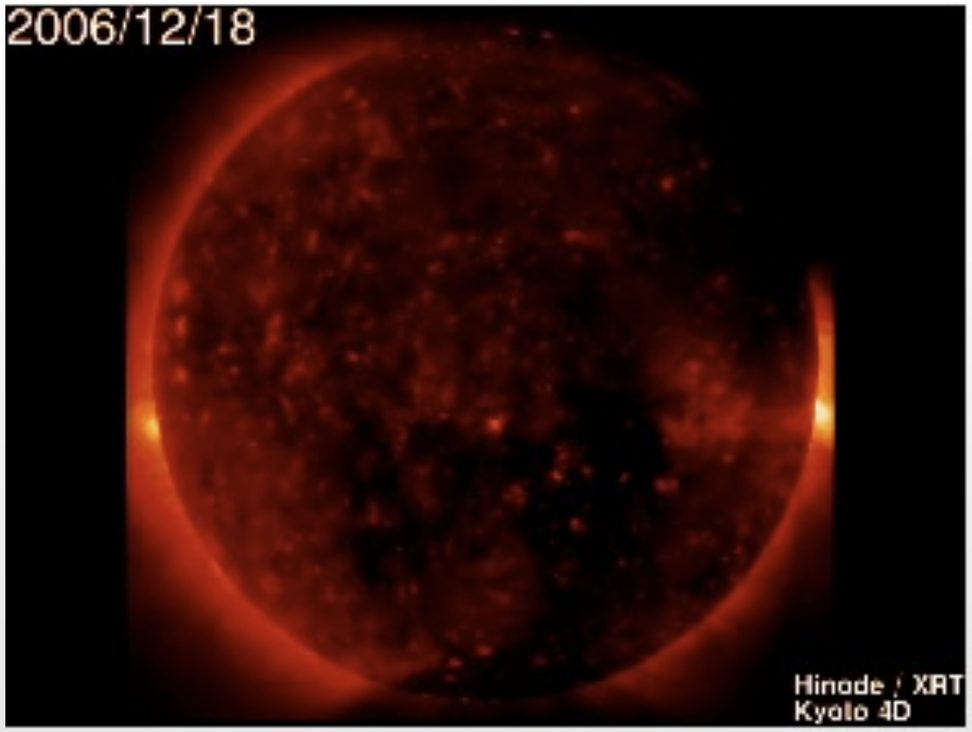
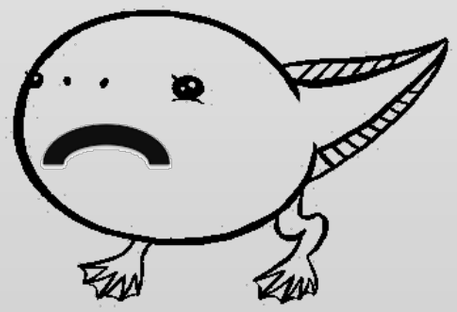


A History of Supra-Arcade Downflows & Their Connection to Reconnection

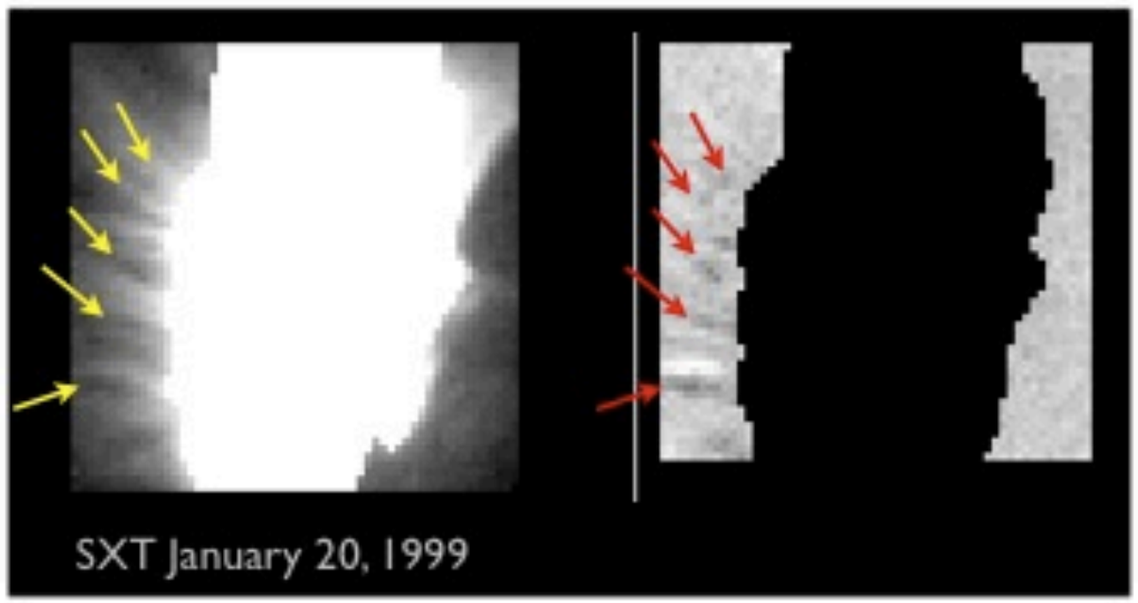
Sabrina Savage
Marshall Space Flight Center

"Sadpoles"

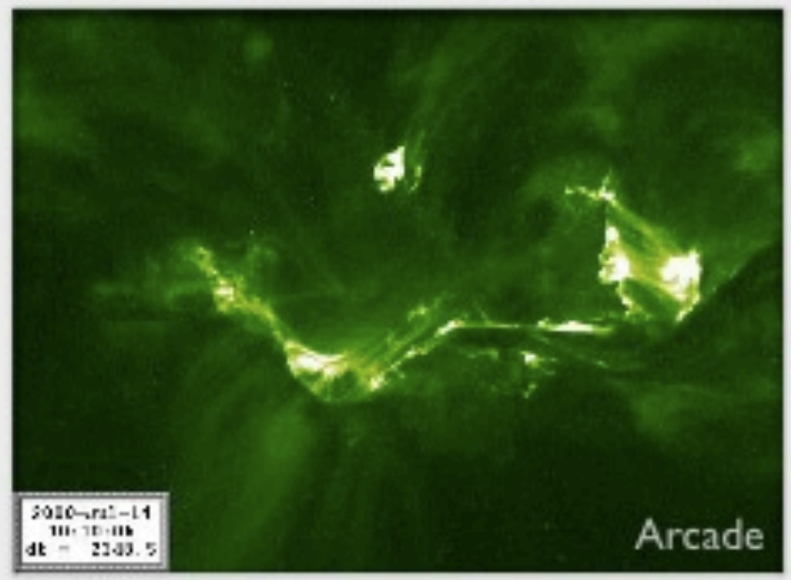


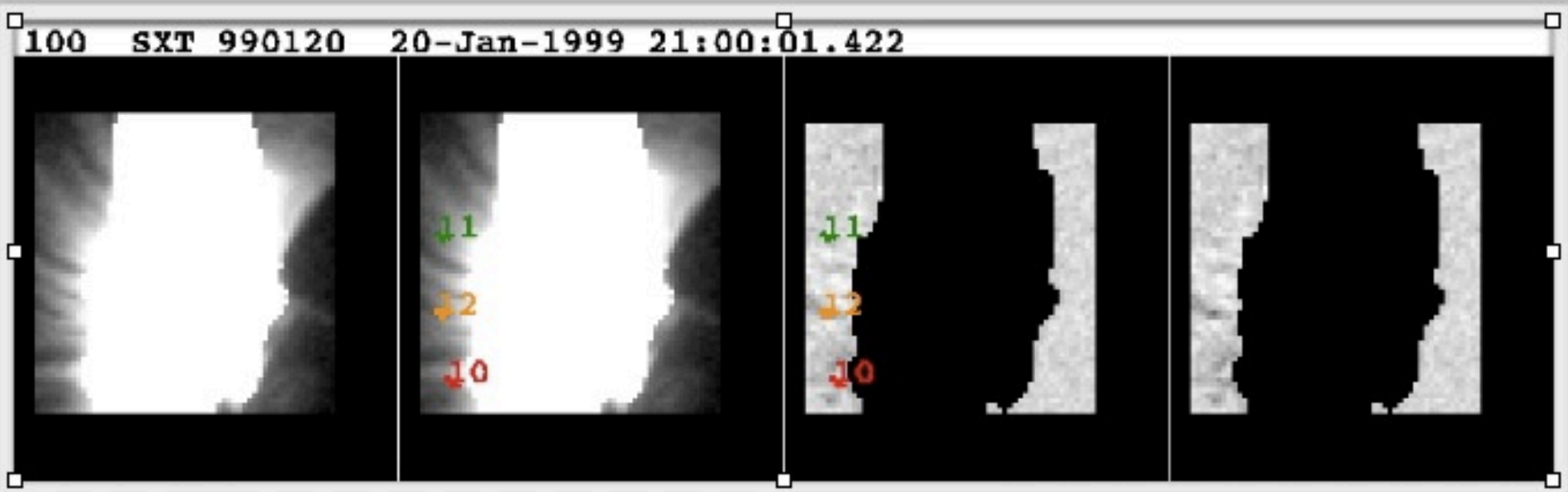
Collaborators:
Gordon Holman (GSFC), David McKenzie (MSU),
Katharine Reeves (SAO), Dan Seaton (ROB-SIDC)

