Cascading Solar Eruptions

Alphonse C. Sterling

QuickTime™ and a
MPEG-4 Video decompressor
are needed to see this picture.

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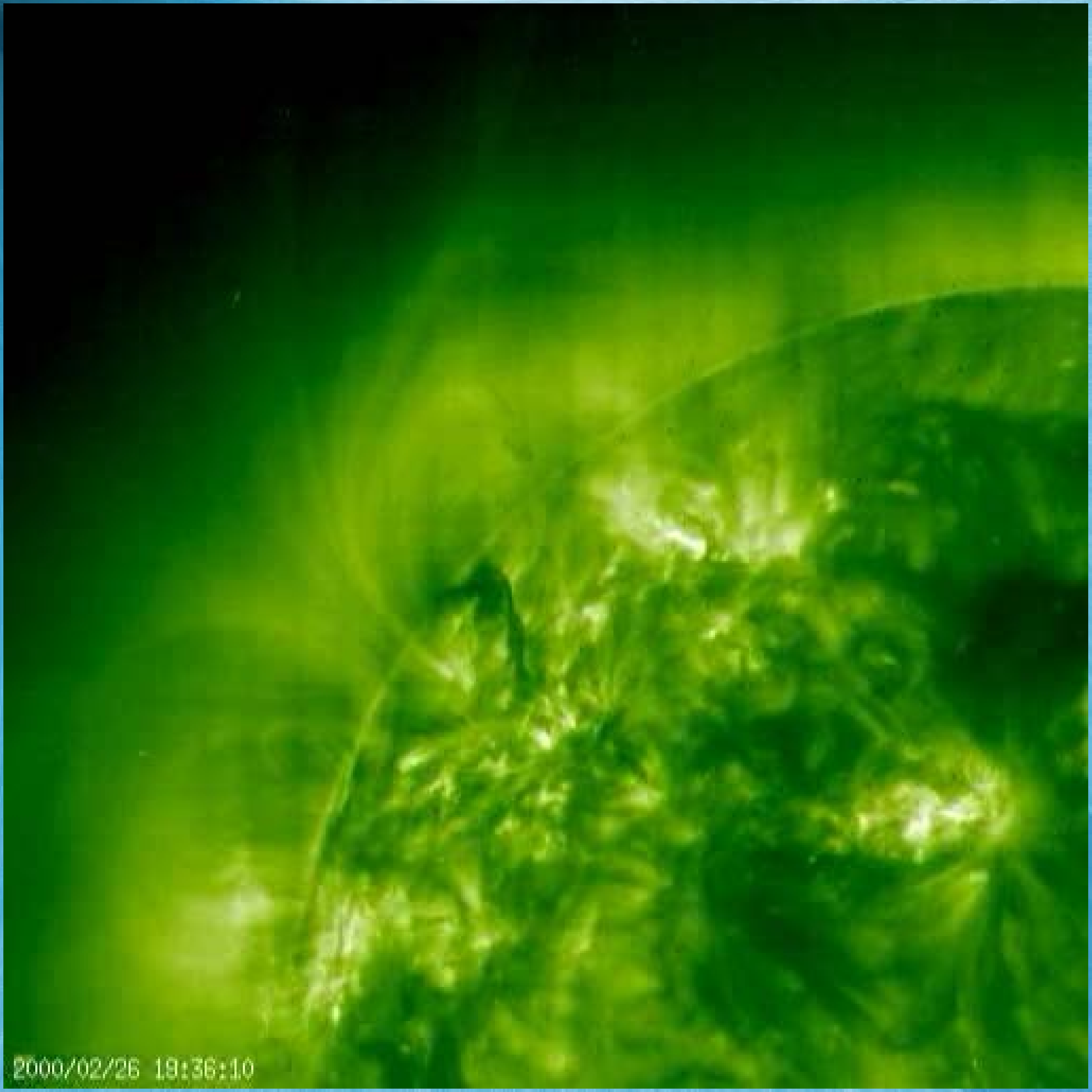
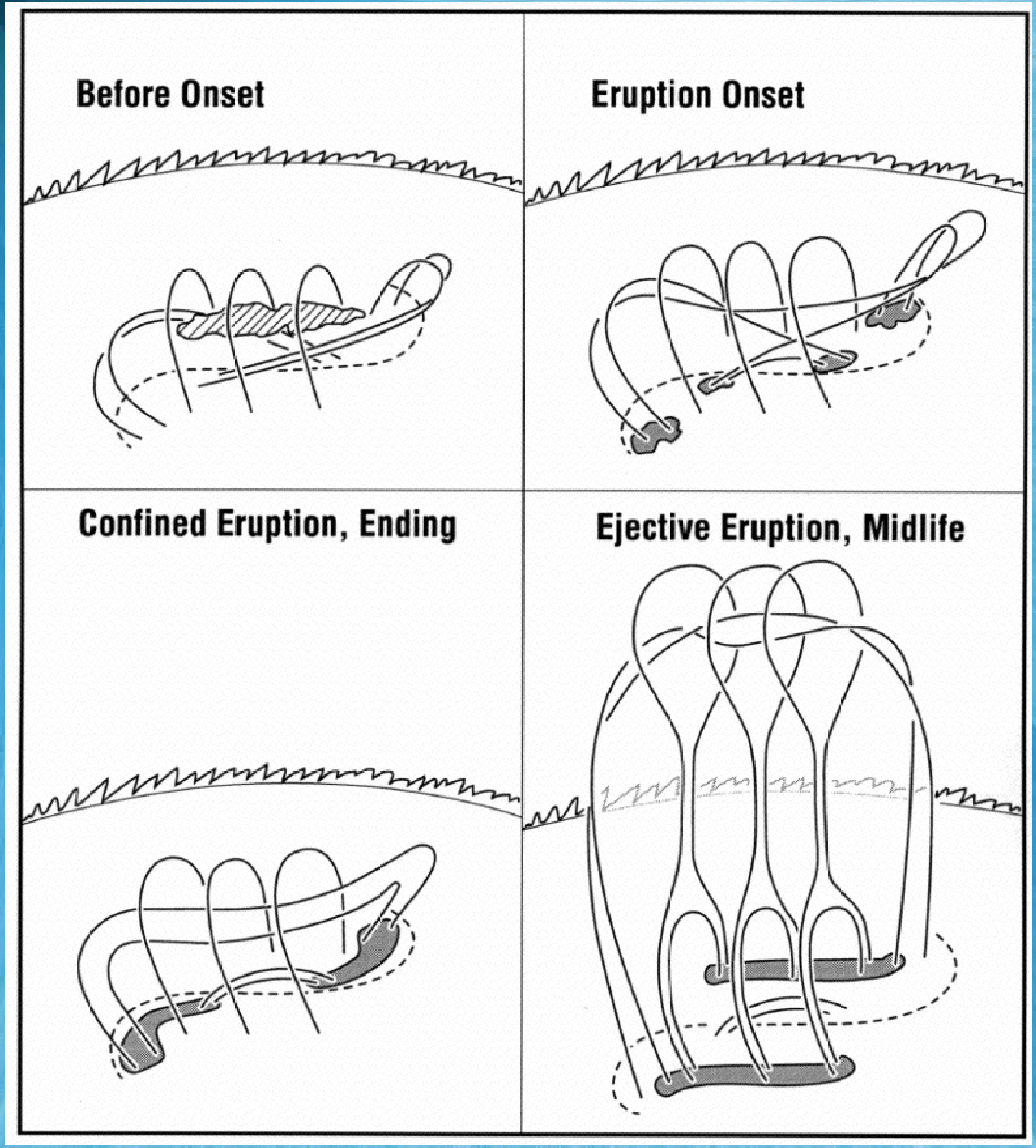
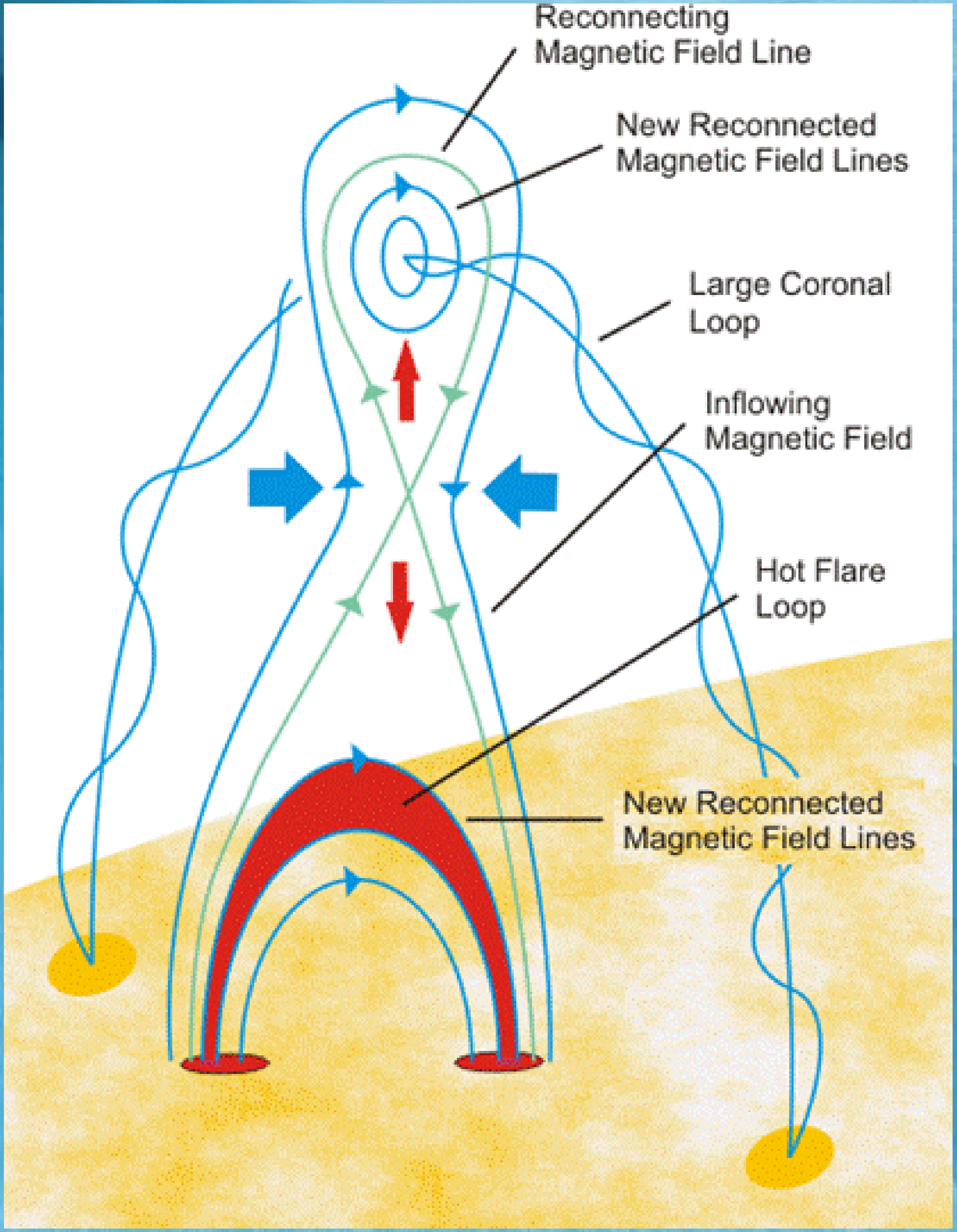


(Cf. Sterling & Moore 2004)



(Moore et al. 2001)



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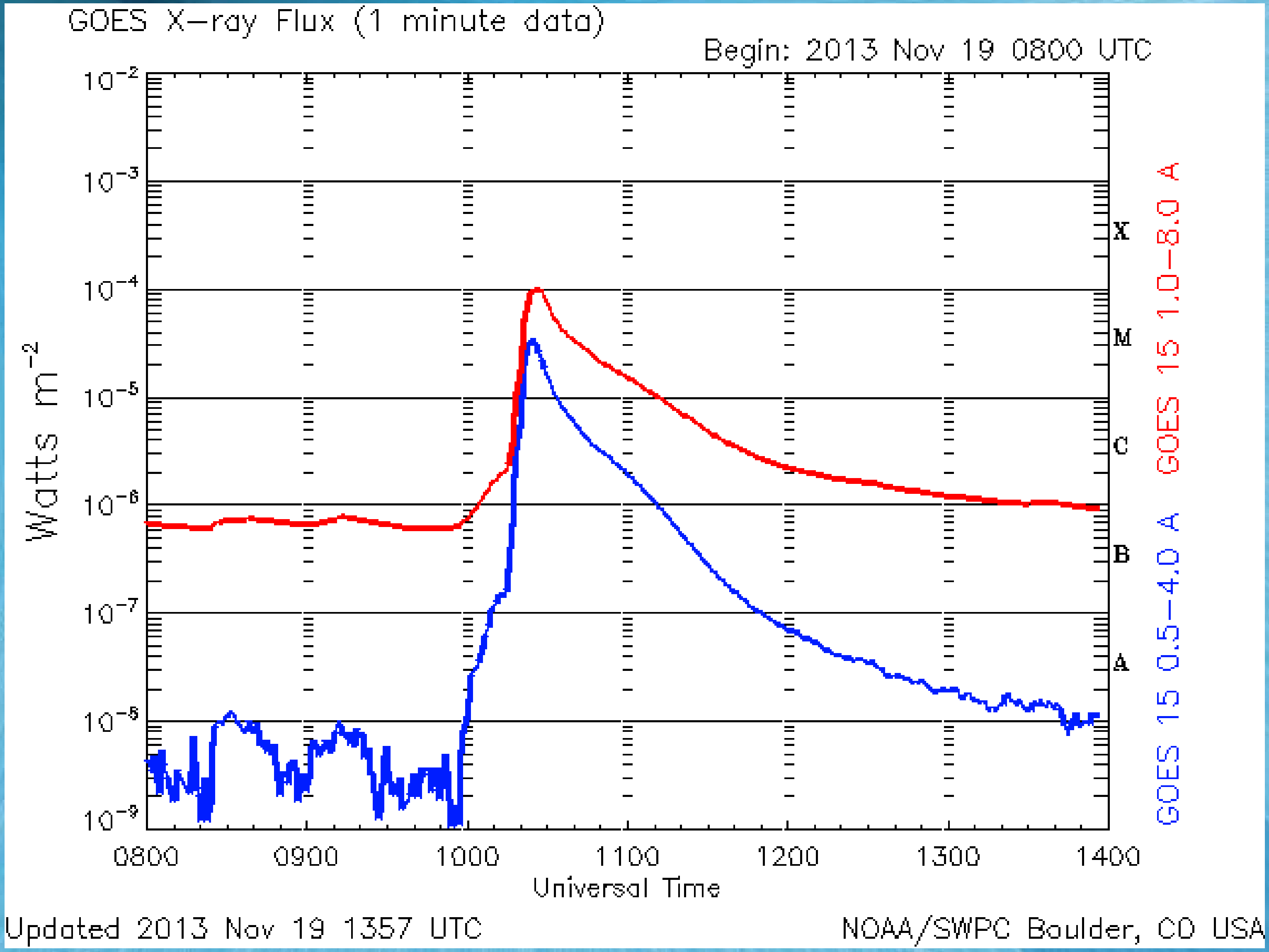
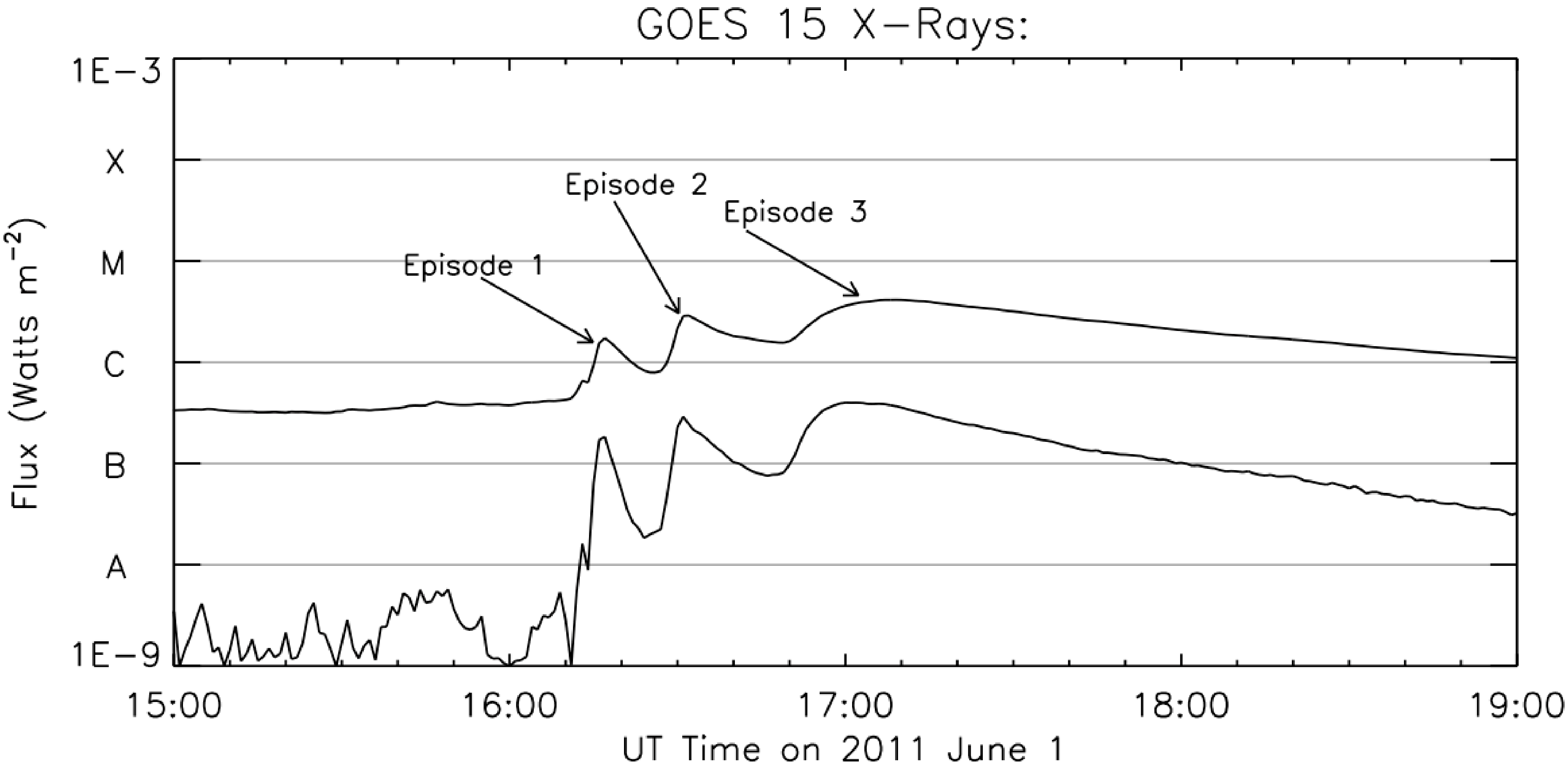
(Gordon Holman; RHESSI Nugget)



Cf. Hori et al. 1997, 1998)



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Observations from *SDO* and *Hinode* of a Twisting and Writhing Start to a Solar-filament-eruption Cascade

Alphonse C. Sterling, Ronald L. Moore, NASA/MSFC;
Hirohisa Hara, NAO Japan

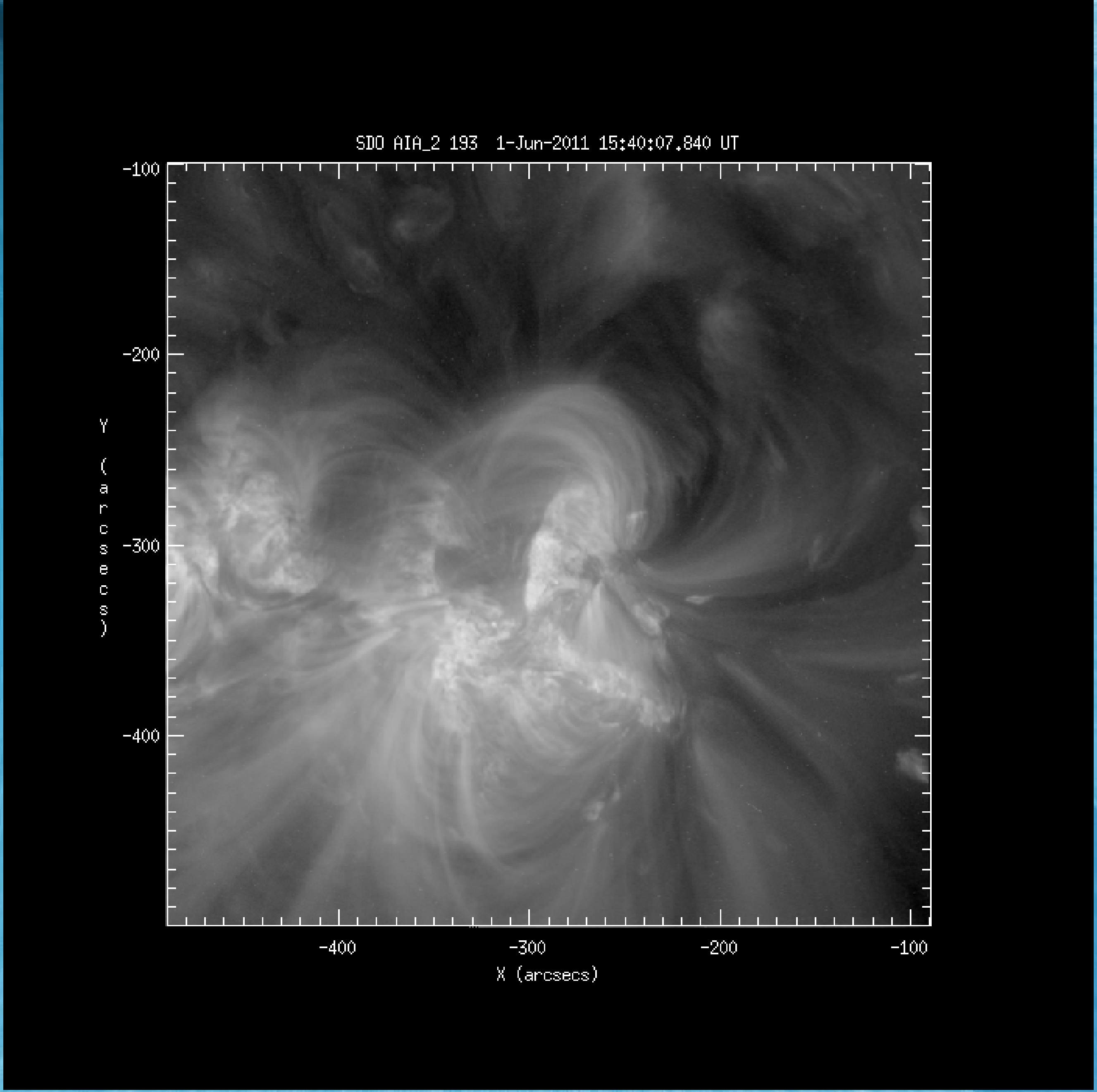
(ApJ 2012, 761, 69)

An AR Ejective Eruption from SDO and Hinode

- Active region eruption of 1 June 2011.
- Ejective eruption.
- GOES class C4.1 flare.
- SDO/AIA, various filters (94, 131, 171, 193, 211, 304, 335 Ang.)
- High time cadence (24 s) and high spatial resolution (0’’.6 pixels).
- SDO/HMI line-of-sight magnetograms.
- Hinode observed the onset, and the later decay phase.

