science)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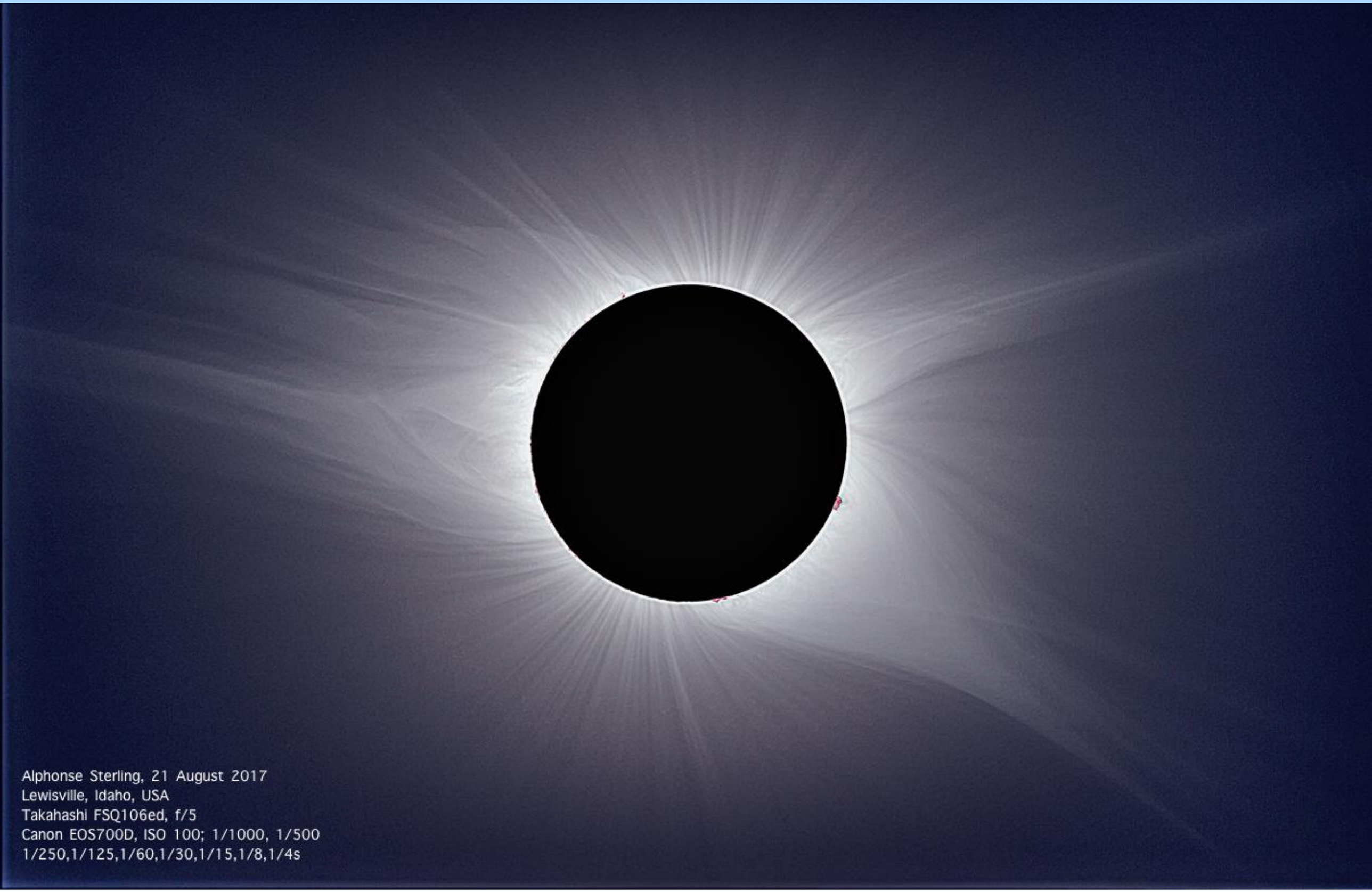
Some Outstanding Questions

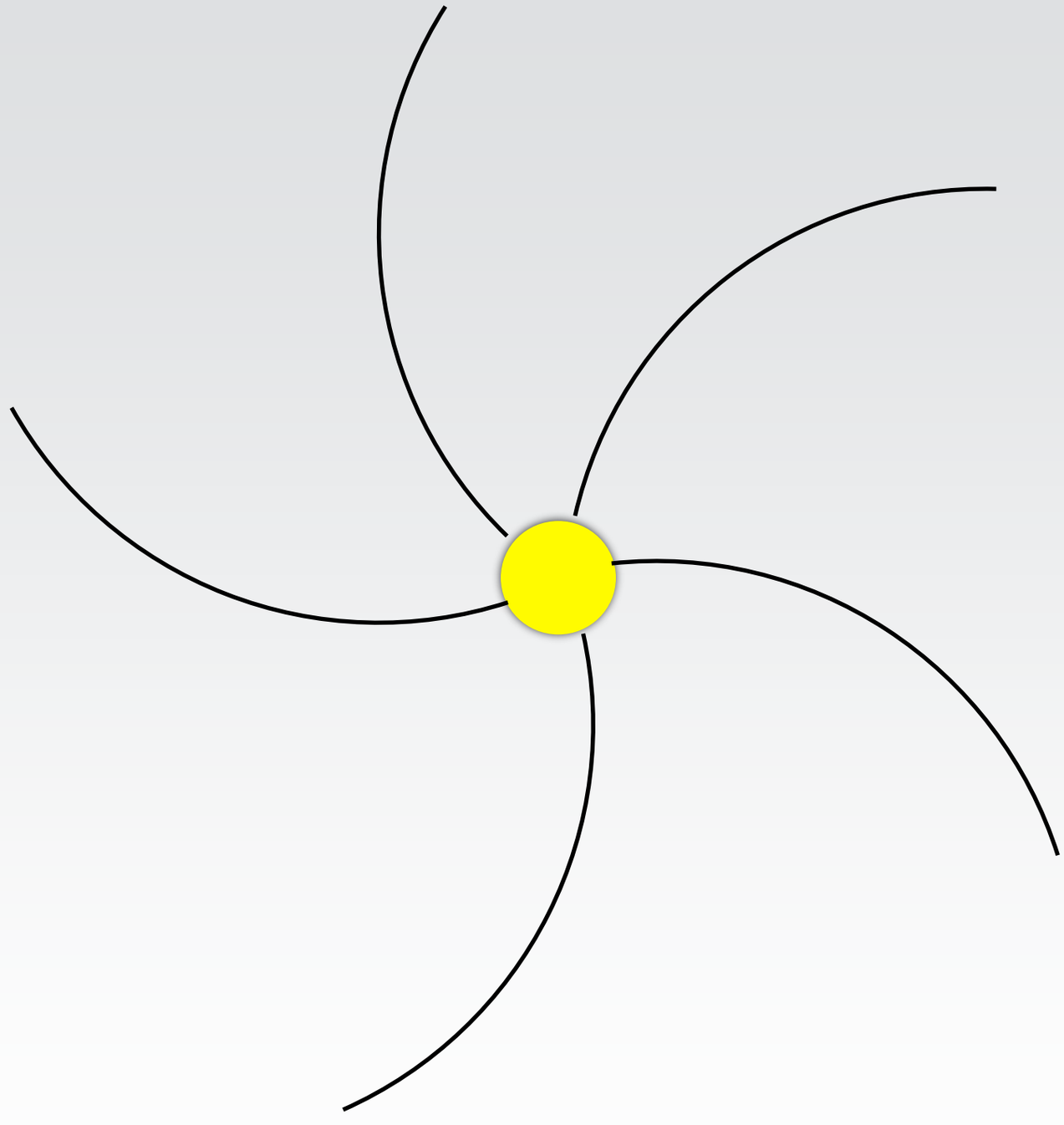
- What causes jets? Strong evidence that it is flux cancelation in quiet Sun and CHs. Still must study more! (Shear only?? Kumar et al. 2018.)
- AR jets: Minifilaments sometimes less obvious (absent?). Also, ``brightest'' bright points sometimes in unexpected locations. (Result of complex field, multiple 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)). Some spicules? (Sterling et al. 2020.)
- If most jets result from flux cancelation, what about smaller jets, and spicules? (Samanta et al. 2019.)
- Role of *twist* in powering jets, and maybe spicules.

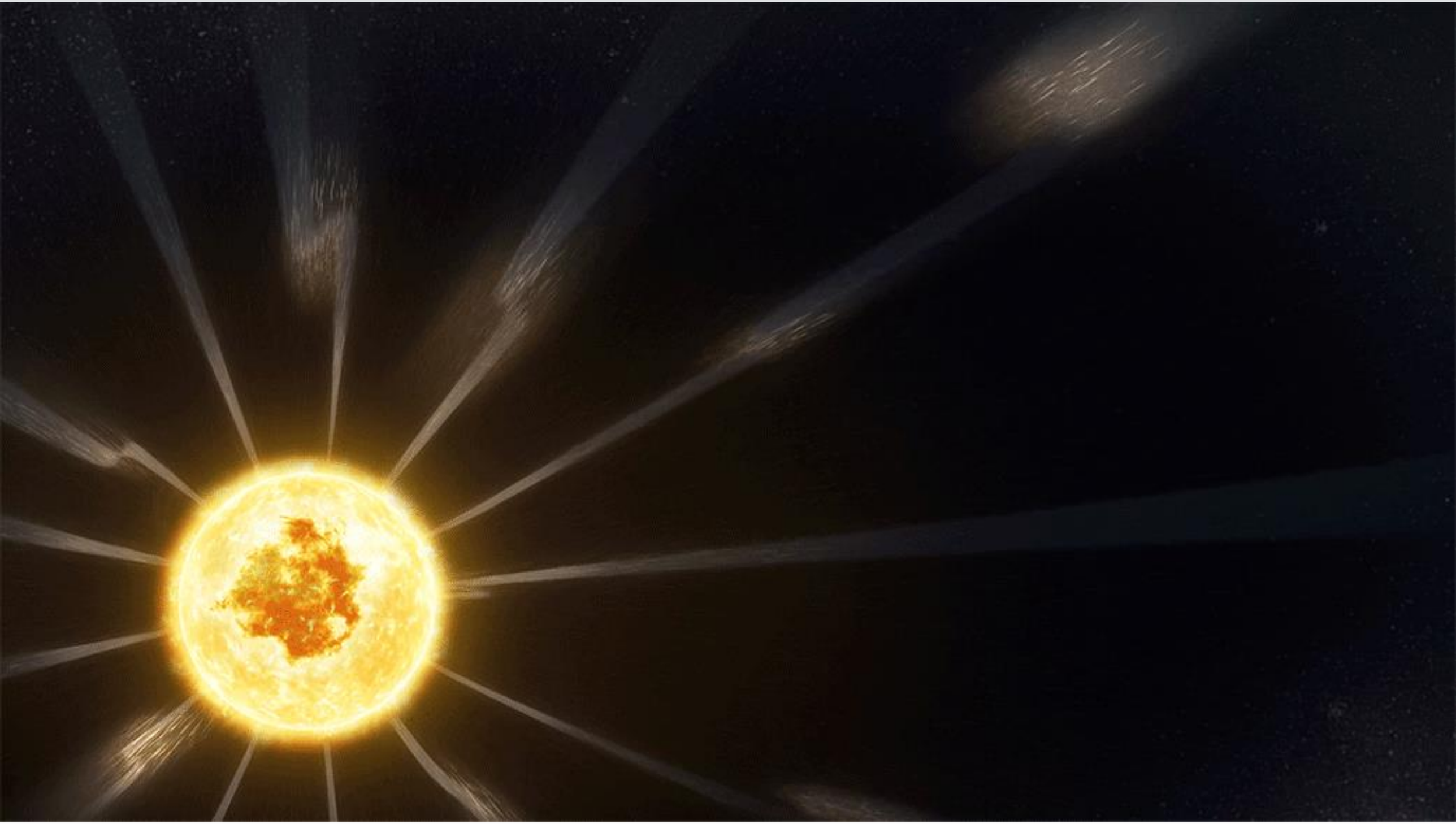
The Solar Wind, and “Switchbacks”



Corona – The Sun's outermost atmosphere

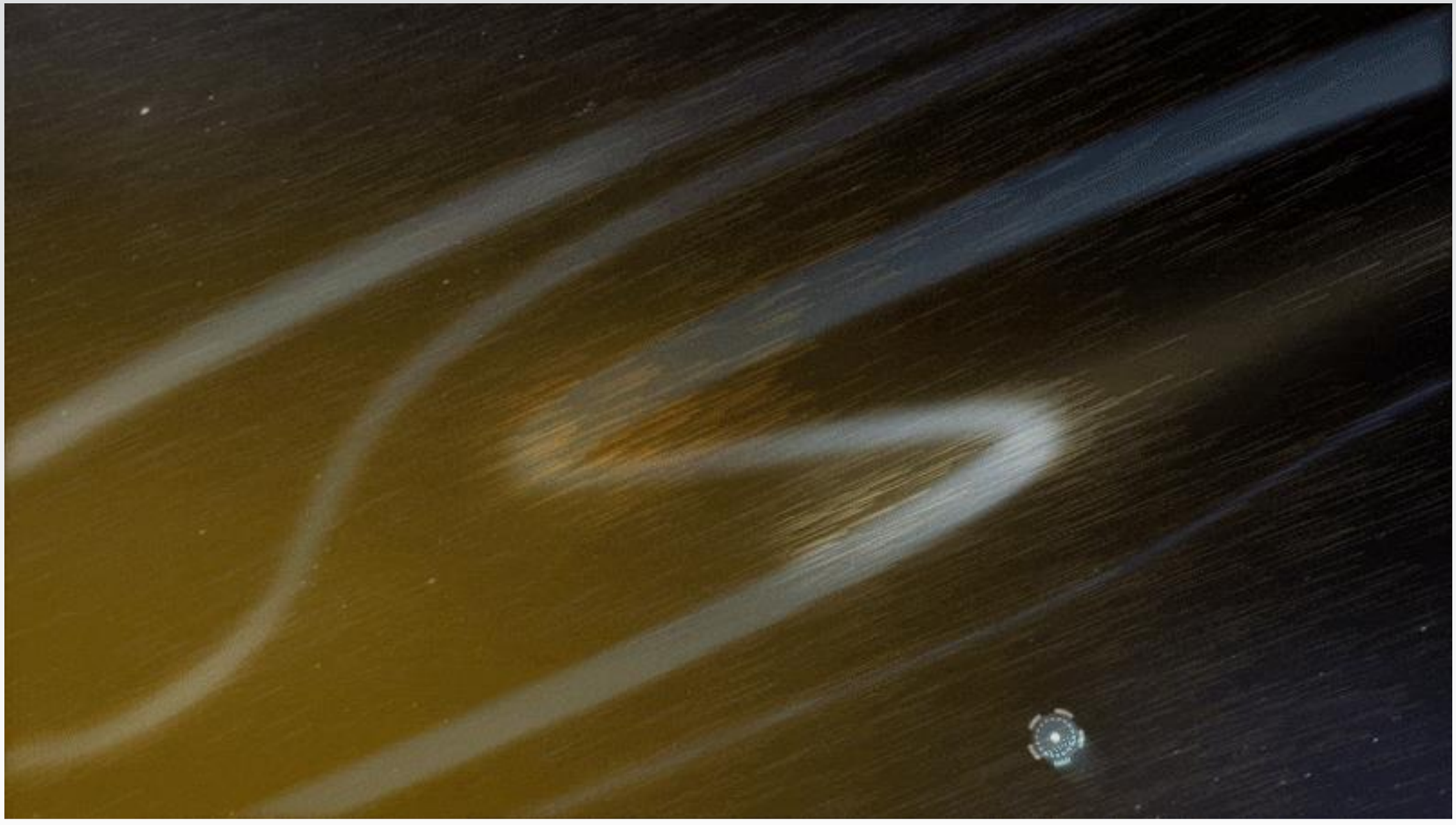
The Solar Wind, and “Switchbacks”





GSFC/Adriana Marique Gutierrez

https://www.nasa.gov/feature/goddard/2021/switchbacks-science-explaining-parker-solar-probe-s-magnetic-puzzle