SADs - Some Early Observations

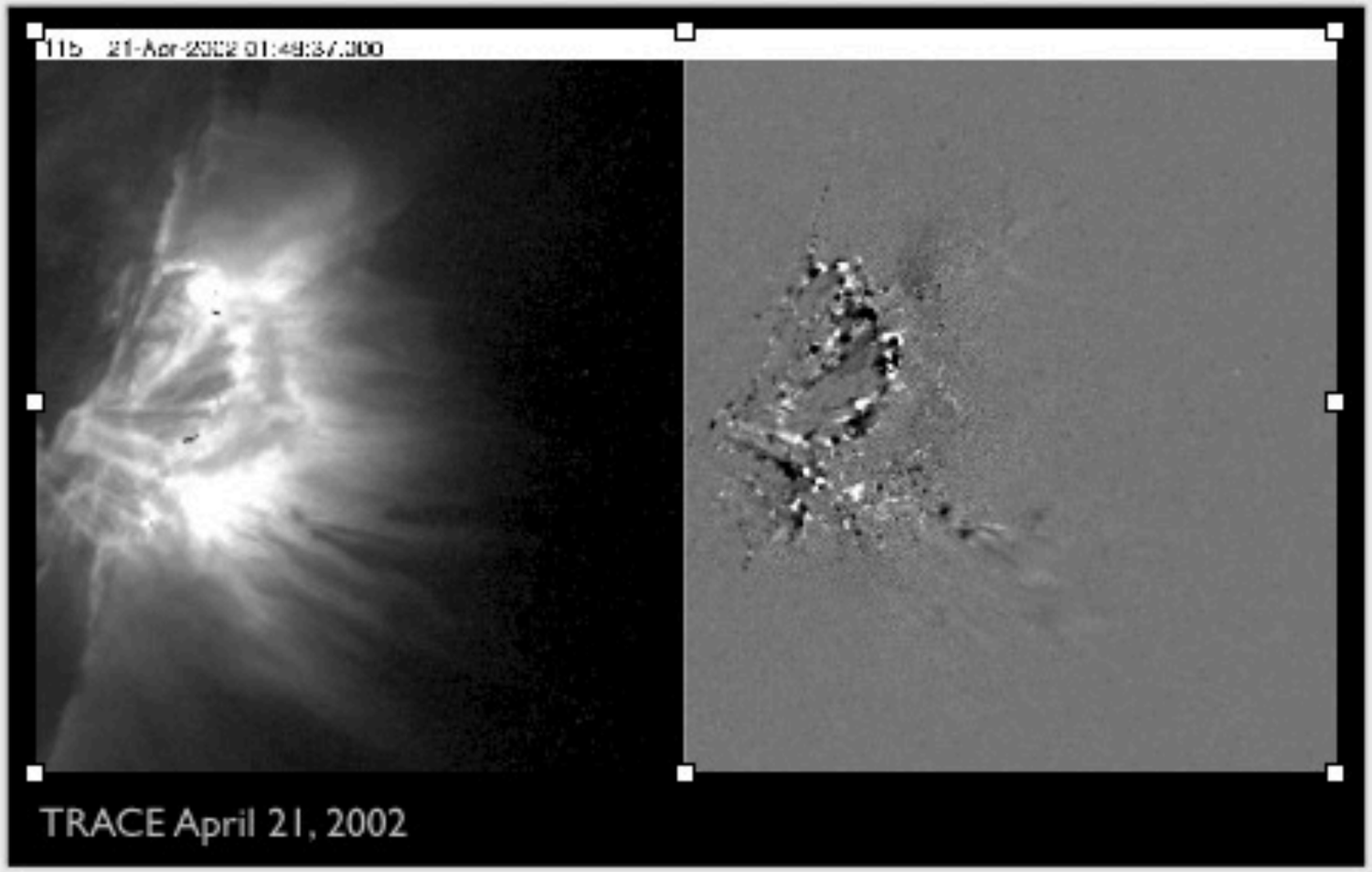


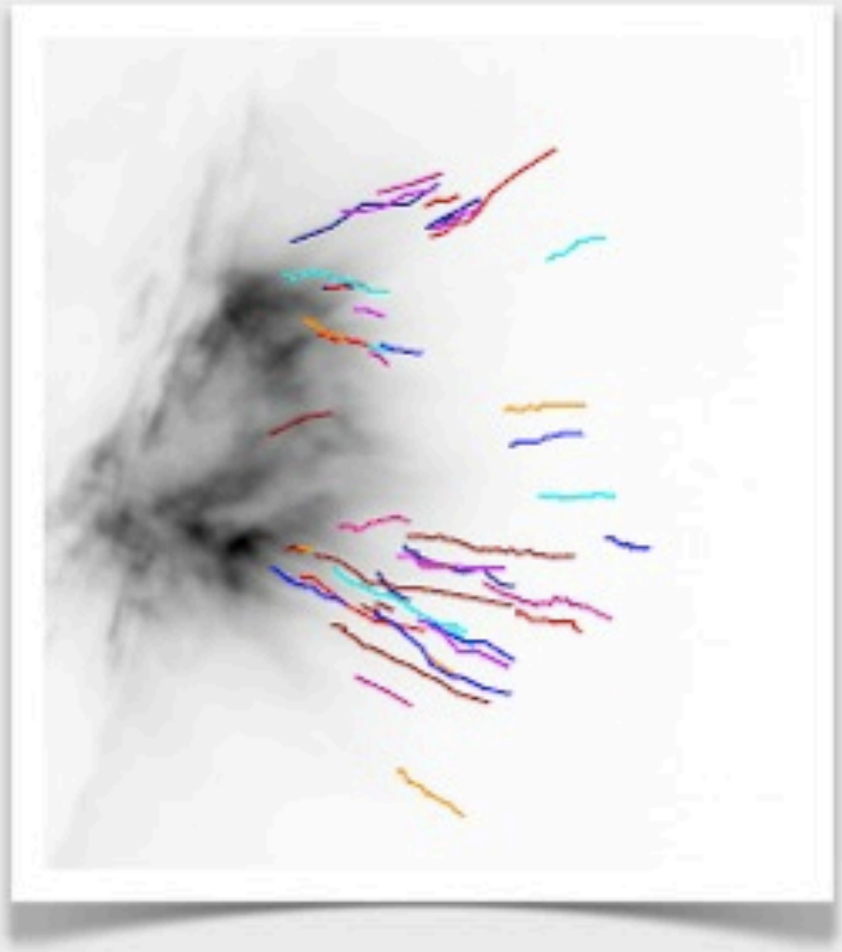
McKenzie & Hudson 1999





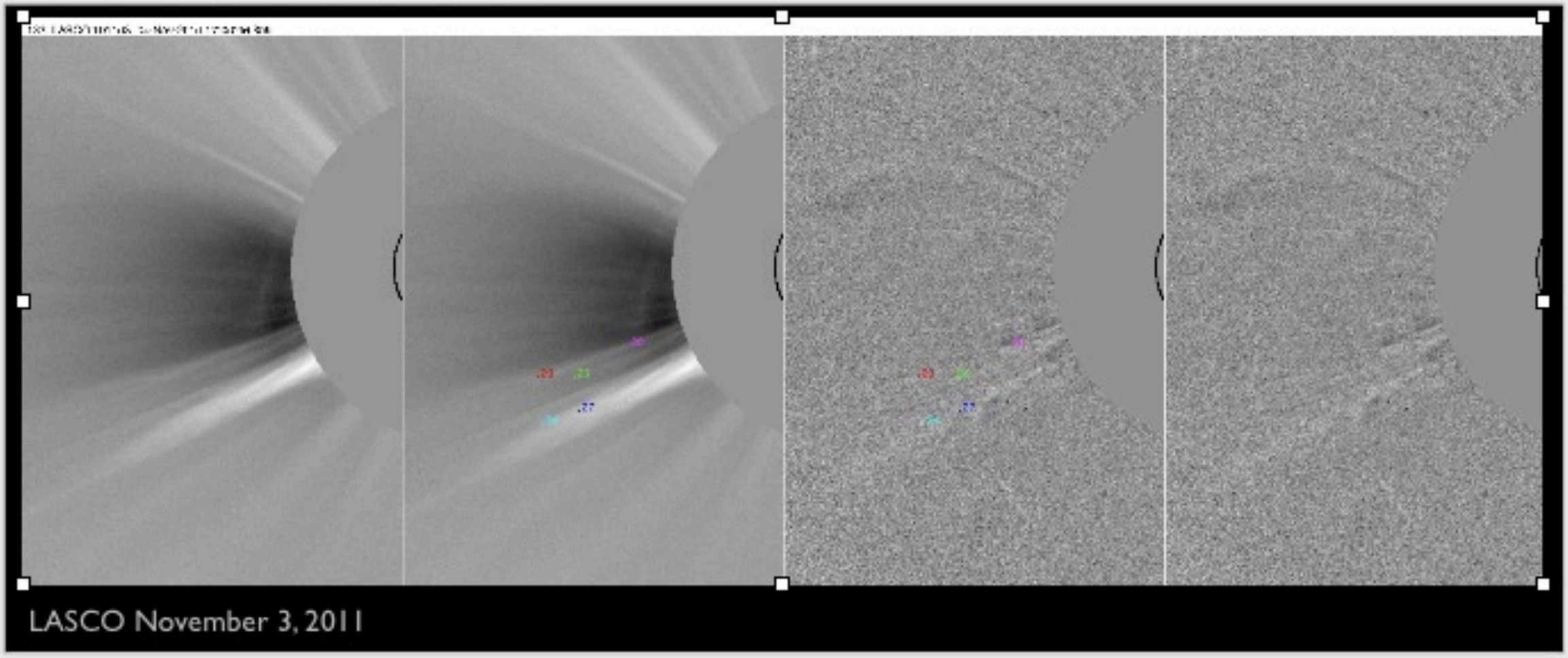
SADs



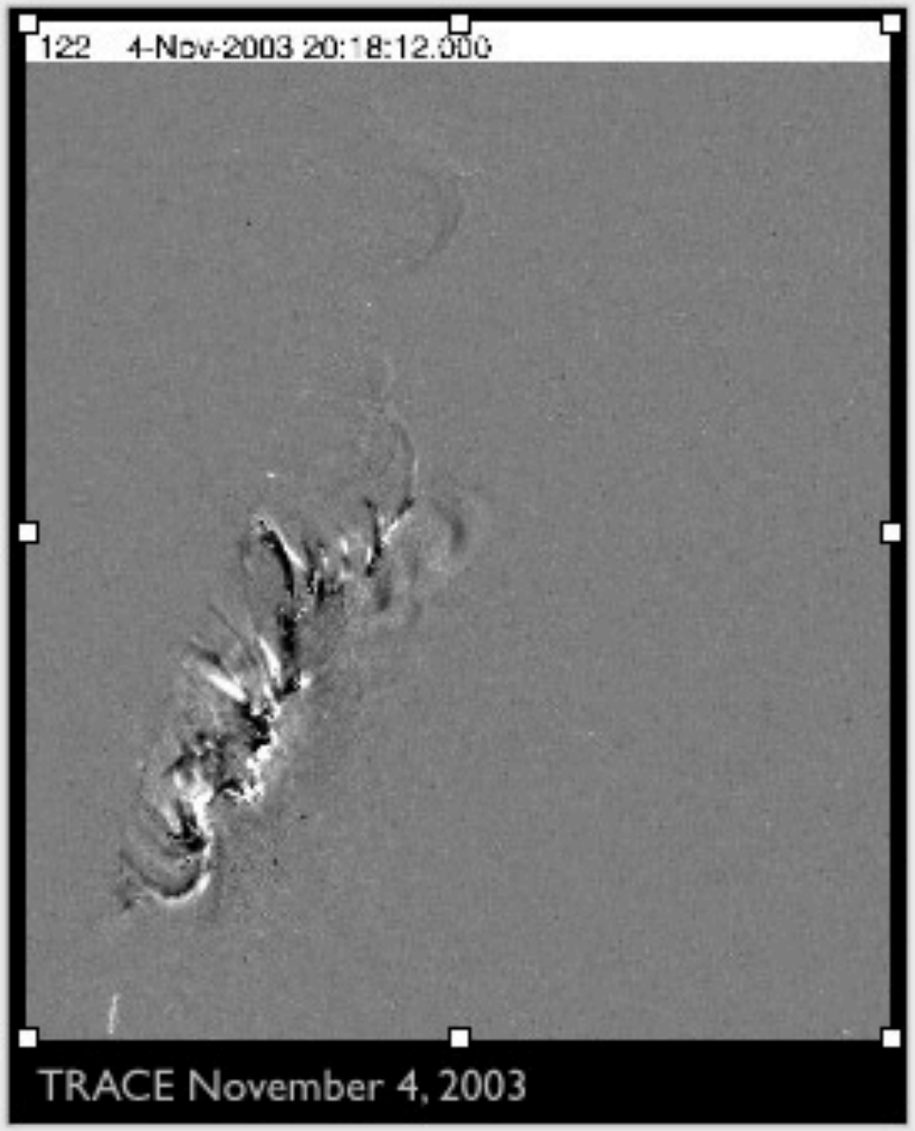


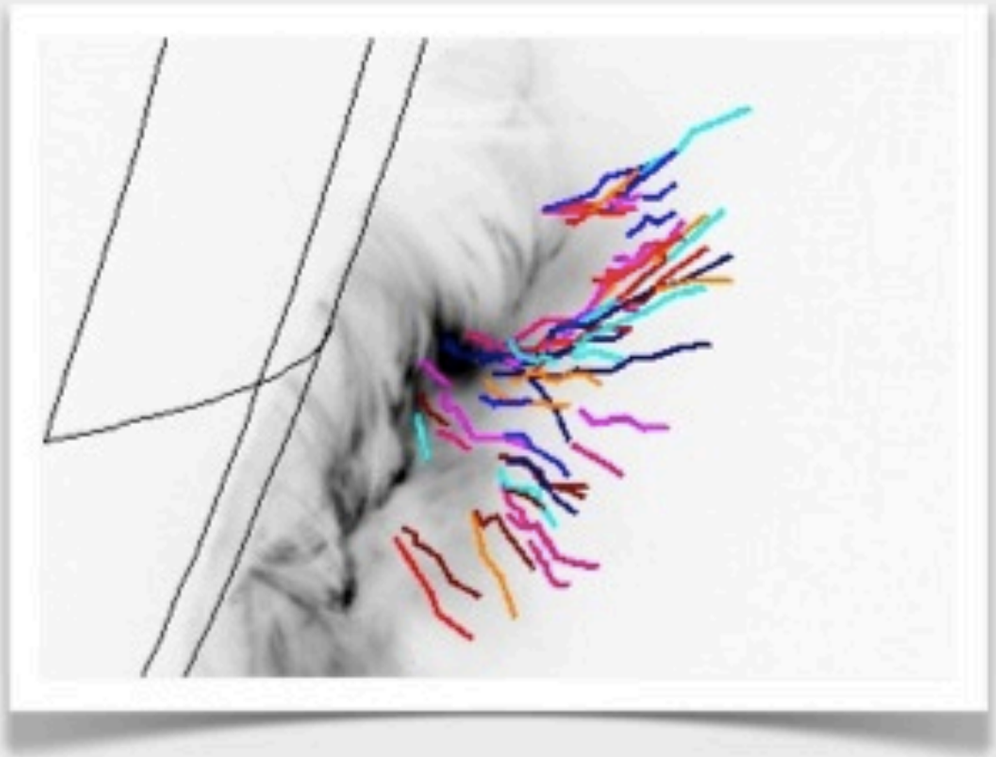
McKenzie & Savage 2009

SADs



And SADLs (Supra-Arcade Downflowing Loops)

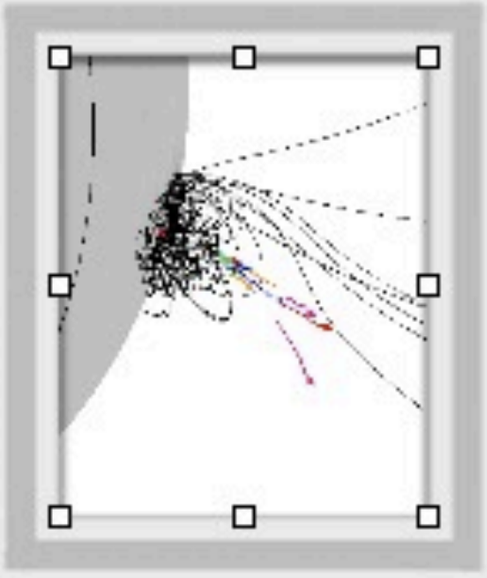




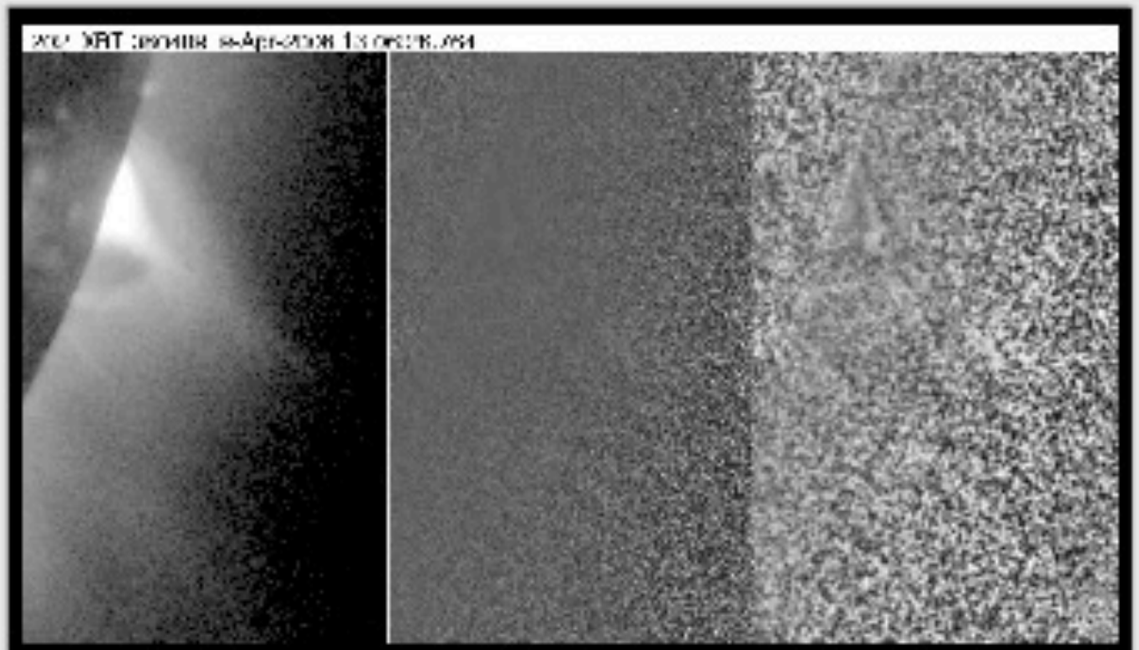
McKenzie & Savage 2009

SADLs (Supra-Arcade Downflowing Loops) / Plasmoids

Savage et al. 2010

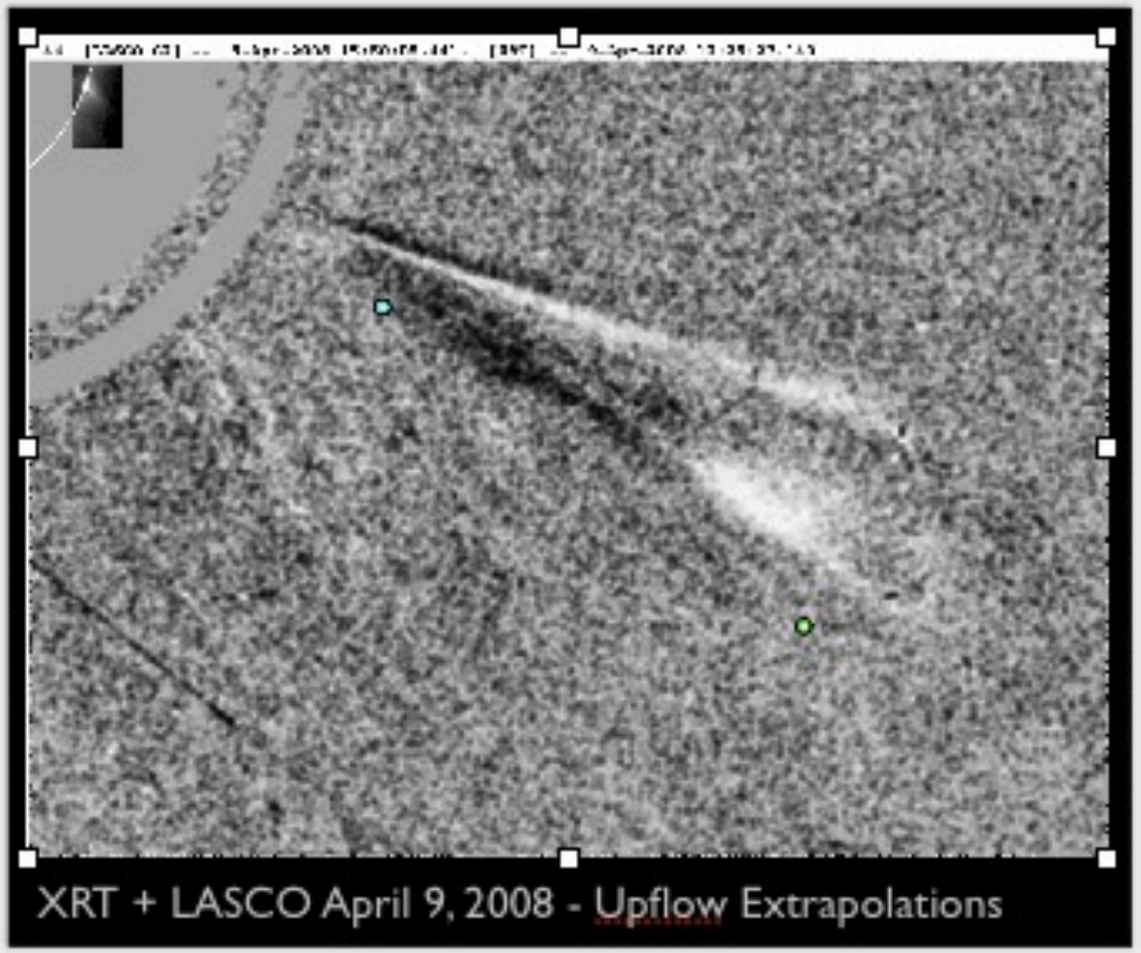


SADLs / Plasmoids

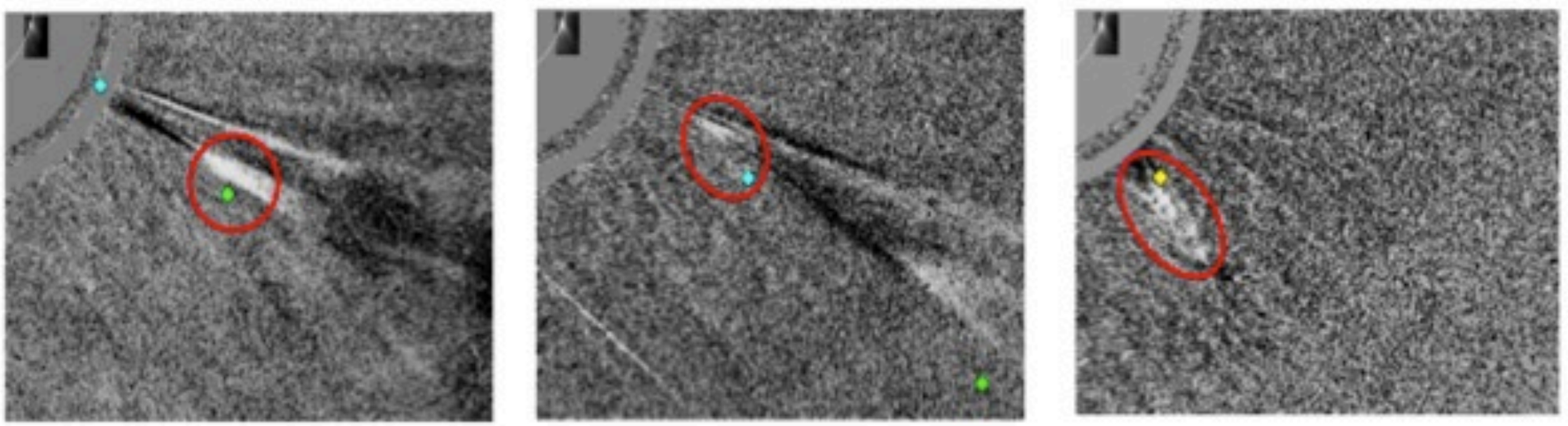


XRT April 9, 2008 - Disconnection Event

Savage et al. 2010



XRT + LASCO April 9, 2008 - Upflow Extrapolations



Analysis

Table 1: List of flares exhibiting downflow signatures.