A question: What causes the humps in the GOES lightcurve?

Main focus: What’s going on in the onset phase (what gets it going)?



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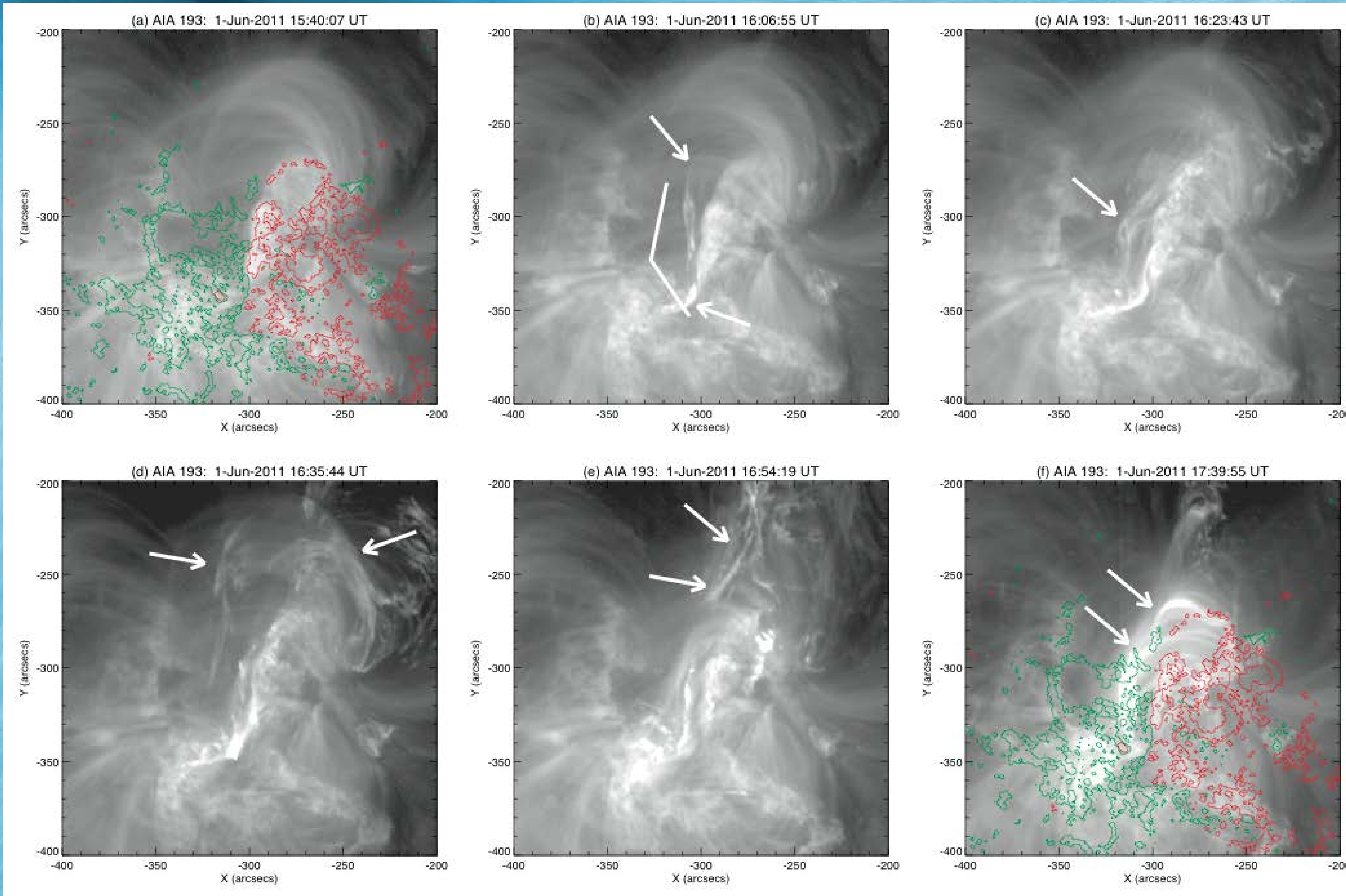

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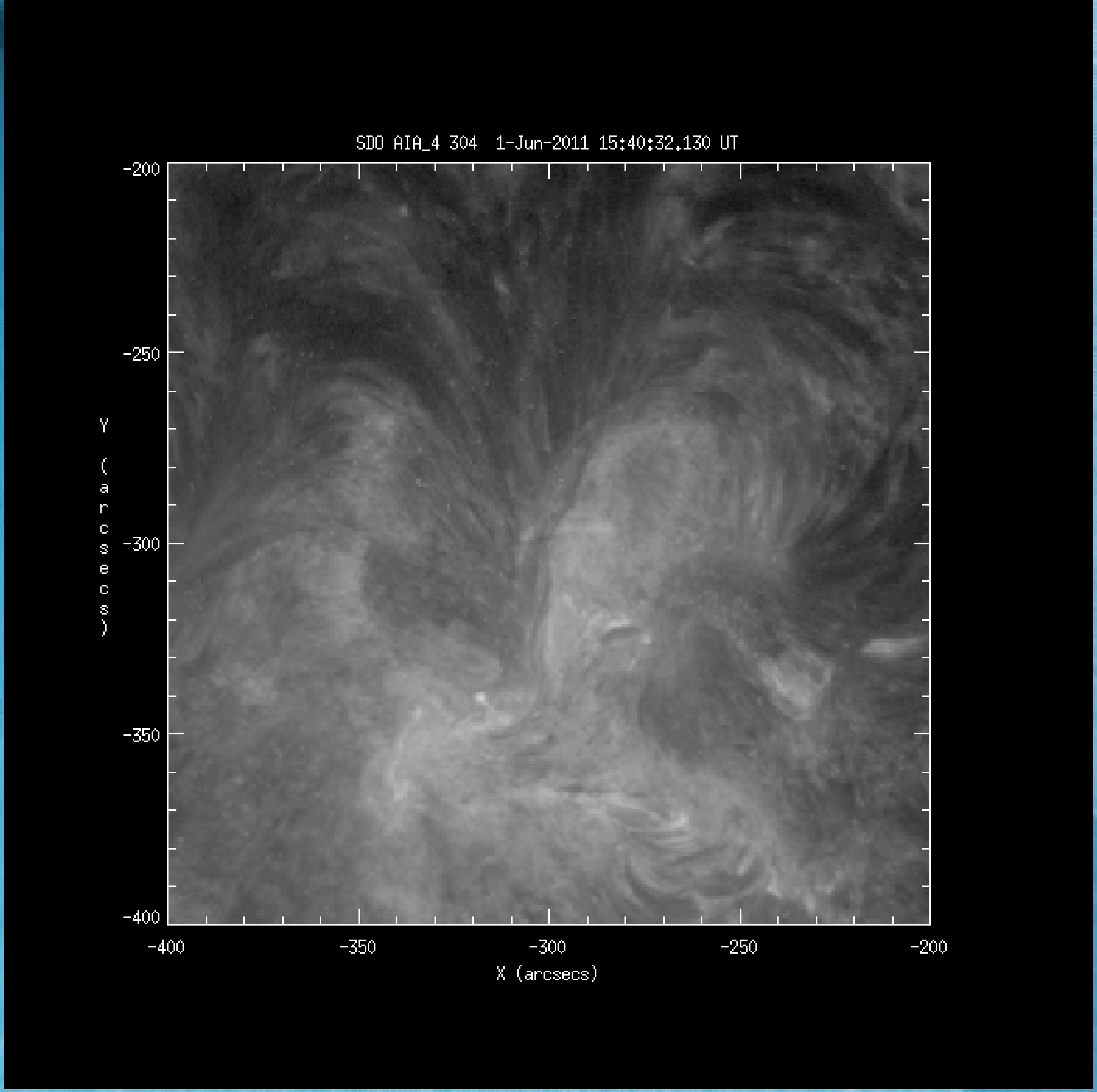
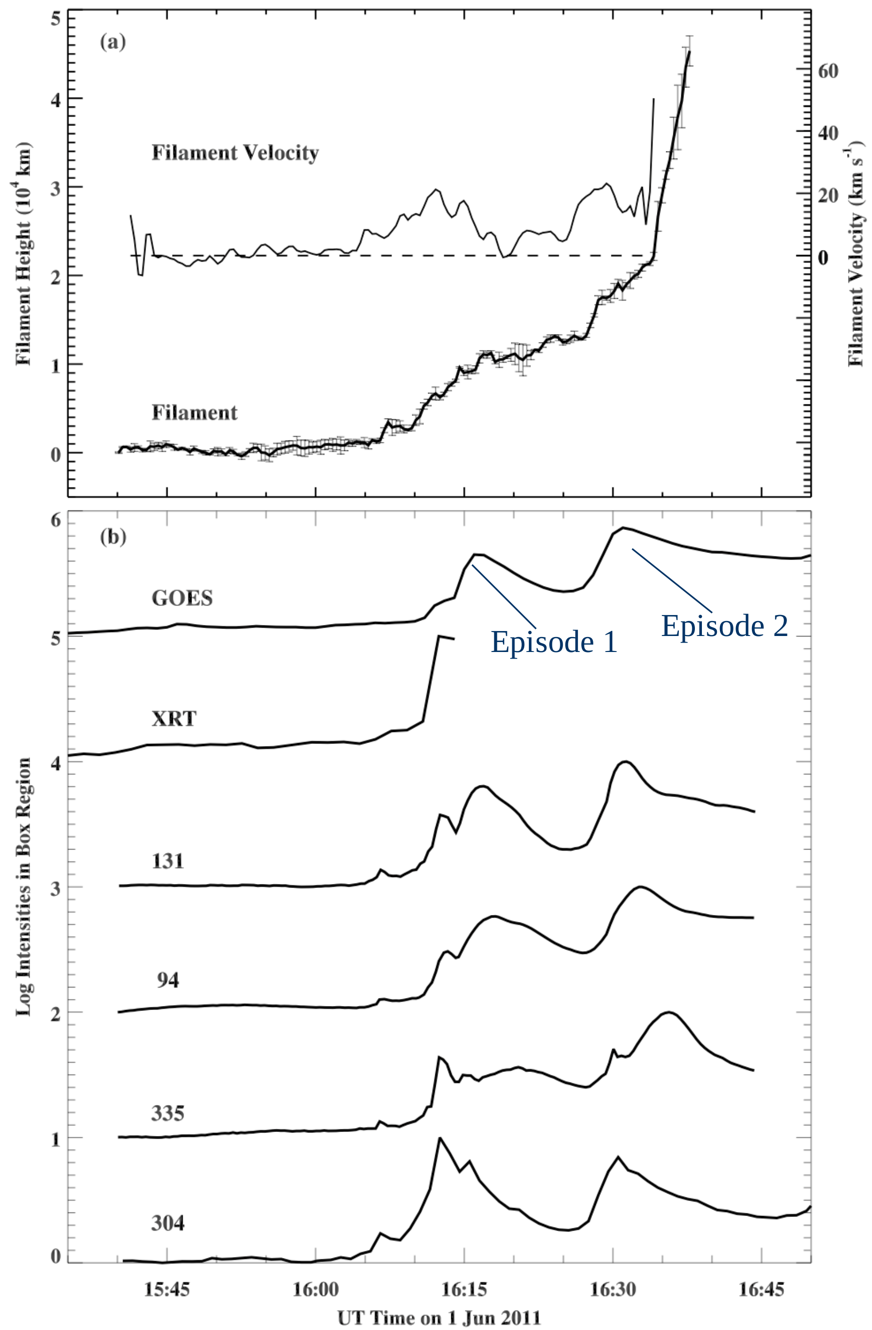

SDO AIA_4 304 1-Jun-2011 15:40:32.130 UT
-200
-250
-300
-350
-400
Y (arcsecs)
-400
-350
-300
-250
-200
X (arcsecs)



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• There are two filament eruptions (filament 1 and filament 2).

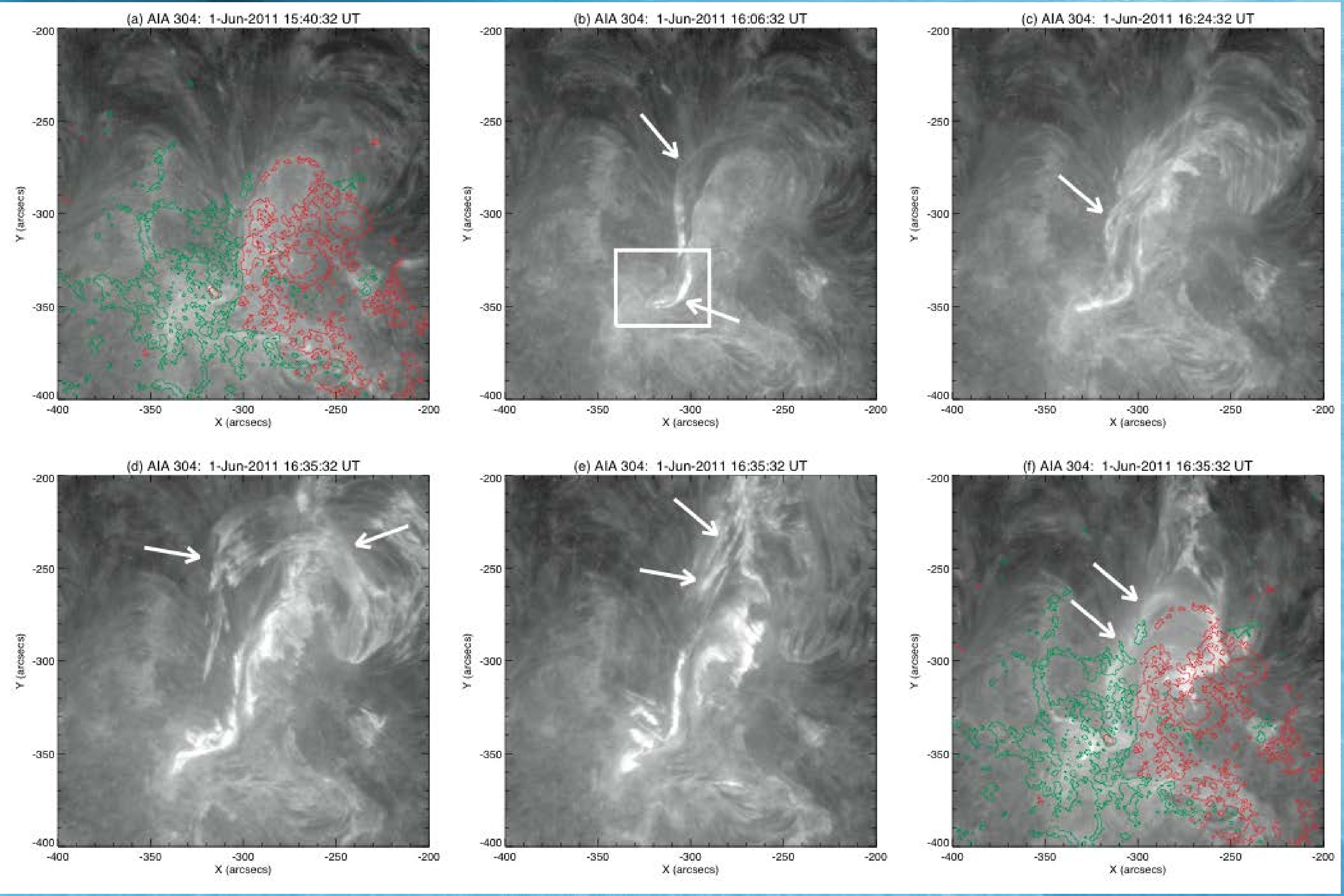
• Filament 1 has slow rise with steps, as in several previous cases. GOES “episodes” play role of “microflares” in other events; that is, filament jumps <=> intensity peaks.

• Episode 1 brightening: Accompanied by filament 1’s initial motions. (Rest of talk.) Filament 1 becomes unstable, and…

• Episode 2 brightening: Flare ribbons following filament 1’s fast liftoff. This destabilizes neighboring filament 2, and…

• Episode 3 brightening: Flare ribbons of whole system following filament 2’s eruption.

What goes on at the southern end, near time of Episode 1 brightening?



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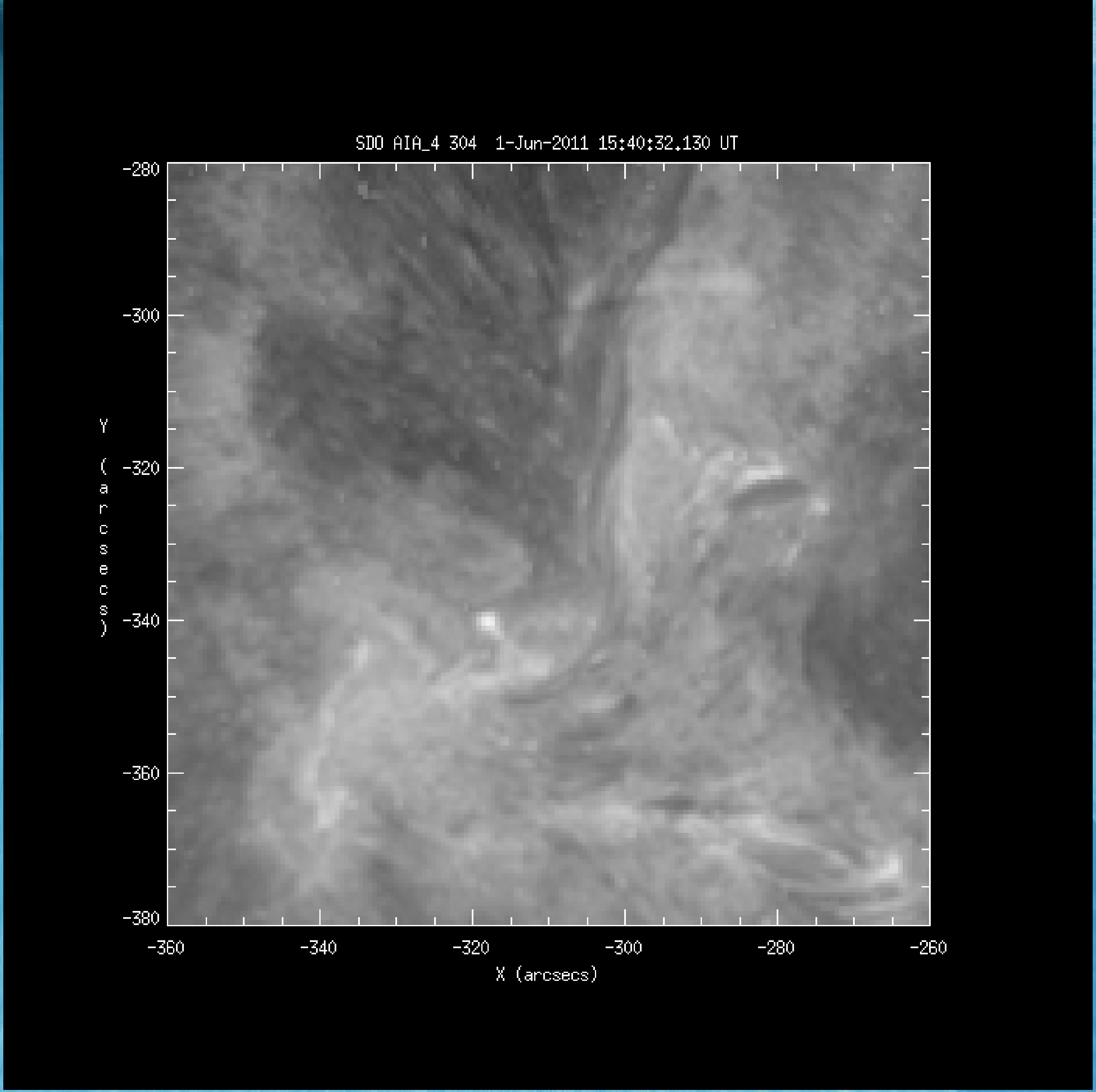