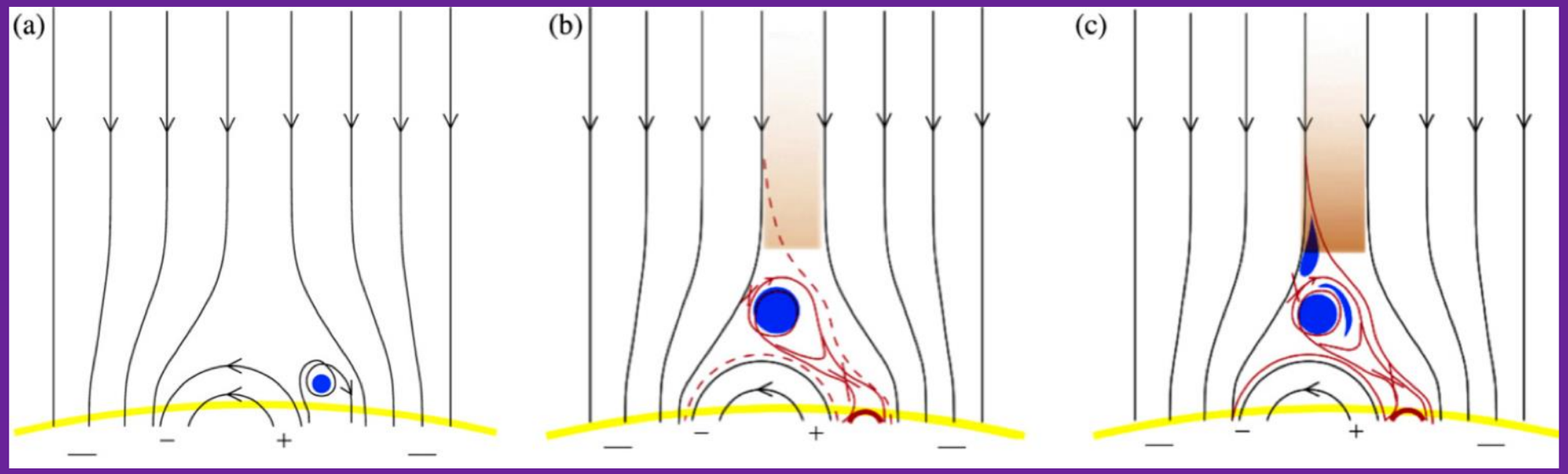


GSFC/Adriana Marique Gutierrez

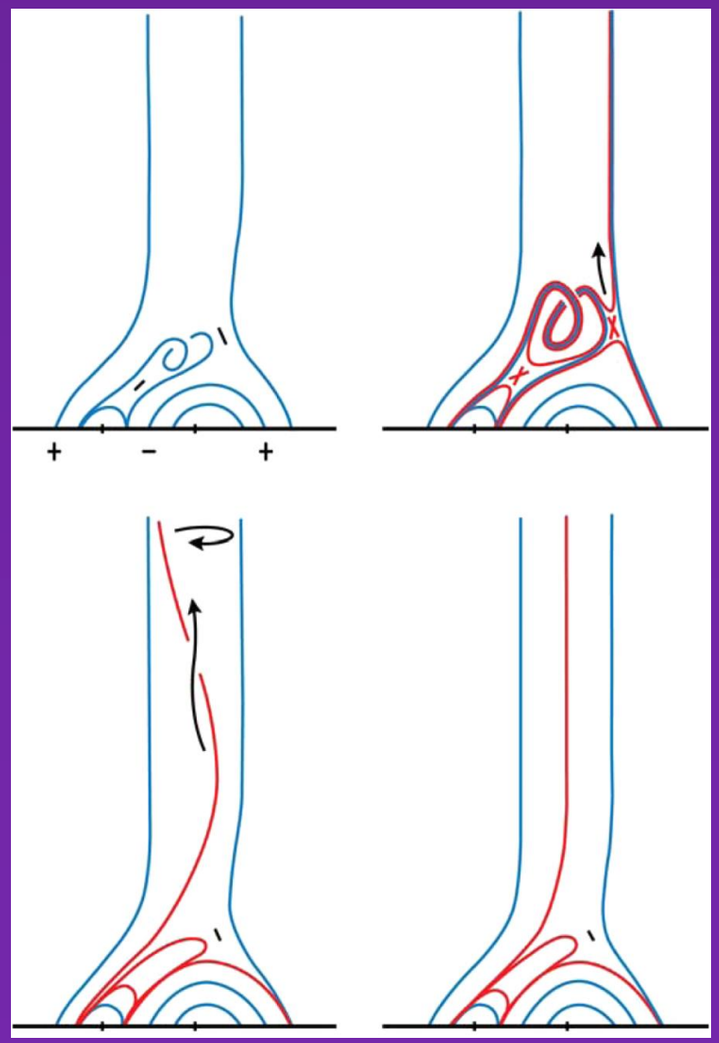
https://www.nasa.gov/feature/goddard/2021/switchbacks-science-explaining-parker-solar-probe-s-magnetic-puzzle

Parker Solar Probe (PSP) Switchbacks, and Coronal Jets

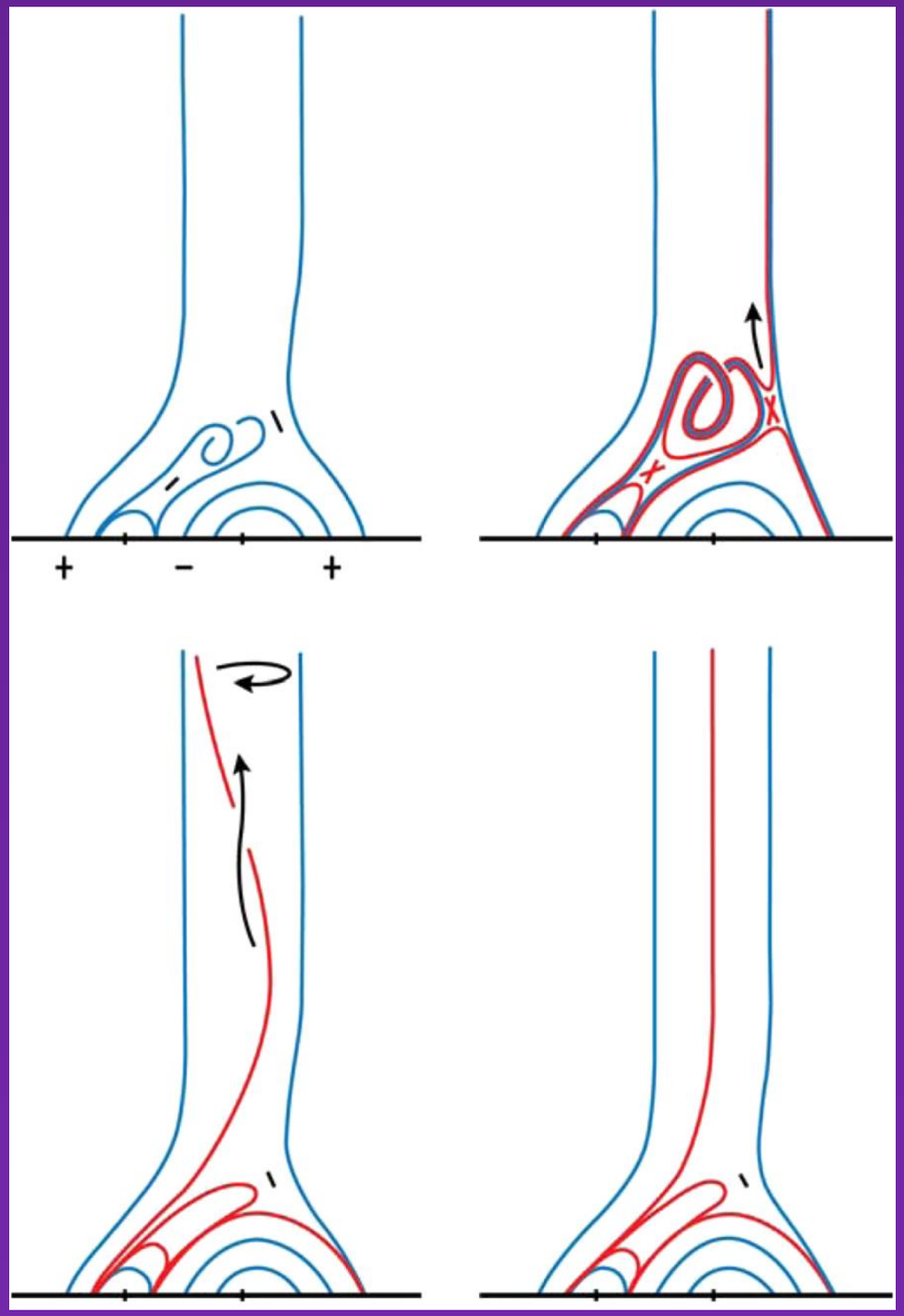
Sterling & Moore (2020) present an argument for how the PSP-observed switchbacks might result from coronal jets, based on the minifilmament-eruption mechanism. (Also: Neugebauer & Sterling 2021.)



(Sterling et al. 2015)



(Moore et al. 2015)



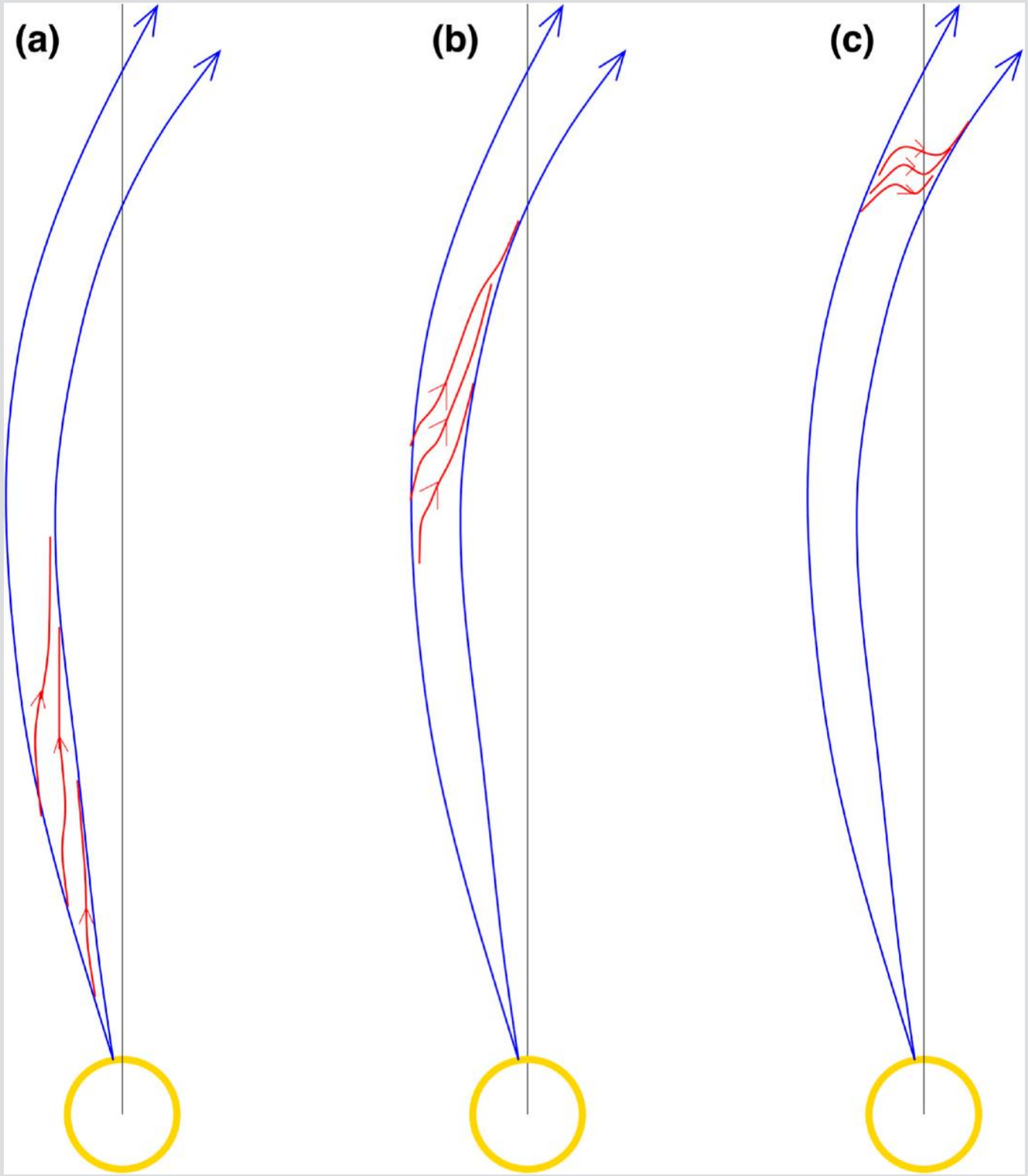
Moore et al. (2015). (Shibata & Uchida 1986-type mechanism; Patsouraos et al. 2008; Pike & Mason 1998; Yang et al. 2019.)

That packet would propagate out along the field at the Alfvén speed.

- That speed varies with distance from the Sun: ~1000 km/s in the corona, and ~100 km/s at 35 R_sun.

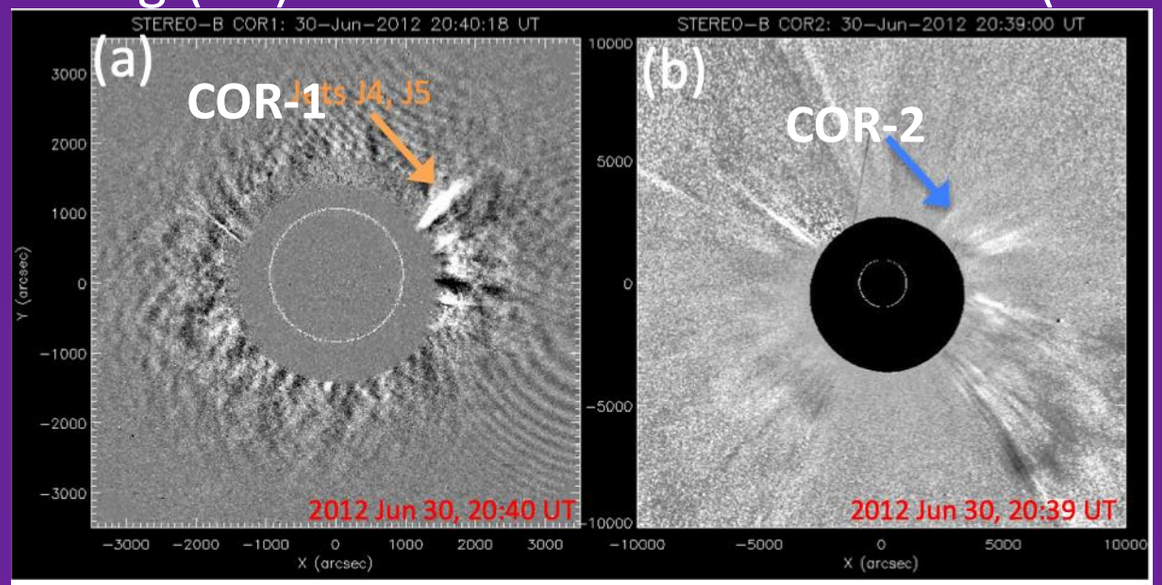
- The wave packet, initially of size ~R_sun (Moore et al. 2015, Sterling & Moore 2020), will feel different Alfvén speeds at its front and near-Sun sides; this Alfvén-speed gradient will result in the wave packet becoming more compact with distance from the Sun.

- The result will be a feature that PSP could detect as a switchback.



Sterling & Moore (2020)

Far-Reaching (AR) Coronal Jets from STEREO-B (and AIA)



(Sterling & Moore 2020; also see, e.g., Yu et al. 2014, 2016)

It is plausible that the jet mechanism occurs on smaller size scales, with increasing frequency, with “jetlets” (widths ~4000 km, Raouafi & Stenborg 2014; Panesar et al. 2018), and maybe even some spicules (widths ~ few x10^2 km; Sterling & Moore 2016).

If all can become switchbacks, the rates would be much larger than then the few x 100/day from canonical coronal jets.

Summary

- Approaching a good understand of coronal jets, especially in QS and CHs: At least many jets are miniature filament eruptions triggered by flux cancelation. AR jets are likely similar, but altered due to the more-complex AR field.

- Needed: Jet simulations based on minifilament eruptions (e.g. Wyper et al), and *flux cancelation*!