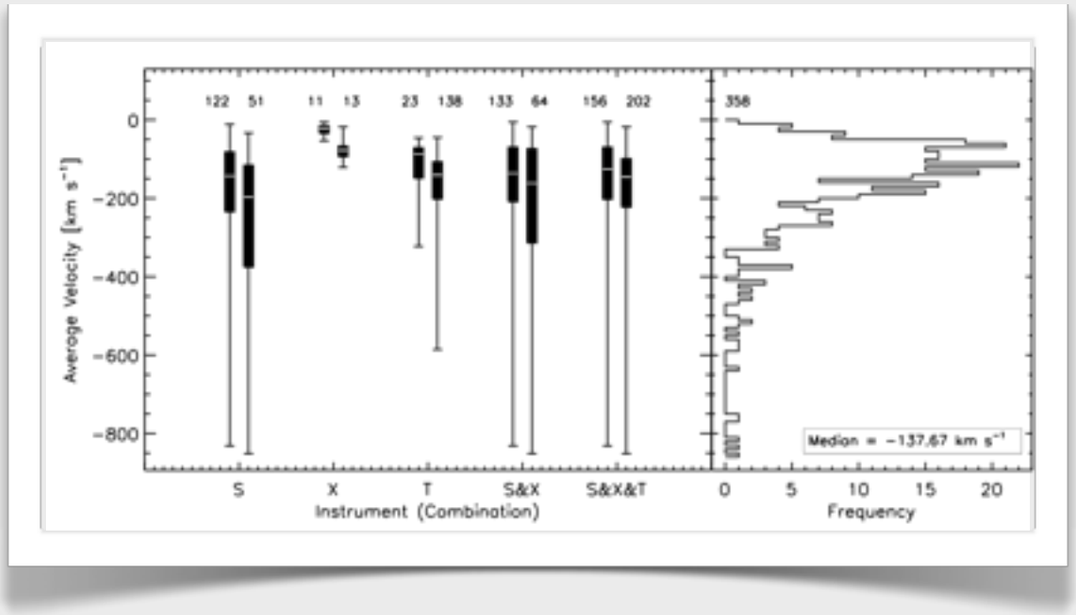
#	YYYYMMDD	Approx. Time	AR	GOES	FOV Coords	Instrument
1	19911216	12:30 - 14:30	06972	M3.2		
2	19920731	00:45 - 05:30	07244			
3	19921102	05:00 - 11:00	07321	X1.9		
4	19930514	22:00 - 00:00	07500	M4.4		
5	19930624	07:45 - 08:30	07529	M9.7		
6	19940227	09:00 - 10:00	07671	M2.8		
7	19980420	09:15 - 11:00	08202	M1.4		
8	19980423	05:30 - 07:15	08210	X1.2		
9	19980427	09:30 - 12:00	08210	X1.0		
10	19980506	07:30 - 10:00	08210	X2.7		
11	19980509	03:00 - 06:00	08210	M7.7		
12	19980816	18:30 - 19:30	08306	M3.2		
13	19980818	22:15 - 00:30	08306	M5.4		
14	19980920	02:30 - 03:30	08340	M1.9		
15	19980930	13:15 - 14:15	08340	M2.9		
16	19981123	11:00 - 12:30	08392	M3.2		
17	19981223	05:45 - 07:45	08421	M2.3		
18	19990120	19:00 - 23:00	08446	M5.2		
19	19990216	13:15 - 04:15	08458	M3.3		
20	19990503	06:00 - 07:00	08530	M4.4		
21	19990508	11:15 - 11:30	08541	M1.6		
22	19990508	14:30 - 15:00	08526	M4.7		
23	19990511	21:45 - 22:15	08542	C1.6		
24	19990725	13:00 - 14:00	08639	M2.4		
25	19991128	18:15 - 22:15	08771	M1.6		
26	19991207	01:00 - 01:30	08781	C8.7		
27	20000101	15:00 - 00:00				
28	20000222	20:15 - 21:30	08882	M1.1		
29	20000712	02:30 - 03:45	09087	C5.3		
30	20000712	21:00 - 22:00	09066	M1.9		
31	20000930	17:45 - 18:45	09178	M1.0		

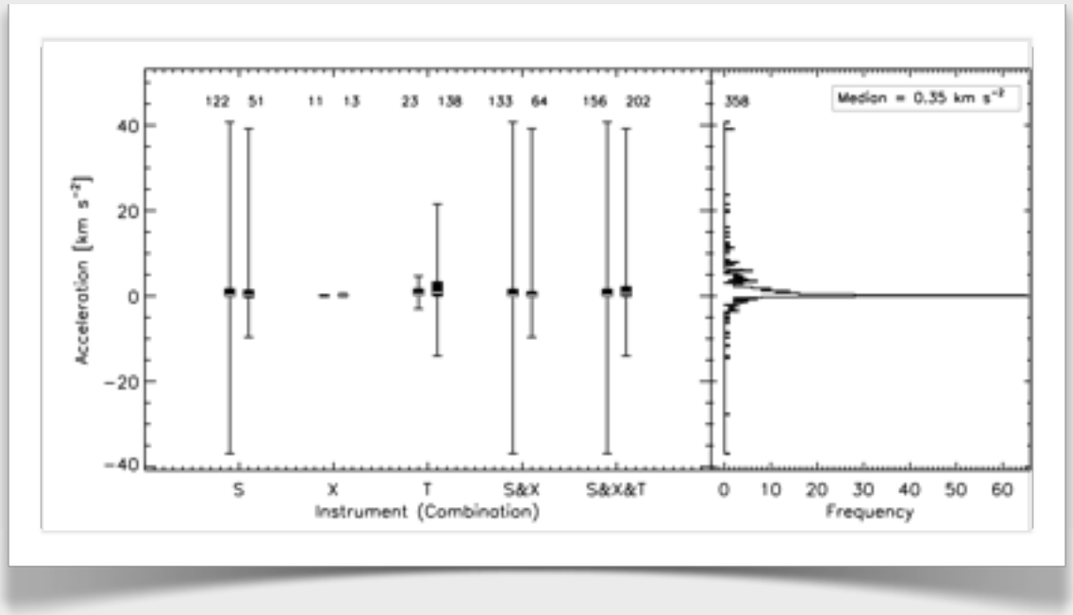
Table 1 Continued.

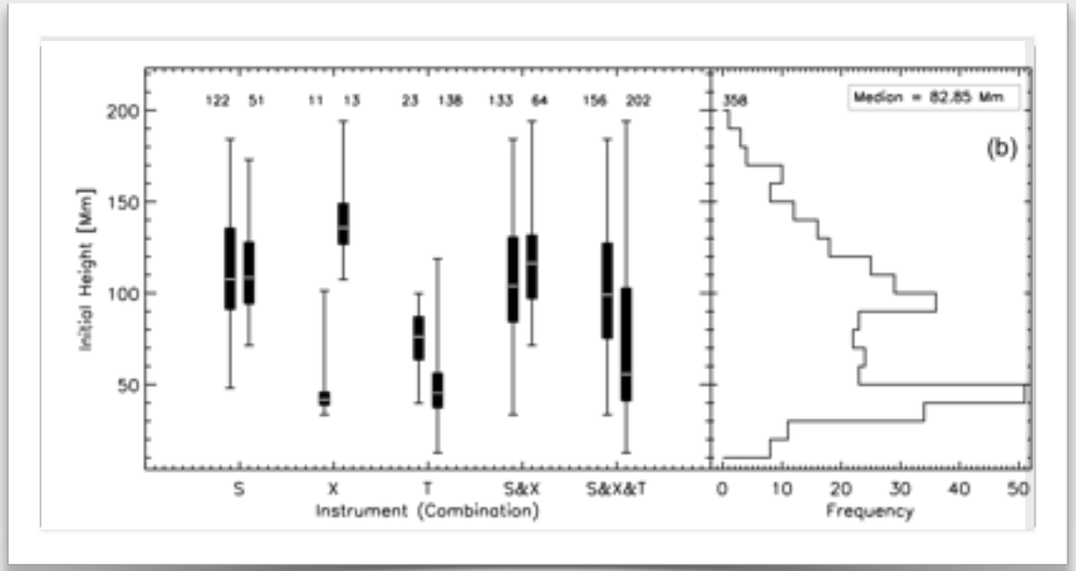
#	YYYYMMDD	Approx. Time	AR	GOES	FOV Coords	Instrument
32	20001016	06:30 - 07:30	09193	M2.5	N05 W75	SXT
33	20001025	14:00 - 18:00	09199	C2.1	W69 N10	SXT
34	20001108	23:15 - 00:15	09213	M7.5	W90 N10	SXT
35	20001125	01:00 - 02:30	09240	M8.3	E51 N08	SXT
36	20010119	17:15 - 18:15	09313	M1.2	E58 S08	SXT
37	20010402	21:15 - 22:00	09393	X20	W70 N16	SXT
38	20010402	23:45 - 02:30	09393	M1.2	W70 N16	SXT
39	20010403	03:30 - 07:15	09415	X1.2	E89 S22	SXT
40	20010404	10:00 - 12:00	09415	M1.6	E59 S22	SXT
41	20010405	20:45 - 23:30	09415	M5.1	E47 S21	SXT
42	20010626	15:00 - 19:00			E90 S20	SXT
43	20010825	16:30 - 17:00	09591	X5.4	E28 S18	SXT
44	20010927	10:00 - 15:00	09628	M1.0	W39 S18	SXT
45	20011001	04:30 - 11:30	09632	M9.1	W75 S18	SXT
46	20011009	11:00 - 11:30	09653	M1.4	E11 S22	SXT
47	20011030	19:00 - 21:00	09687	C5.0	E90 S19	SXT
48	20011101	14:00 - 17:30	09687	M1.8	E90 S19	SXT
49	20011109	18:30 - 19:15	09687	M1.9	W31 S19	SXT
50	20011214	09:45 - 10:15	09742	M3.6	E90 N09	SXT
51	20020421	01:00 - 03:00	09906	X1.5	W91 S14	TRACE
52	20020723	00:15 - 01:30	10039	X4.8	E54 S12	TRACE
53	20031104	19:45 - 23:45	10486	X28	W89 S17	TRACE
54	20061212	20:00 - 23:00	10930		W21 S05	XRT
55	20061213	02:30 - 05:00	10930	X3.4	W35 S06	XRT
56	20070313	01:00 - 11:00	10946		W86 N07	XRT
57	20070509	03:00 - 06:00	10953		W91 S11	XRT
58	20070520	19:45 - 20:30	10956		W21 N02	XRT
59	20071217	06:00 - 10:00	10978	C2.2	W79 S10	XRT
60	20071218	06:00 - 10:00	10978		W91 S09	XRT
61	20080409	08:00 - 18:00	10989		W90 S18	XRT
62	20100613	02:00 - 05:30	11081		W72 N24	XRT

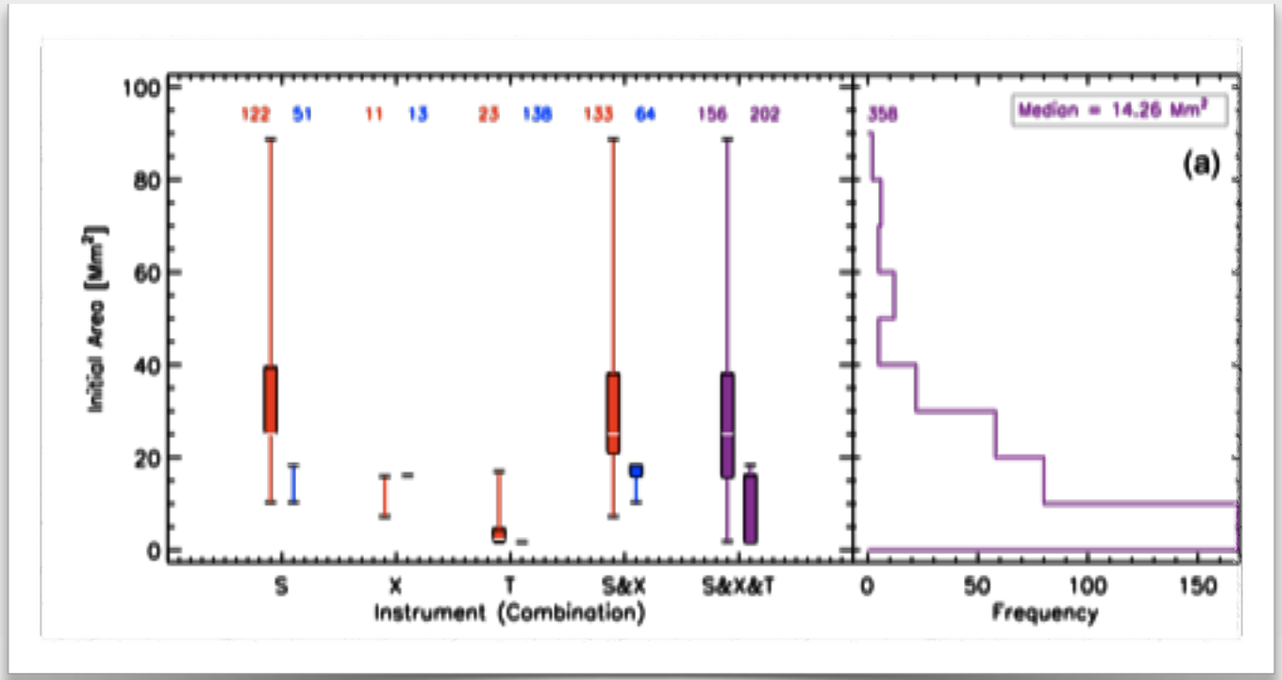
Savage & McKenzie 2011

Analysis

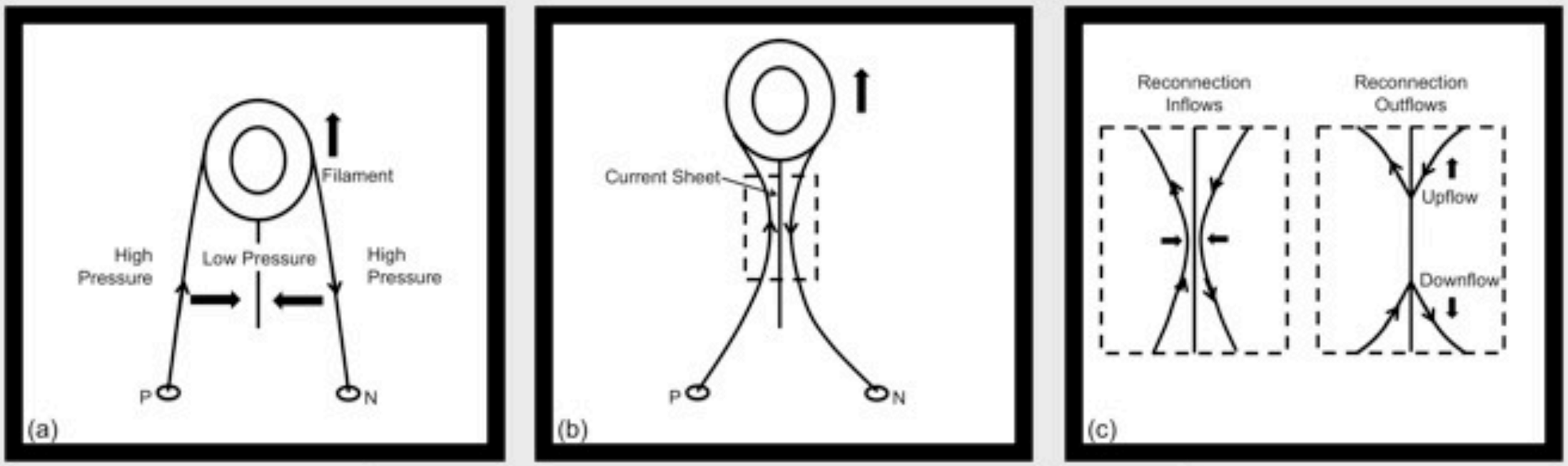

122 51 11 13 23 138 133 64 156 202
358
Median = −137.67 km s⁻¹
Average Velocity [km s⁻¹]
0
−200
−400
−600
−800
S X T S&X S&X&T
Instrument (Combination)
0 5 10 15 20
Frequency

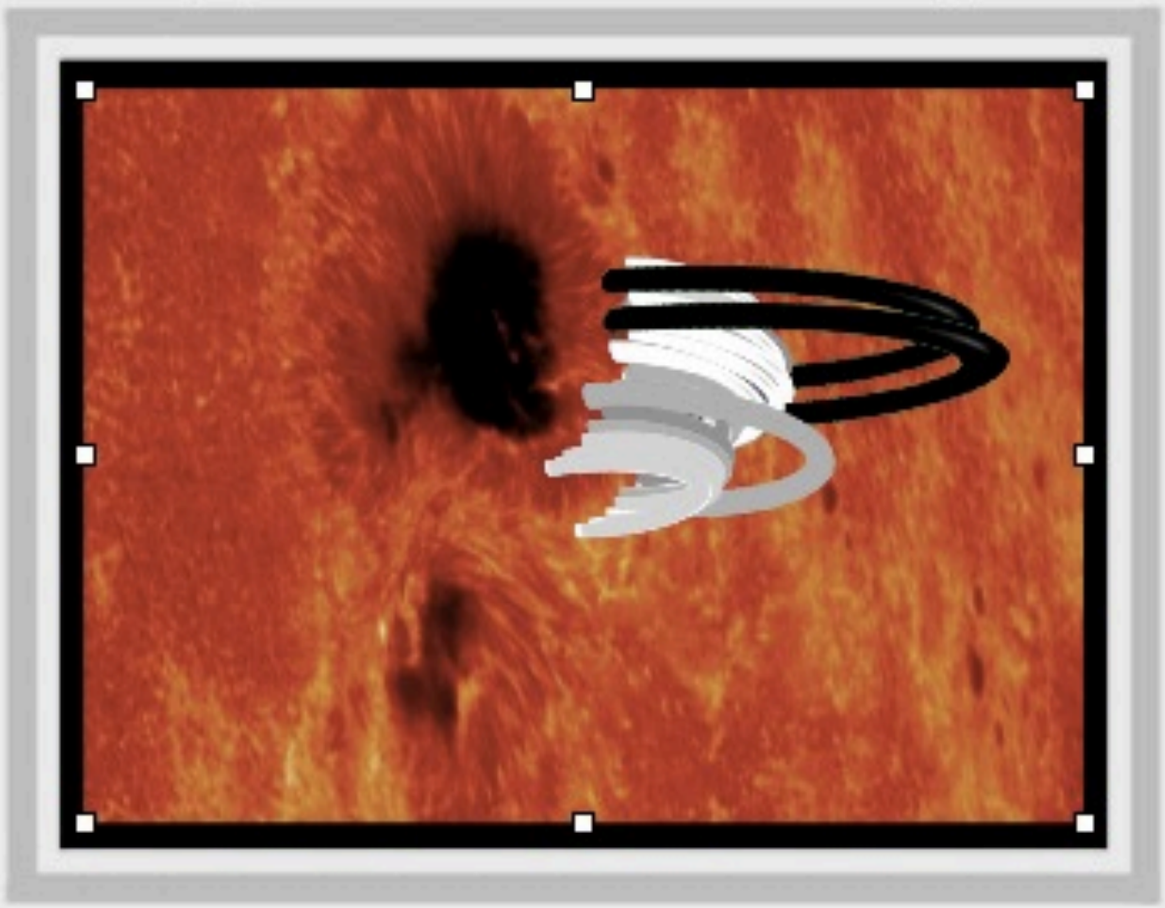

122 51 11 13 23 138 133 64 156 202
358
Median = 0.35 km s⁻²
Acceleration [km s⁻²]
40
20
0
−20
−40
S X T S&X S&X&T
Instrument (Combination)
0 10 20 30 40 50 60
Frequency


122 51 11 13 23 138 133 64 156 202
358
Median = 82.85 Mm
(b)
Initial Height [Mm]
200
150
100
50
S X T S&X S&X&T
Instrument (Combination)
0 10 20 30 40 50
Frequency