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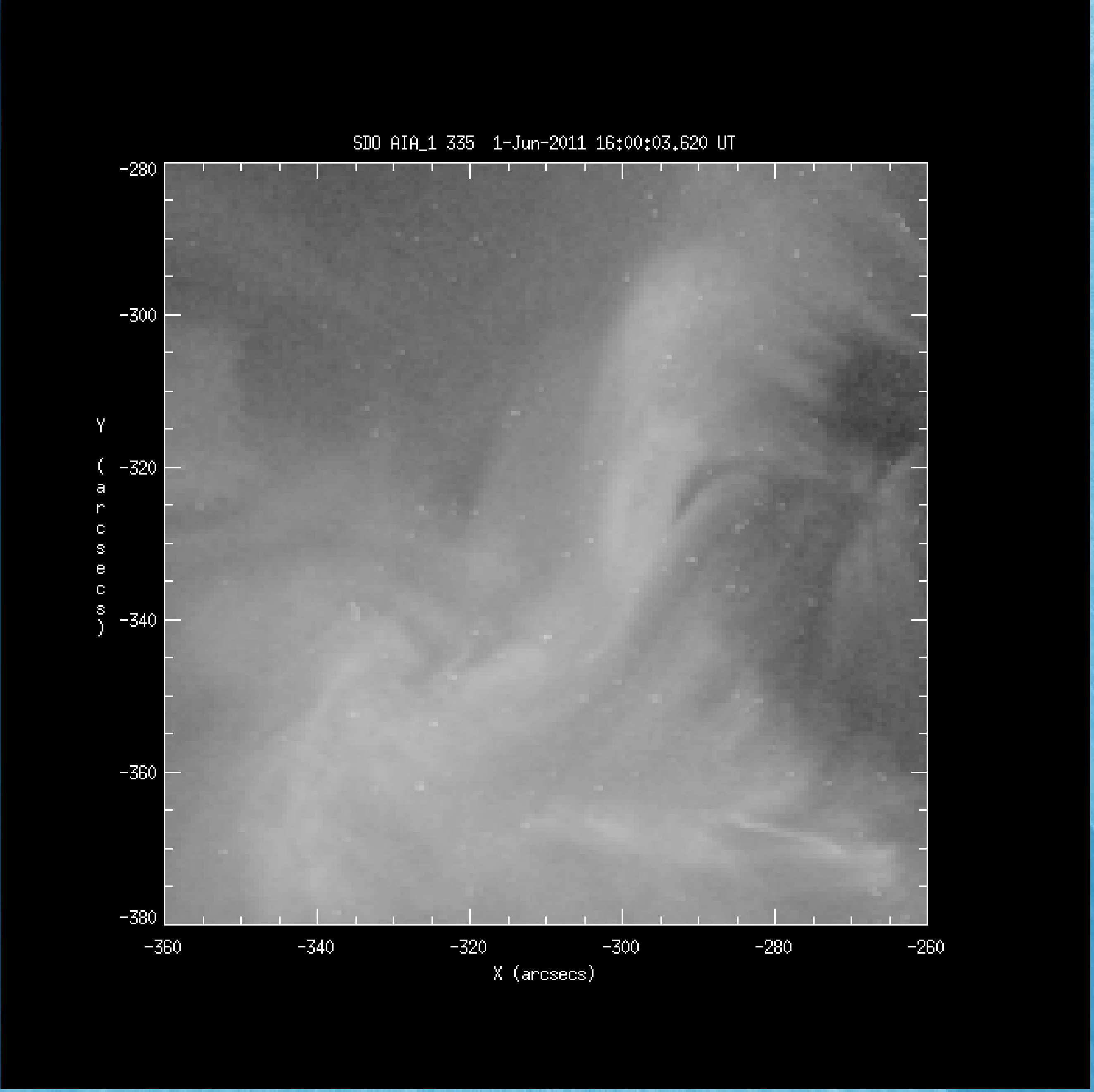

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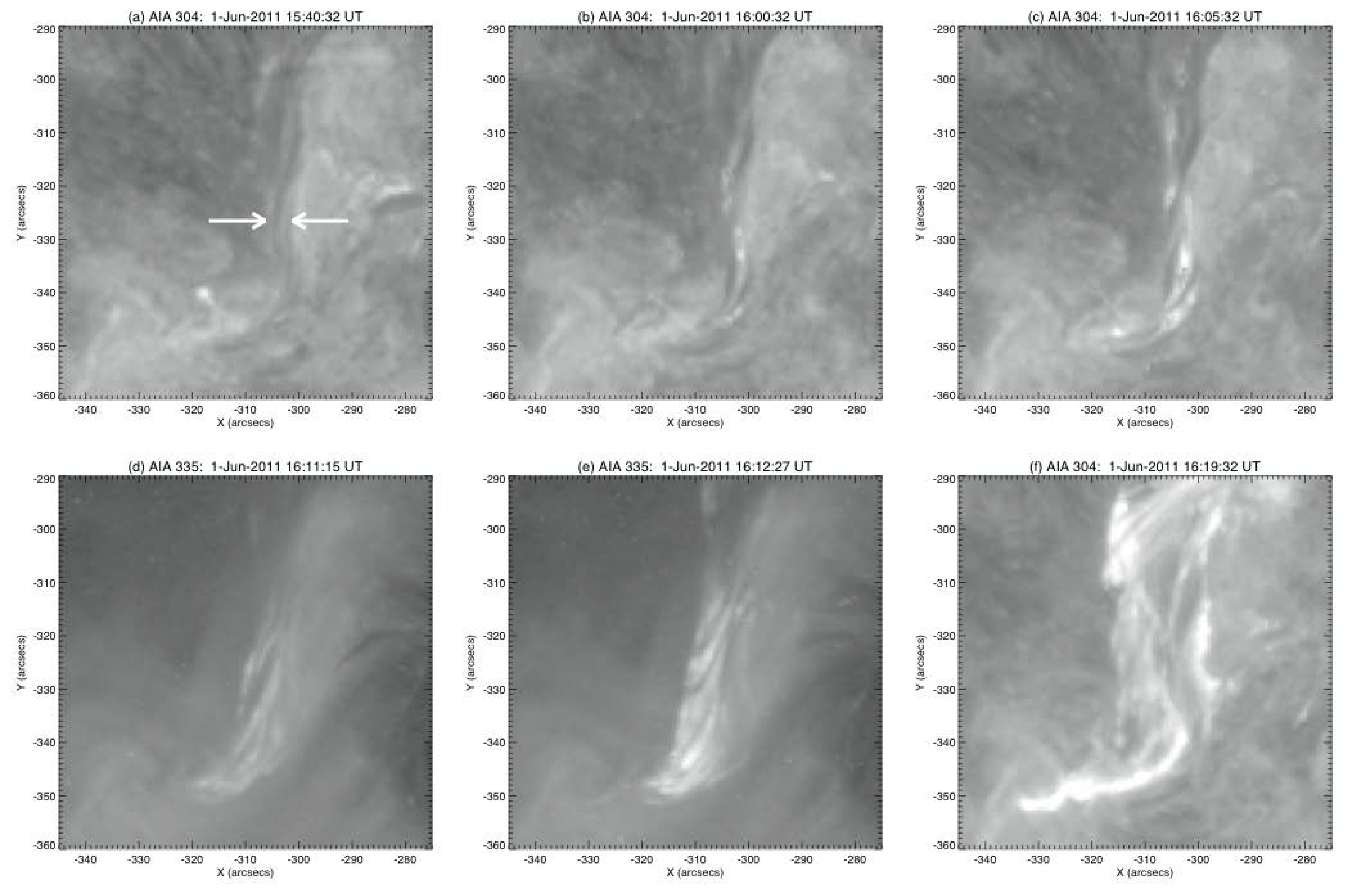
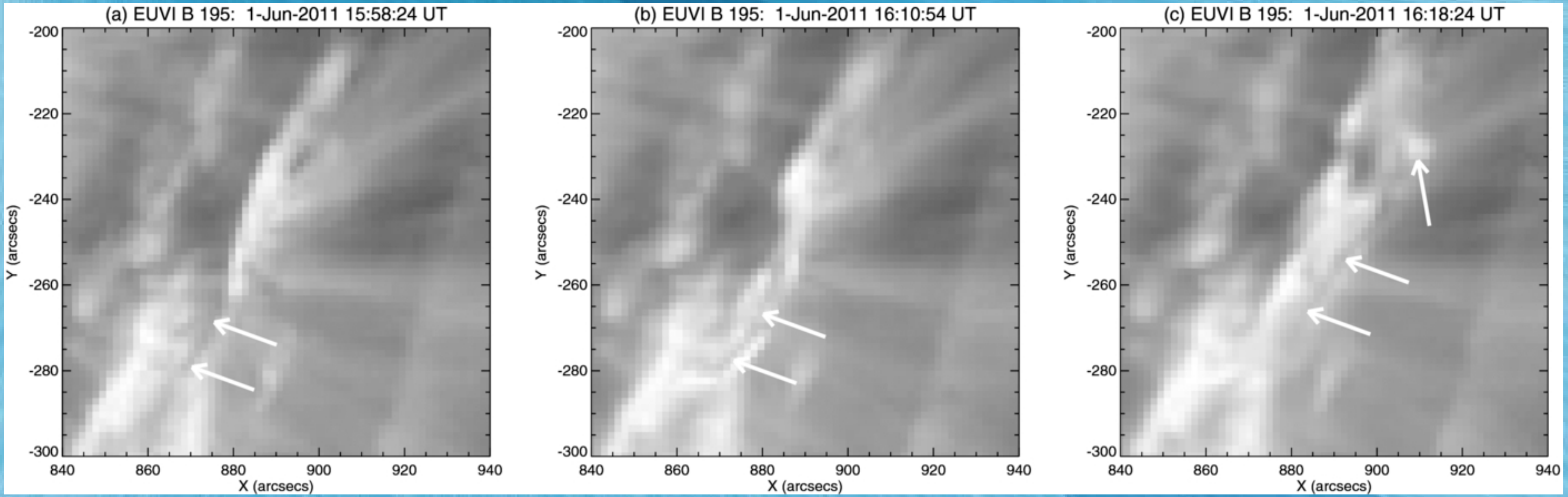

(a) AIA 304: 1-Jun-2011 15:40:32 UT
(b) AIA 304: 1-Jun-2011 16:00:32 UT
(c) AIA 304: 1-Jun-2011 16:05:32 UT
(d) AIA 335: 1-Jun-2011 16:11:15 UT
(e) AIA 335: 1-Jun-2011 16:12:27 UT
(f) AIA 304: 1-Jun-2011 16:19:32 UT
Y (arcsecs)
X (arcsecs)
-290
-300
-310
-320
-330
-340
-350
-360
-340
-330
-320
-310
-300
-290
-280



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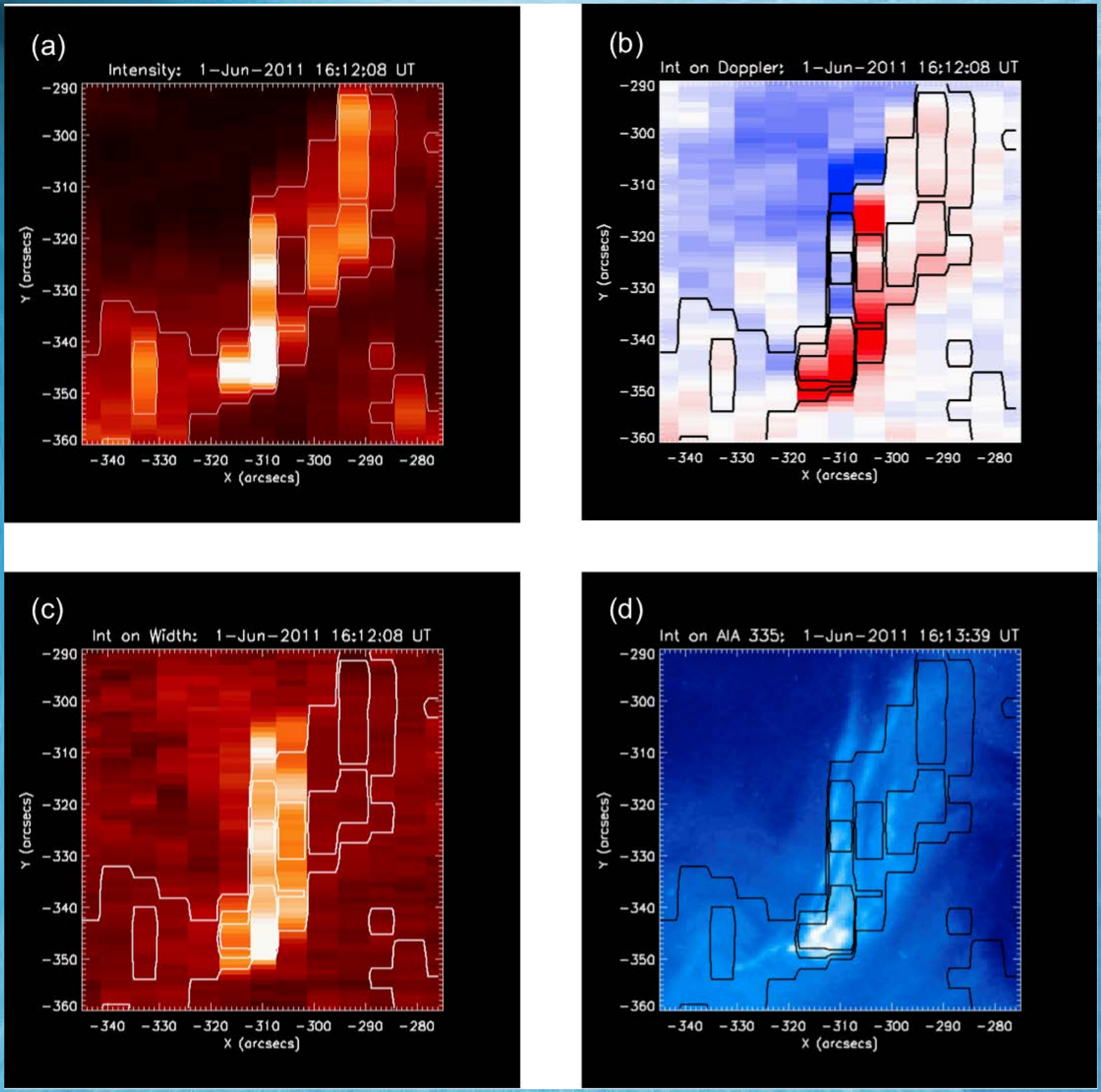
Is the "Flux Rope" Structure Twist-Unstable?

Some history of twist-induced instability in filament eruptions:
e.g., Sakurai, Török & Kliem, Fan & Gibson, Gilbert et al.,
van Driel-Gesztelyi et al.

Criterion : Kink instability for line-tied tube (Hood & Priest): 2.5π;
for Titov & Démoulin loop (Török et al): $\sim 3.5\pi$

We observe here: ~1.5 turns (3.0π) over ~50″
=> consistent with kink instability acting.

(Cf. Srivastava et al. (2010): Small flare seen in TRACE and
Hinode: $\sim 6.0\pi$)



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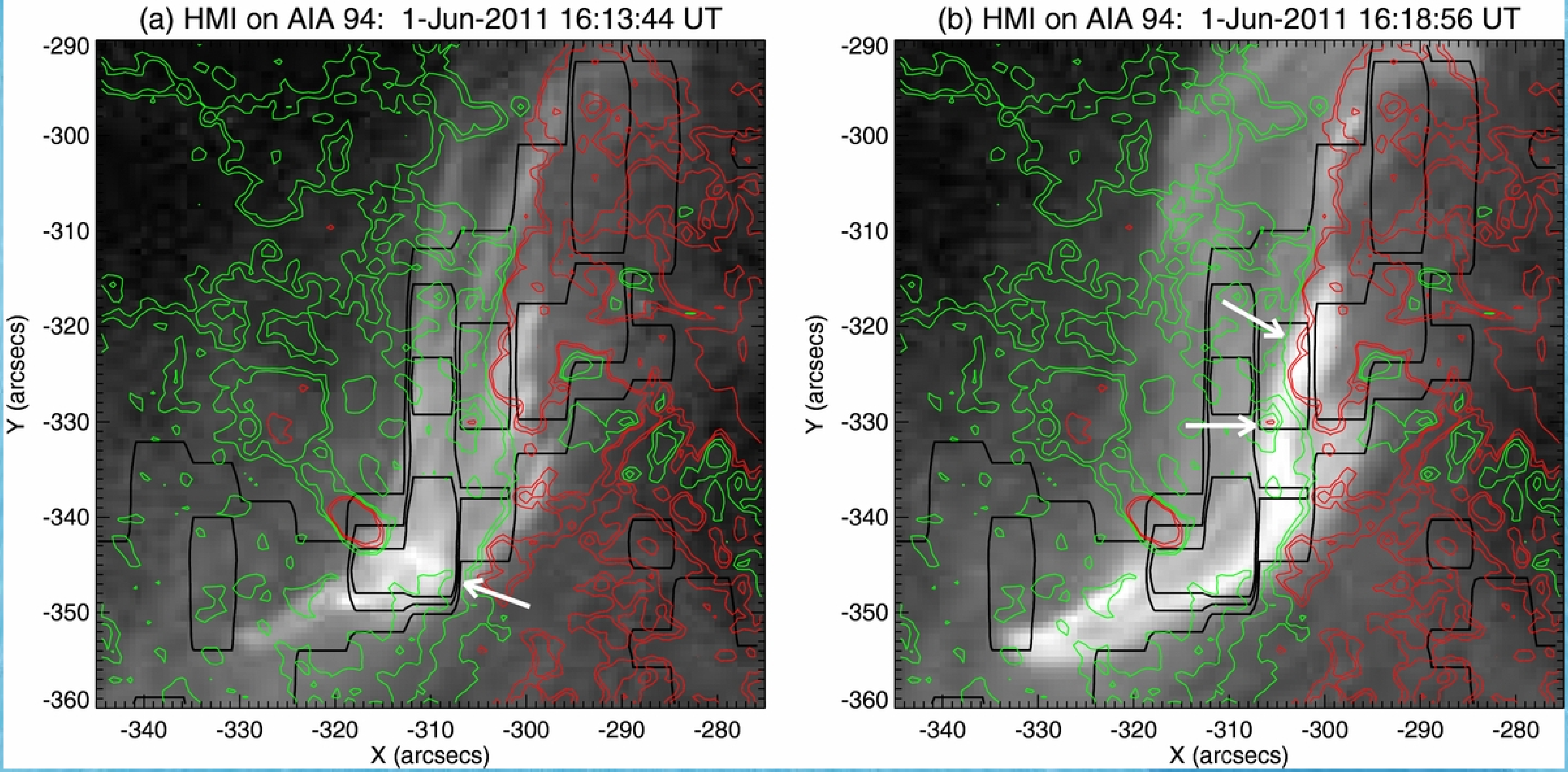
EIS Spectral Properties

- "Picket fence" mode; 1'' in N-S, ~6'' in EW
- Slit crosses ROI ~ 16:13:36 UT
- Alignment good to ~3'', based on intensity matching
- Doppler velocities:
  - Max blue in E strip ~ 23+-17 km/s
  - Max red in S, ~ 85+-60 km/s
  - Max red in W strip ~ 62+-25 km/s
- Non-thermal velocities:
  - ~ 70 km/s in two strips
  - ~ 125 km/s in s
  - These max are similar to C- and M-flares of Kay et al. (2006)
- What leads to blue and red Doppler shifts?
  - Not twisting....
  - Maybe "flare" loops?