- How does jet physics scale to different sizes? (Large eruptions? ``Jetlets''? Spicules??)

- Might jets (and/or jet-like features) be the source of the PSP-observed switchbacks?

Image:
Alphonse Sterling
21 August 2017,
Lewisville, Idaho

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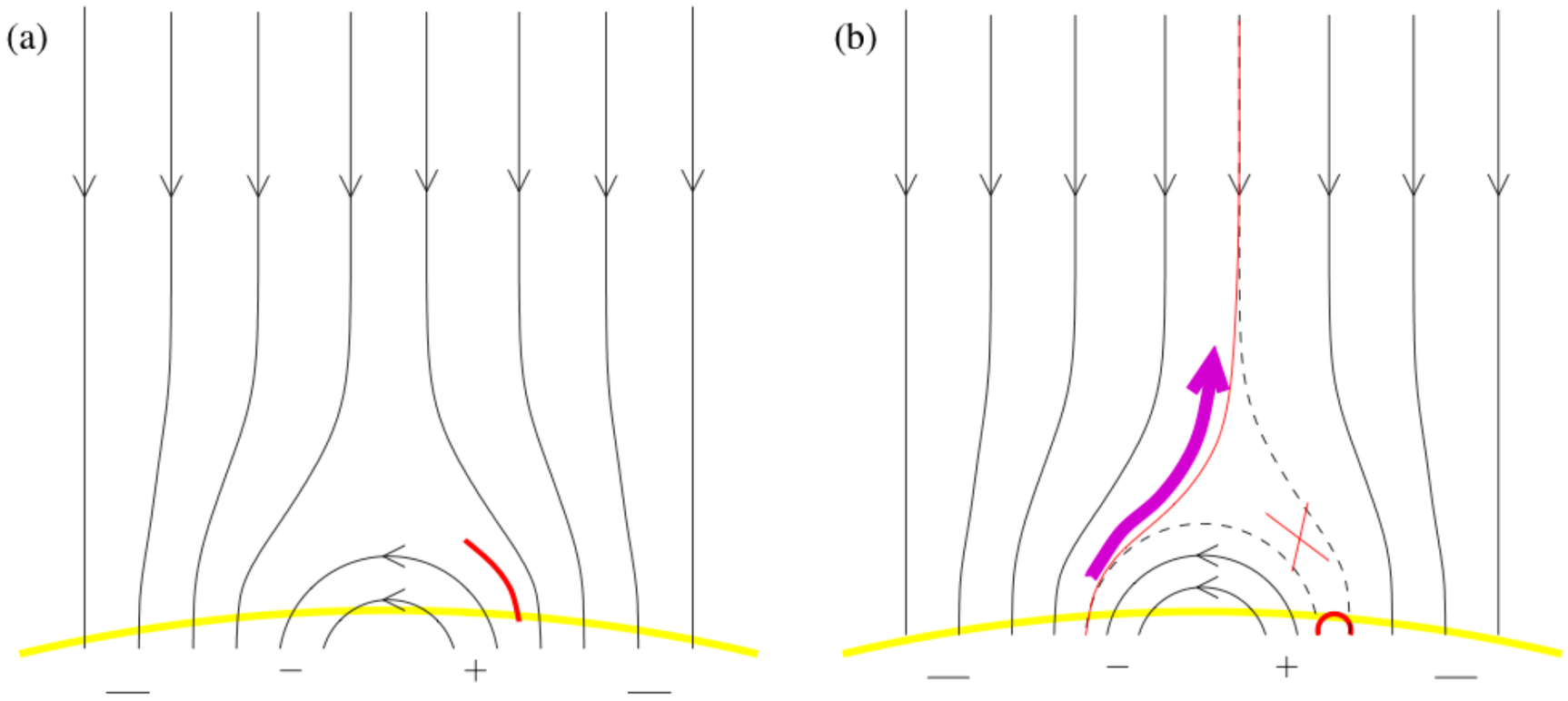
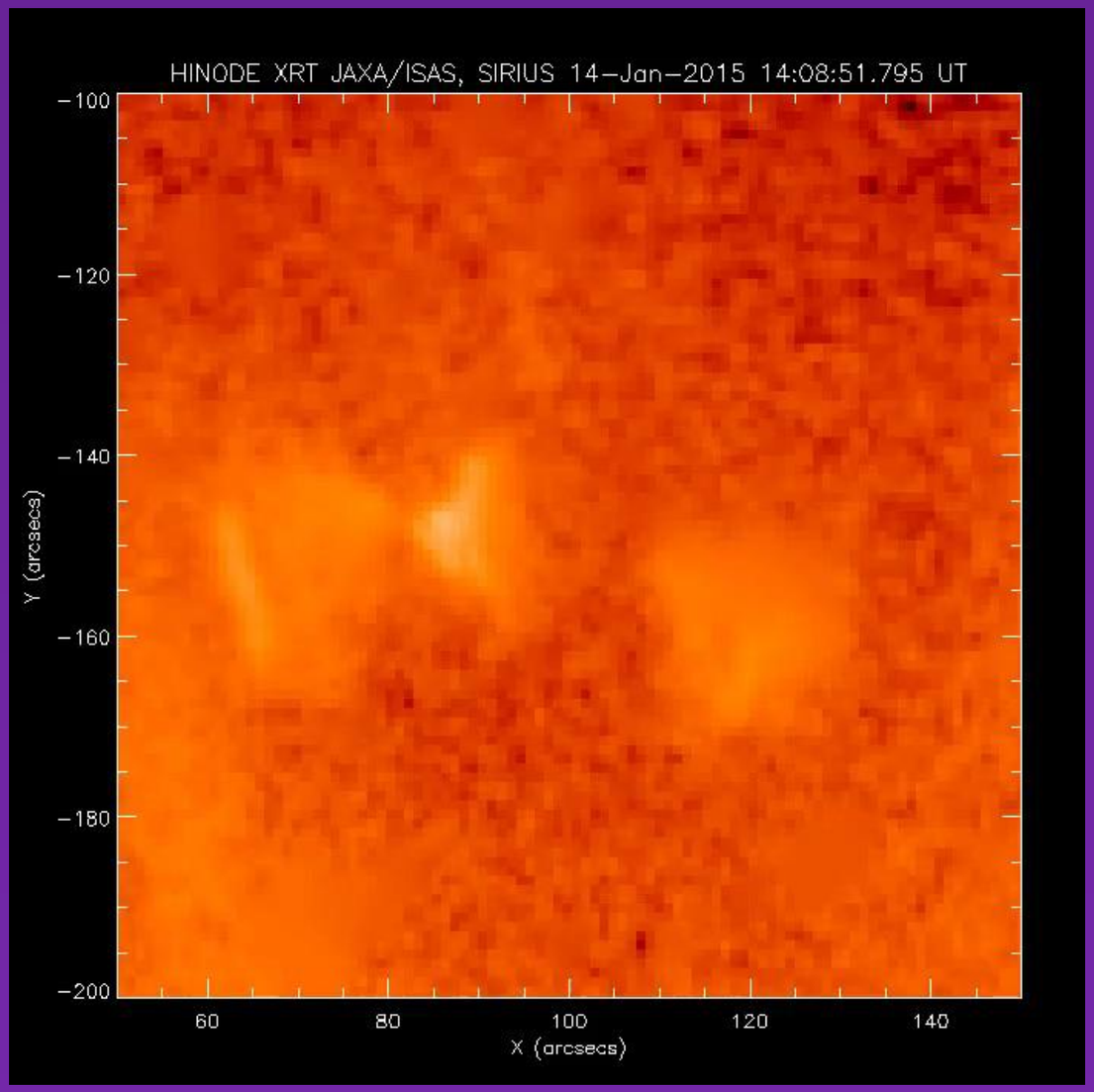
Emerging-Flux Model for (X-Ray) Jets

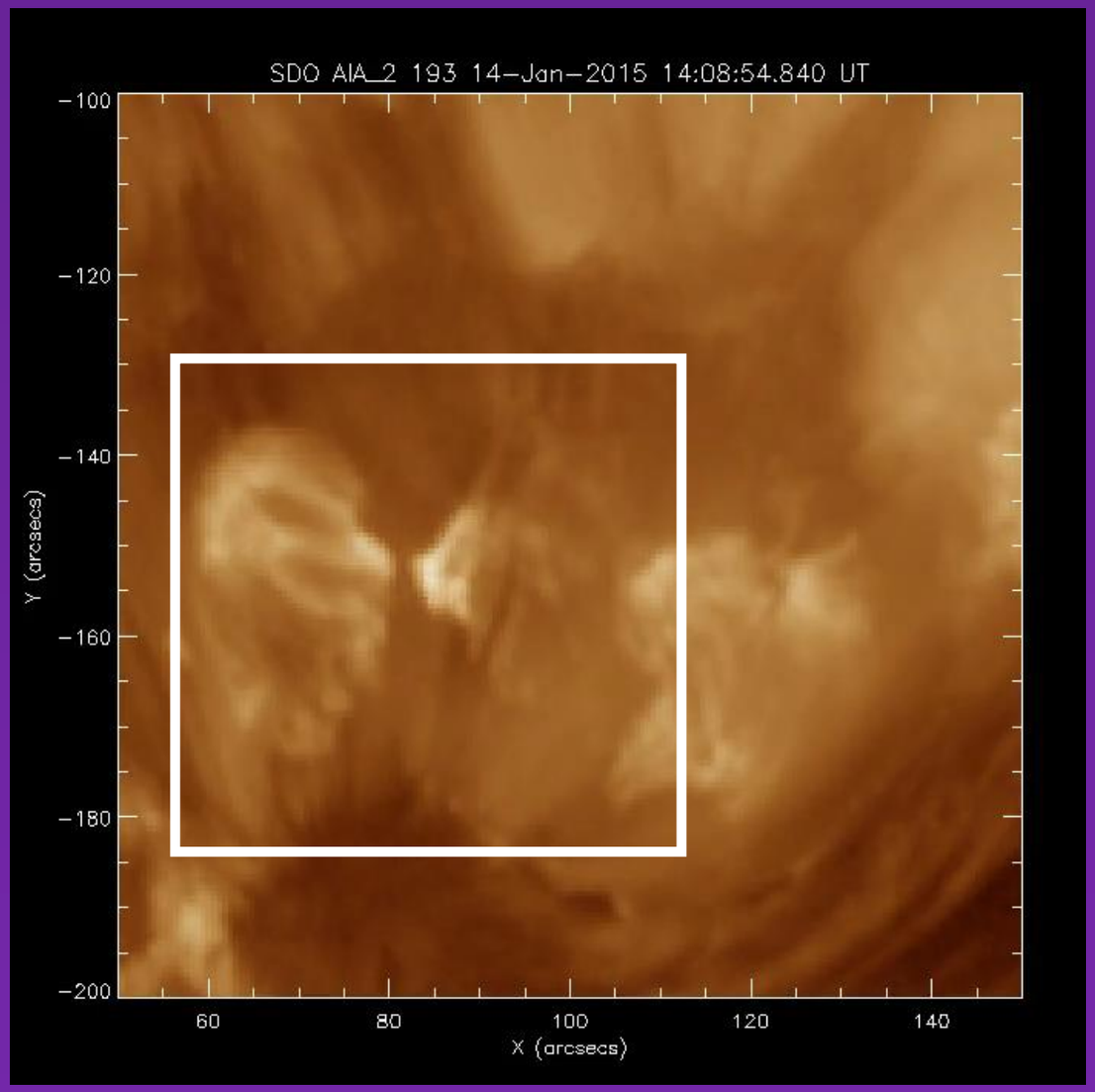


Supported by numerical simulations: Yokoyama & Shibata (1995), Nishizuka et al. (2008), Archontis et al. (2013), Moreno-Insertis et al. (2013), Fang et al. (2014), etc. (Cf. Heyvaerts, Priest, & Rust 1977.)