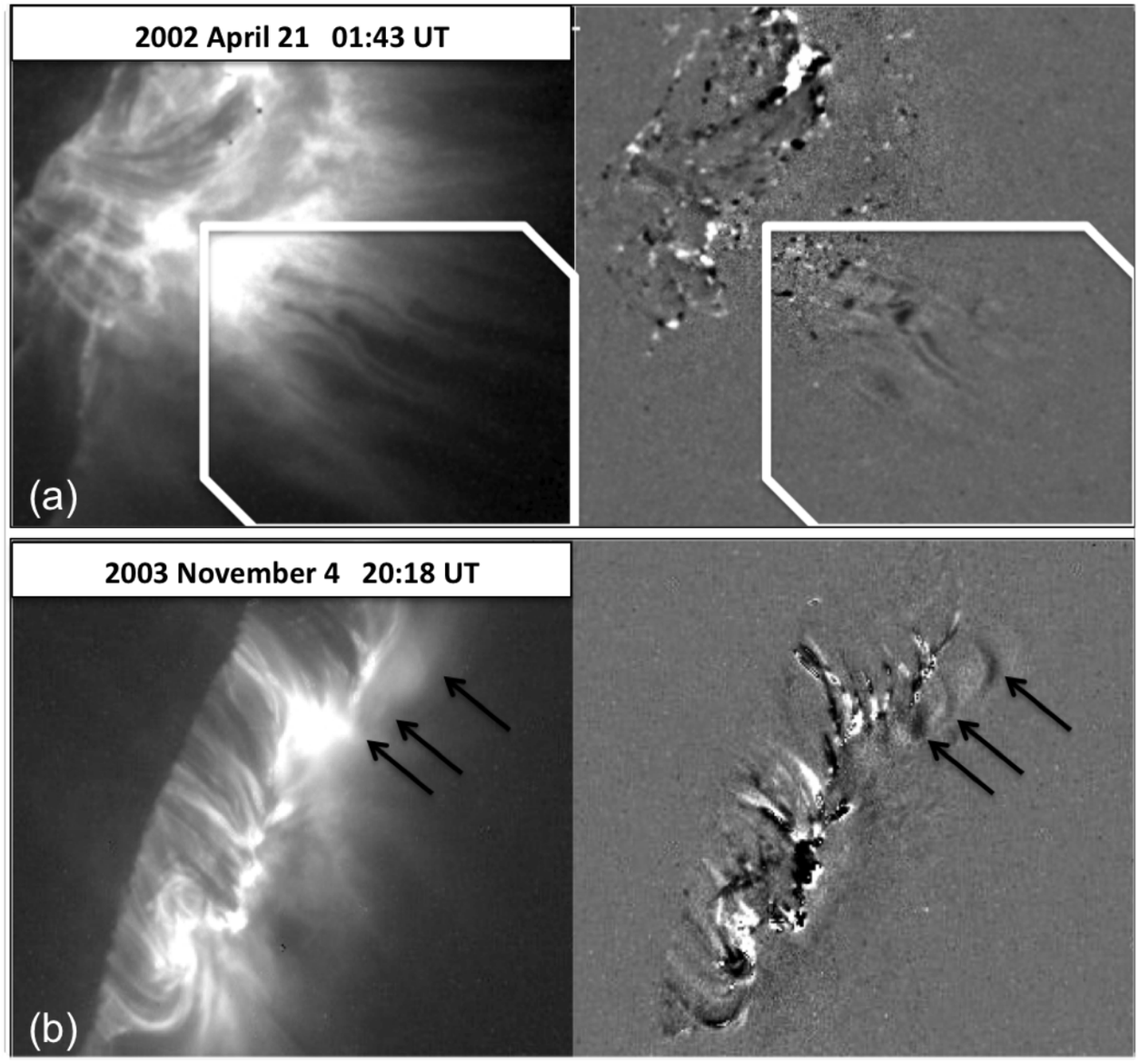

122 51 11 13 23 138 133 64 156 202
358
Median = 14.26 Mm²
(a)
Initial Area [Mm²]
100
80
60
40
20
0
S X T S&X S&X&T
Instrument (Combination)
0 50 100 150
Frequency

Simple Model(s)