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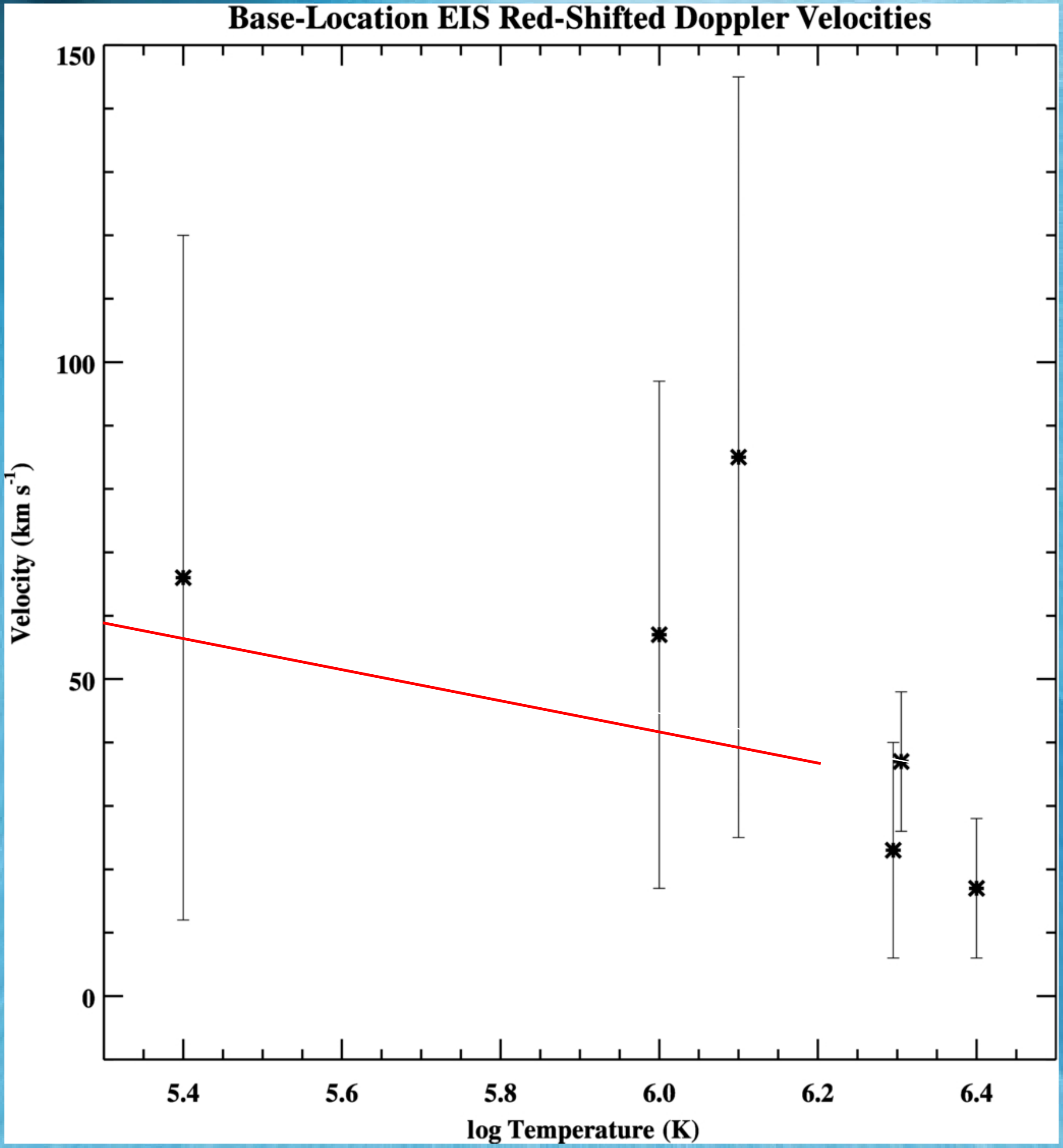


Red= Milligan & Dennis (2009), Evaporation red shift.

Can this drive the entire eruption sequence?

Estimate amount of free energy in newly-twisted field (cf. Moore 1988):

$$B_{norm} \approx B_{par}$$

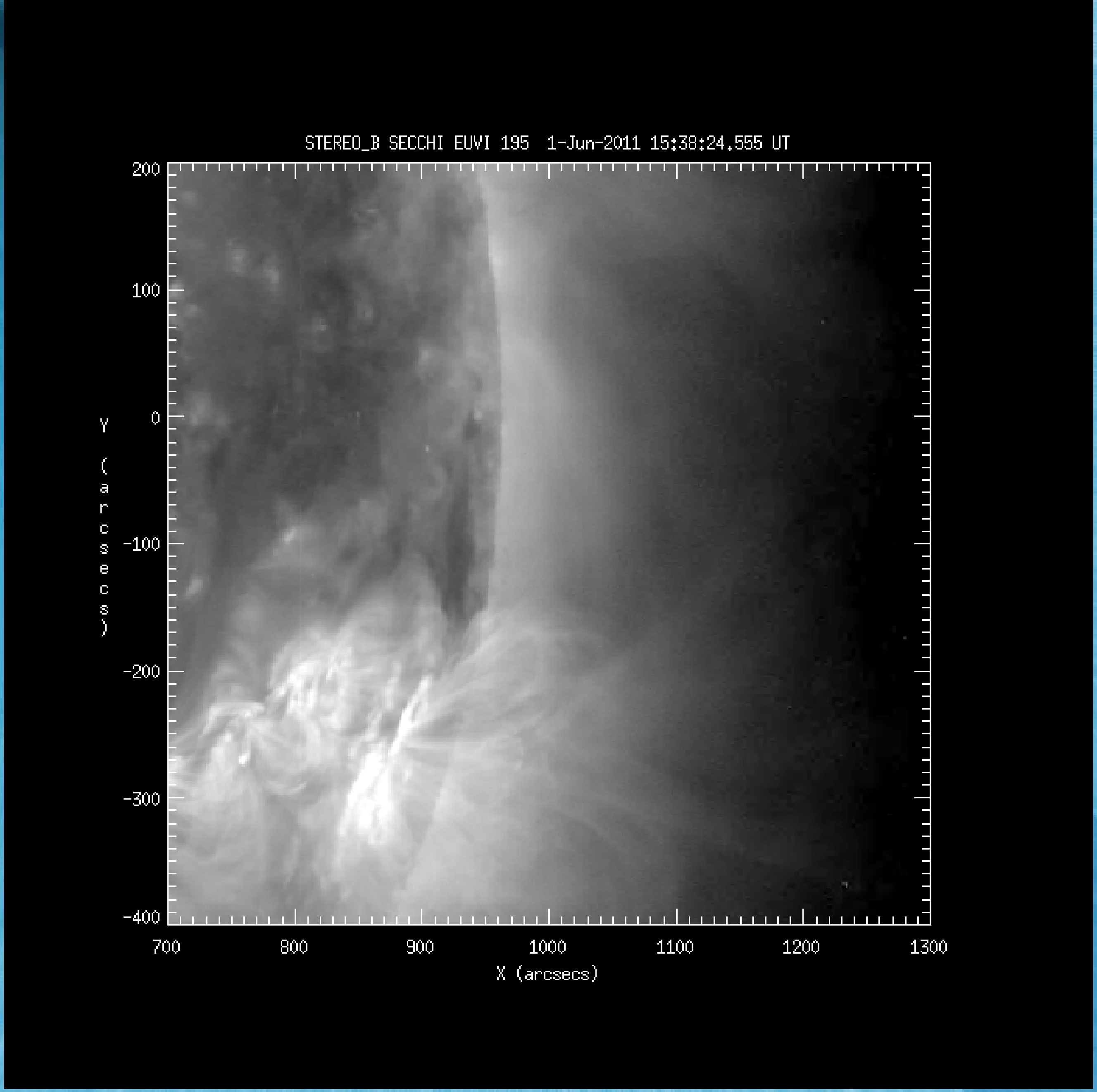
$$E_{free} \sim B_z^2 / 8\pi \times (\pi r^2 L)$$

$$\sim 10^{29} \text{ ergs}$$

where we have taken L and r = 50, 3 arcsec; B~100 G.

Estimate energy of the total system ~10^{30} ergs, from GOES flux. So "no" is answer to question.

Additional energy comes from remainder of sheared large loop, shear (free energy) of second filament, etc. (Normally assumed situation.)



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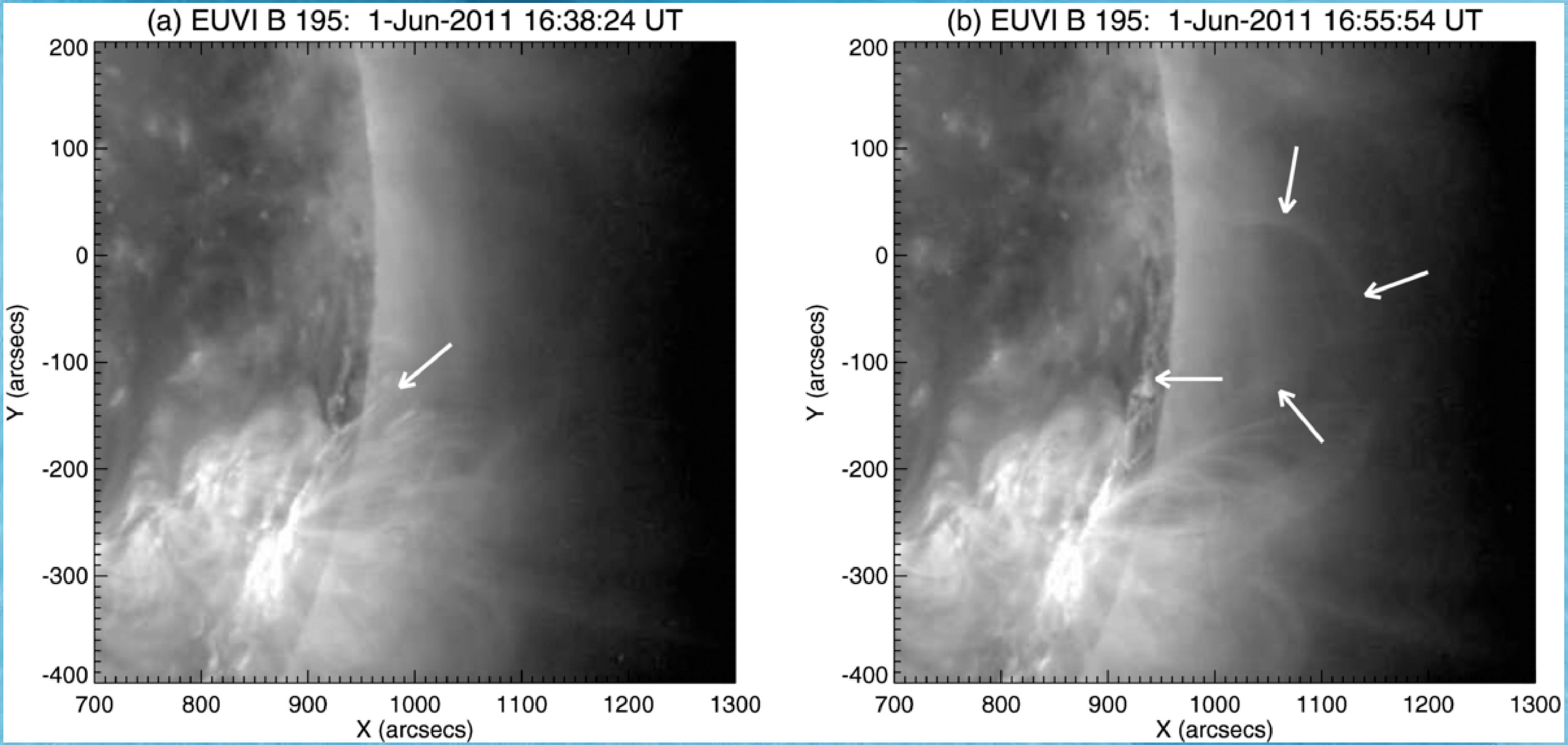

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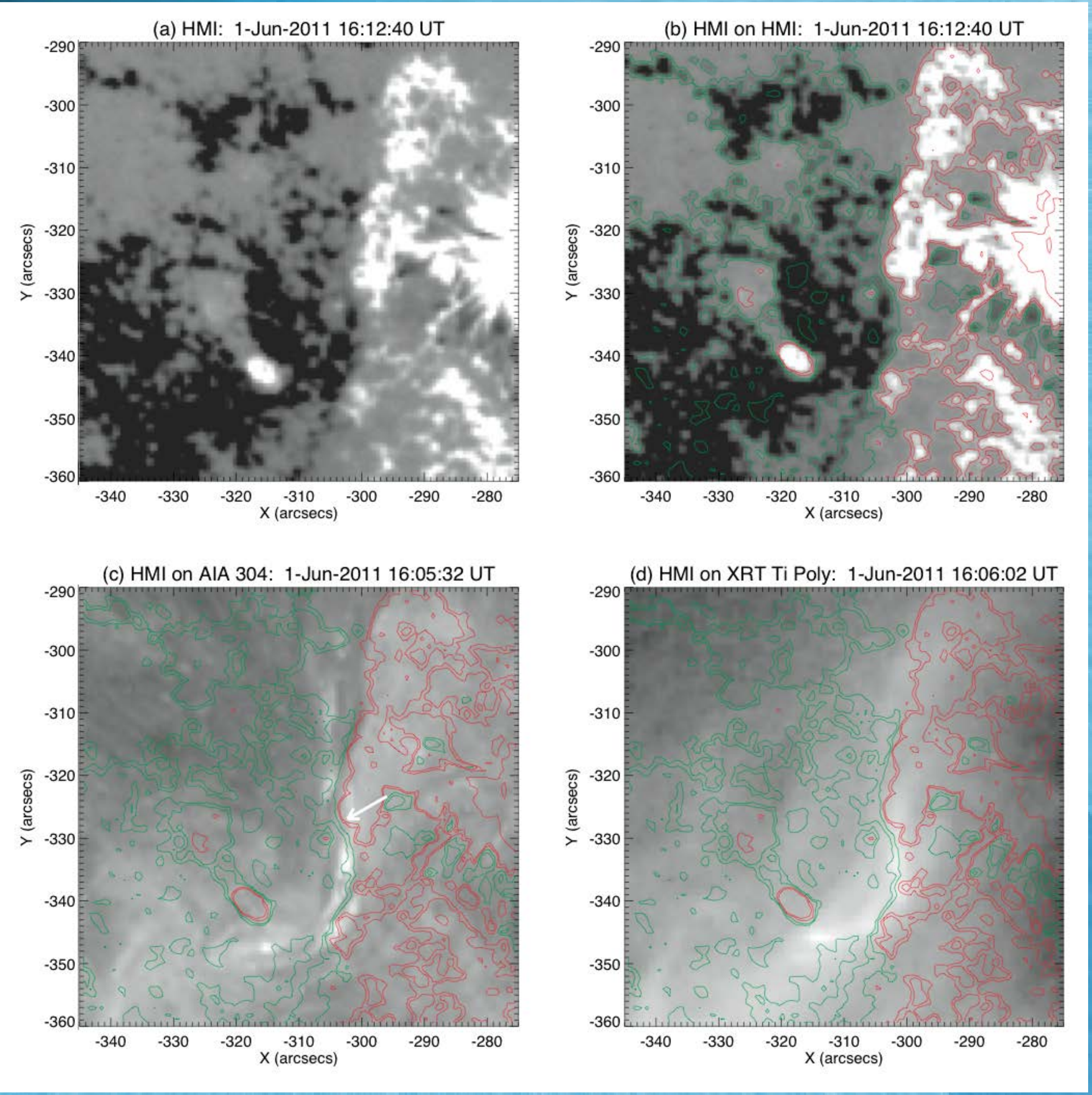
What causes the initial reconnection at the base?



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QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

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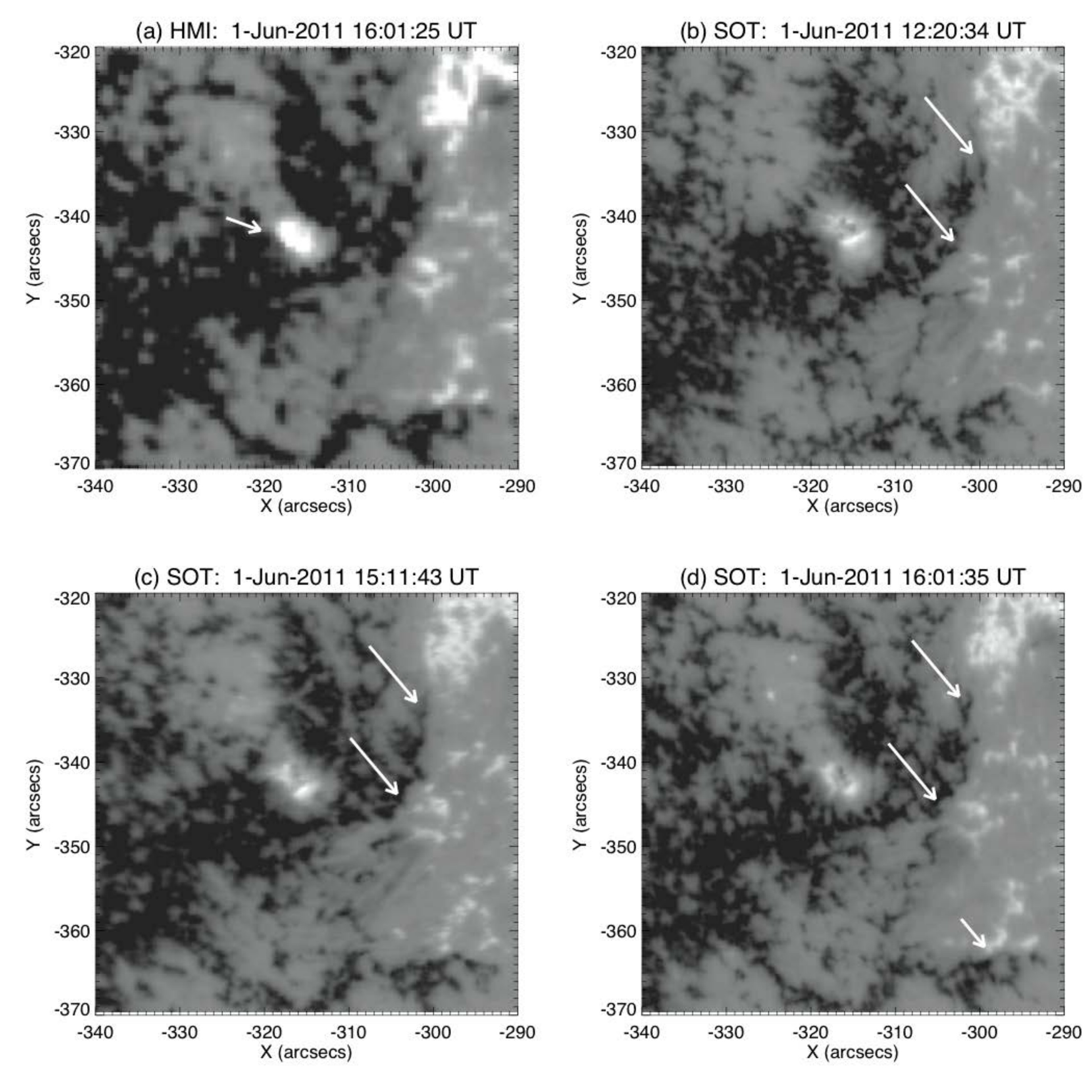

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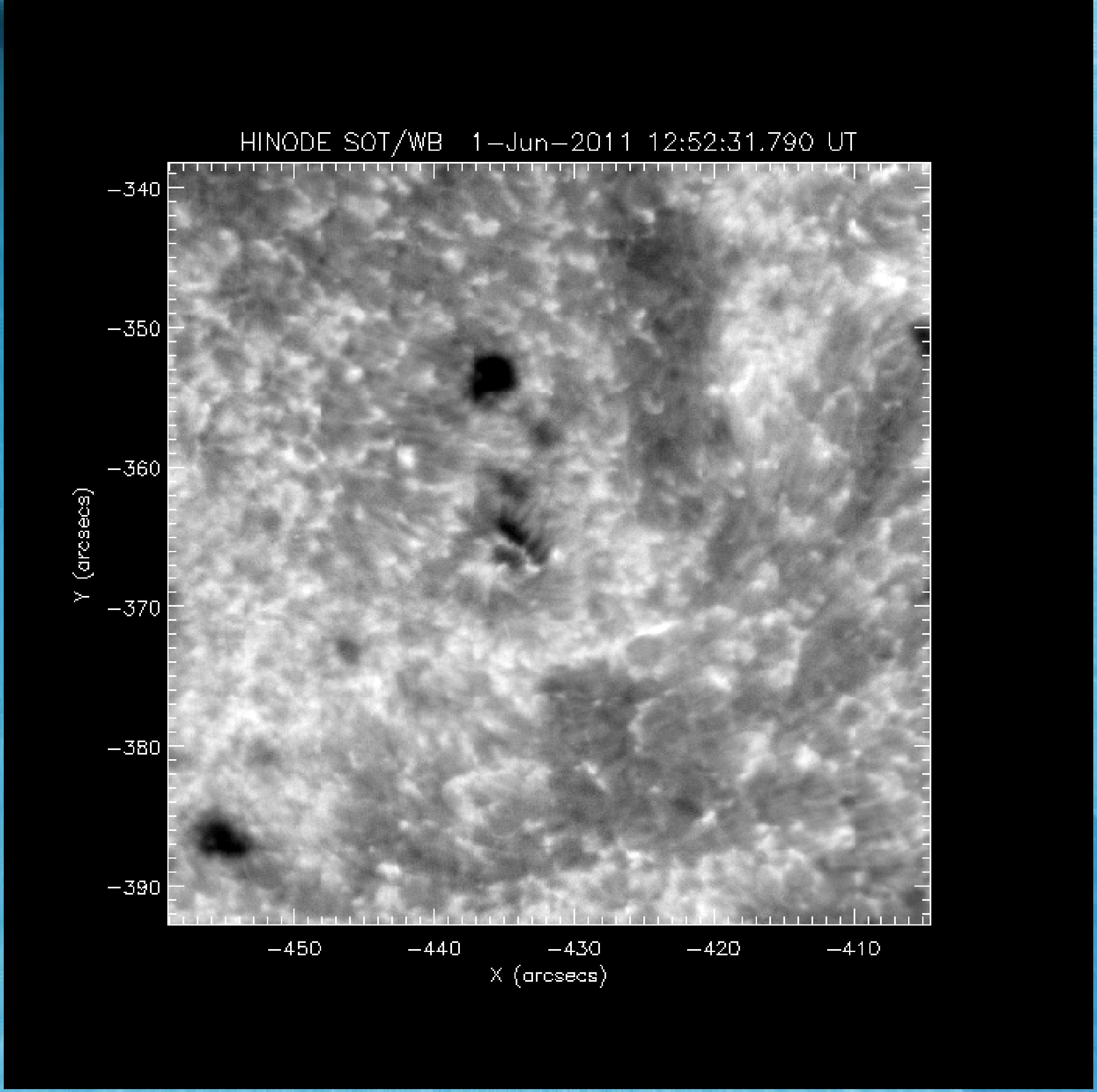