An Example: AR Jets

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

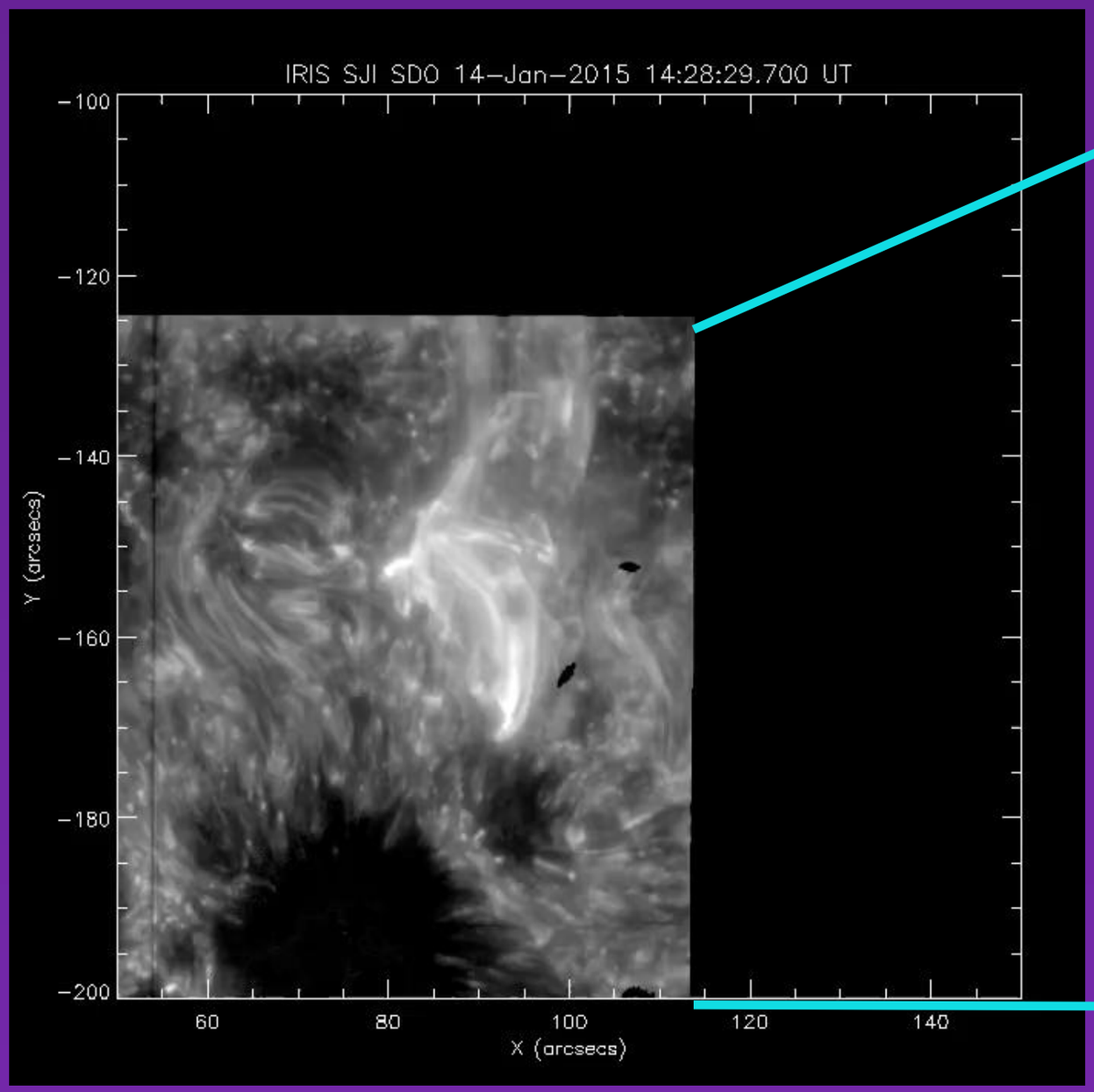


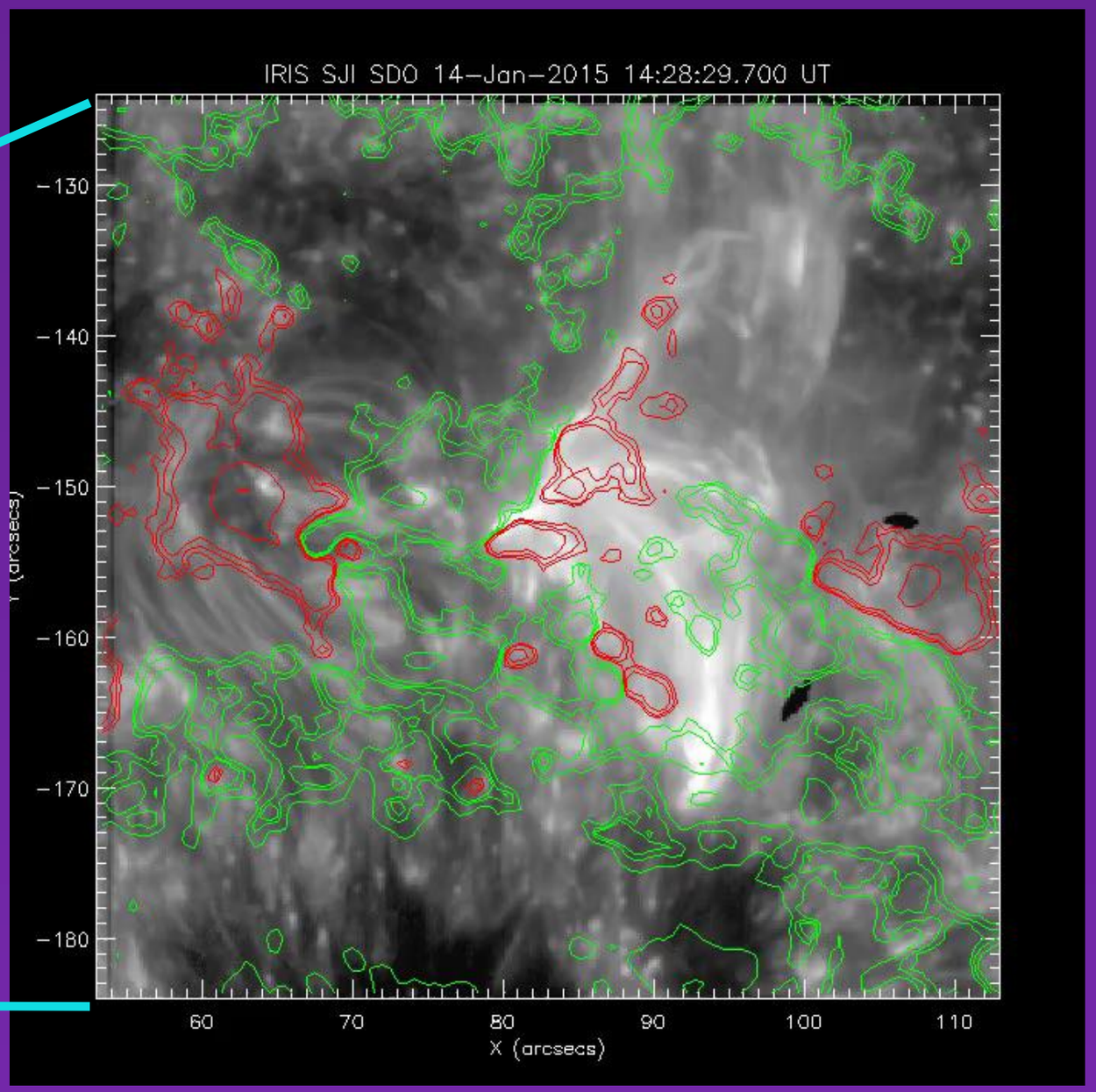


Hinode/XRT AIA 193

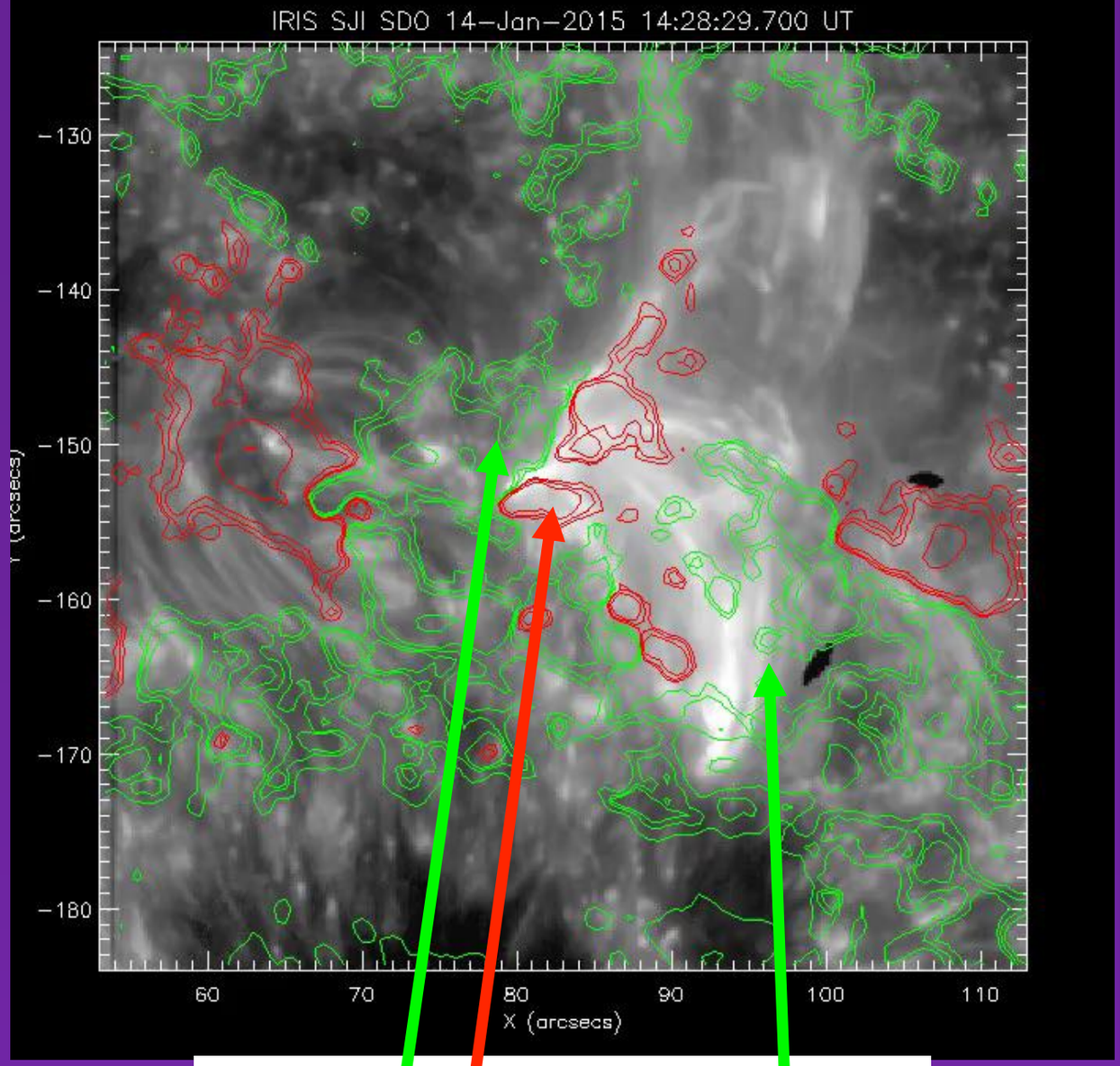
Minifilament hard to see (absent?). Work the same way??

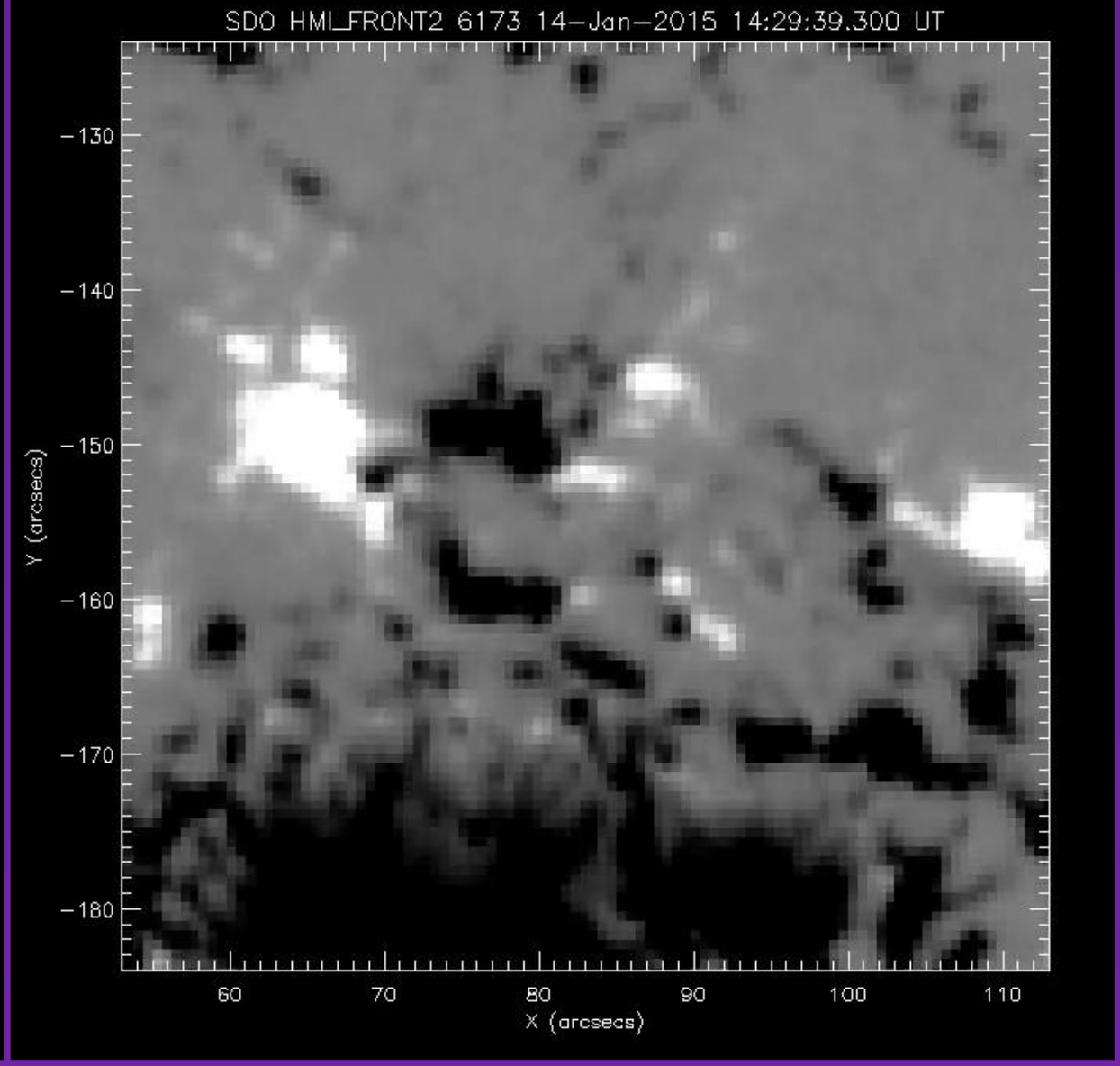
Coronal Jets in Active Regions

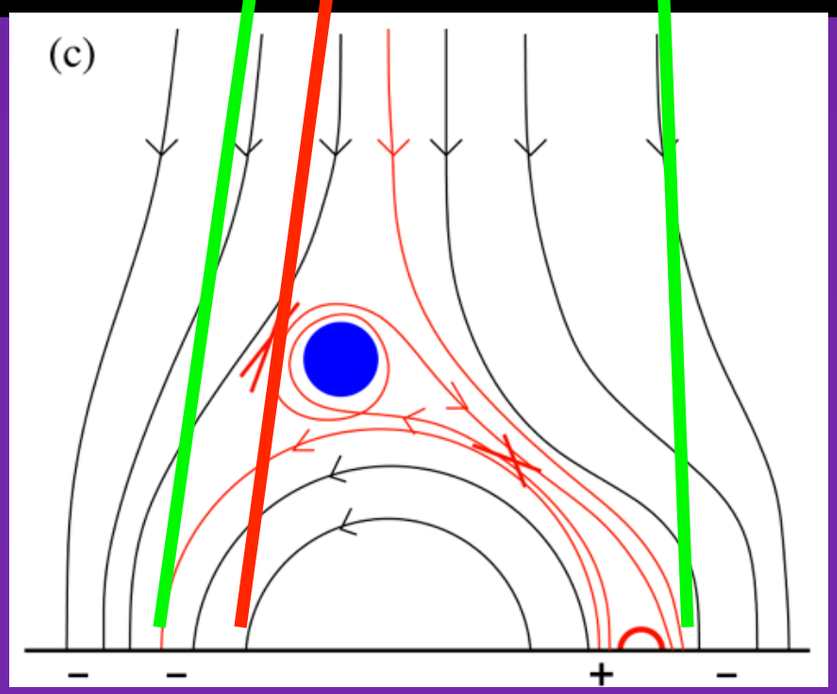




Sterling et al. (2017)

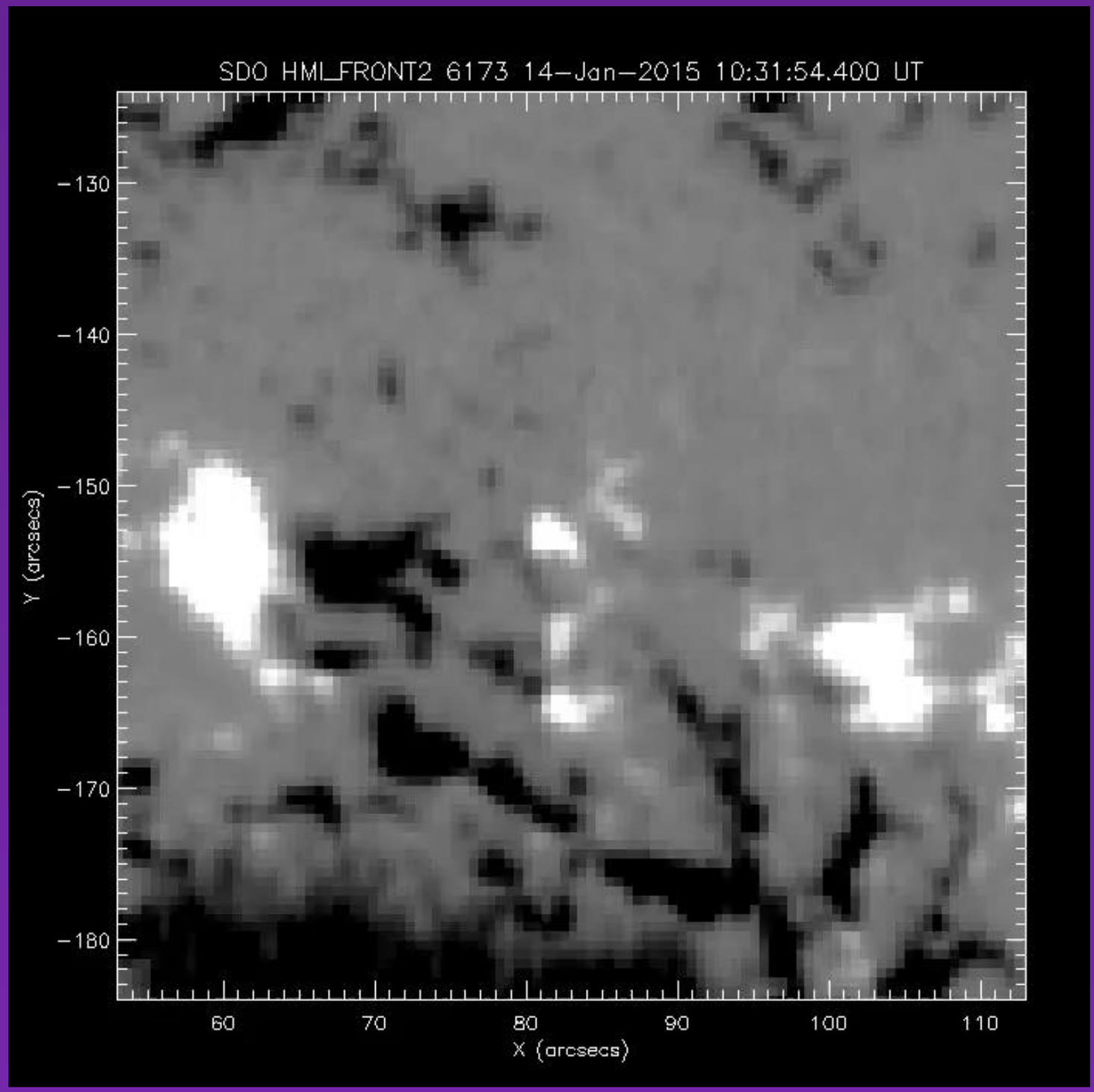






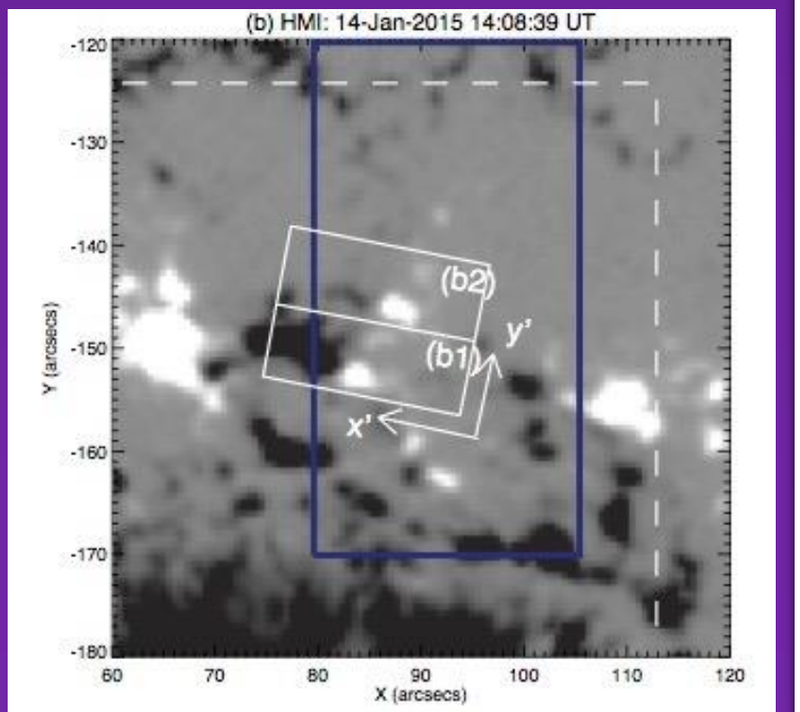
Sterling et al. (2017)