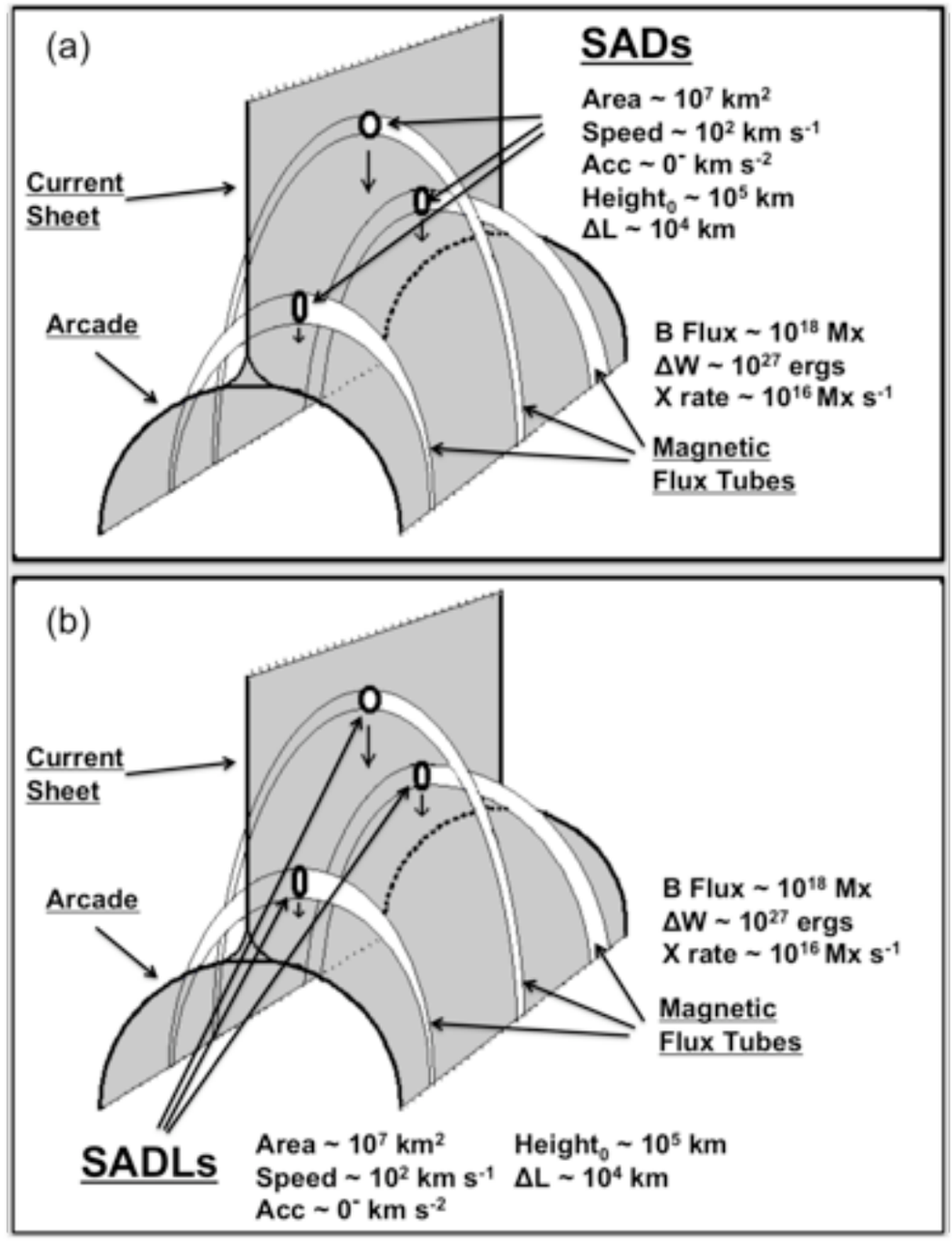




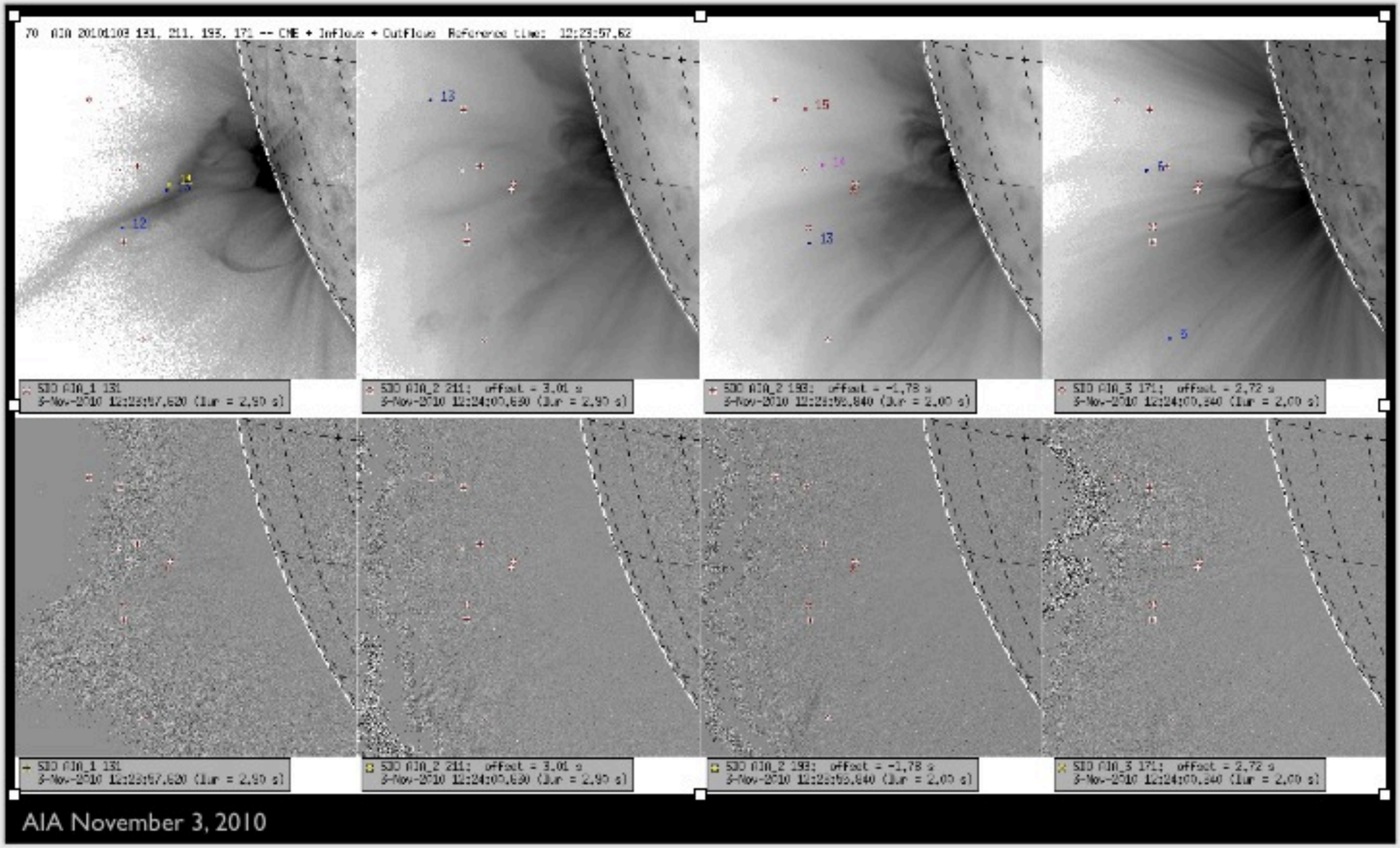
Original Interpretation: Geometry-based



Savage & McKenzie 2011

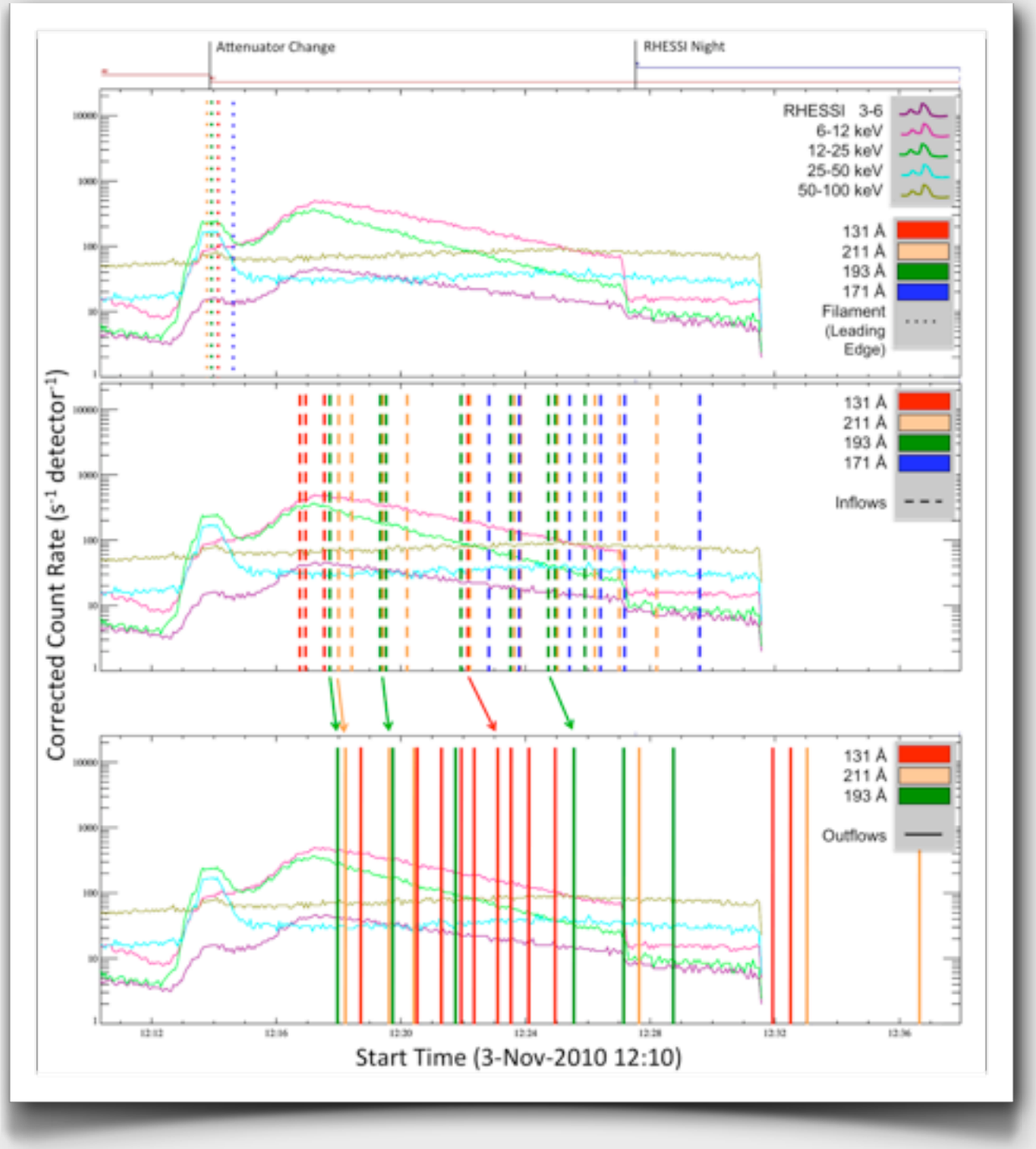


Newer Supporting Observations



Savage et al. 2012

Newer Supporting Observations

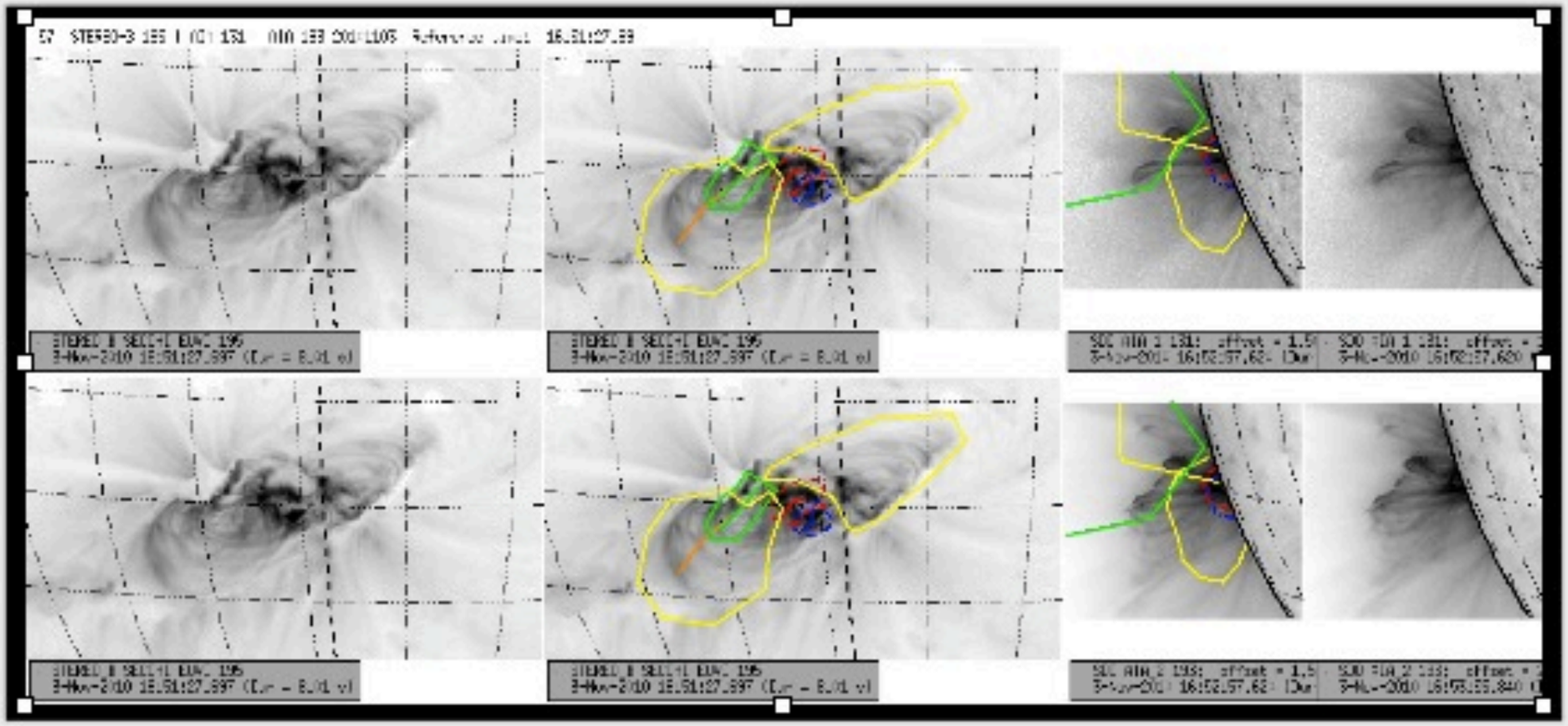


CME to Inflows to Outflows

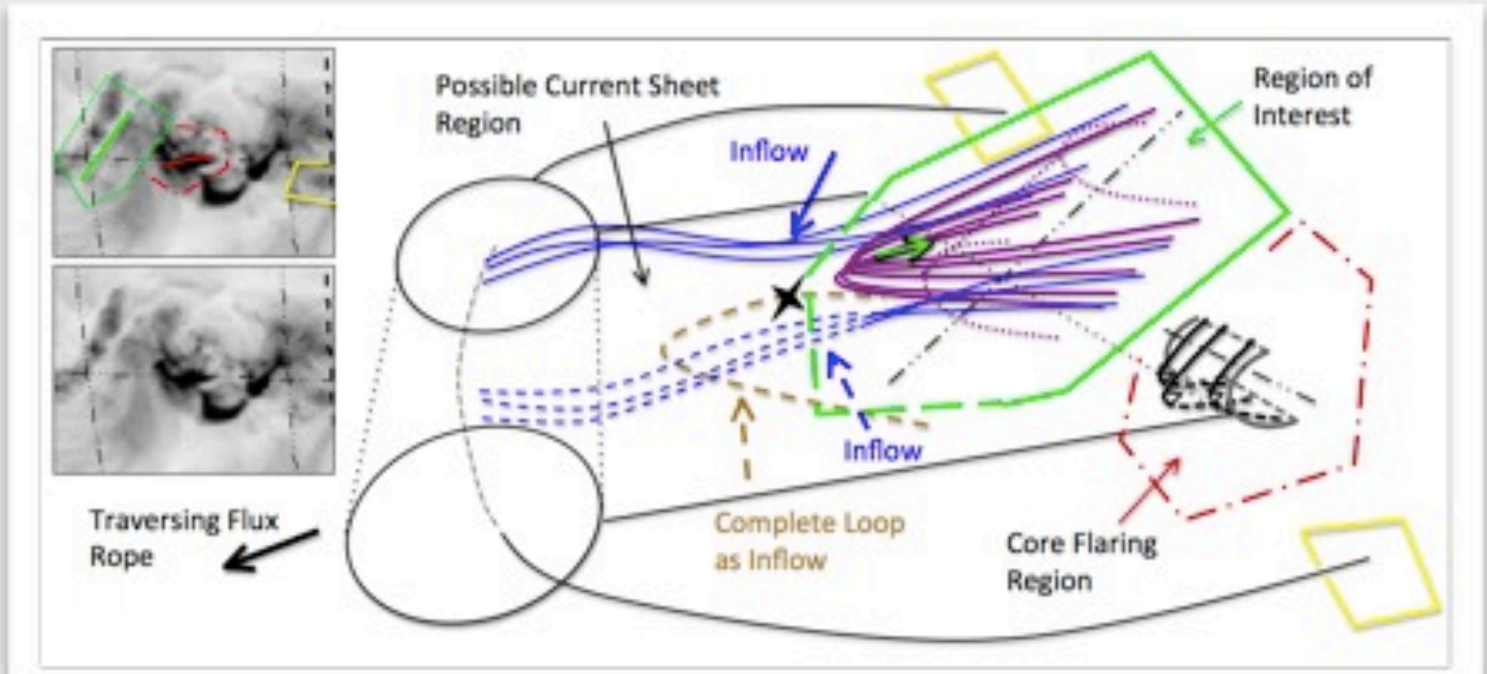
Pair [#]	Wavelength [Å]	Inflow [#]	Outflow [#]	In Speed [km/s]	Out Speed [km/s]	Max Delay [sec]
1	131	8	12	260	310	60
2	211	3	6	130	1000	12
3	193	4	8	150	930	12
4	193	6	10	110	1470	12
5	193	13	16	144	1400	48

Savage et al. 2012

Newer Supporting Observations



Savage et al. 2012



Outputs

- Patchy & Bursty
- Sizes & fluxes of post-reconnection flux tubes
- Impulsive & decay phases
- Shrinkage energy
- Speeds & decelerations
- Hot fan: current sheet sheath

Still true, but....

Now we have AIA...

With continuous full-Sun coverage...

Plus high resolution...

Plus high cadence...

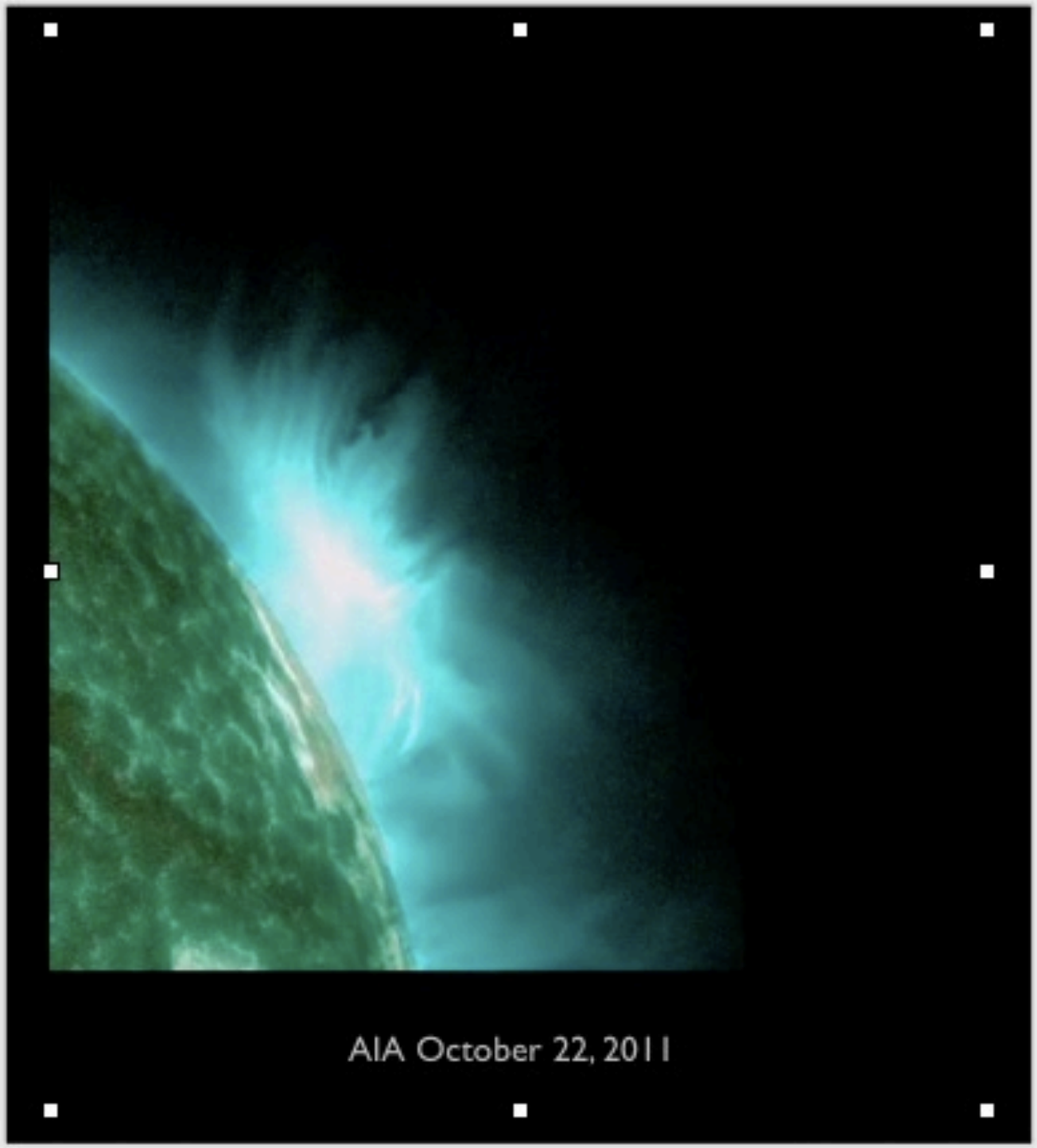
Plus off-limb coverage + STEREO...

Plus a large selection of temperature bands...

Including nice hot ones with high resolution...

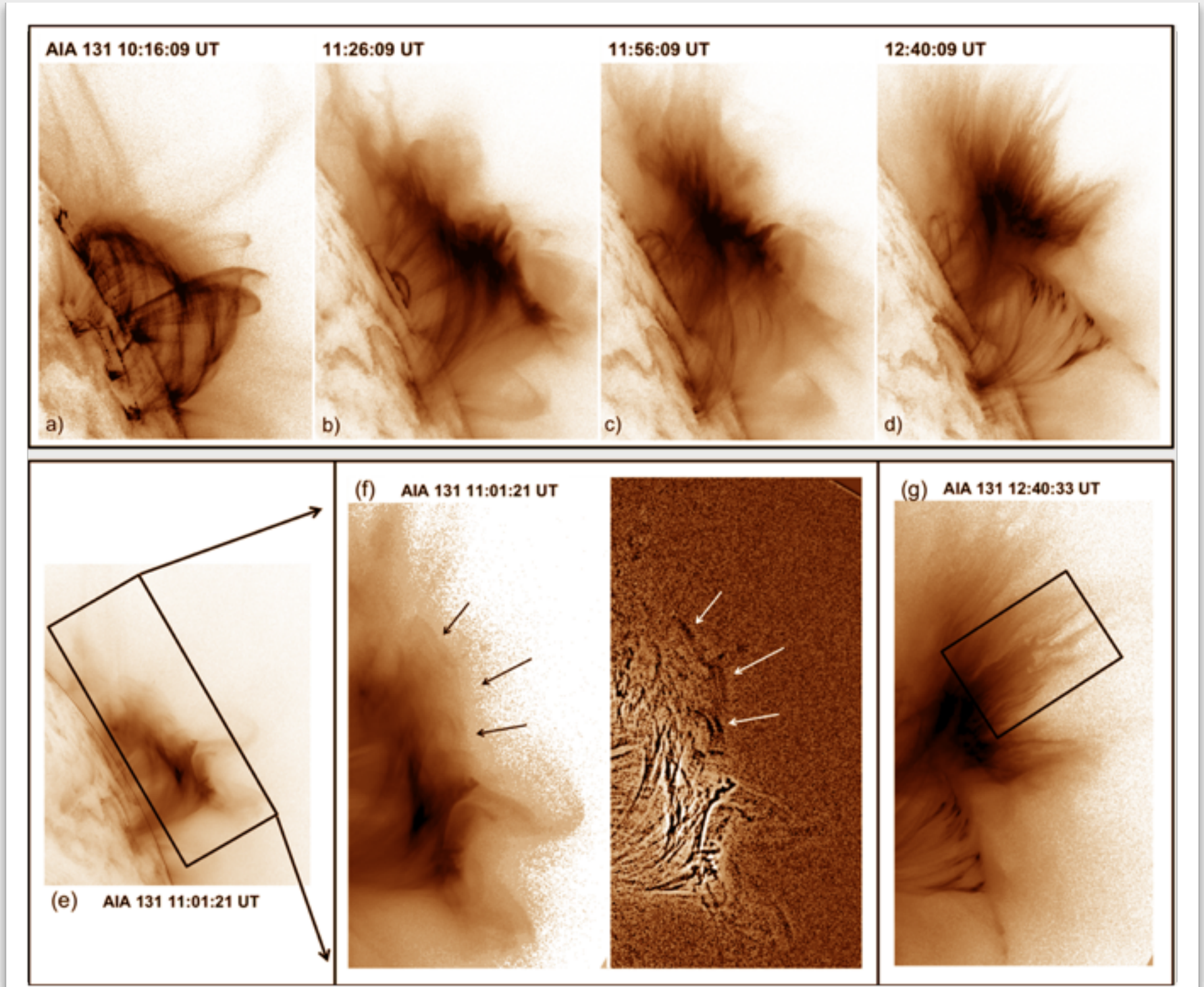
And more flares!