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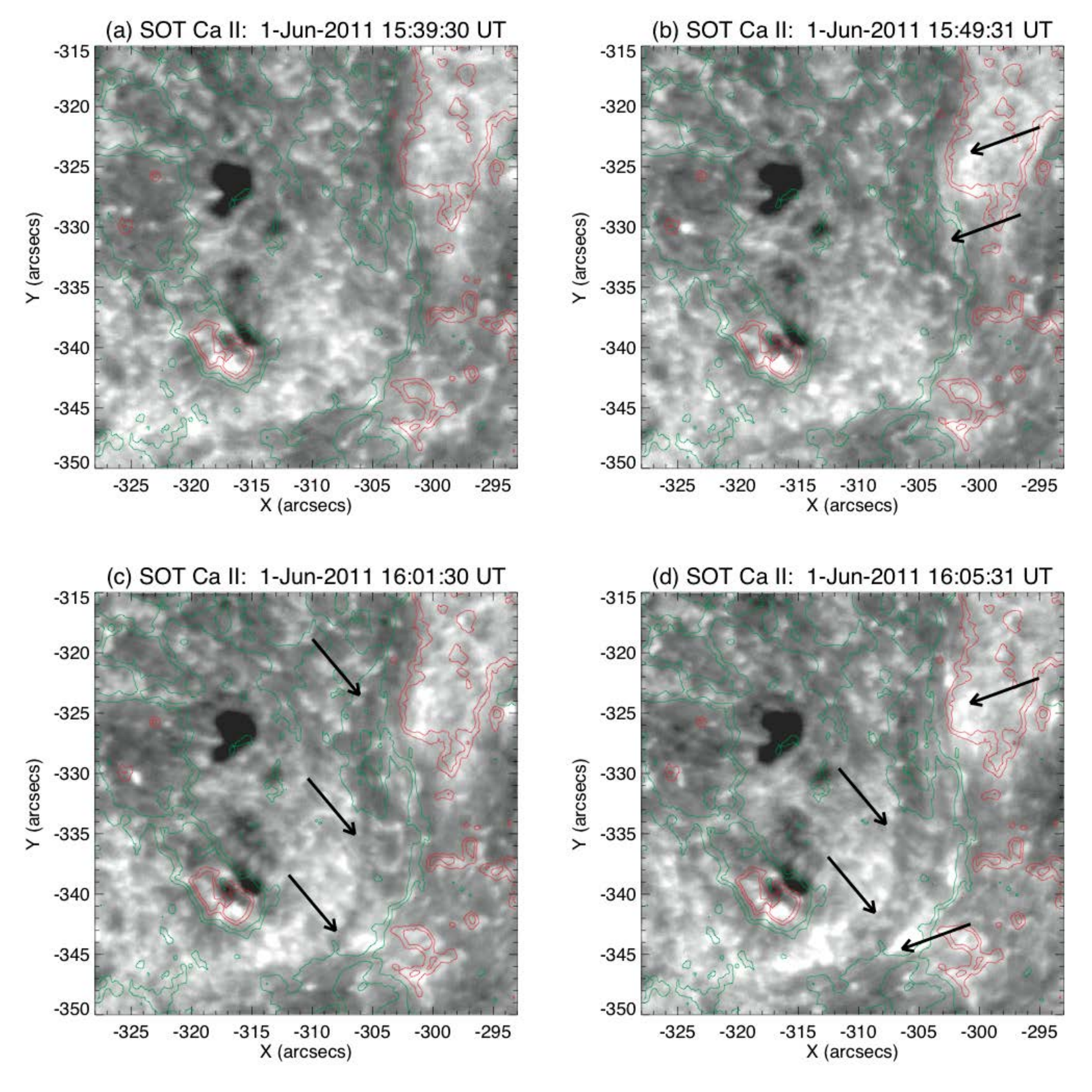
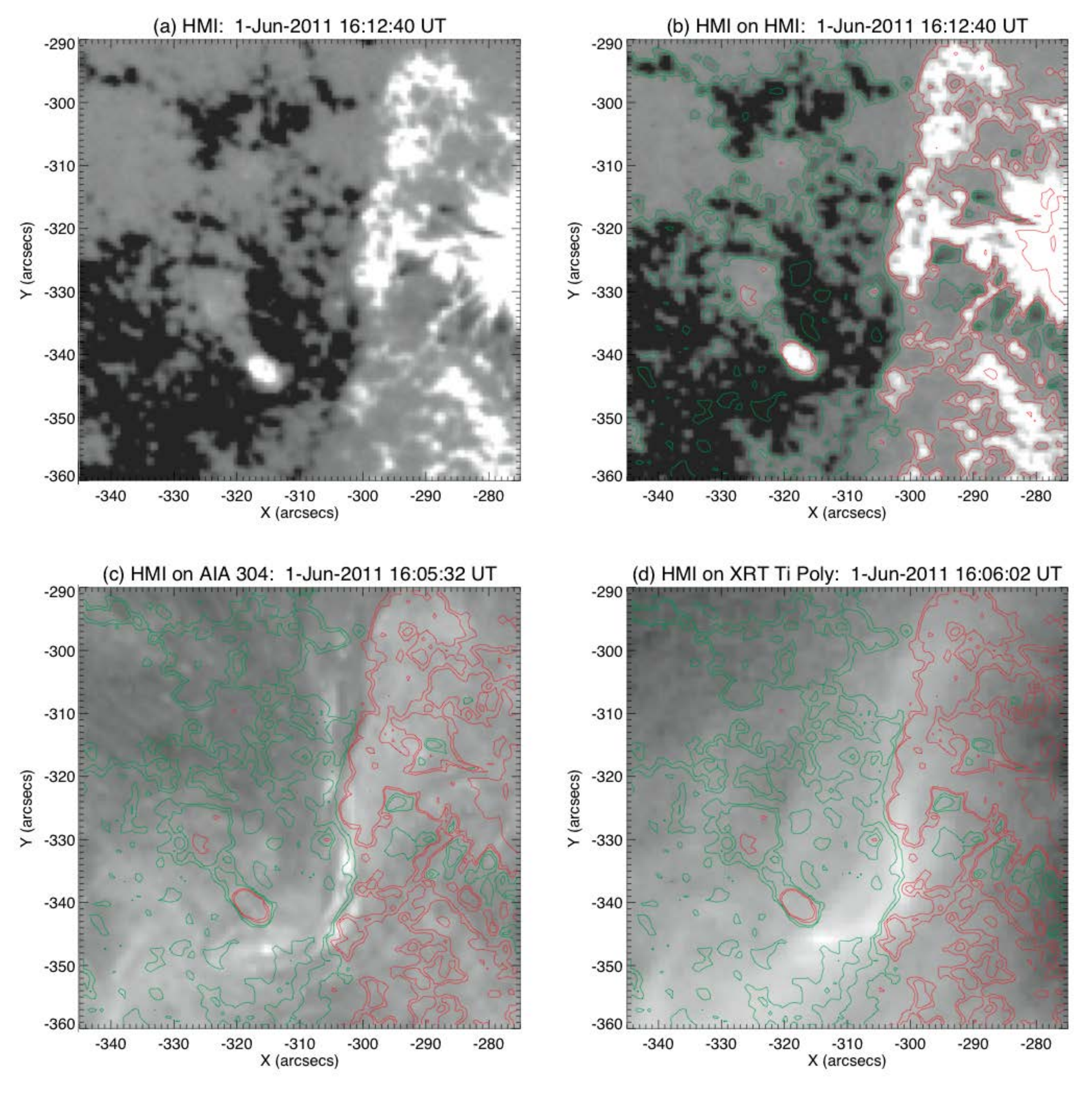

(a) SOT Ca II: 1-Jun-2011 15:39:30 UT
(b) SOT Ca II: 1-Jun-2011 15:49:31 UT
(c) SOT Ca II: 1-Jun-2011 16:01:30 UT
(d) SOT Ca II: 1-Jun-2011 16:05:31 UT
Y (arcsecs)
X (arcsecs)
-315
-320
-325
-330
-335
-340
-345
-350
-325
-320
-315
-310
-305
-300
-295



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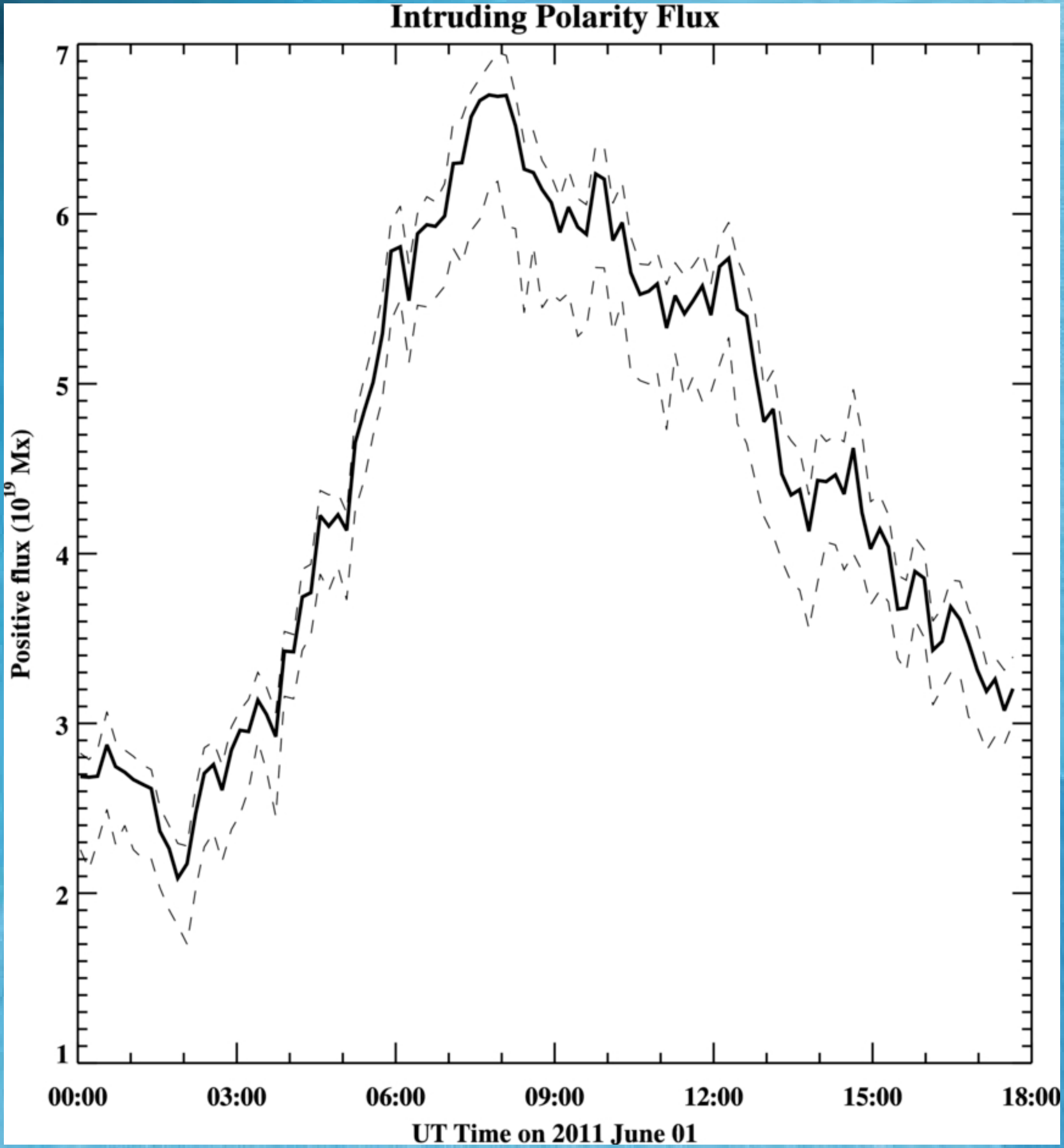

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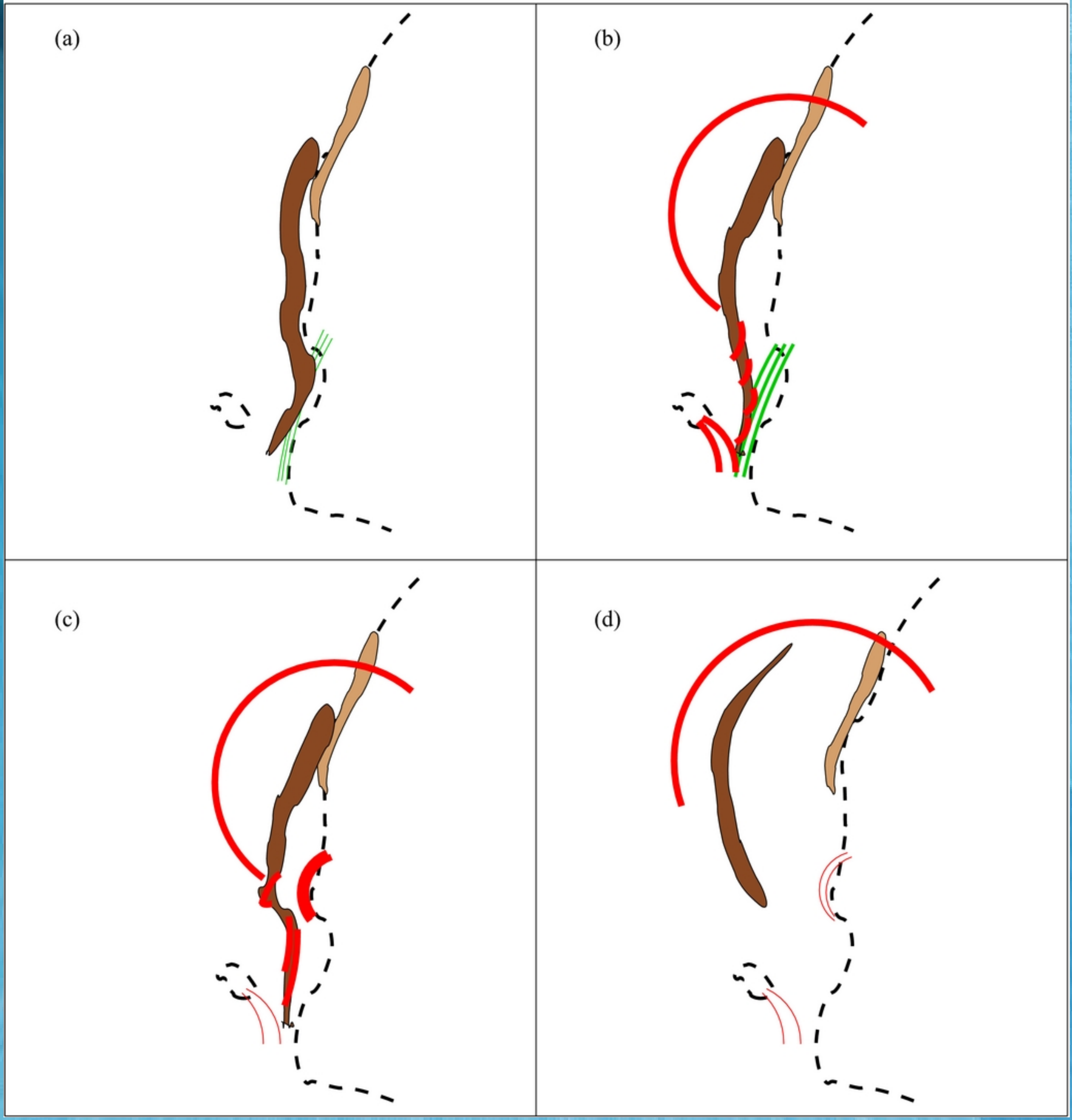
So, What Causes Initial Reconnection and Onset?

- Intruding polarity is candidate, but nothing obvious at eruption time; could be passive, with strong brightening due to strong field.
- Several other candidate regions for flux cancelation, any or several of which may have been the cause.
- Ultimately, we don’t know the answer....



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Conclusions (2011 Jun 1 event)

- Something leads to reconnection; not totally clear what. [Could this be Hi-C-inferred reconnection?]
- Reconnection -> twisted flux rope in ~20 min; episode 1 microflare (flare ribbons; TC) and filament jump.
- Twist -> writhe, via kink instability; filament-trajectory plateau, ~ 20 min.
- Writhe -> jump and eruption of filament 1, via instability; episode 2 microflare (flare ribbons; TC). (E.g., Williams et al.)
- First eruption -> second filament eruption (episode 3 flare ribbons; TC). (E.g., Sterling, Moore; Liu et al.; Torok et al.; Schrijver & Title.)

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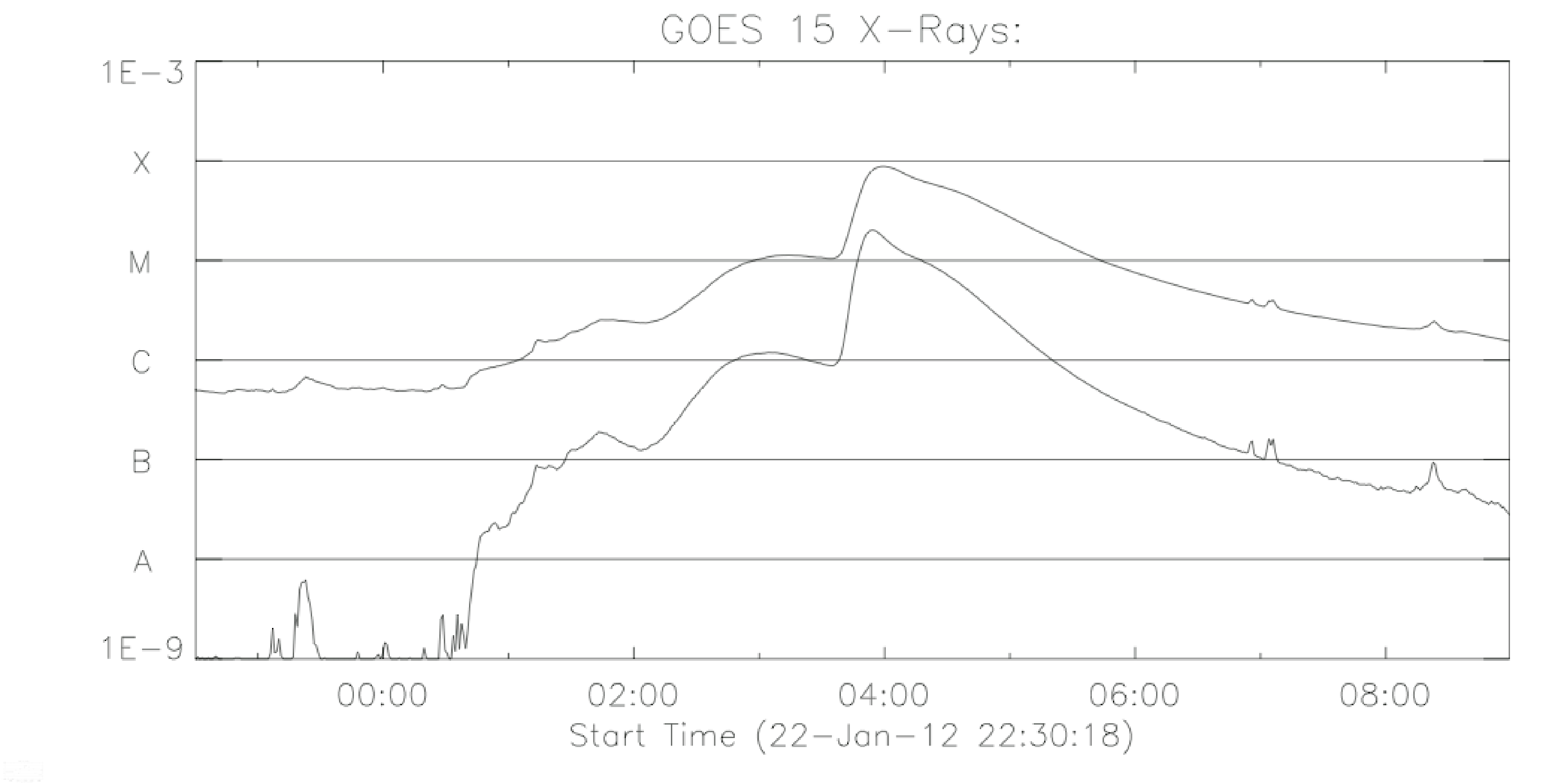

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New Aspects of a Lid-Removal Mechanism in the Onset of a SEP-Producing Eruption Sequence