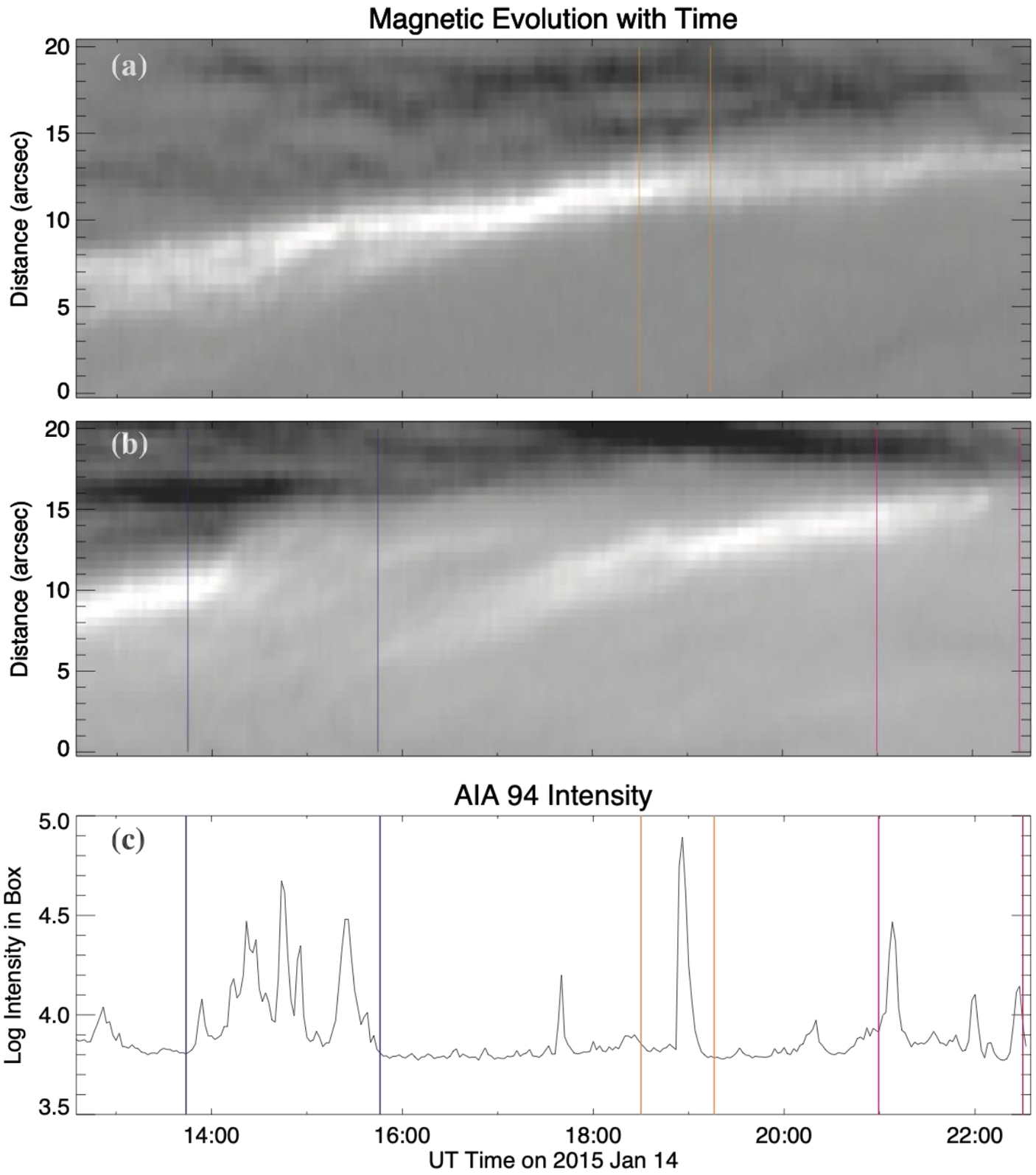
HMI of jetting region



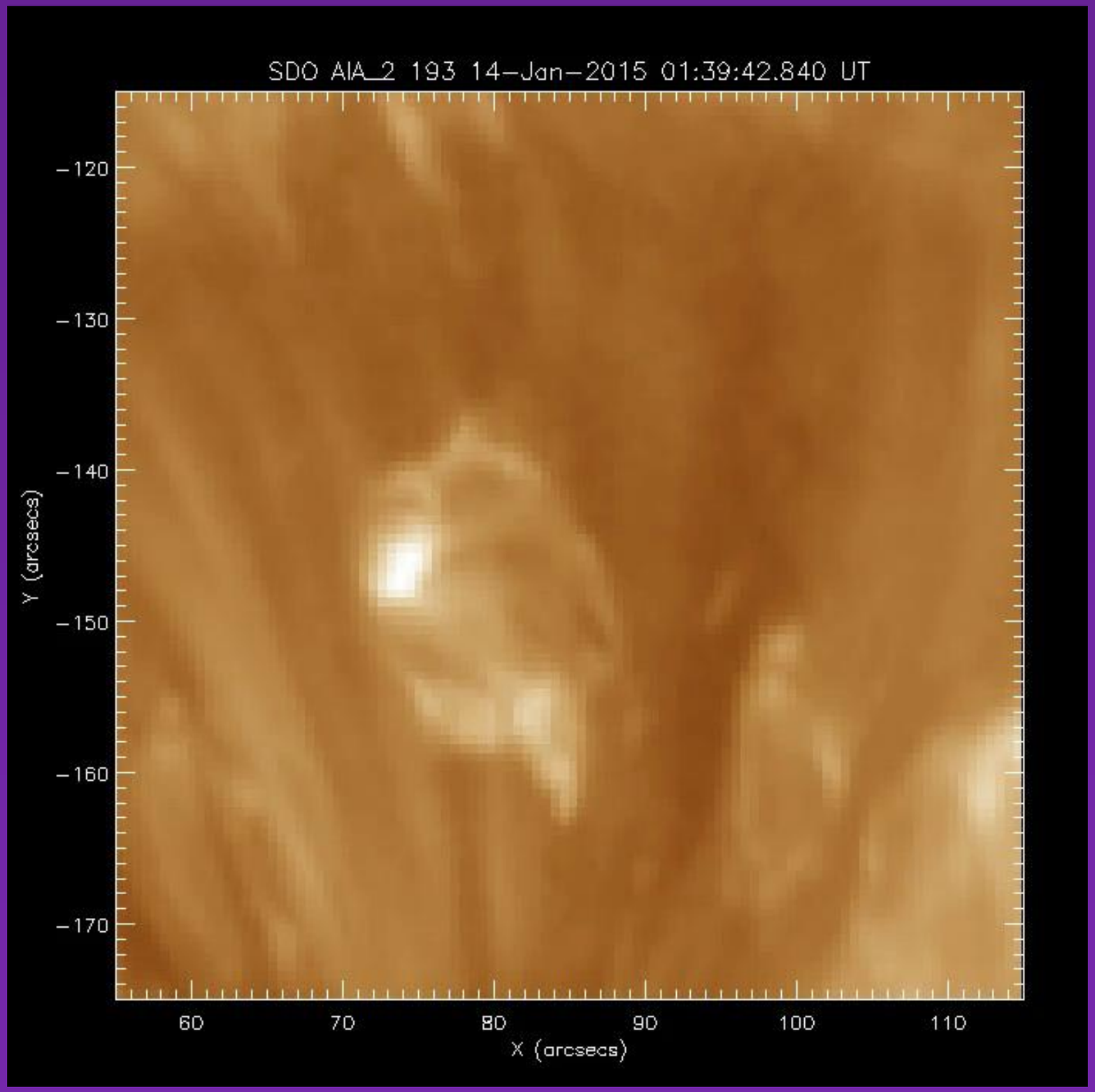
Jets occur at *flux cancelation* locations!

AR jets (Sterling et al. 2017)





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



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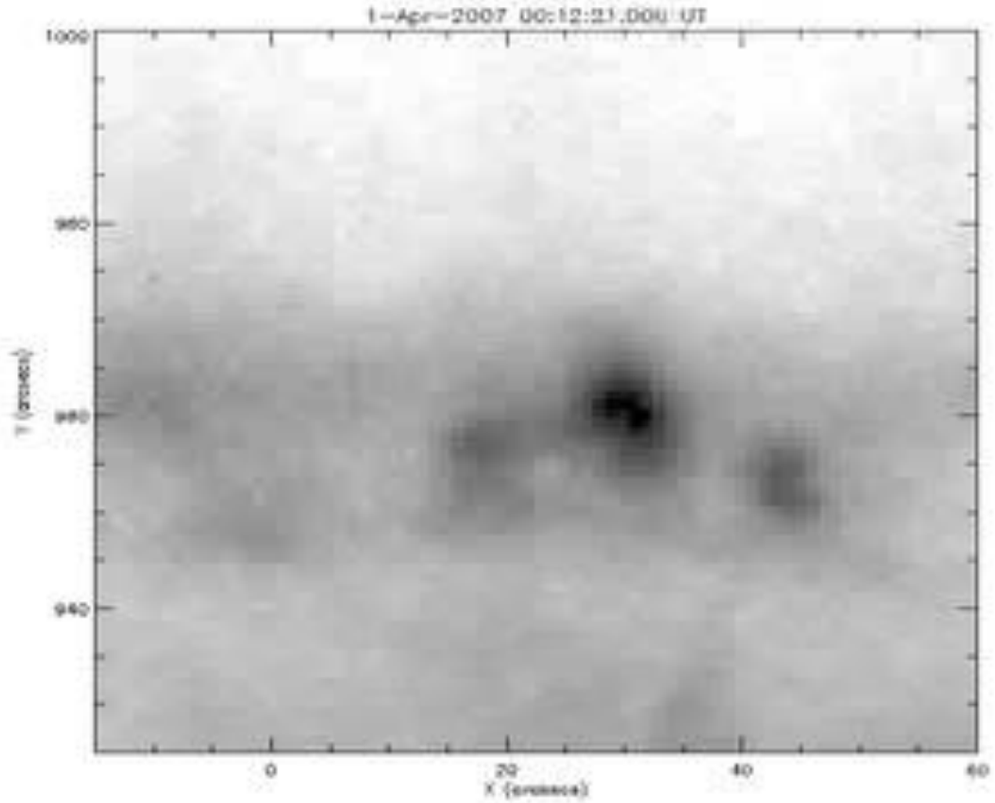
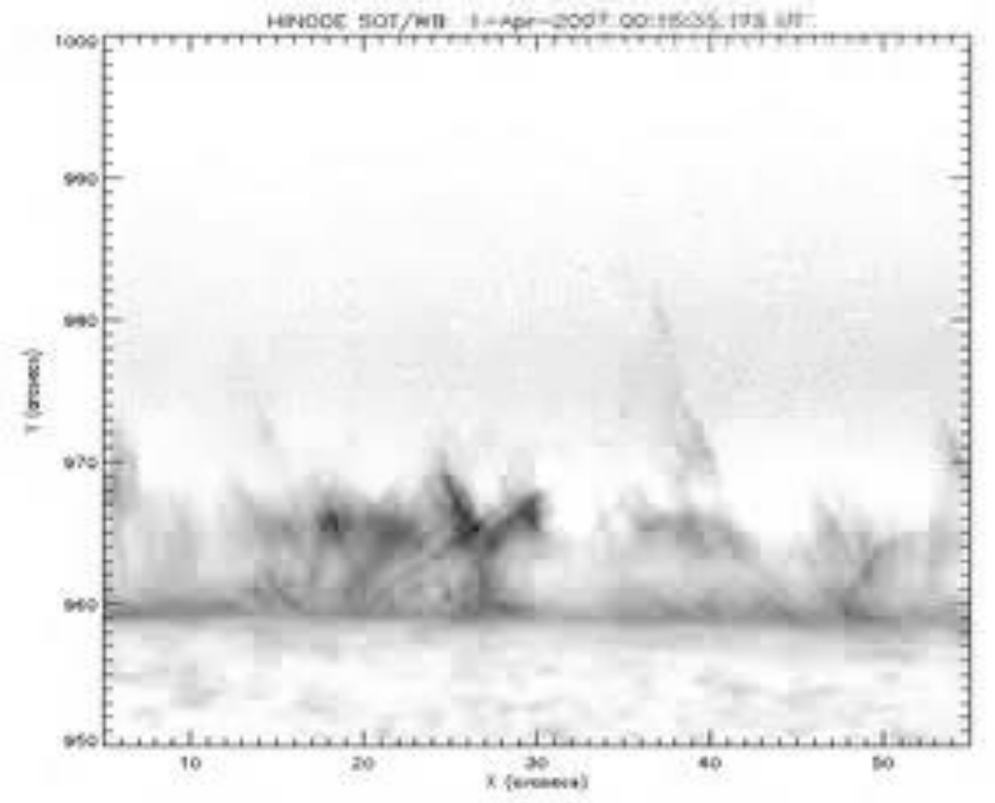
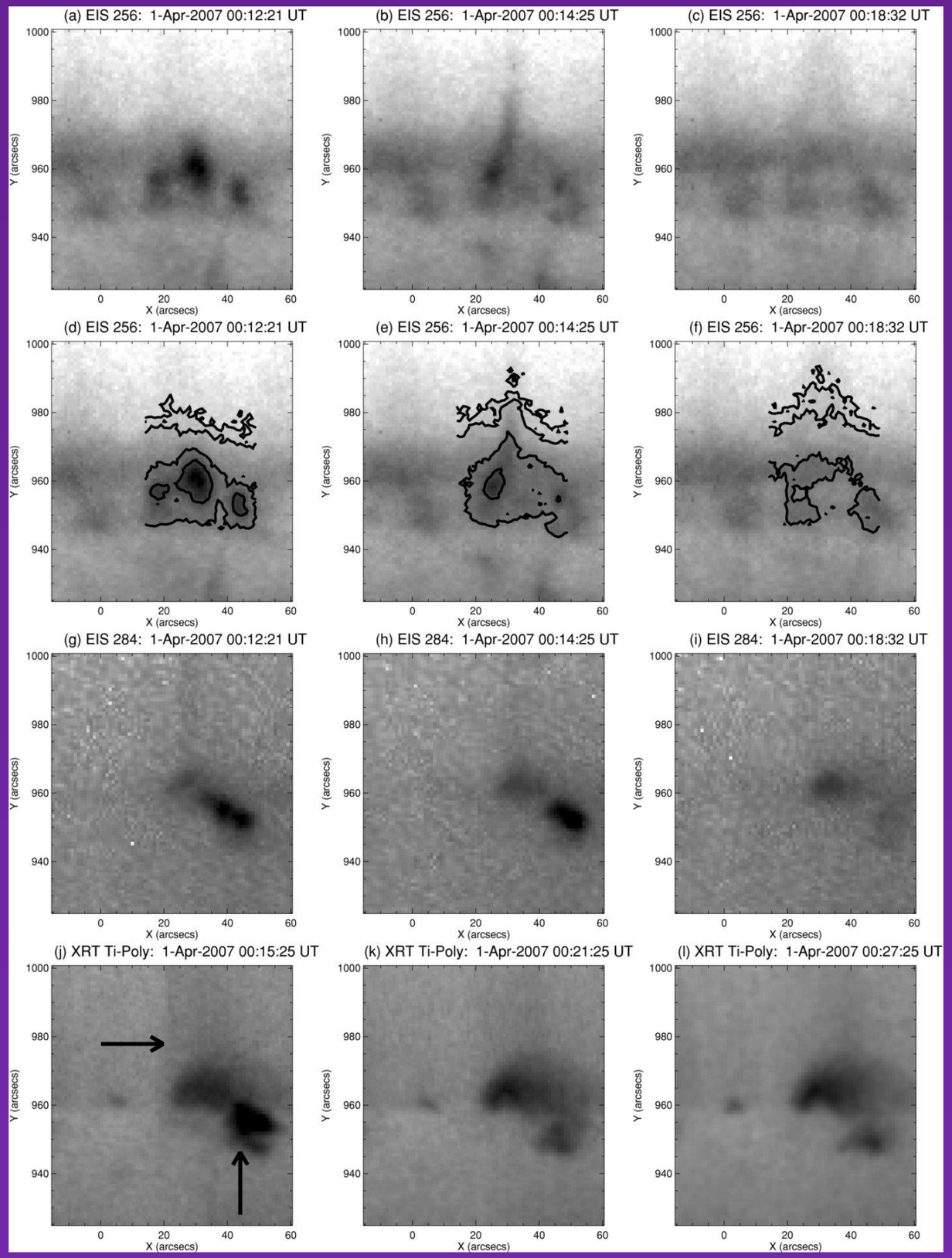
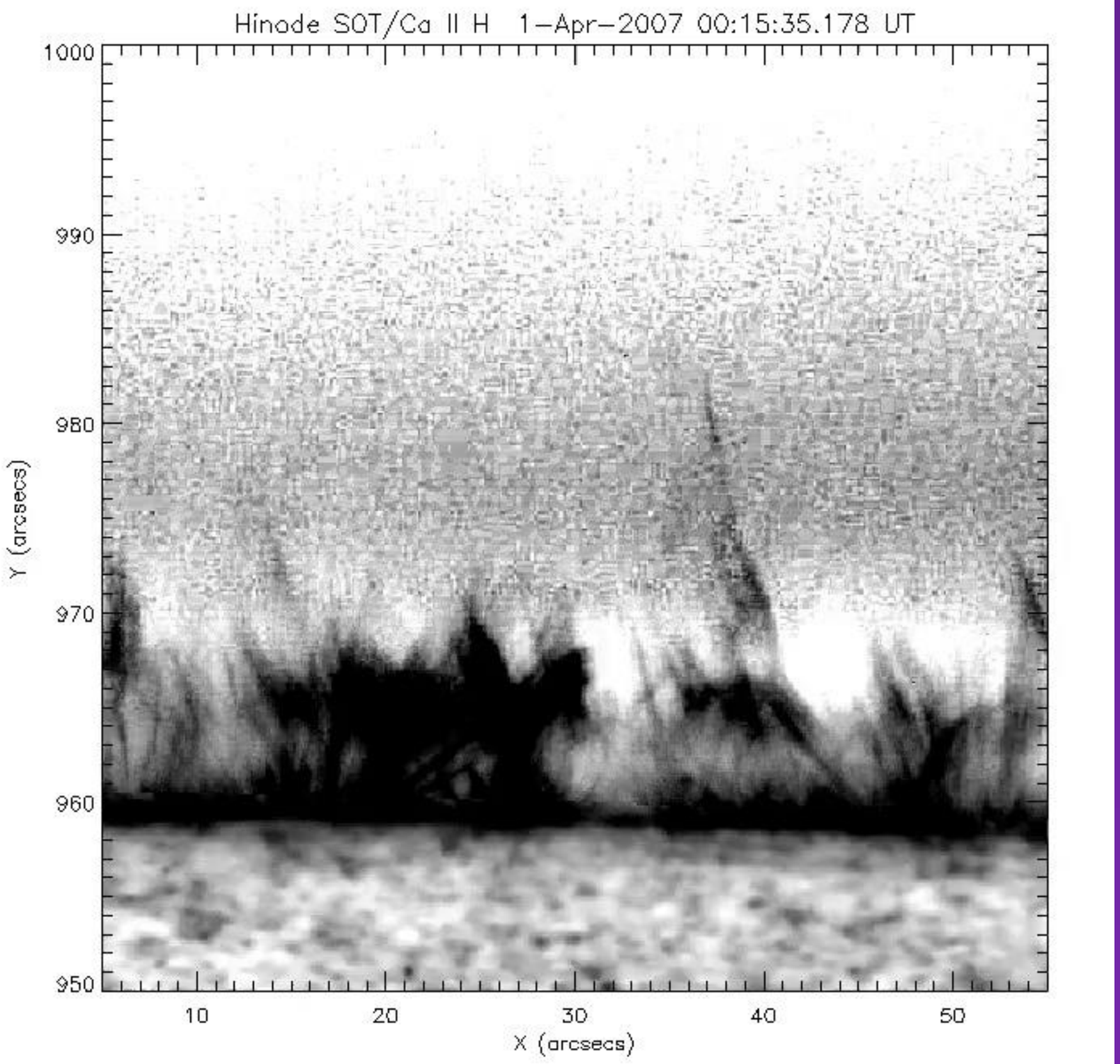