Newest Observations



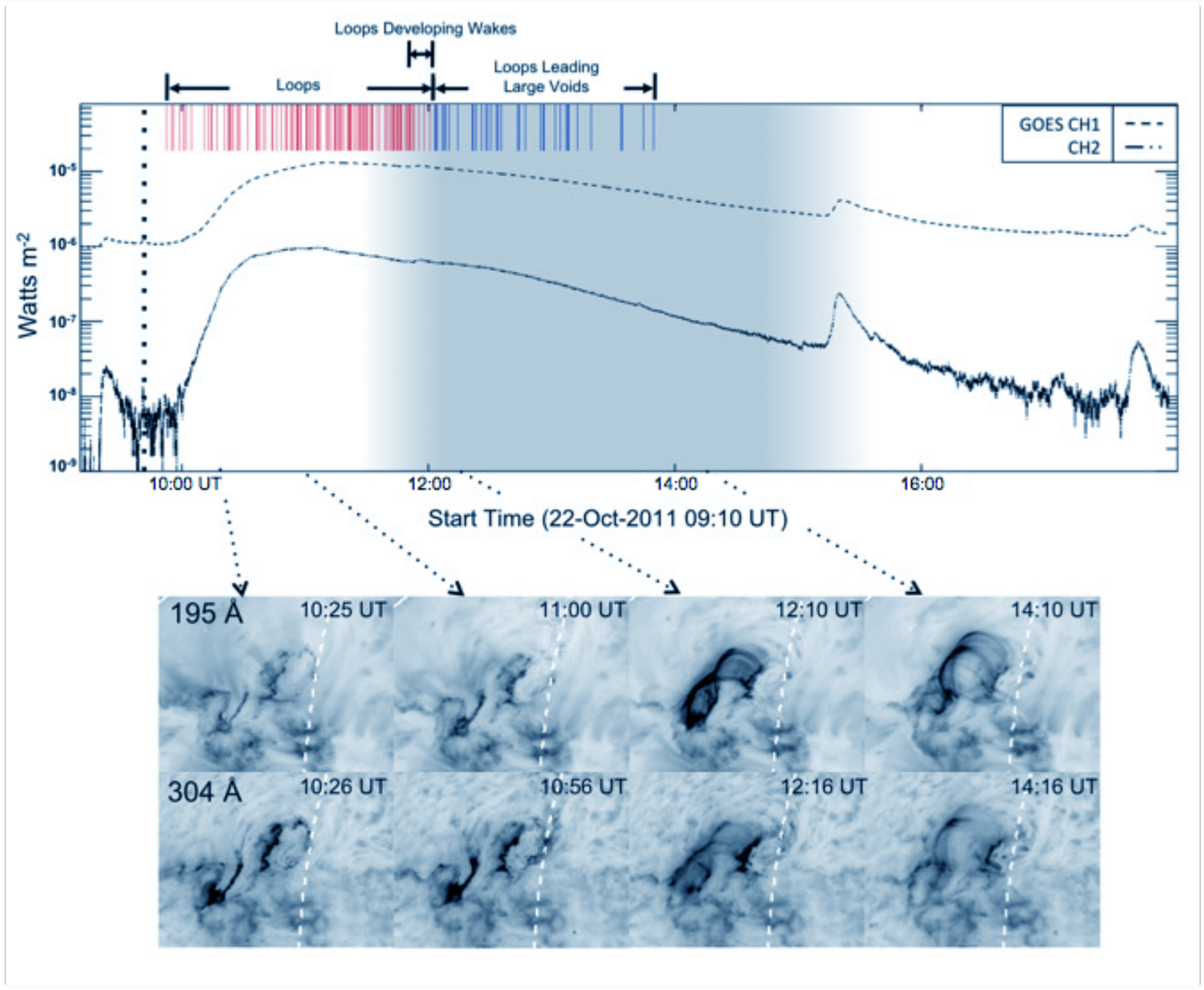
AIA October 22, 2011

Newest Observations



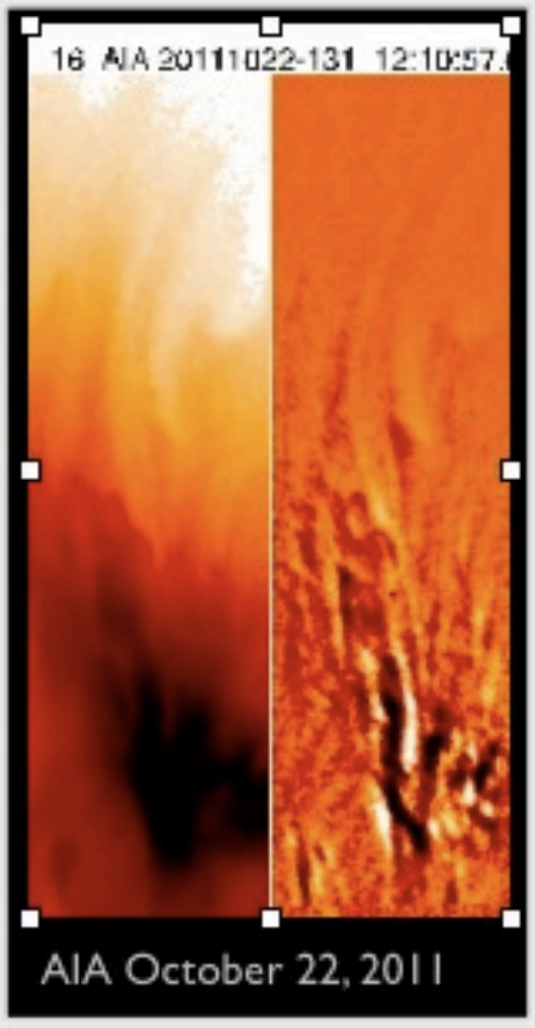
Savage et al. 2012

Newest Observations



Savage et al. 2012

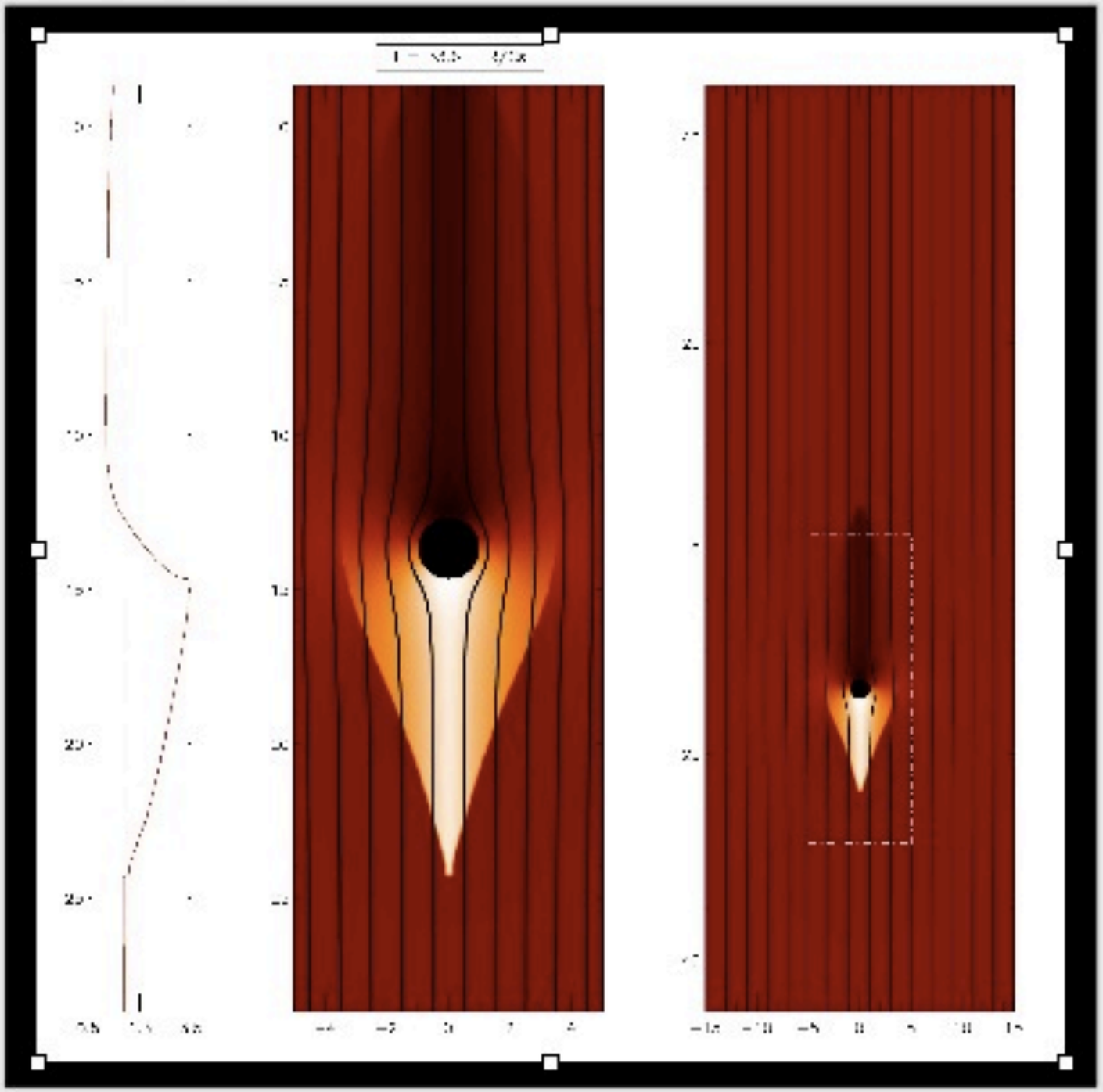
Newest Observations



The large voids appear to be rarefied regions behind thin shrinking loops!

("wakes" -> disturbances in the density of the current sheet, apparently resulting from the passage of the shrinking loops)

Preliminary Remodeling: "Primitive Initial Investigation"



*Roger Scott (MSU):

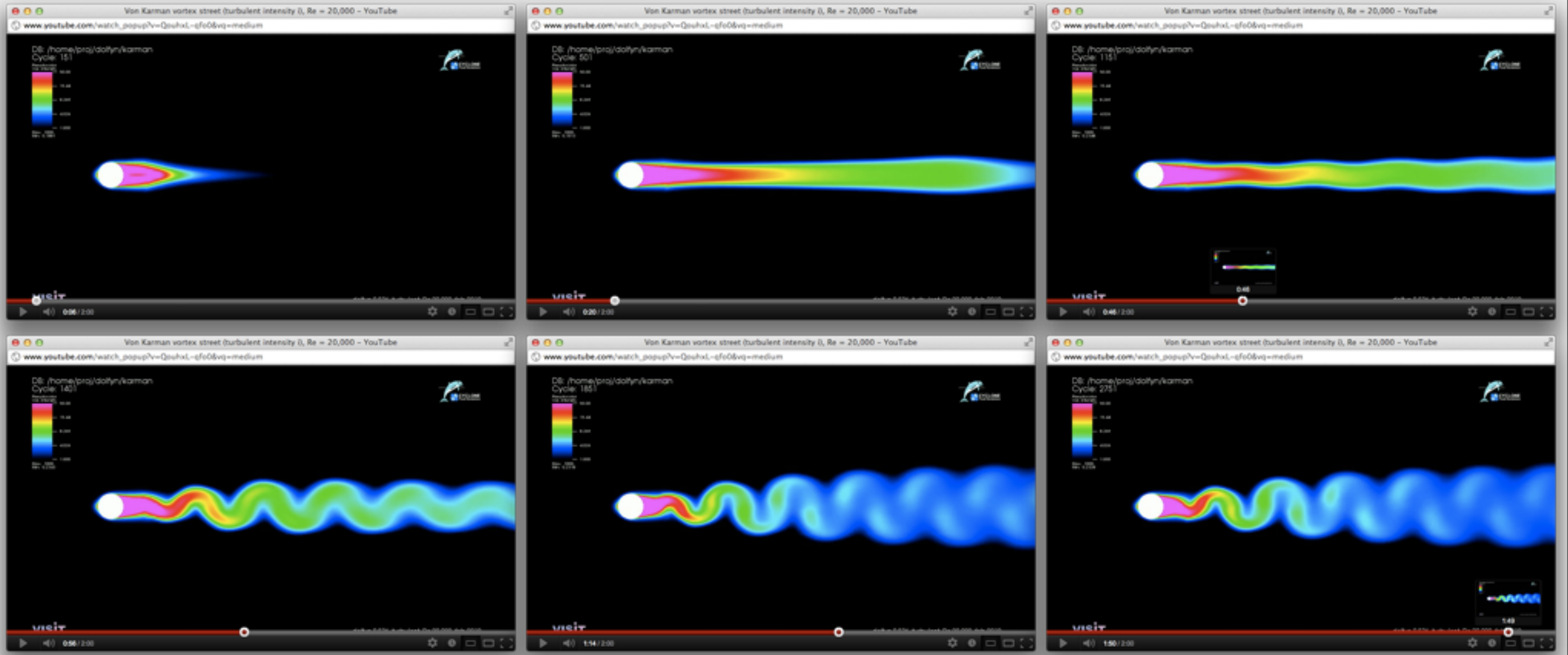
- Intrusion in the current sheet
- B field lines (black) are perturbed by intrusion (which does not evolve)
- 40 acoustic crossing times
- Downflow speed of M = 1.4
- Emission measure in red scale
- Plot on left = Integrated EM
- At T=0, three flow discontinuities introduced to satisfy far-field BCs

- 2 sunward shocks above & below intrusion
- High speed, anti-sunward rarefaction wave behind intrusion
- Rarefied plasma between intrusion & rarefaction wave

Or ?

Von Karman vortex street (turbulent intensity i), Re = 20,000

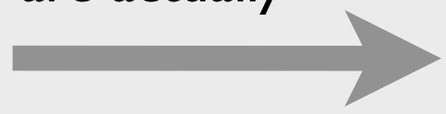
http://www.youtube.com/watch?v=QouhxL-qfo0&feature=youtu.be



*Disclaimer: I know nothing about the creation of this simulation; however, qualitatively speaking, the results of several related simulations are similar to the appearance of SADs. This is merely included as a qualitative guide.

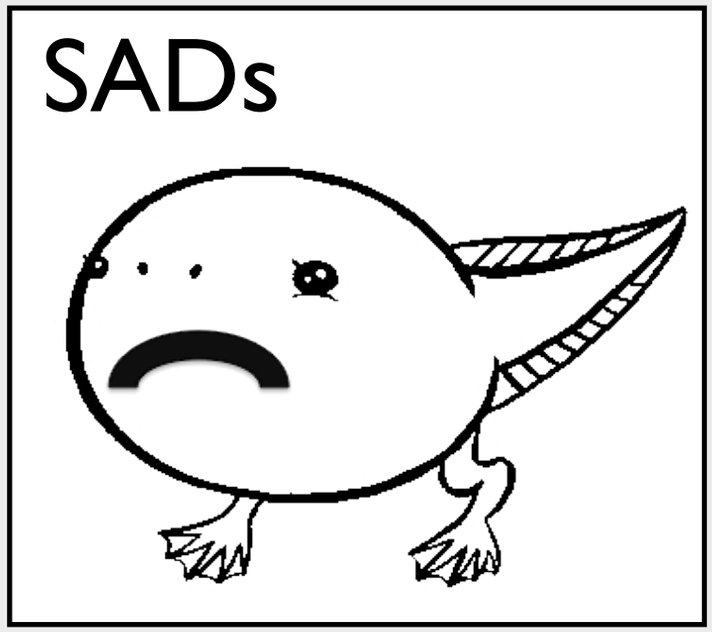
In other words...

Supra-Arcade Downflows

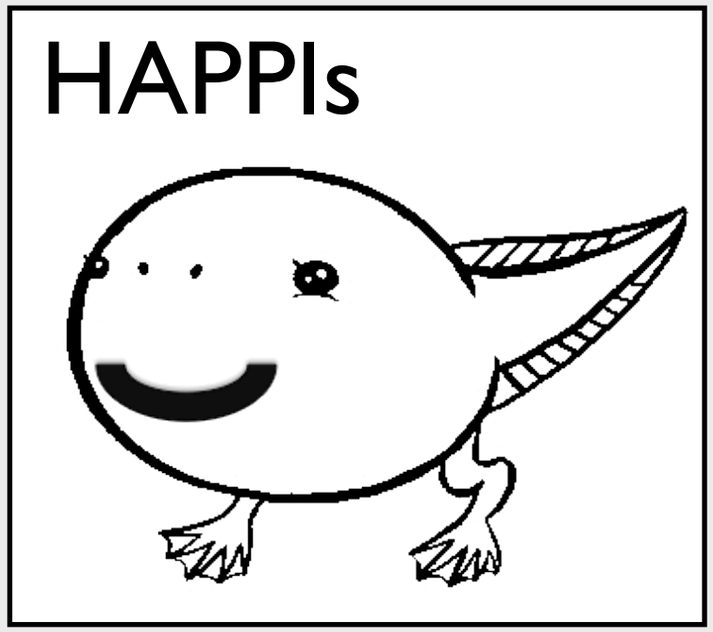


High-Altitude Propagating Pressure Imbalances

Graphically speaking...



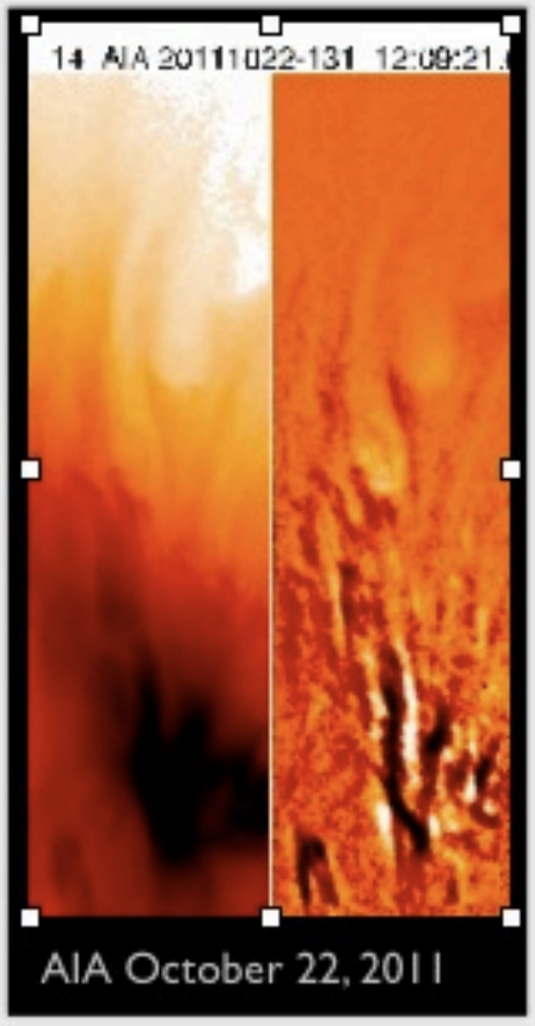
are actually



Supra-Arcade Downflows

High-Altitude Propagating Pressure Imbalances

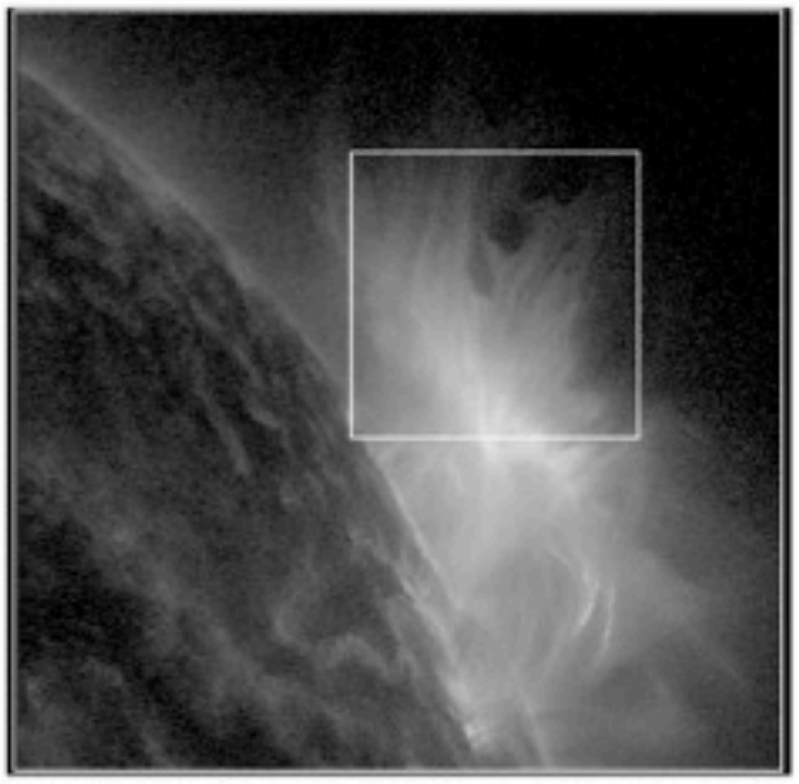
Newest Observations

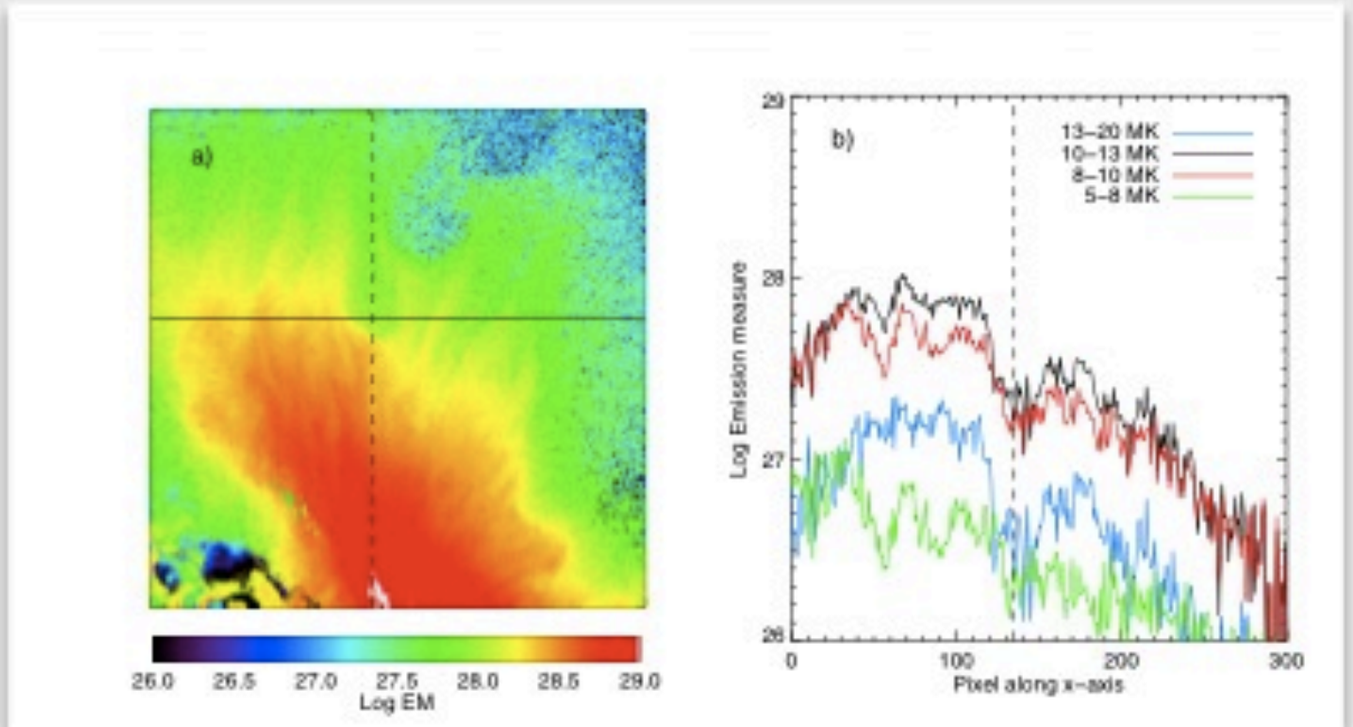


Leading edge of the void has enhanced EUV intensity that evolves to reveal two loop-shaped extensions.