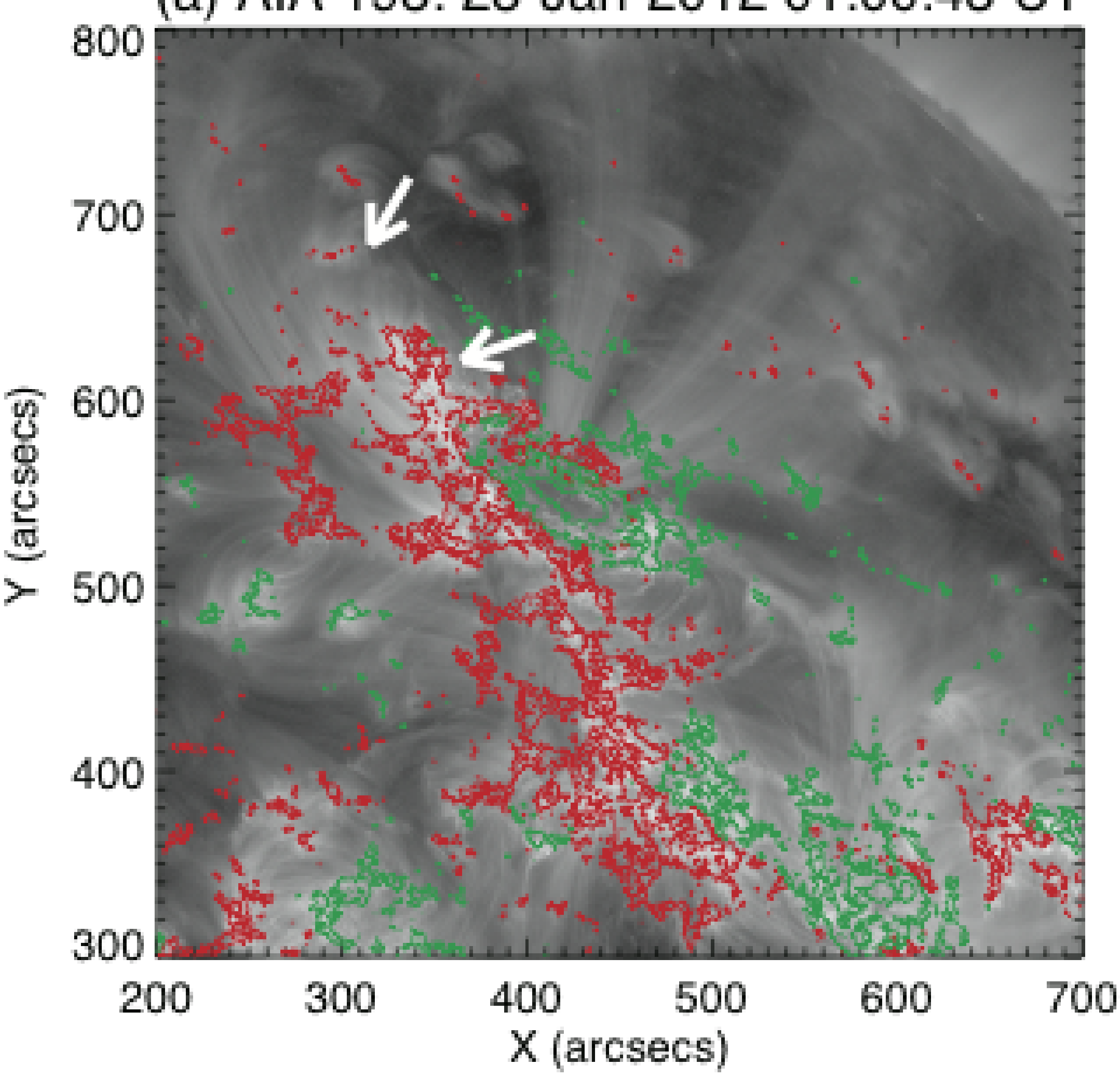
Alphonse C. Sterling & Ronald L. Moore, NASA/MSFC;
David A. Falconer, MSFC, U of Alabama Huntsville;
Javon M. Knox, Norfolk State U, Norfolk, VA

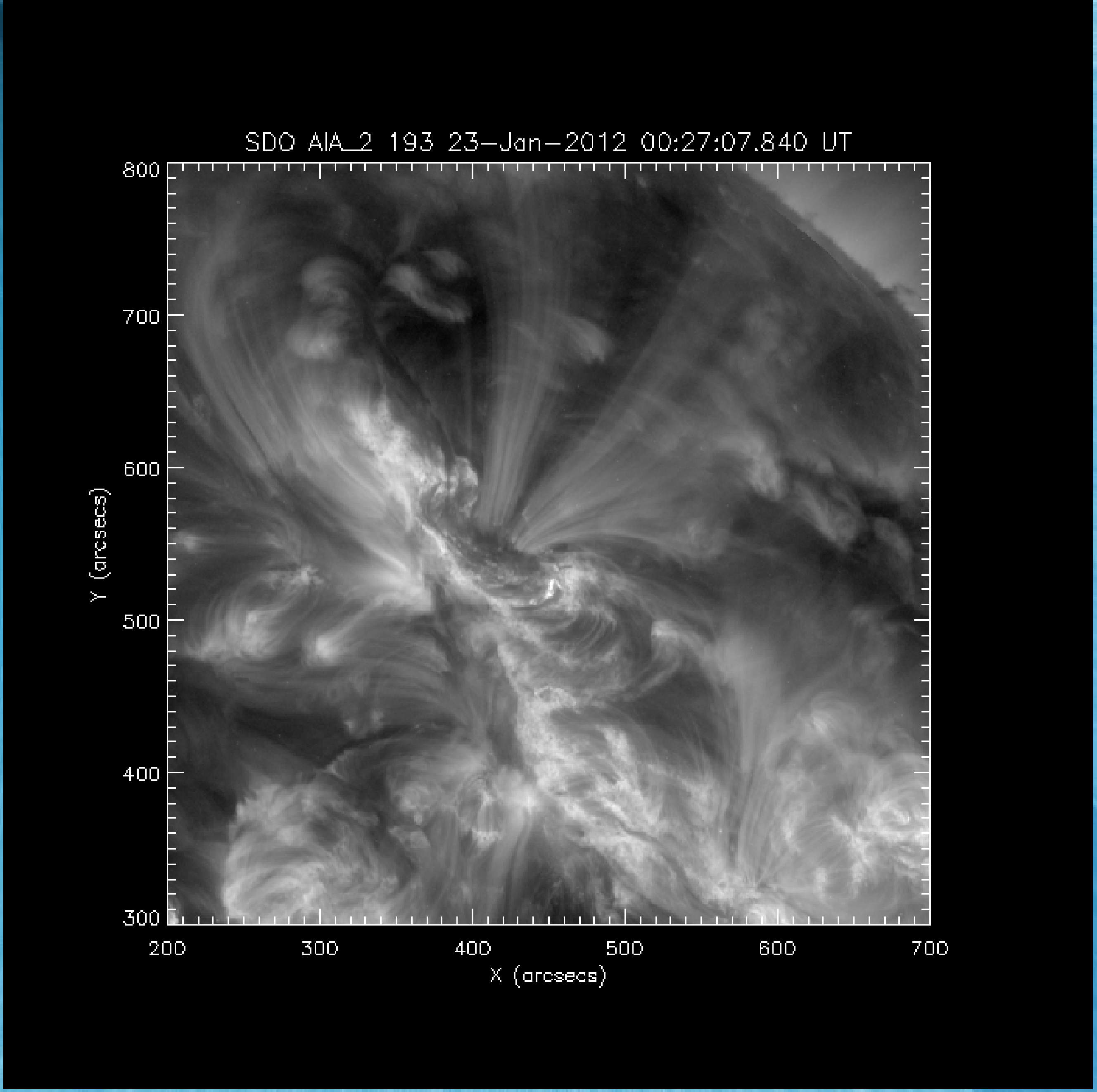
Eruptive Sequence of 2012 January 23

- “Double eruption” (“two flux ropes,” Li & Zhang 2013, Cheng et al. 2013); Eruption 1 and Eruption 2.
- Eruption 2 includes eruption of a filament.
- Two fast CMEs result.
- GOES M8.7, plus two precursor “flares.”
- Results in strong Solar Energetic Particle (SEP) event. (1 MeV proton flux of $>10^3$ pfu for 43 hrs.)
- SEPs not the focus here. See Joshi et al. (2013). Also see Liu et al. (2013) for other interplanetary aspects.
- Instead, we focus on the origin of the eruption on the Sun, including the cause of the precursor flares.

Analysis

- AIA: Adequate time cadence (145 s) and high spatial resolution (0’’.6 pixels).
- SDO/HMI line-of-sight magnetograms.
- On-disk from SDO.
- Limb event from STEREO A (not shown here).
- SDO/AIA, various filters (304, 171, **193**, 211, 131, 335, **94** Ang).


800
700
600
500
400
300
Y (arcsecs)
200
300
400
500
600
700
X (arcsecs)



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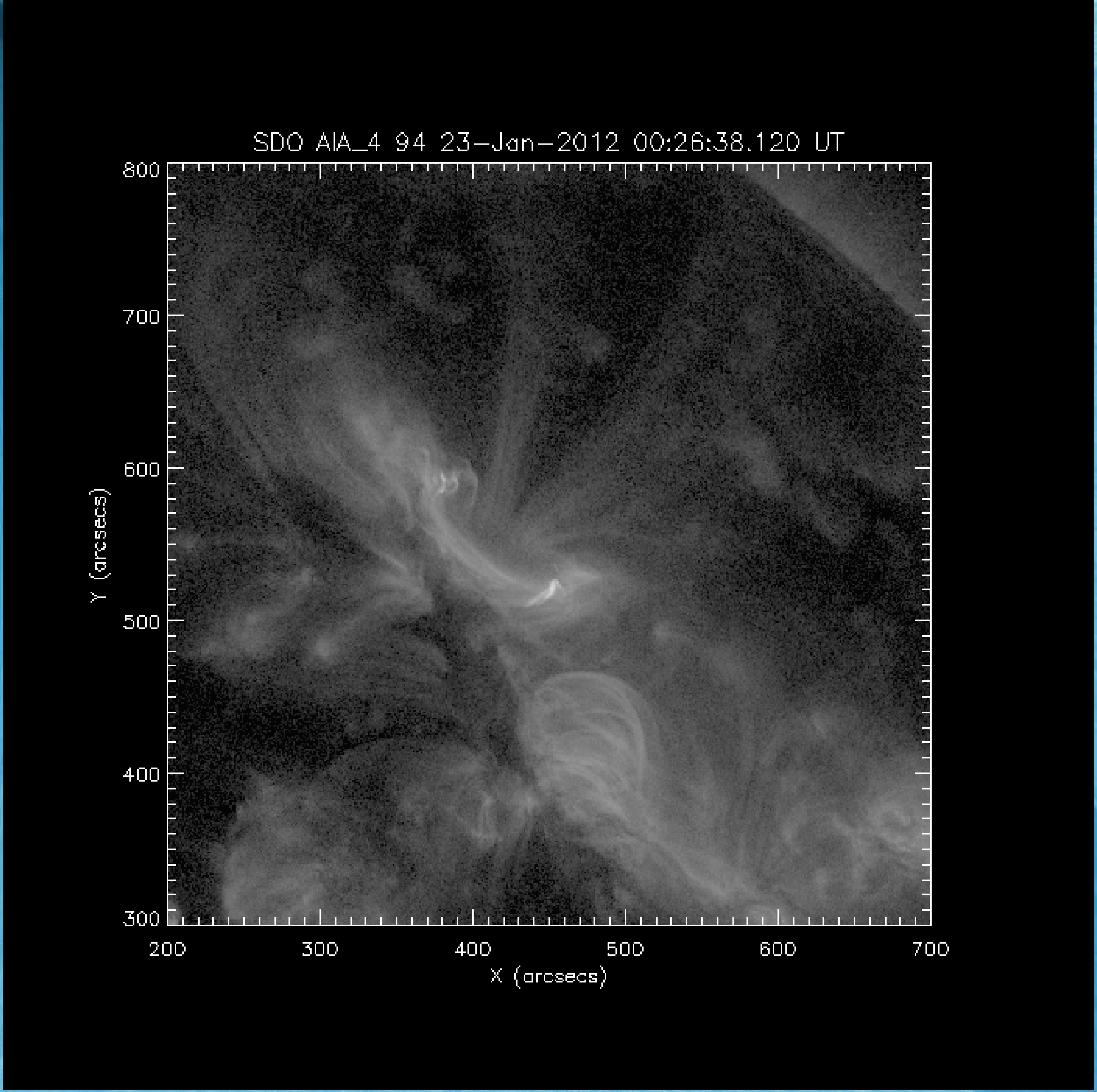

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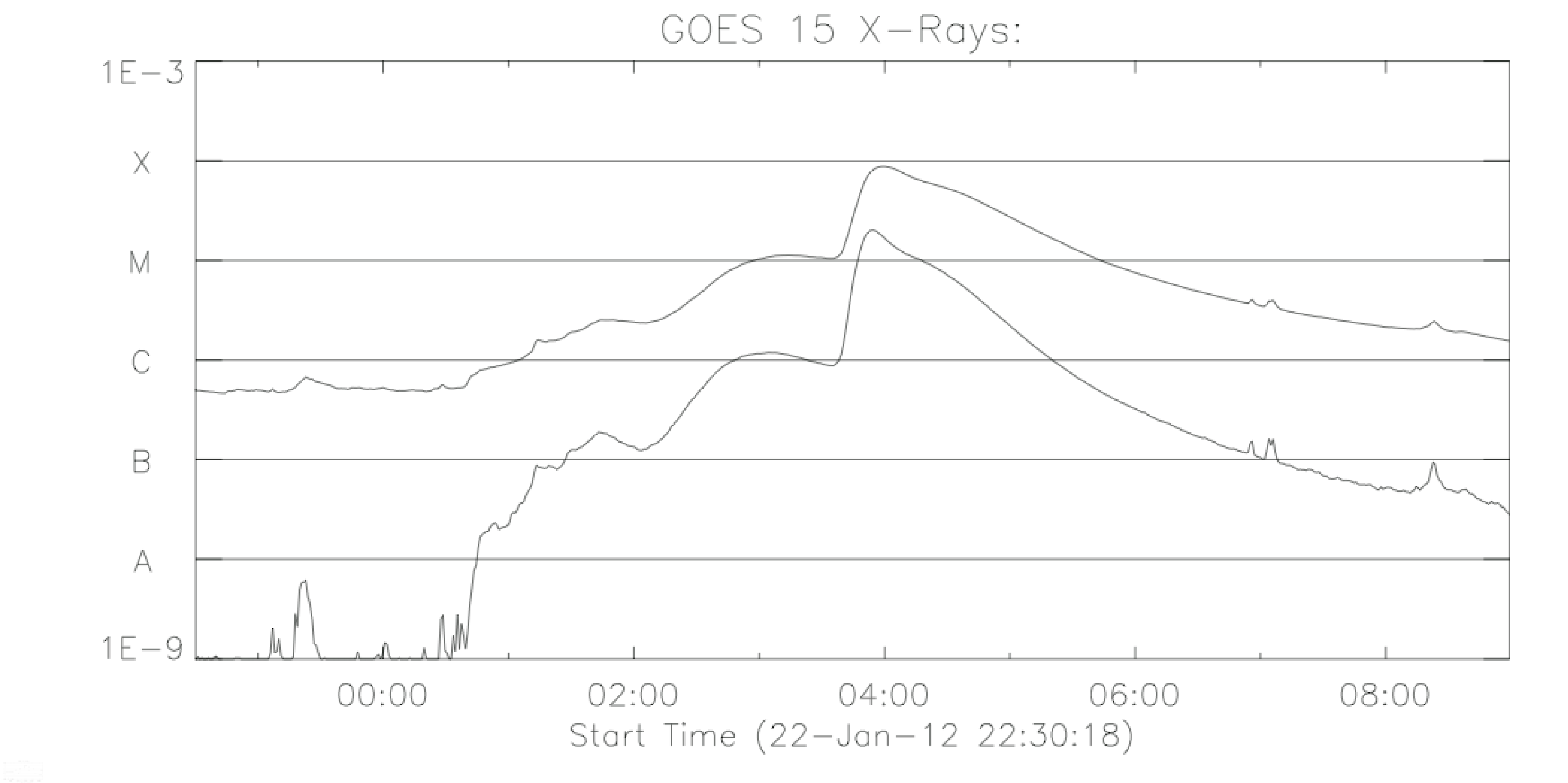

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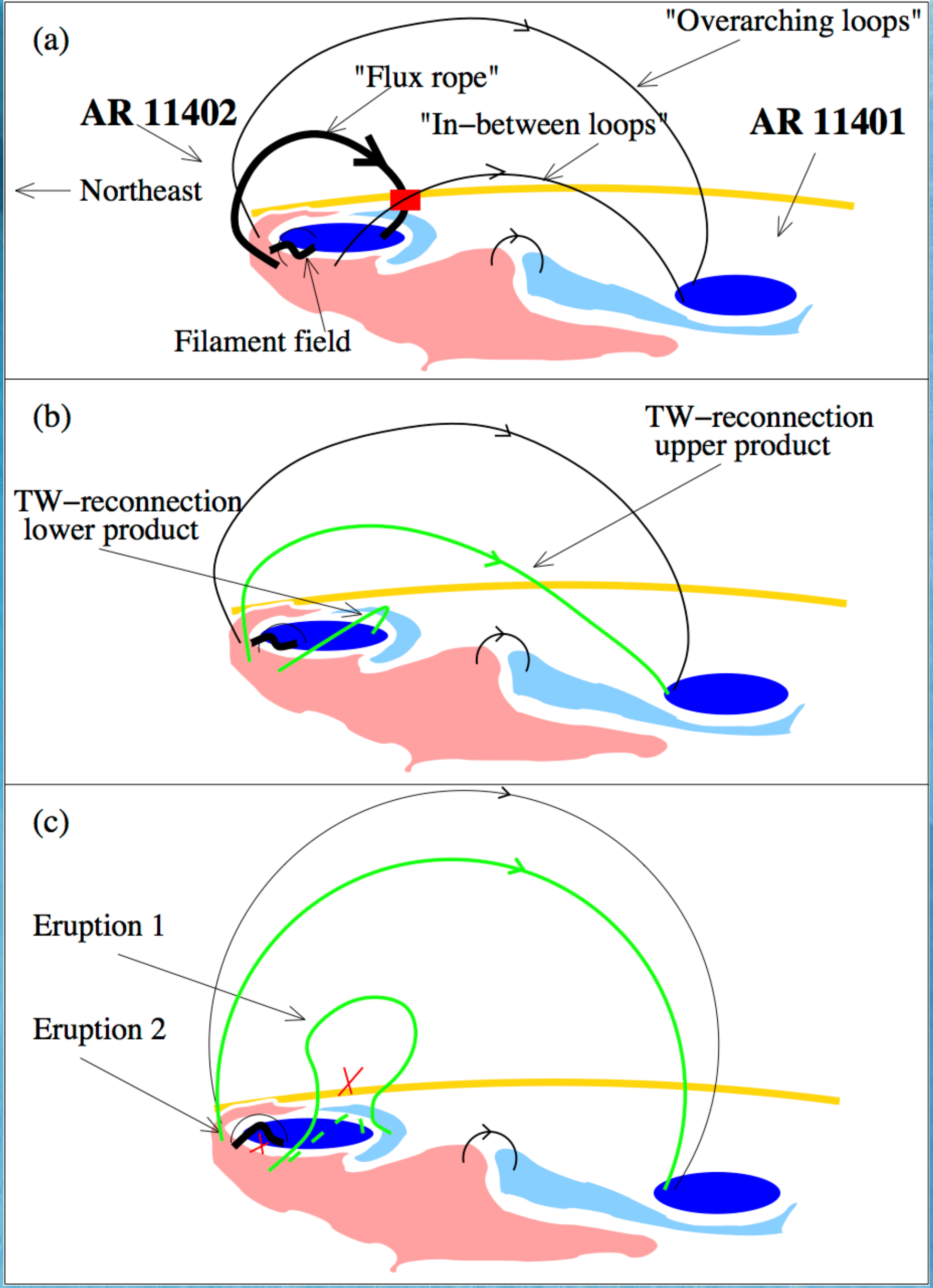