(Sterling, Harra, & Moore 2010)

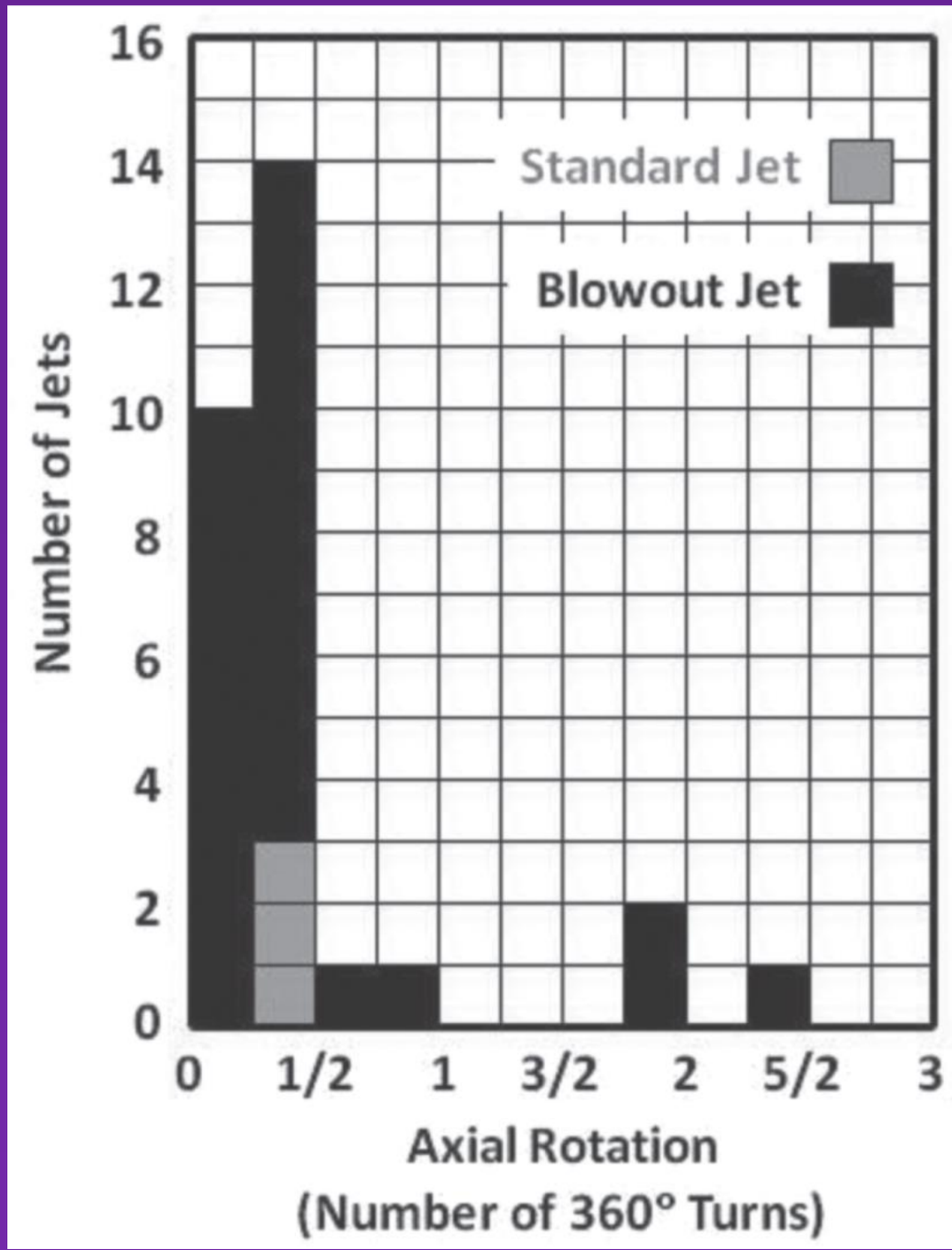


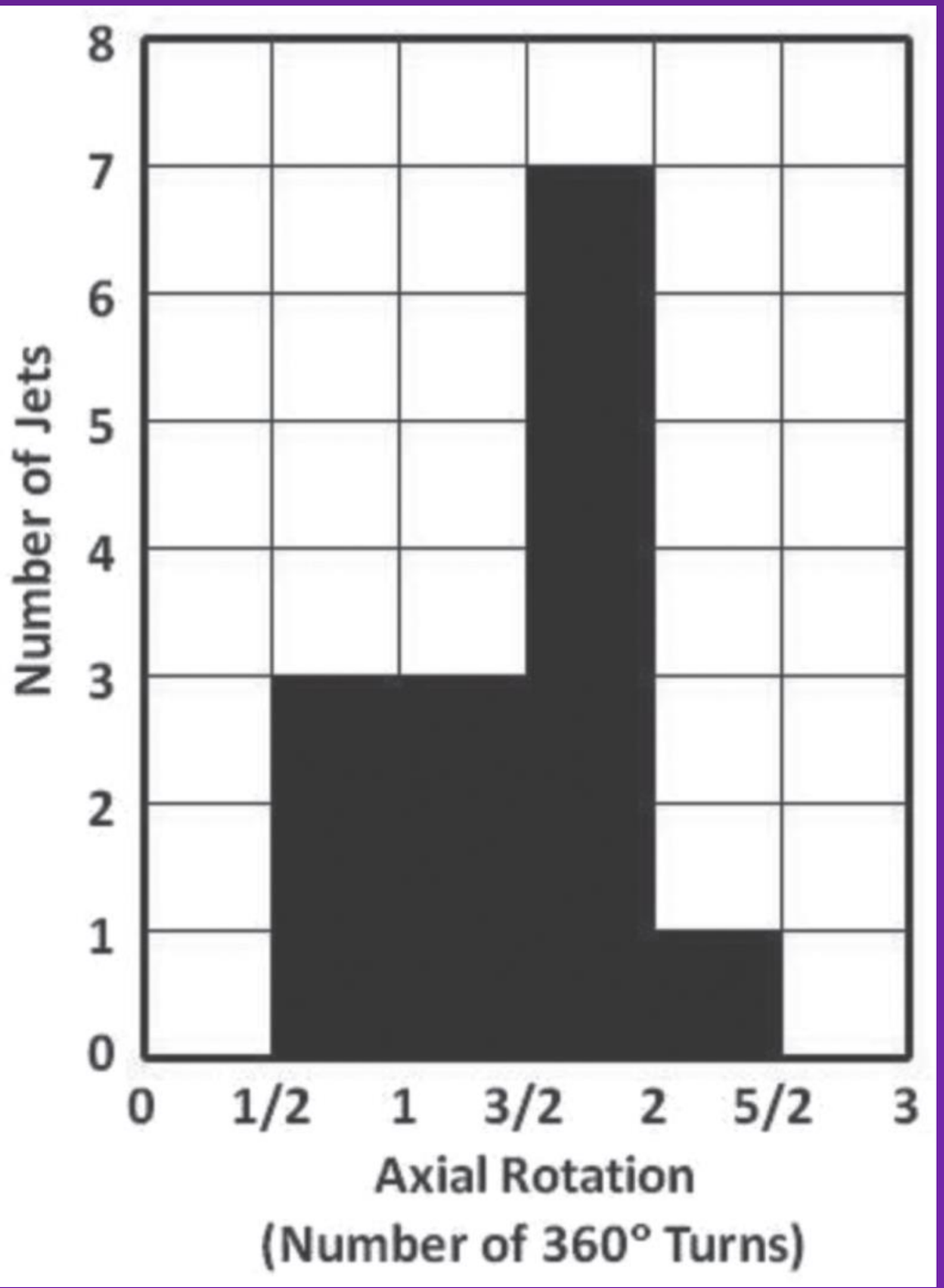
(Sterling, Harra, & Moore 2010)



(Sterling, Harra, & Moore 2010; Sterling et al. 2020)