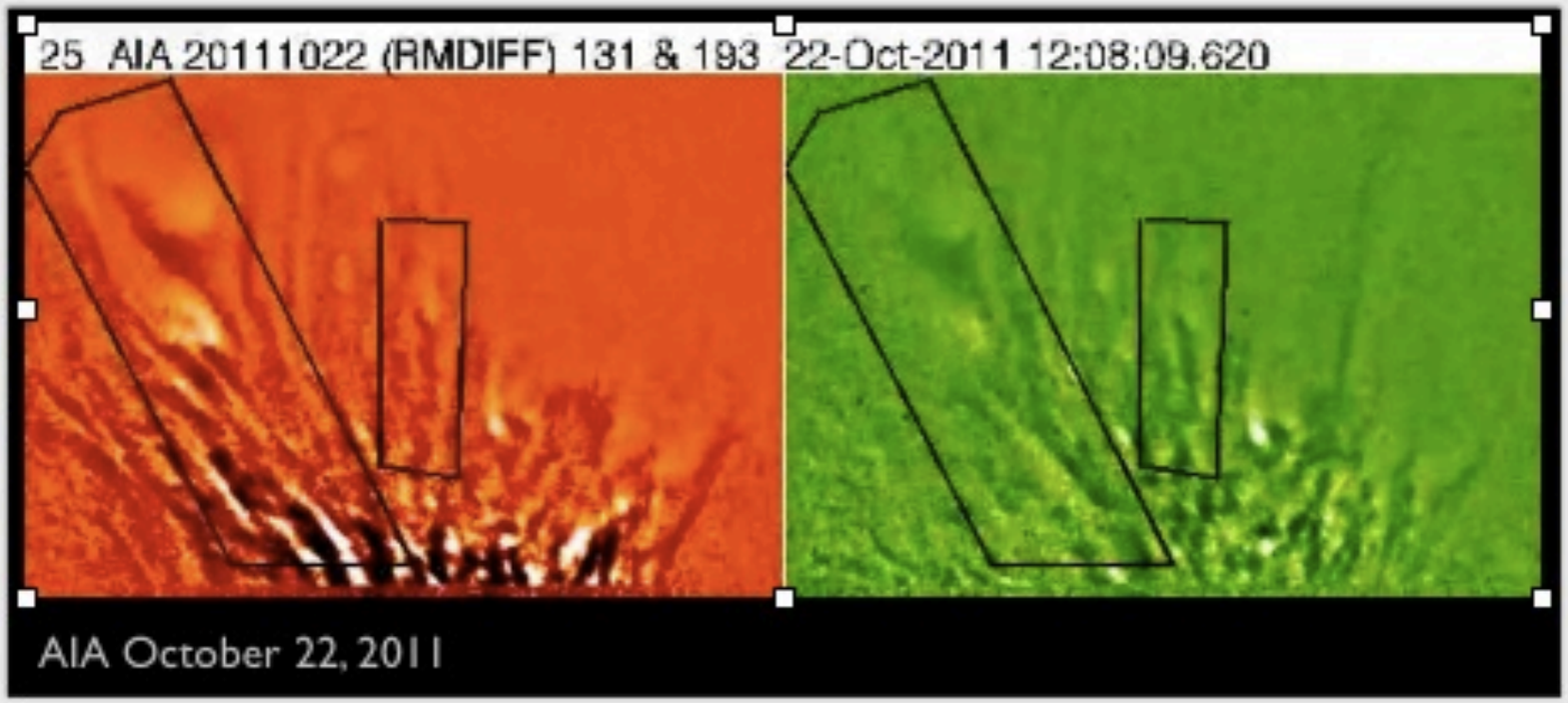
Because the loops are so much smaller than their wakes, only a few can be resolved in the images. Here we have shown only 2 thin loops with a large wake. Smaller voids also show the enhanced leading edges, with linear extensions; but they are difficult to resolve.

Newest Observations

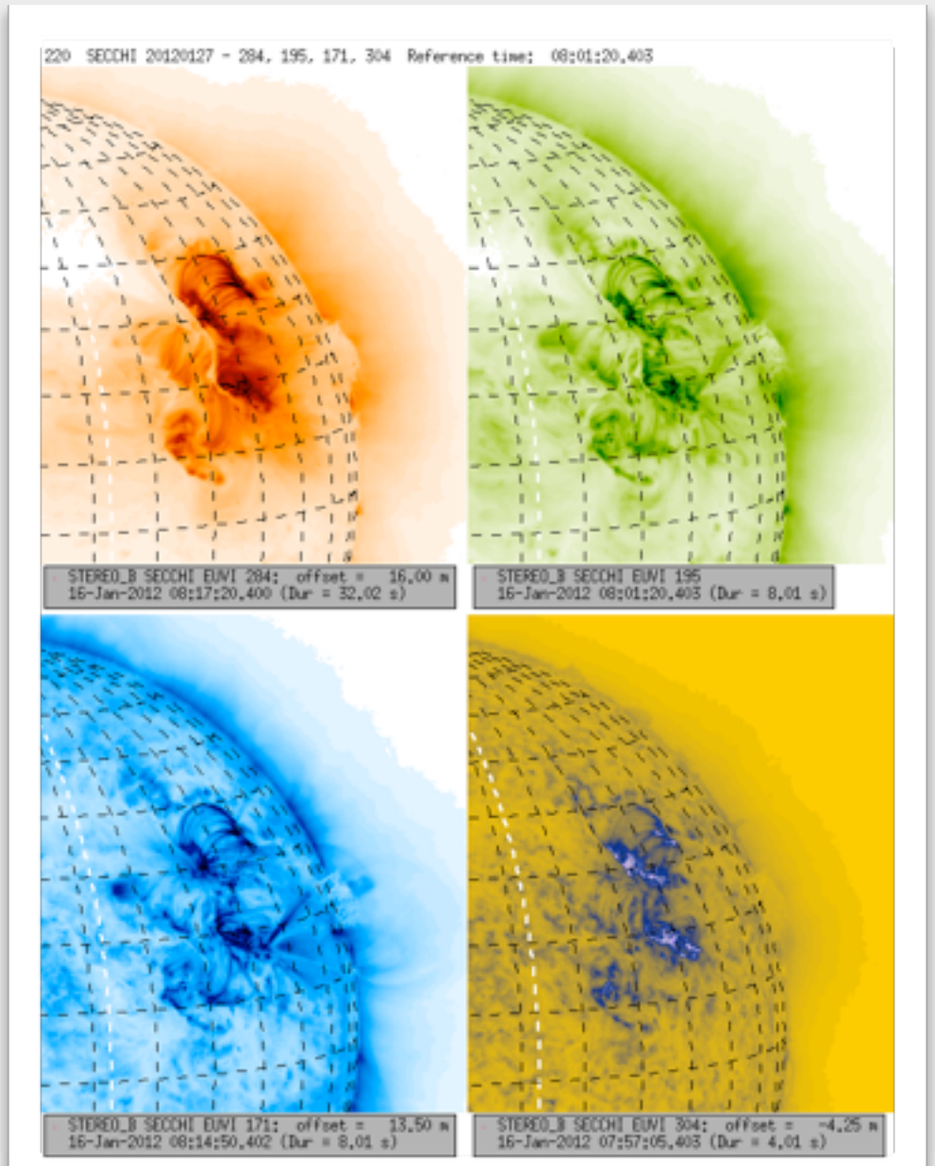


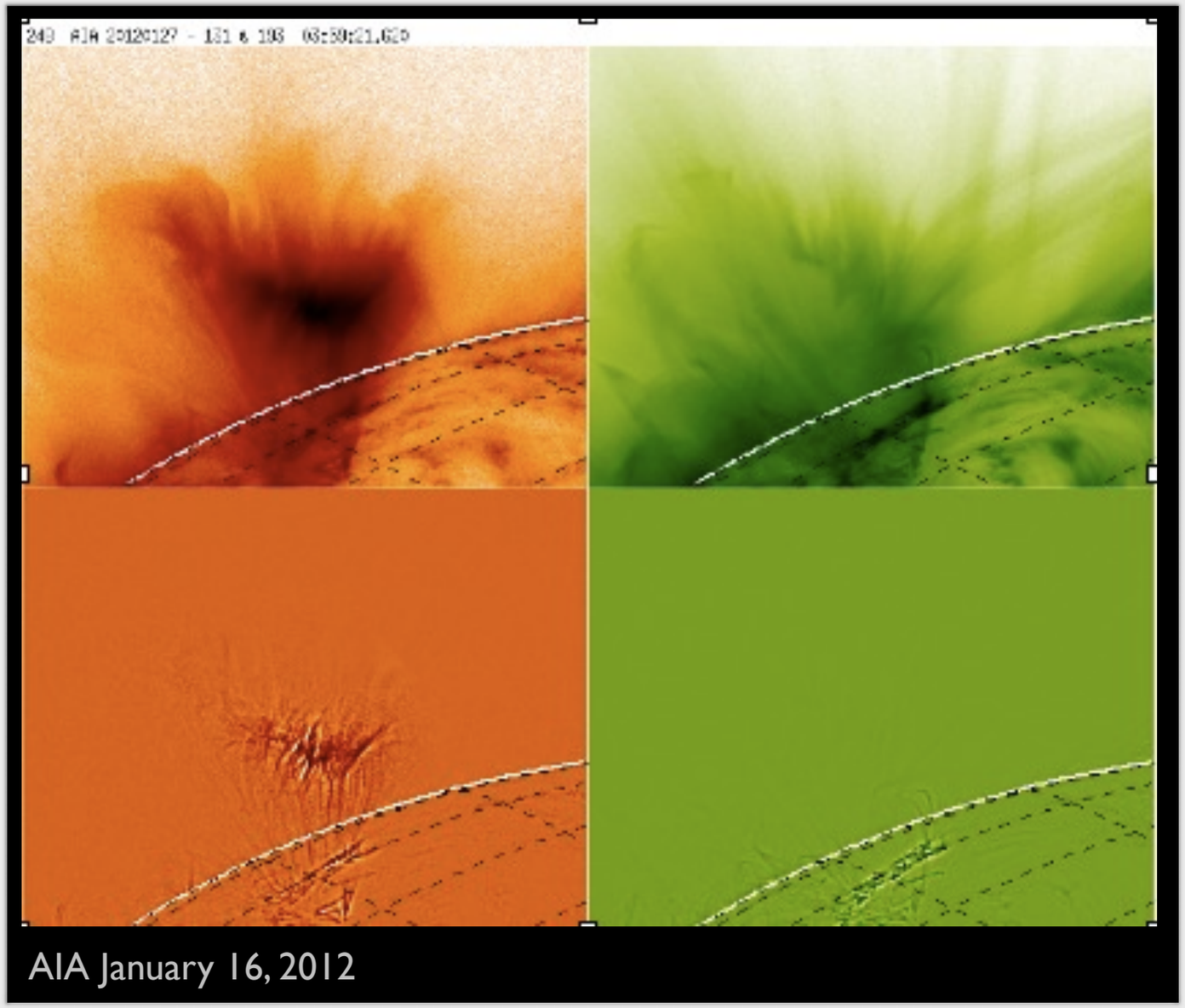


Savage, McKenzie, Reeves 2012



Newest Observations





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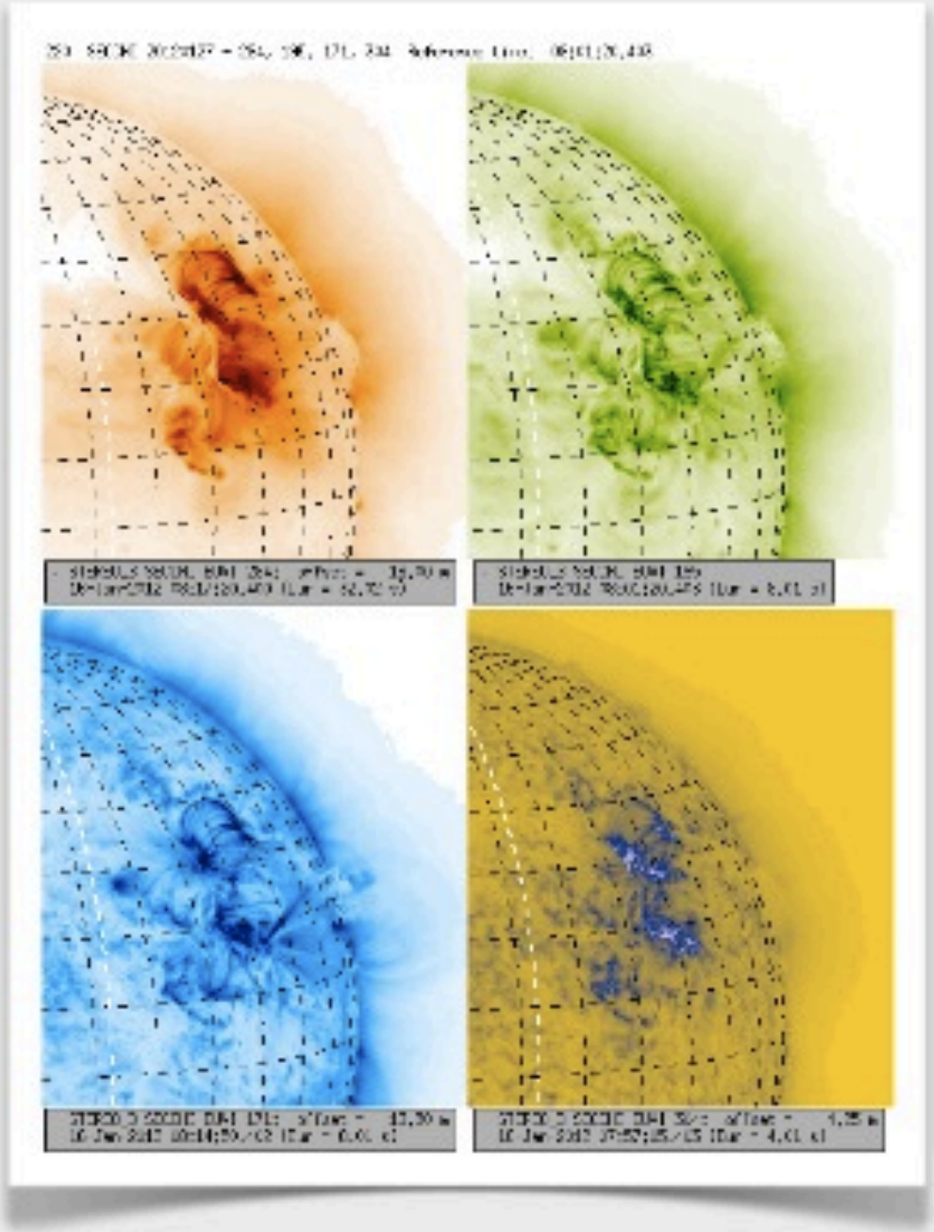