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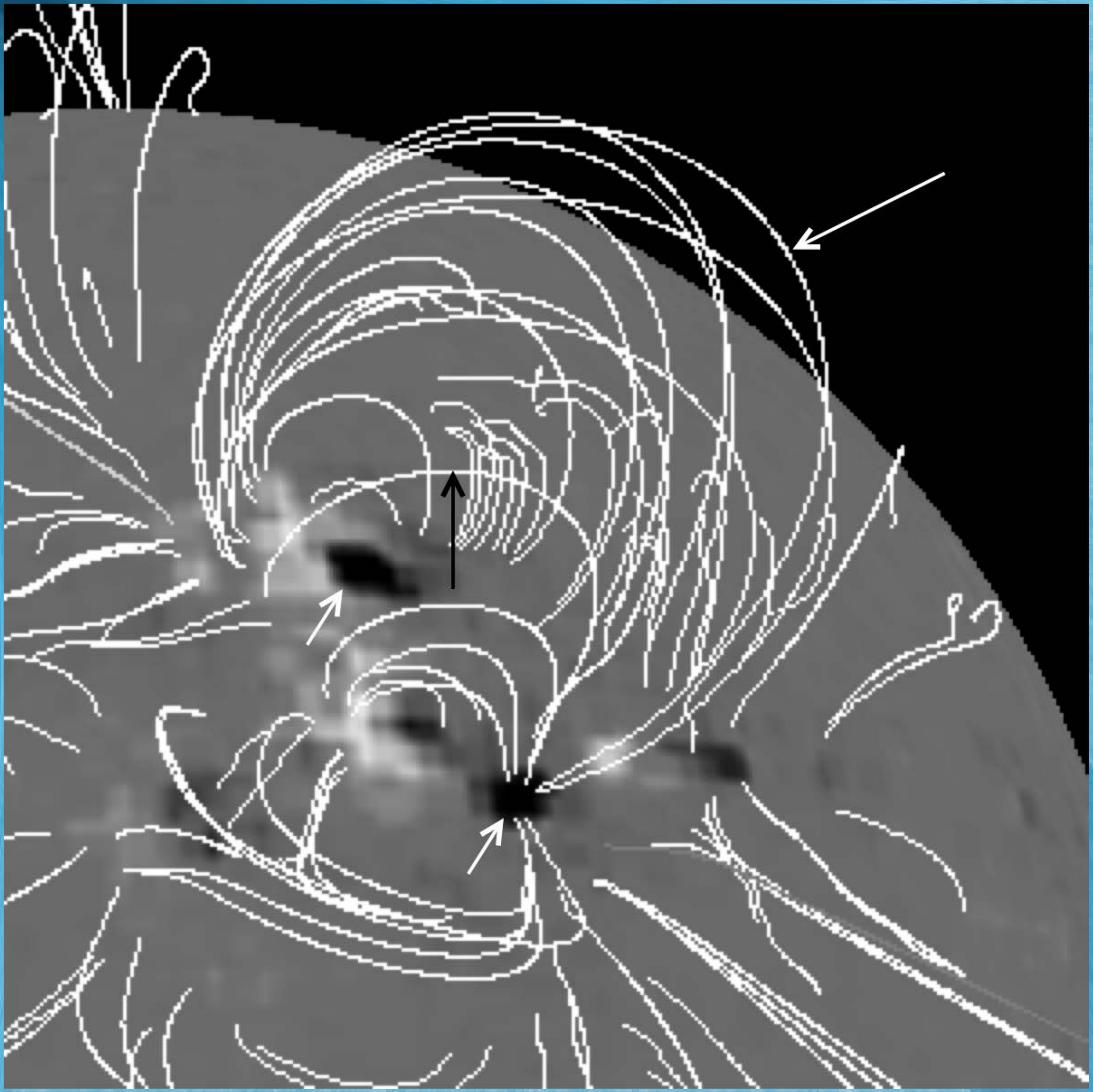
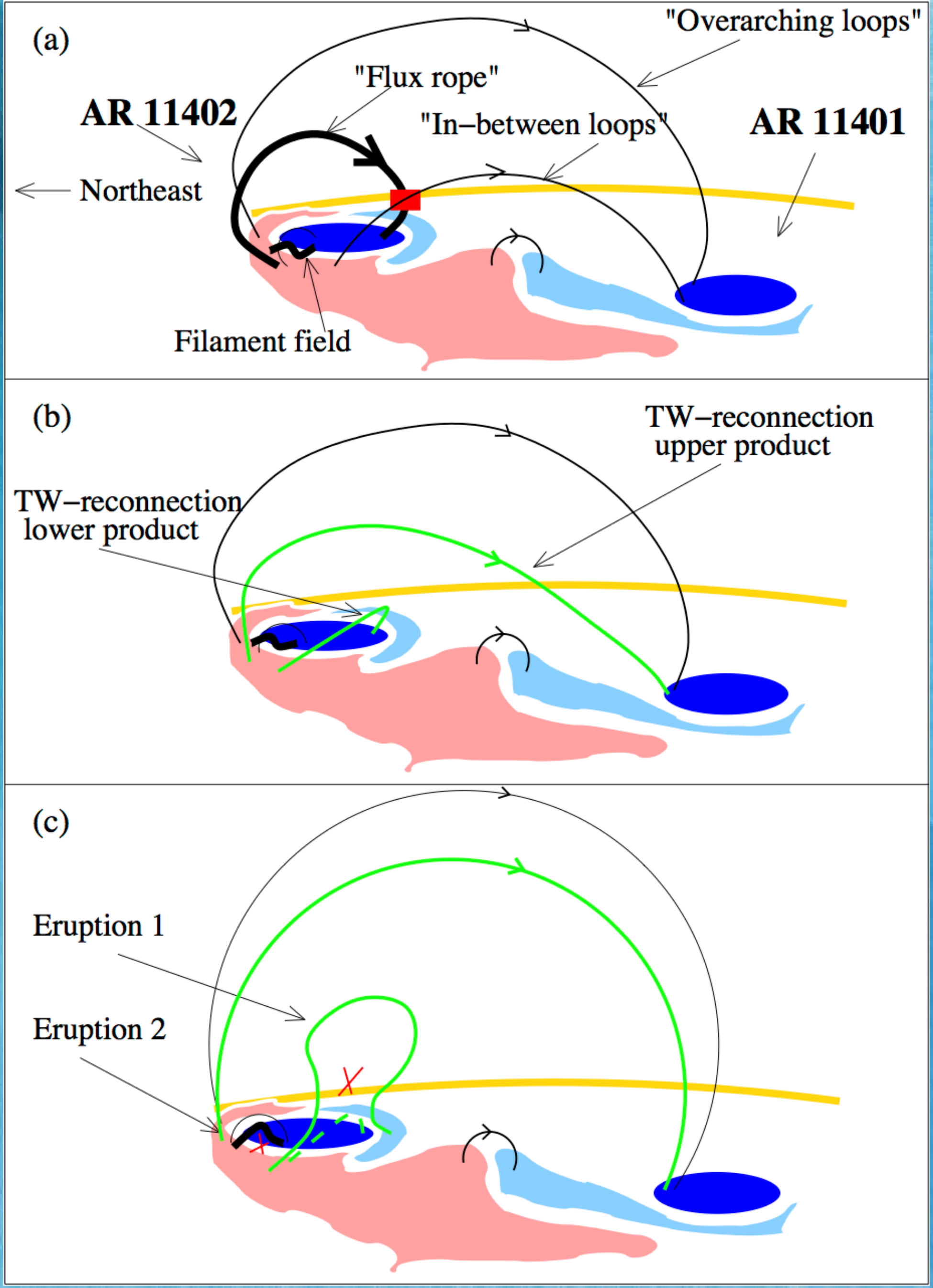
PFSS Model (Schrijver & DeRosa 2003)





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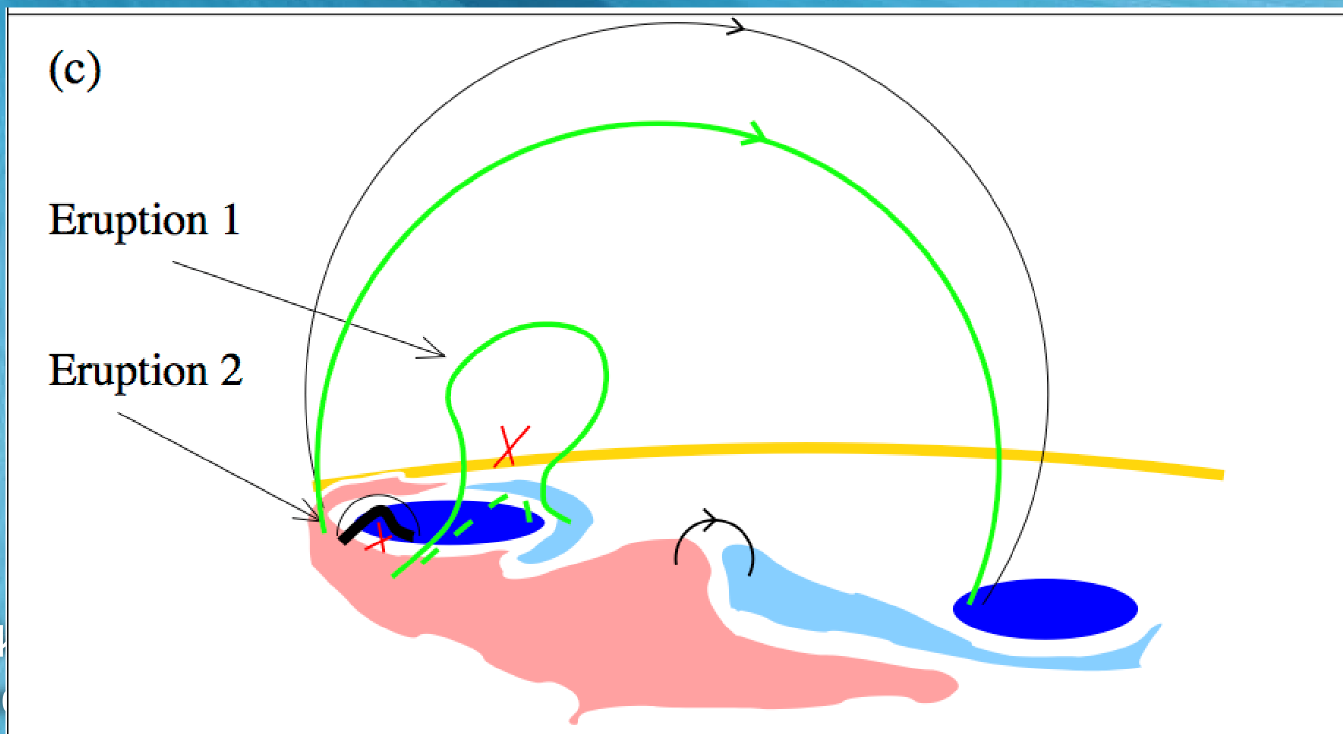
Eruption 2 Via “Lid Removal”

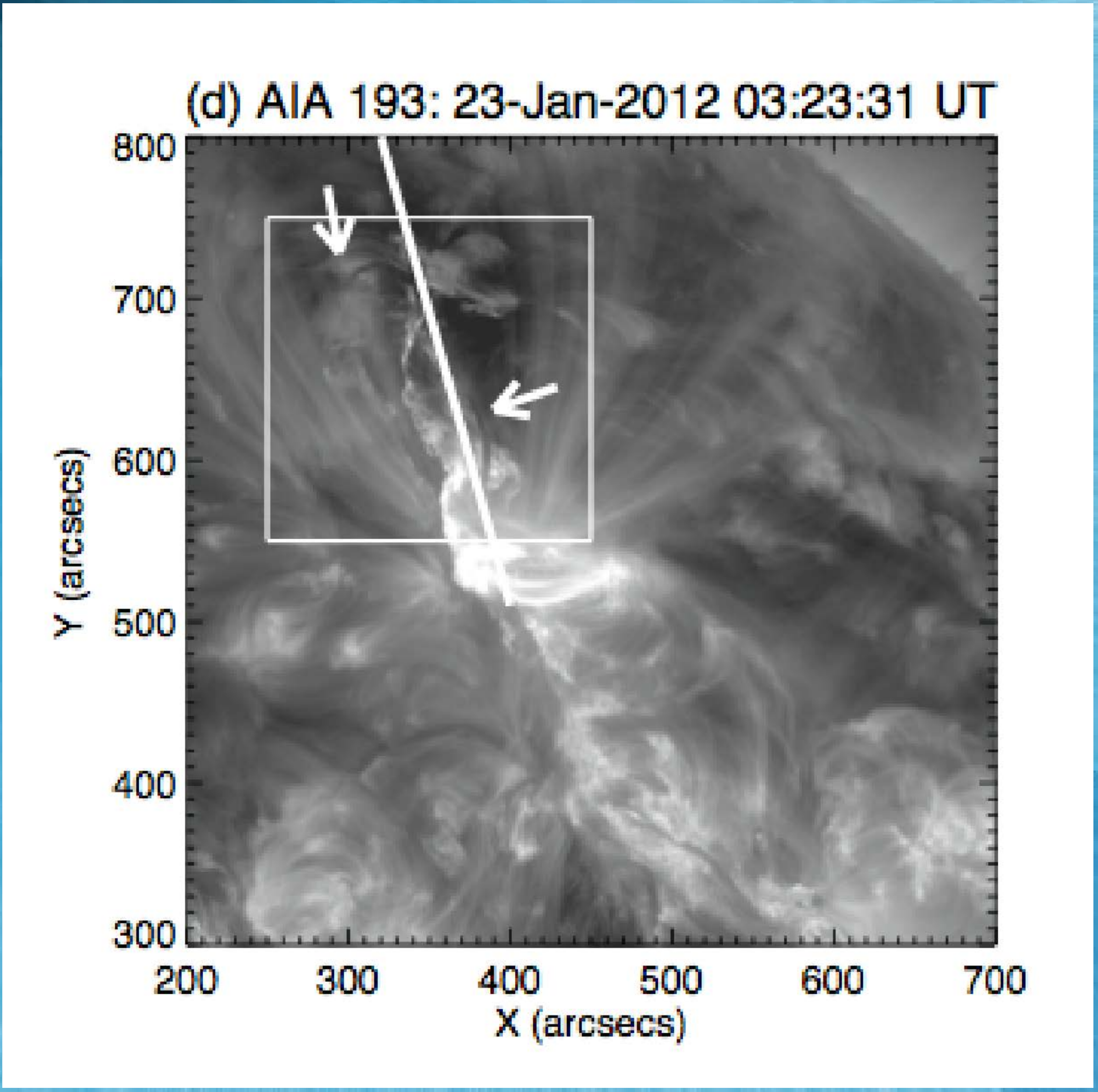
- Eruption 1 removes field above the Eruption 2 flux rope, allowing onset of Eruption 2. (Cheng et al. 2013.)
- We call their explanation for Eruption 2 (including filament) “lid removal.”
- Fundamentally different from eruption-trigger mechanisms we have examined (e.g., tether cutting, breakout…).

Can Lid Removal Work with Eruption 1 Flare Arcade?

- Standard flare model => Eruption 1 flare loops should form over filament arcade, perhaps preventing Eruption 2 ("confined eruption"). (S. Antiochos 2013, private comm.)



- Look
- Need
- Use mixture; 60% hot (=131 Ang), 40% cool (=193 Ang).



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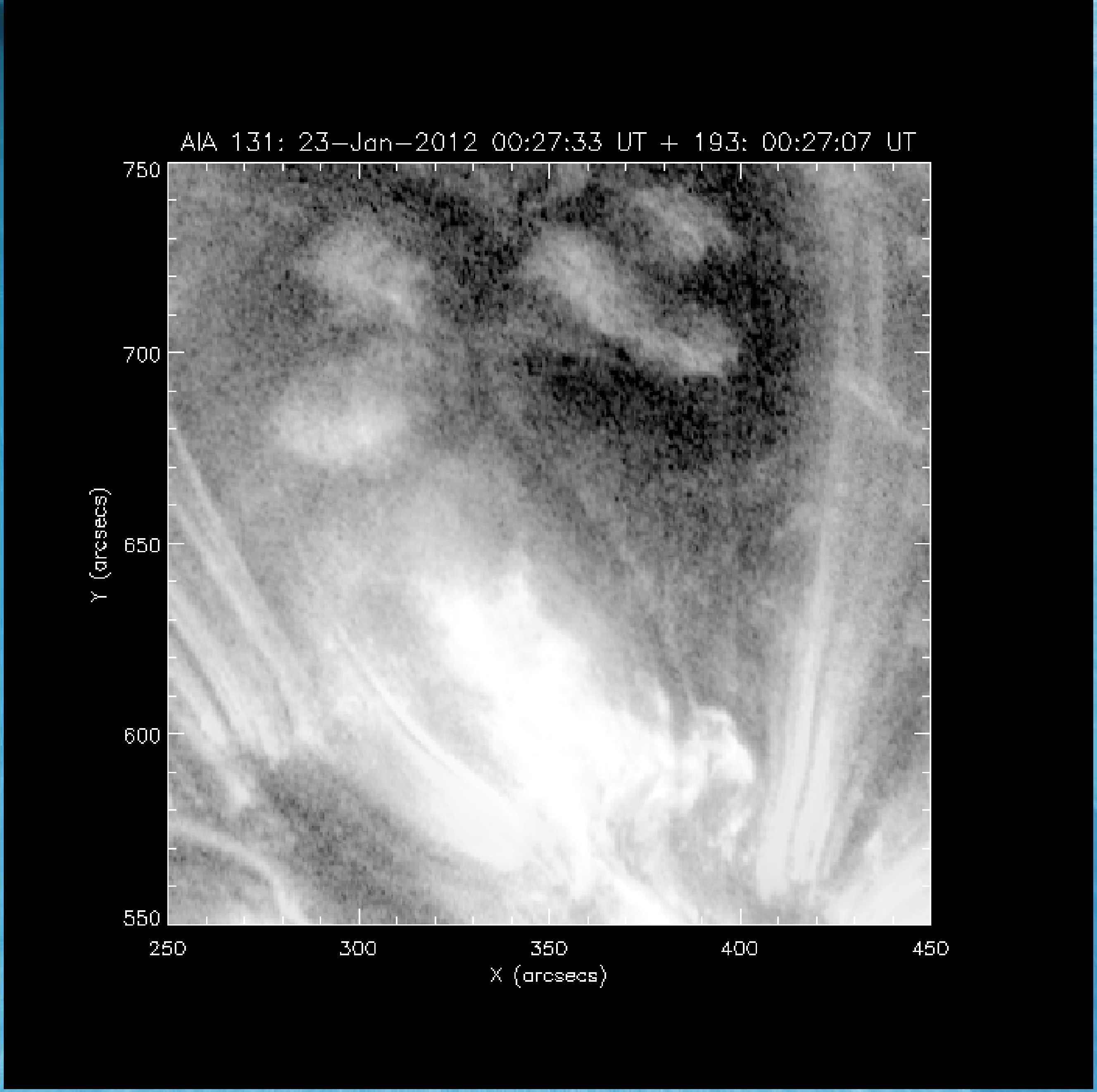

AIA 131: 23-Jan-2012 00:27:33 UT + 193: 00:27:07 UT
750
700
650
600
550
Y (arcsecs)
250
300
350
400
450
X (arcsecs)

Summary (2012 Jan 23 event)

- Two eruptions, with first only seen in AIA hot channels.
- Eruption 1 removes field above filament arcade, leading to destabilization and onset of eruption 2; *Lid Removal*.

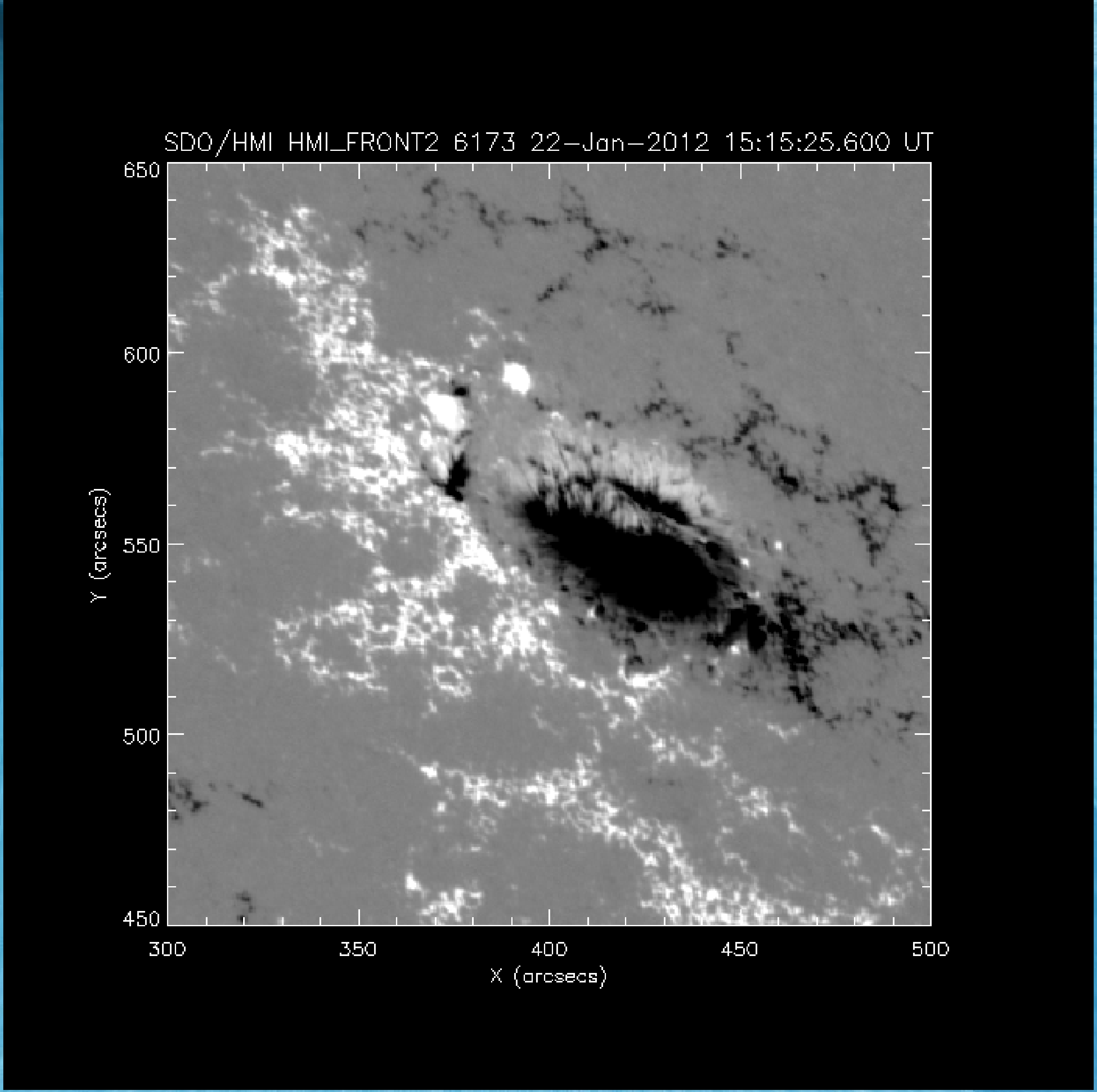
New Aspects:

- Eruption 1 field reconnects with neighboring region, ("tether-weakening reconnection," Moore et al. 1992).
- Two precursor flares, due to TW reconnection and to Eruption 1.
- Eruption 2 blows out Eruption 1 flare loops.

- Lid removal May have been missed prior to AIA. May be common (cf. Schrijver & Title 2011, Török et al. 2011).
- Sterling et al. (2014, ApJ, 788, L20) provide more details.

Overall Summary

- A basic point of solar eruptions is that the “standard flare (eruption) model” holds in most (all??) cases where there is a “sizable” flare.
- Complications of GOES light curves can come from different mechanisms; more work must be done to see whether there are definable categories.
- Apparently, a variety of different mechanisms are possible for triggering eruption onset.