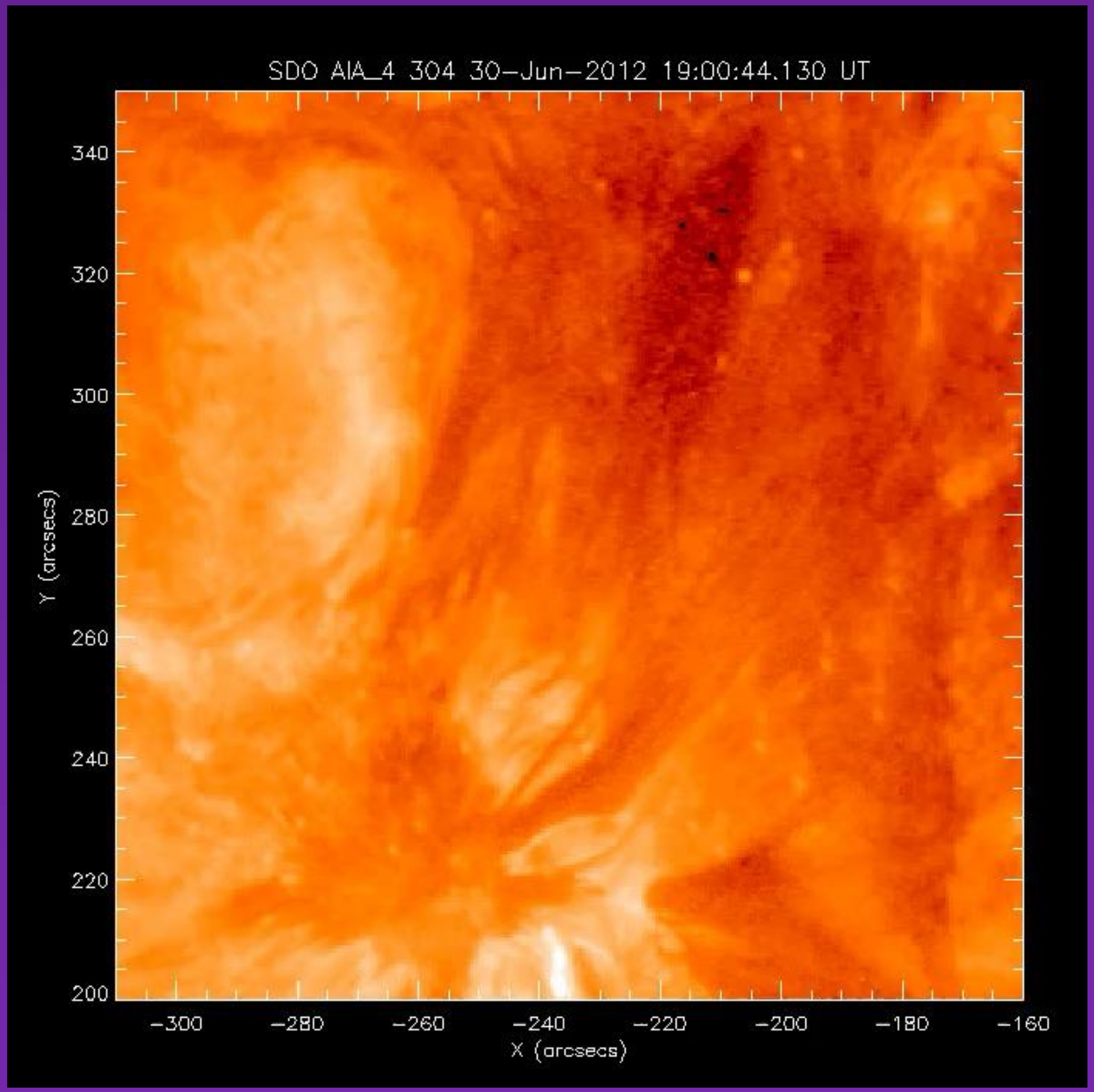
Twist in Jets



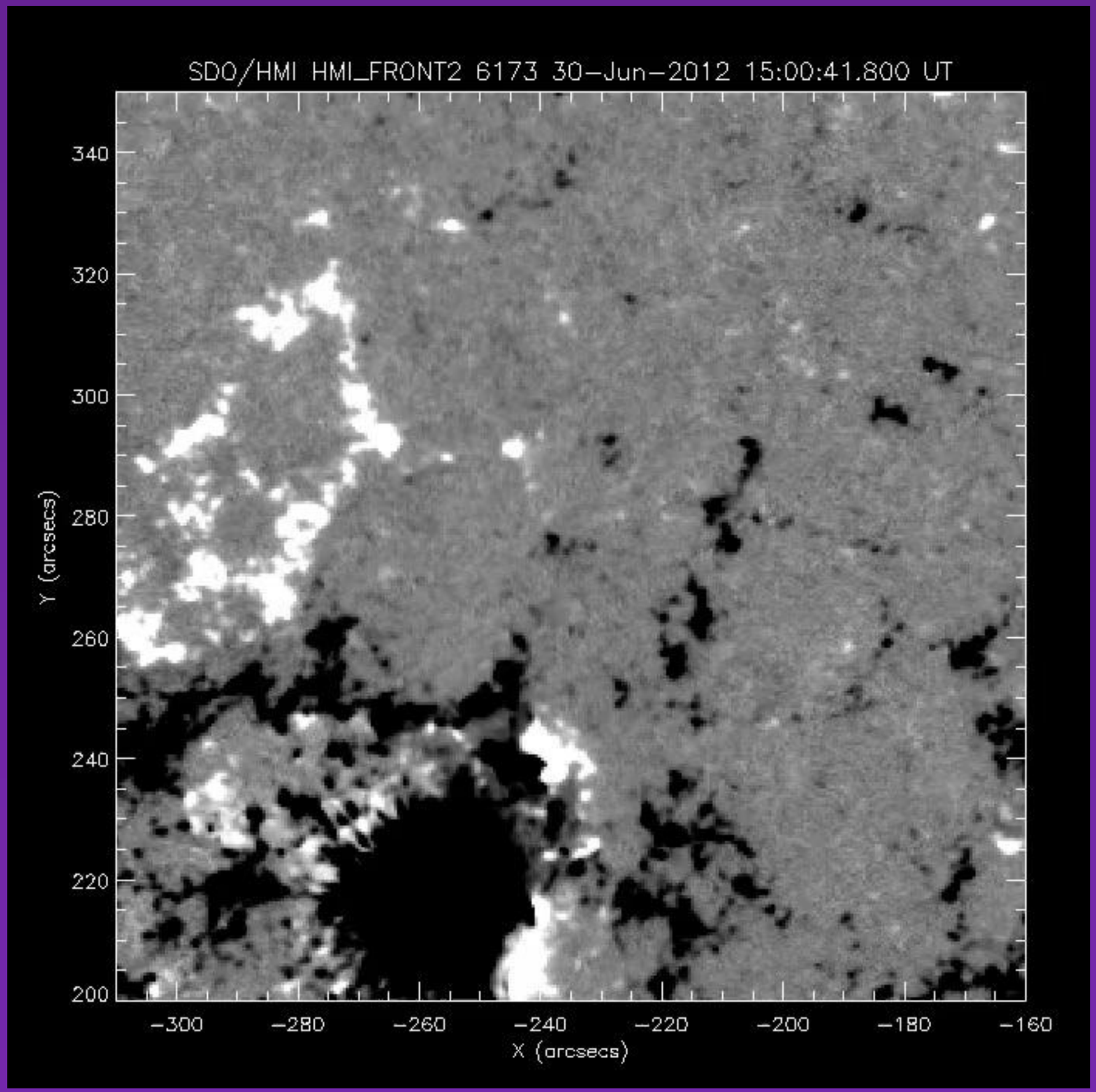


Random twisting PCH jets with cool component: Moore et al. (2013)

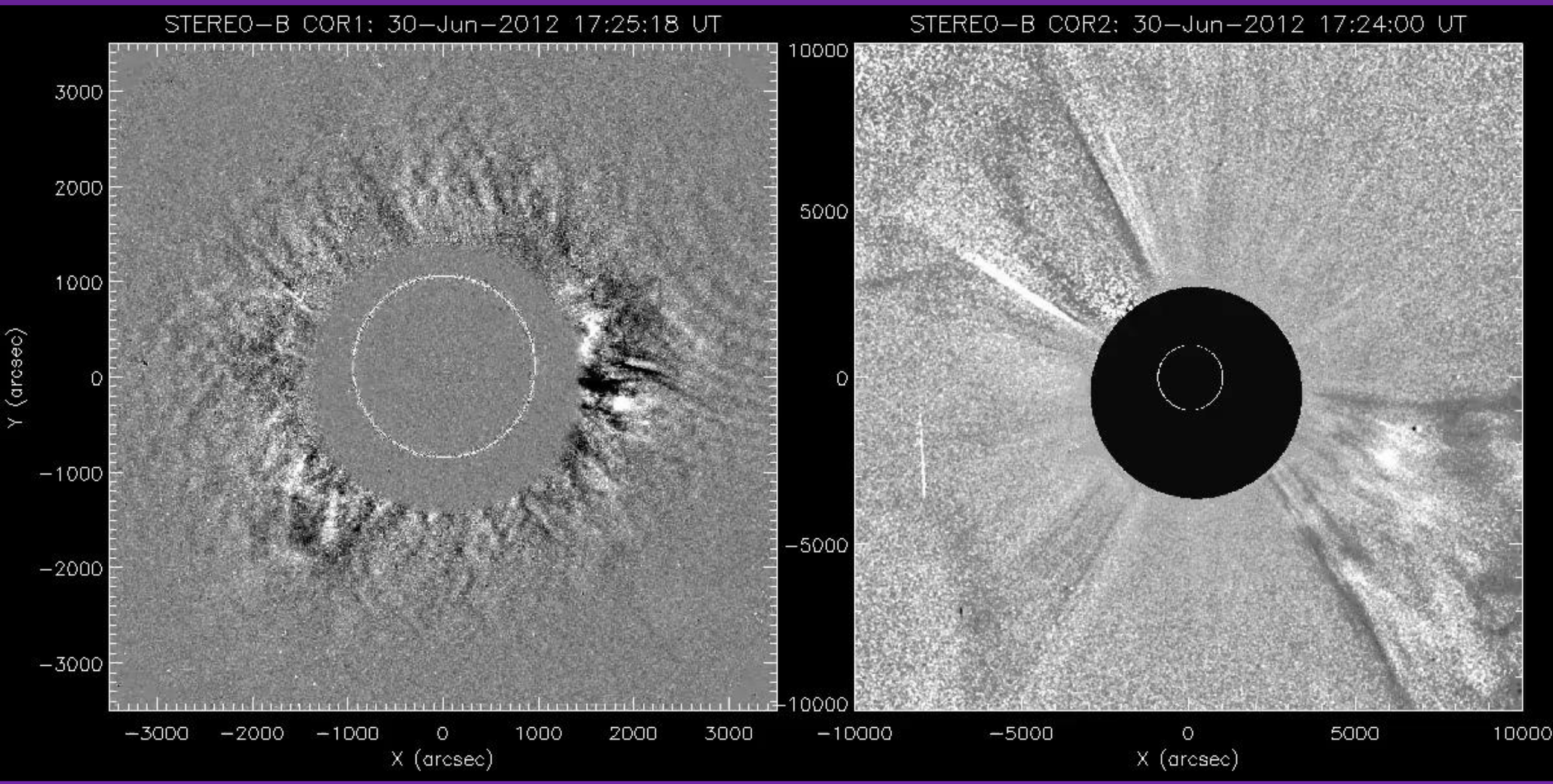
Narrow-CME-Producing Jets: (Moore et al. 2015)



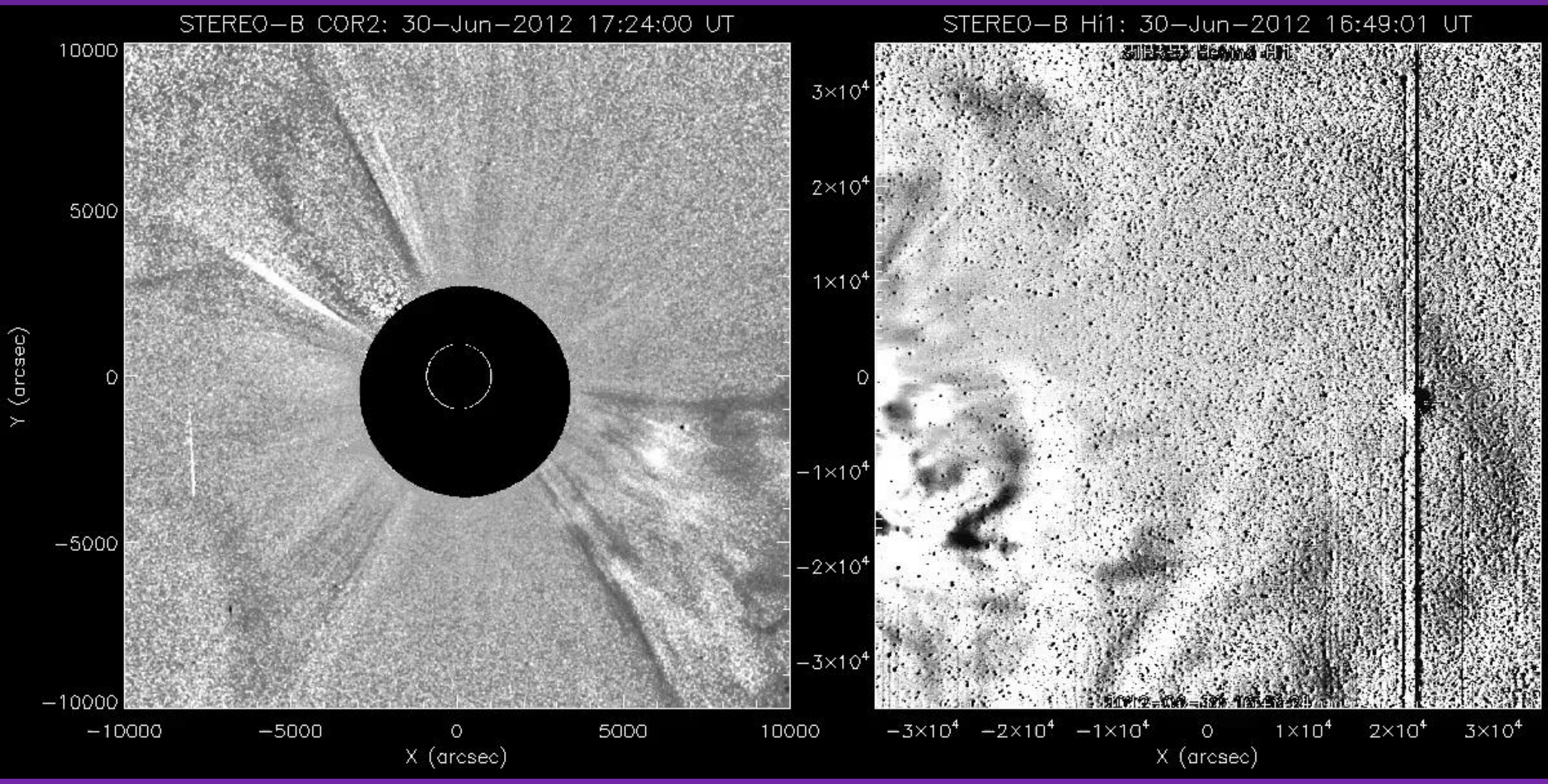
Sterling & Moore (2020)



Sterling & Moore (2020)



Sterling & Moore (2020)



Sterling & Moore (2020)

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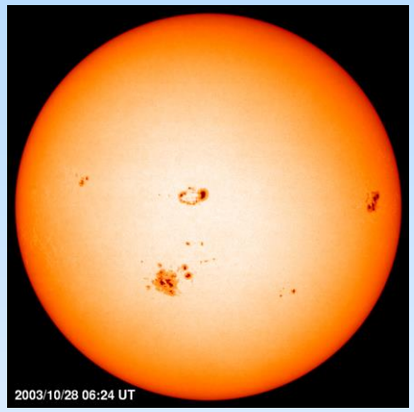
Solar Interior and Atmosphere(s)

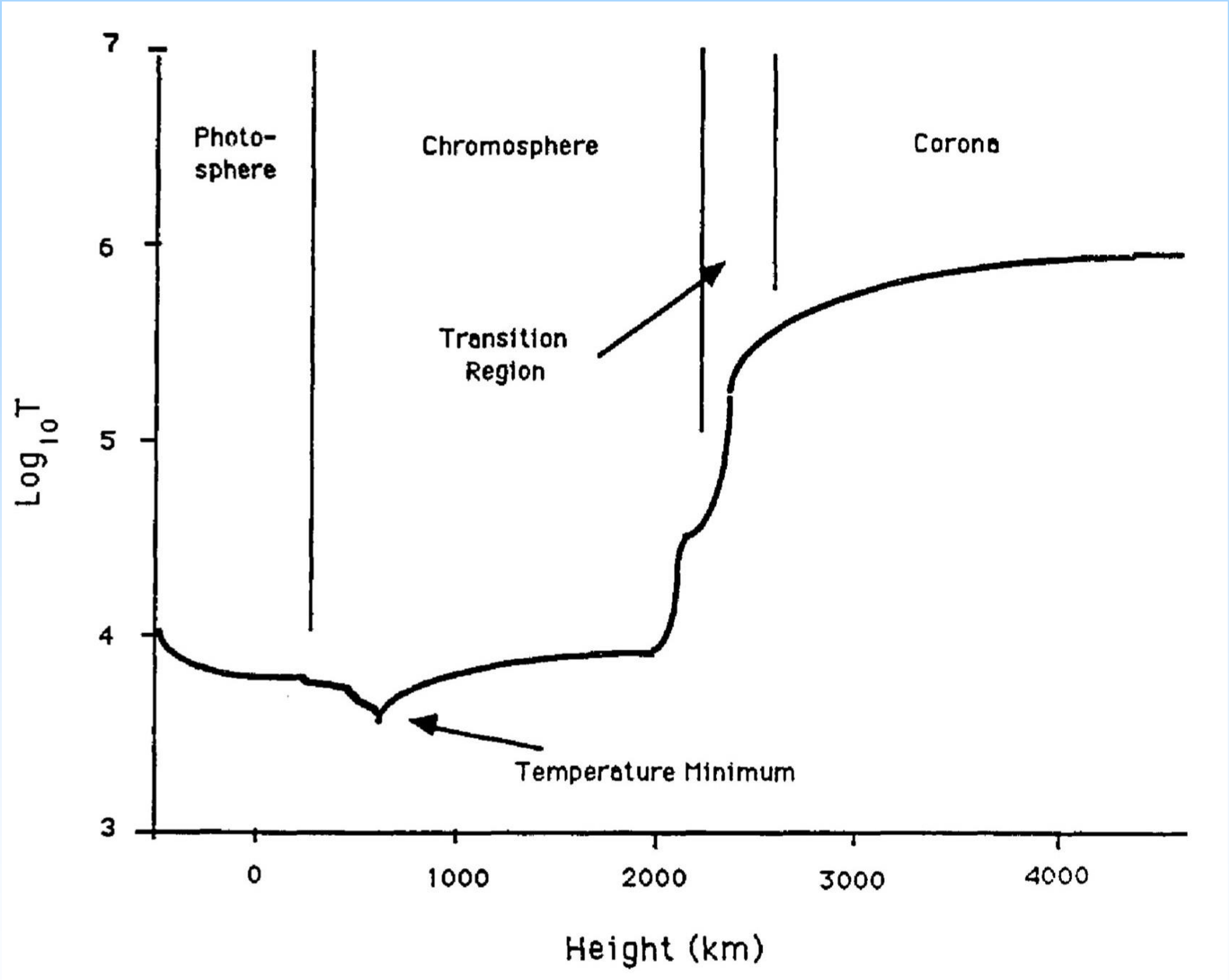
The Outer layers (Atmospheres) of the Sun:

•Photosphere

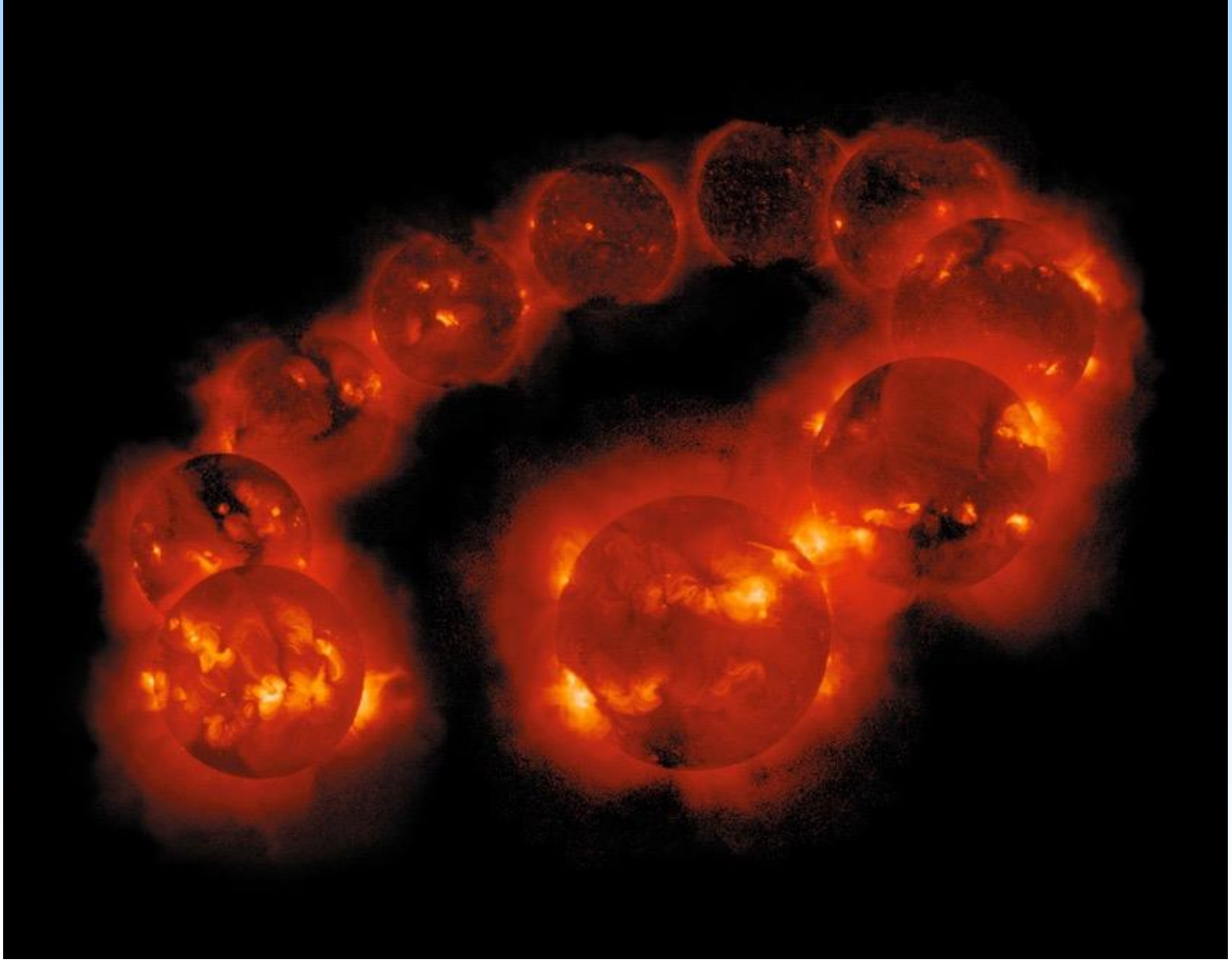


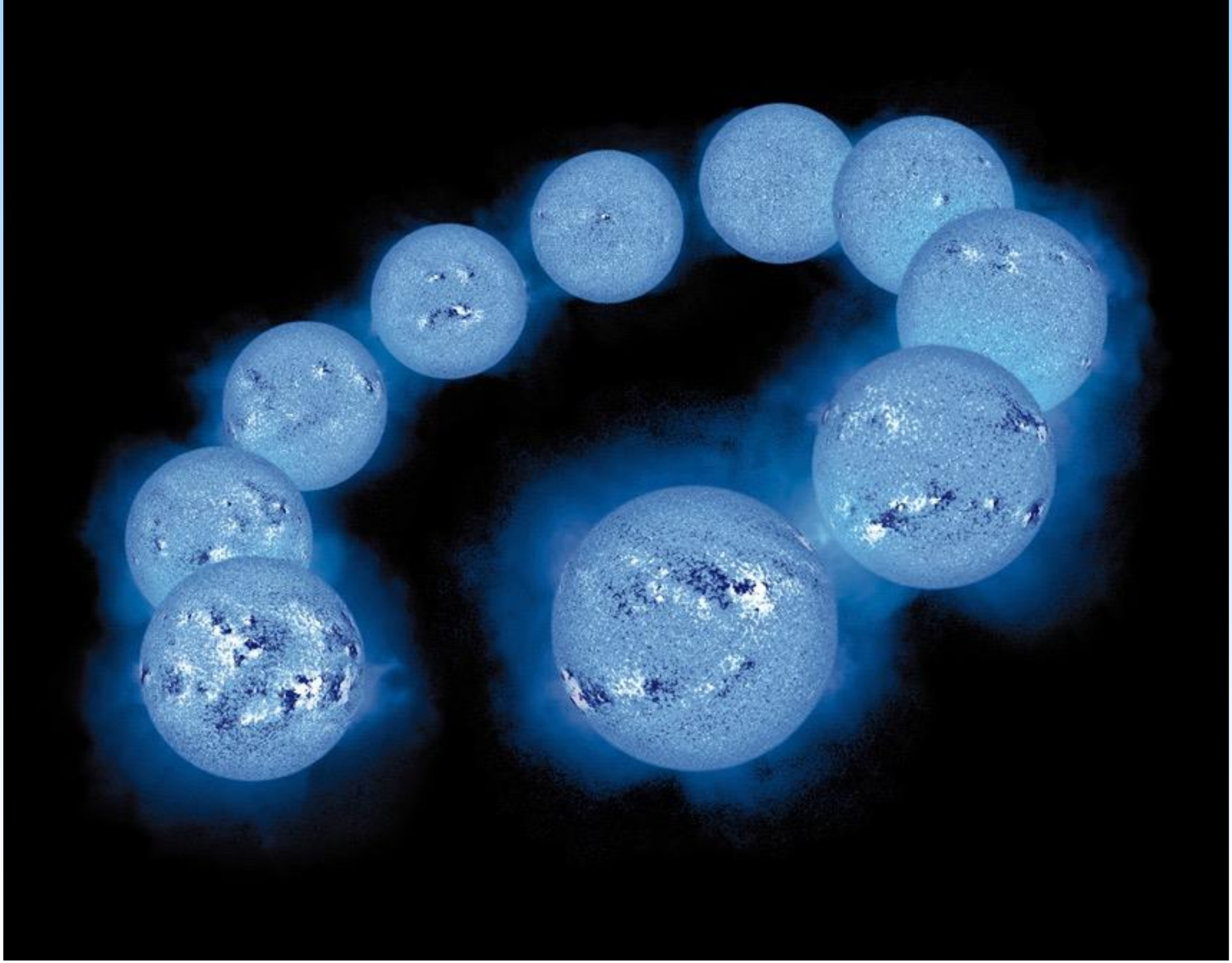
• Chromosphere

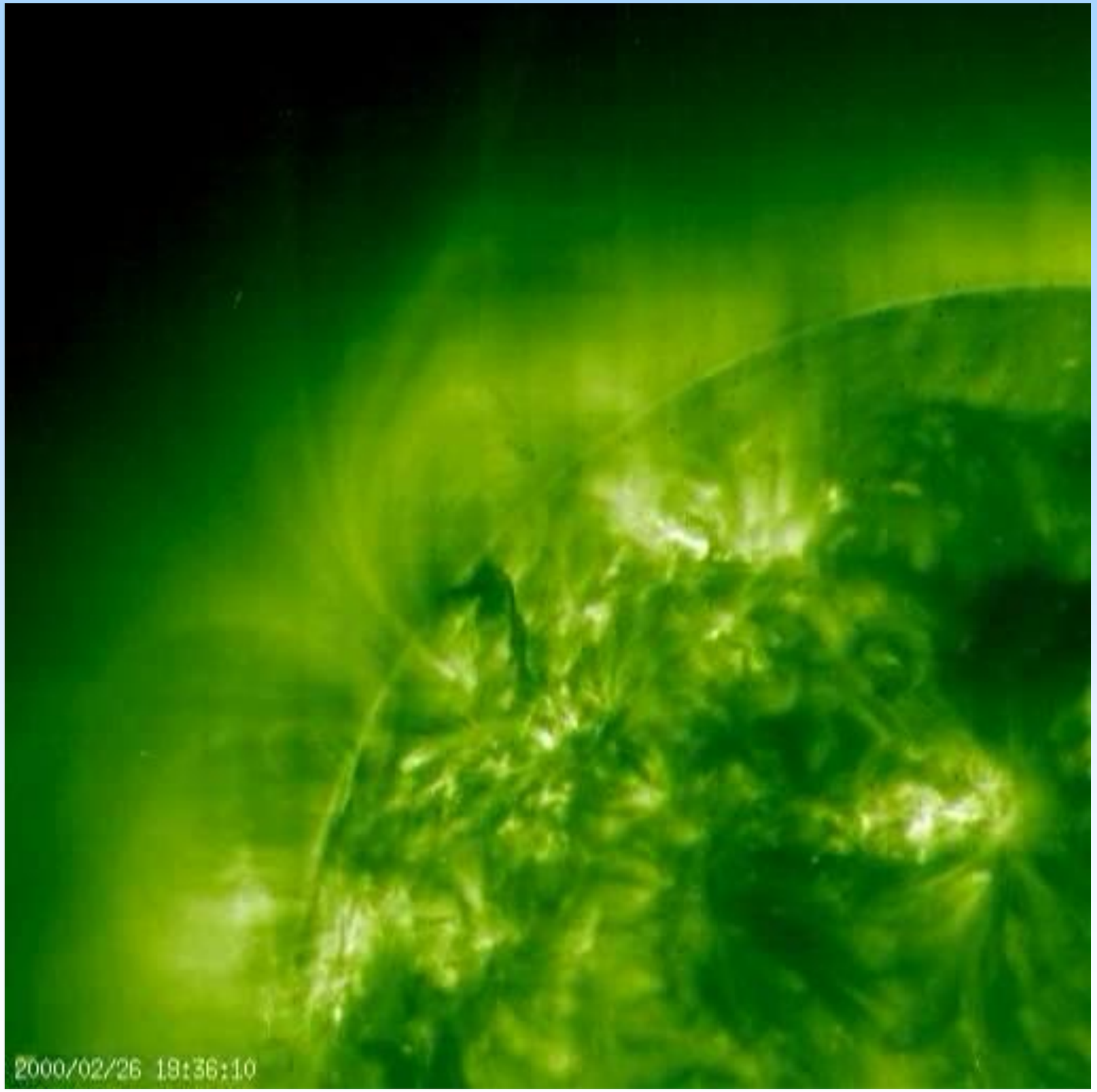
•Corona



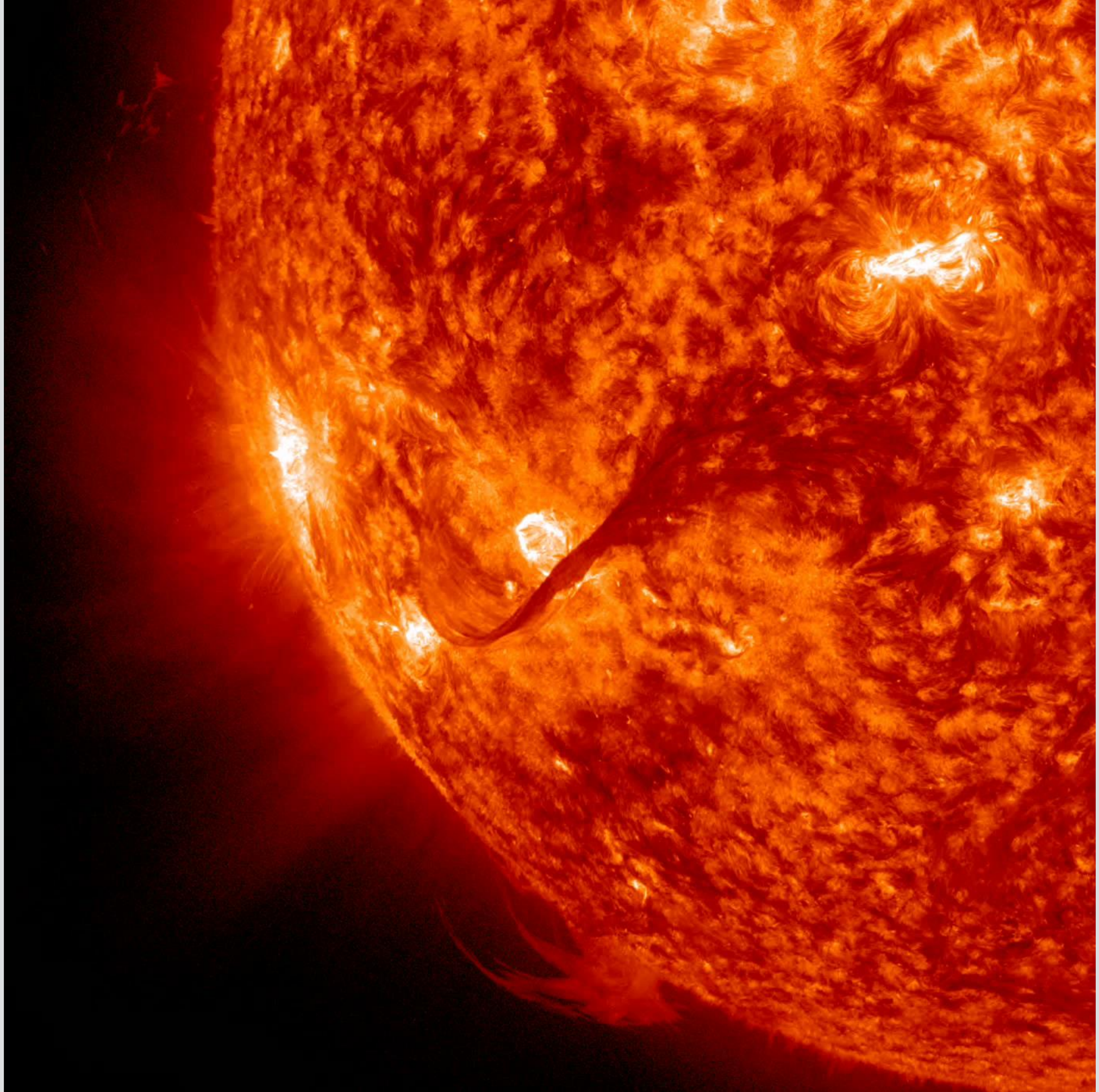
(Sterling, 1988)







(Sterling & Moore 2004)



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