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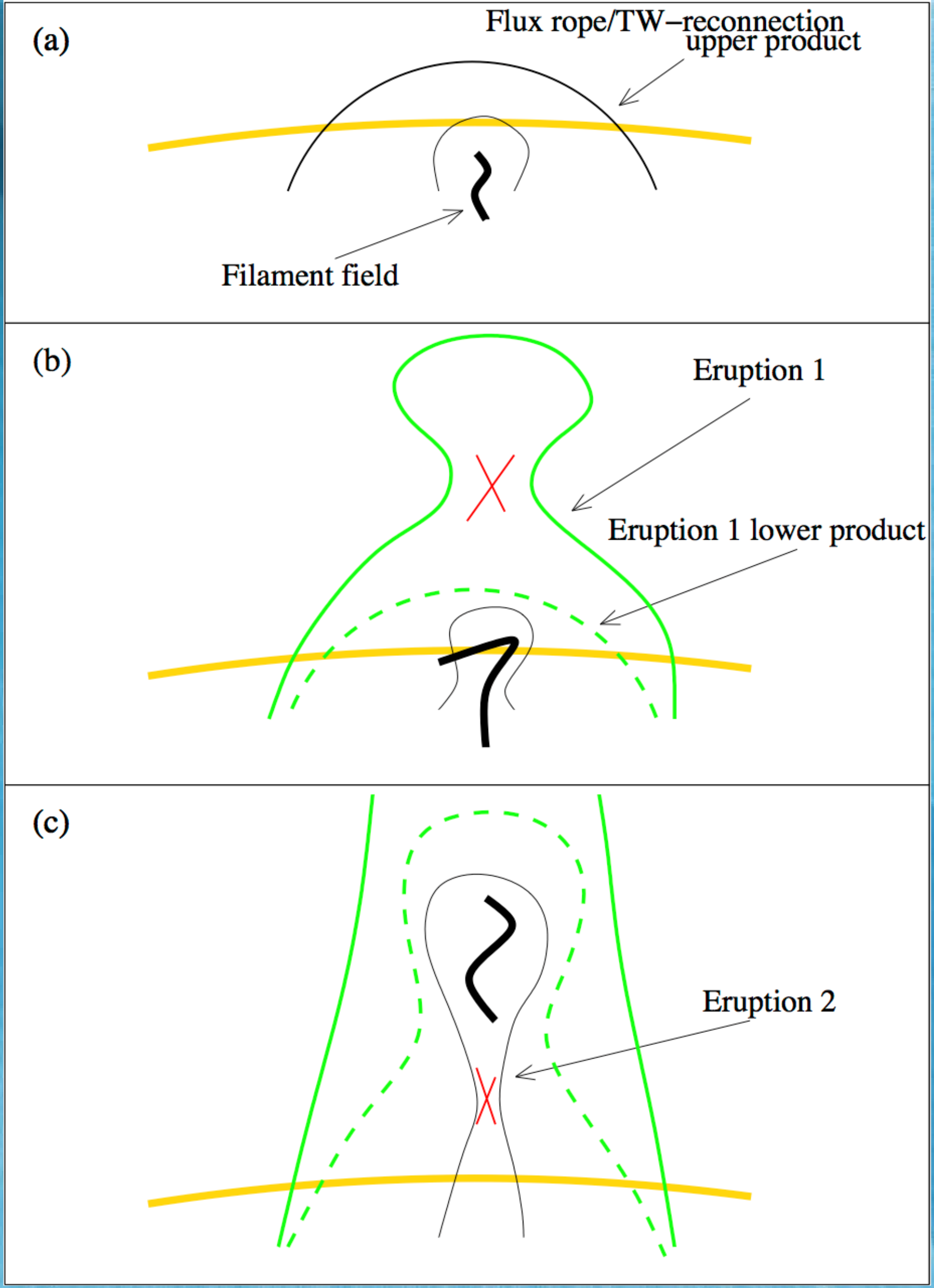
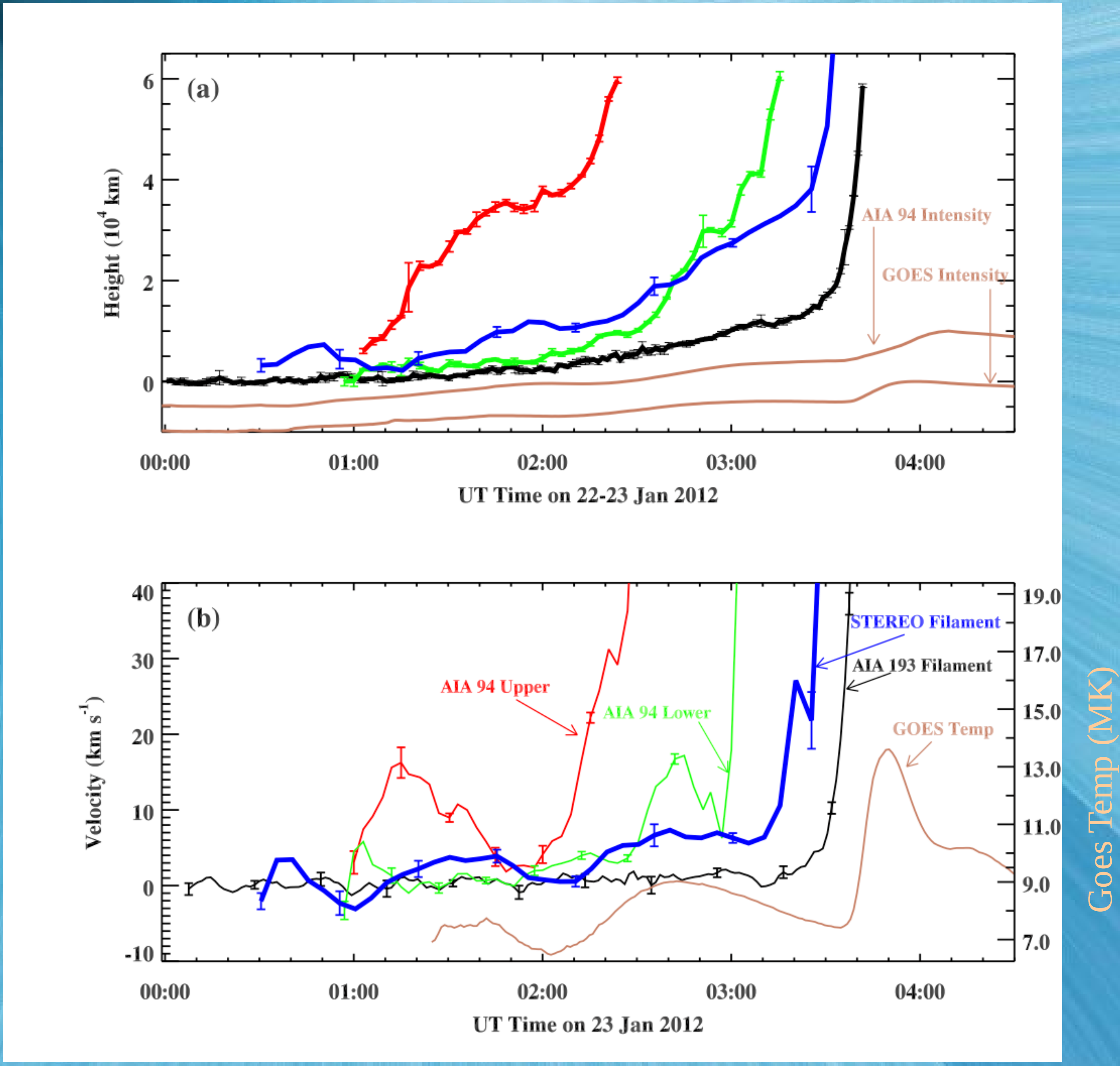

(a)
Flux rope/TW−reconnection
upper product
Filament field
(b)
Eruption 1
Eruption 1 lower product
(c)
Eruption 2



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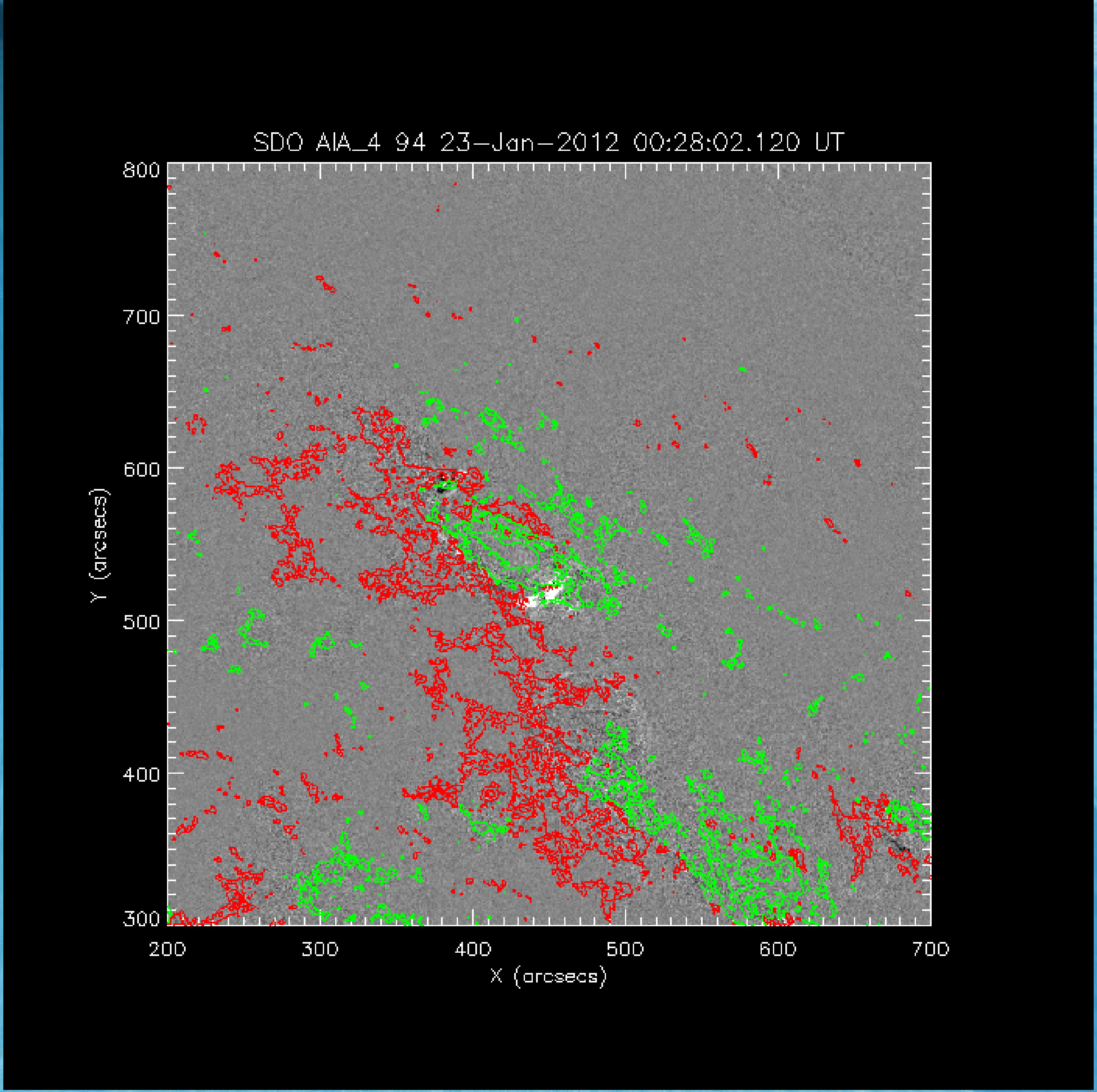

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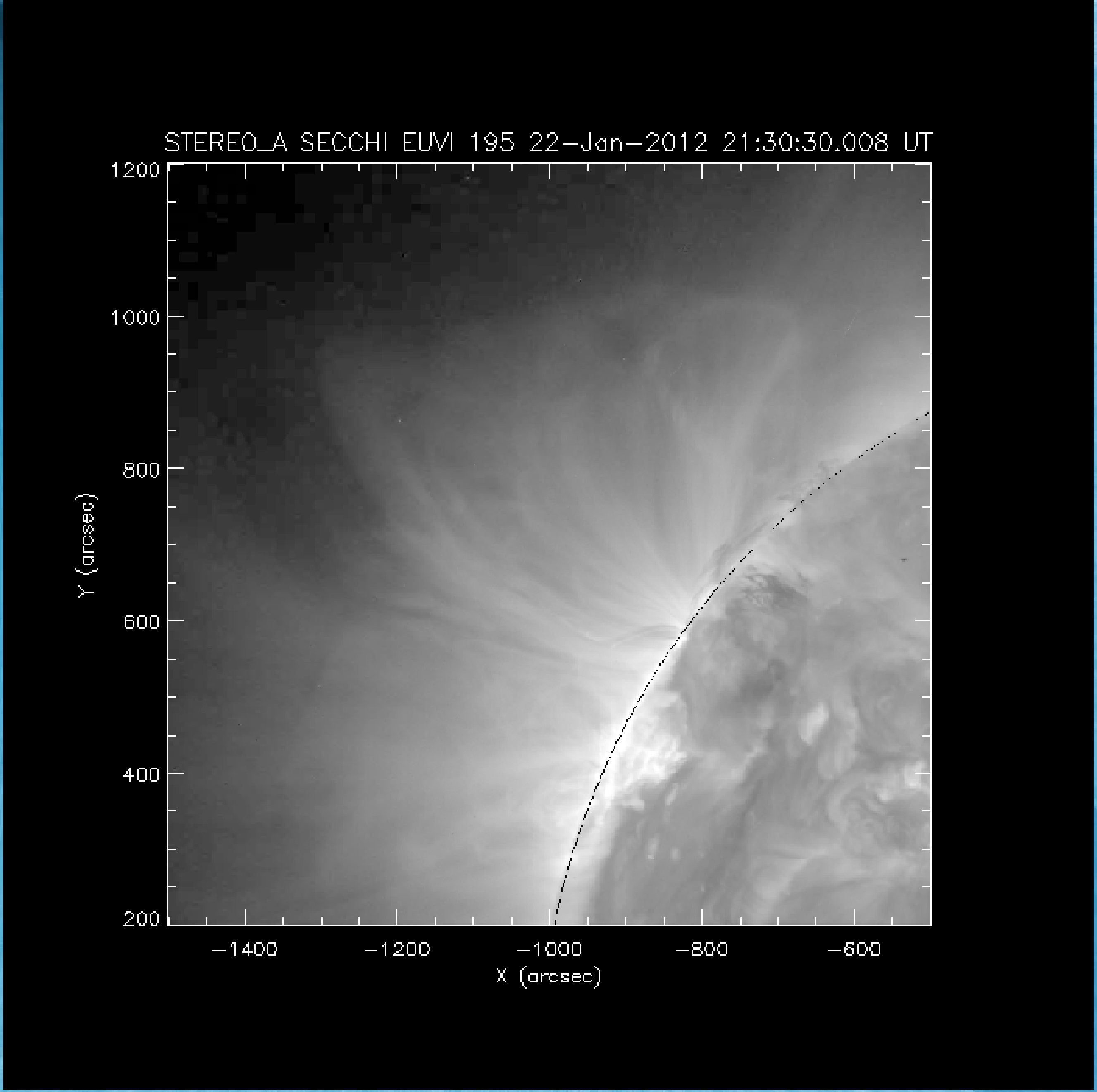

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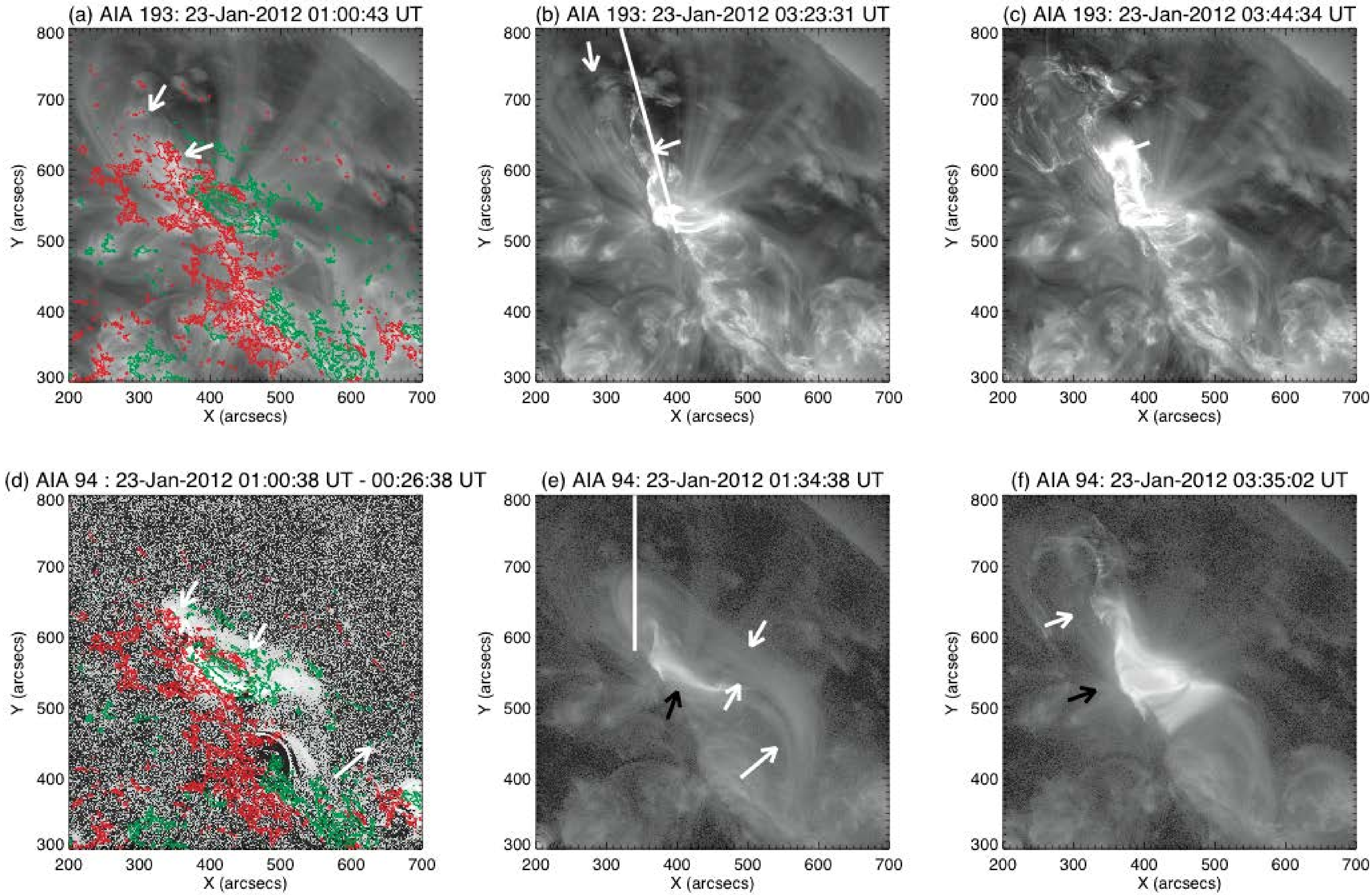

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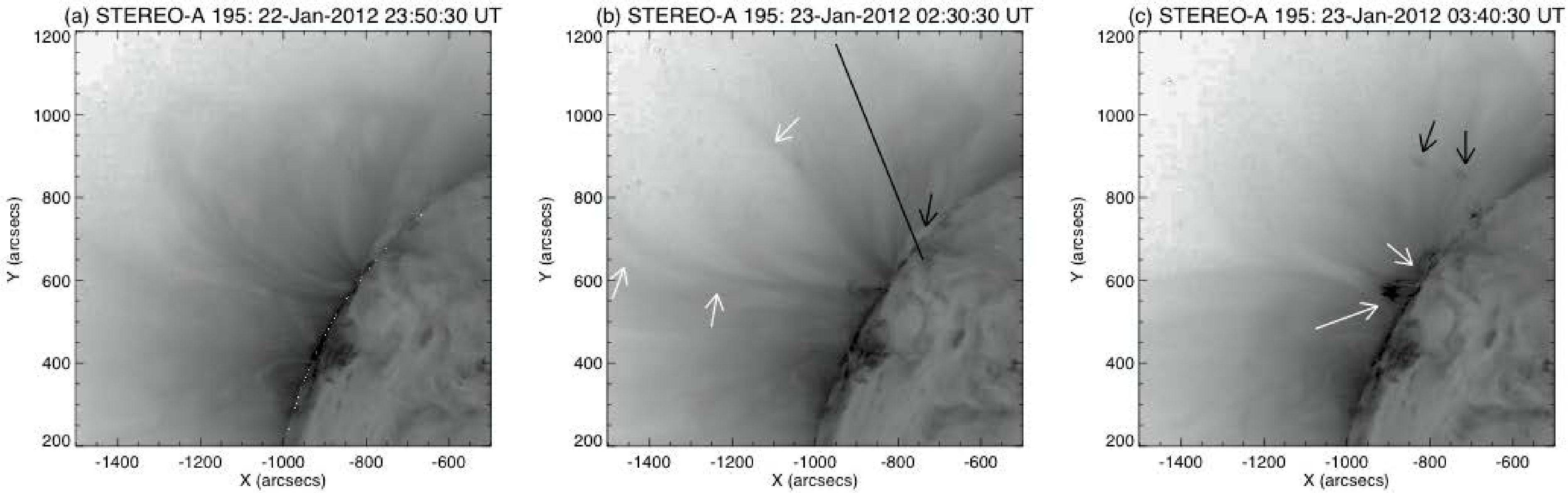
(a) STEREO-A 195: 22-Jan-2012 23:50:30 UT
(b) STEREO-A 195: 23-Jan-2012 02:30:30 UT
(c) STEREO-A 195: 23-Jan-2012 03:40:30 UT
Y (arcsecs)
X (arcsecs)
1200
1000
800
600
400
200
-1400
-1200
-1000
-800
-600