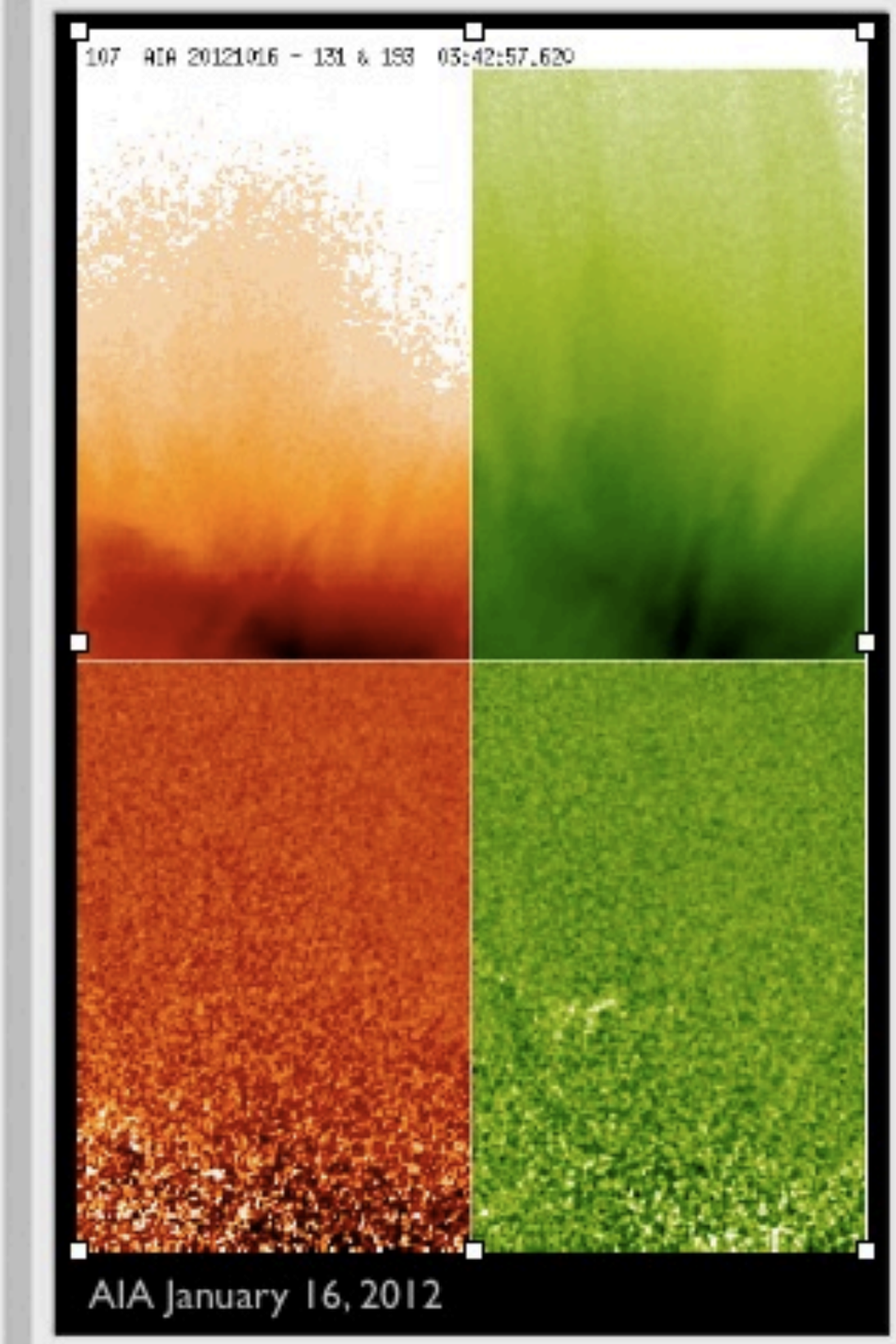

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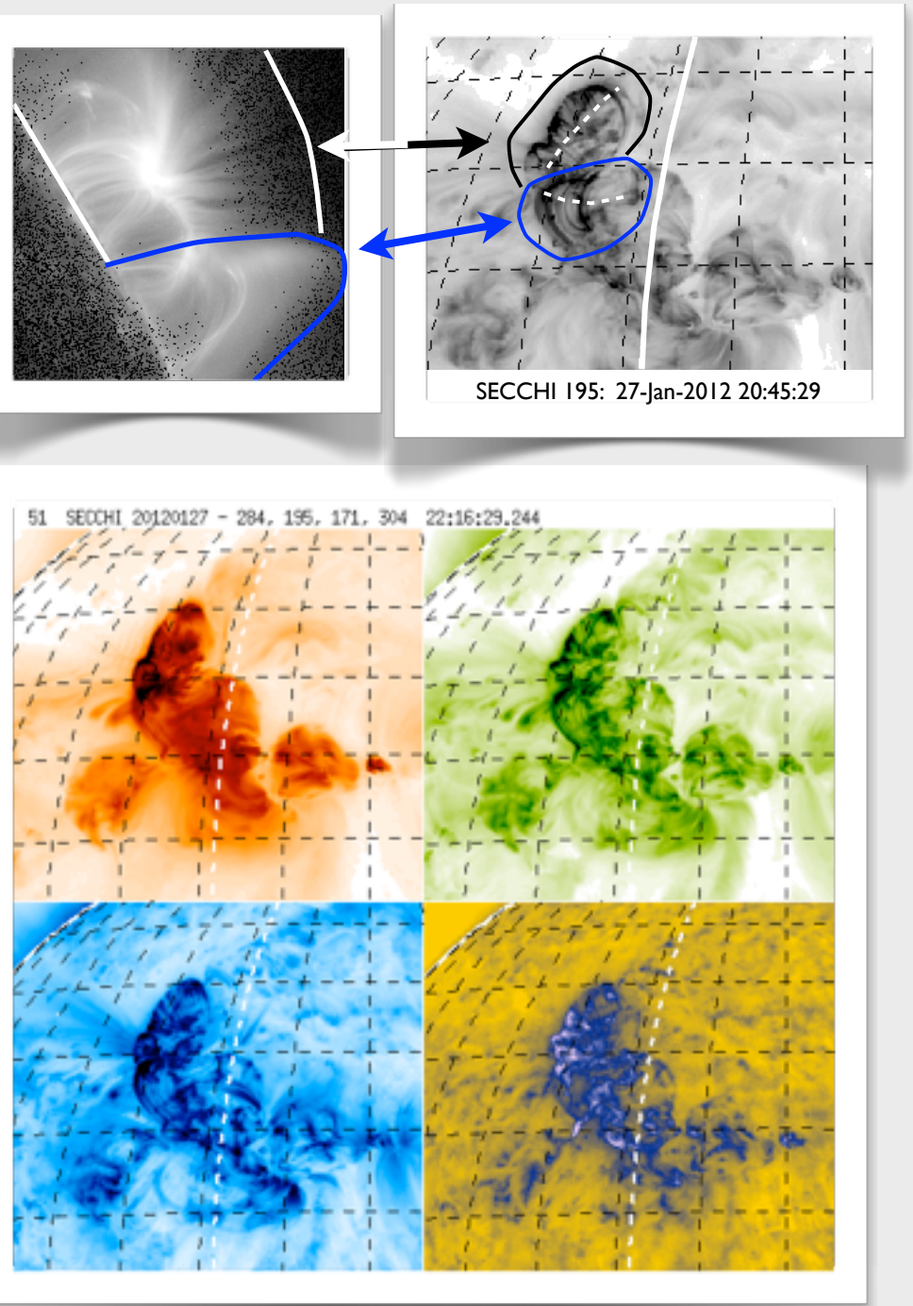

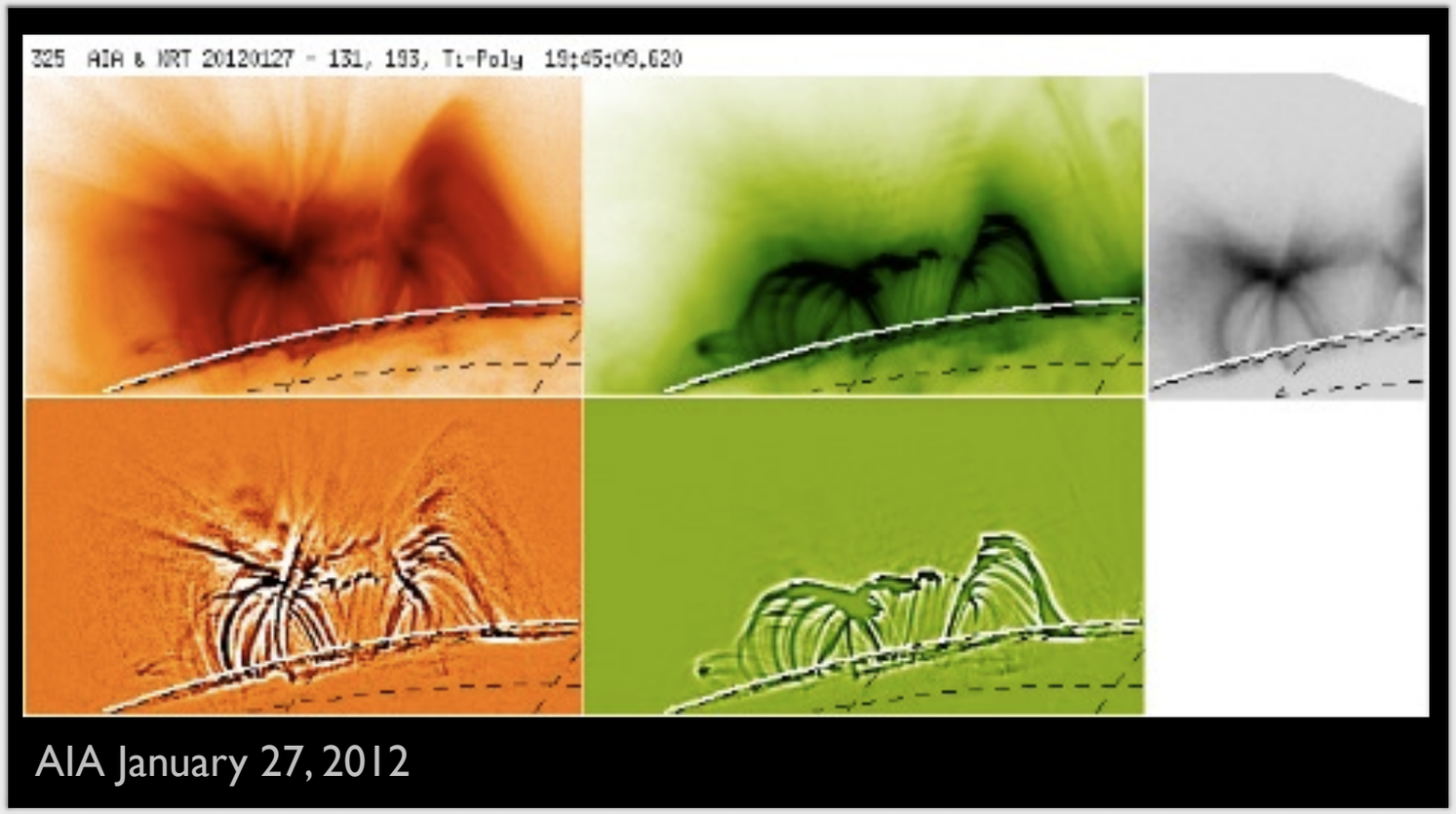

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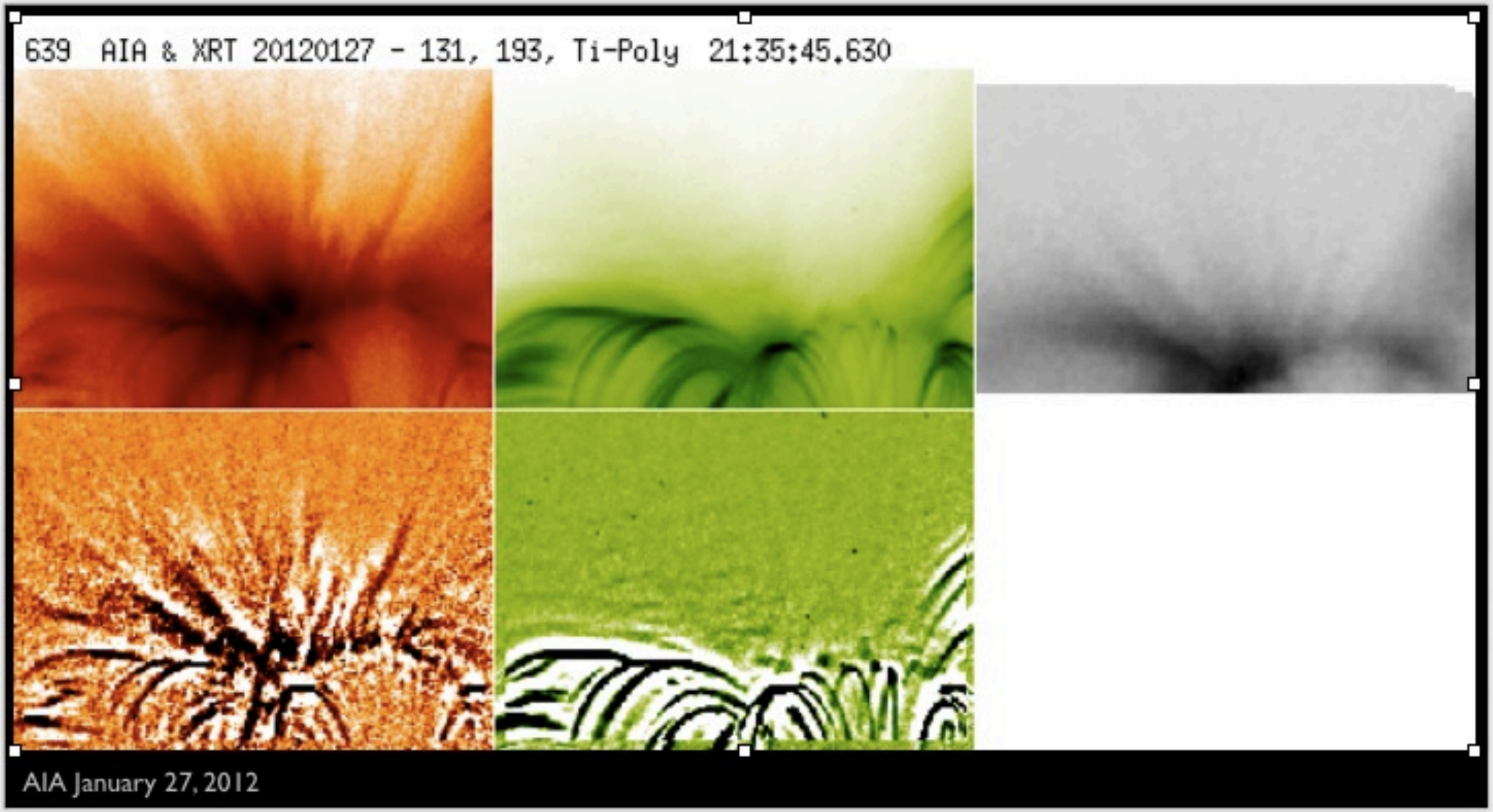
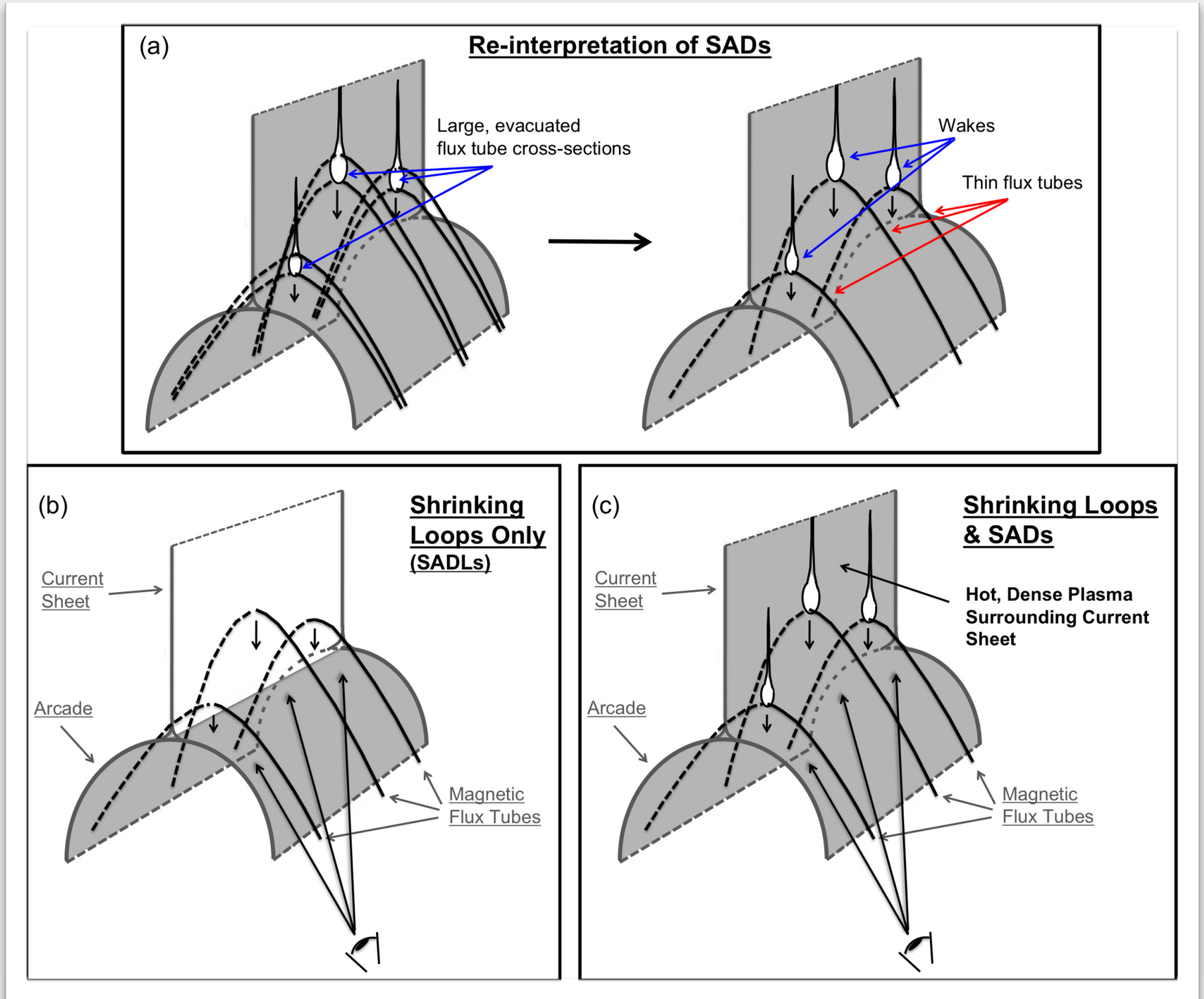


Re-interpretation: Much Better Match to Observations



Savage, McKenzie, Reeves 2012

Outputs

- Patchy & Bursty

- Sizes & fluxes of post-reconnection flux tubes

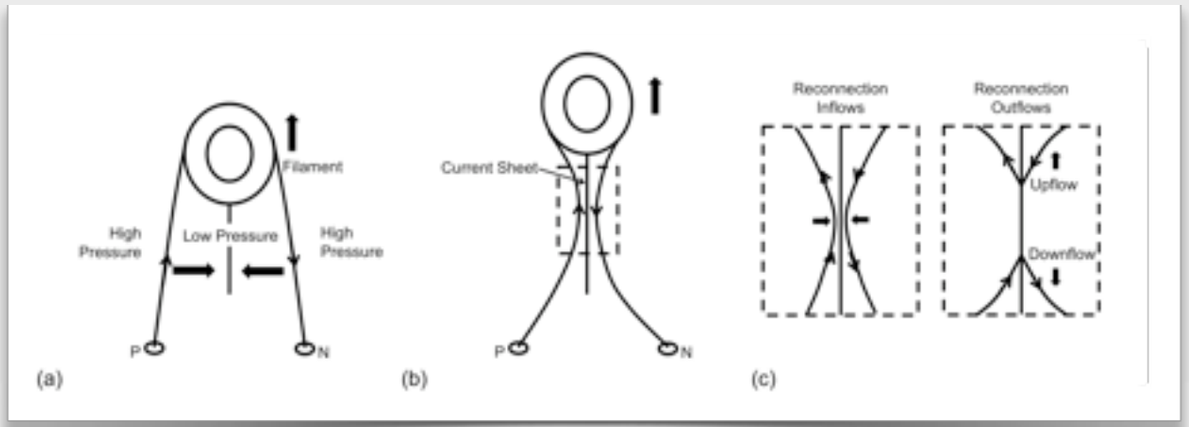
- Impulsive & decay phases

- Shrinkage energy

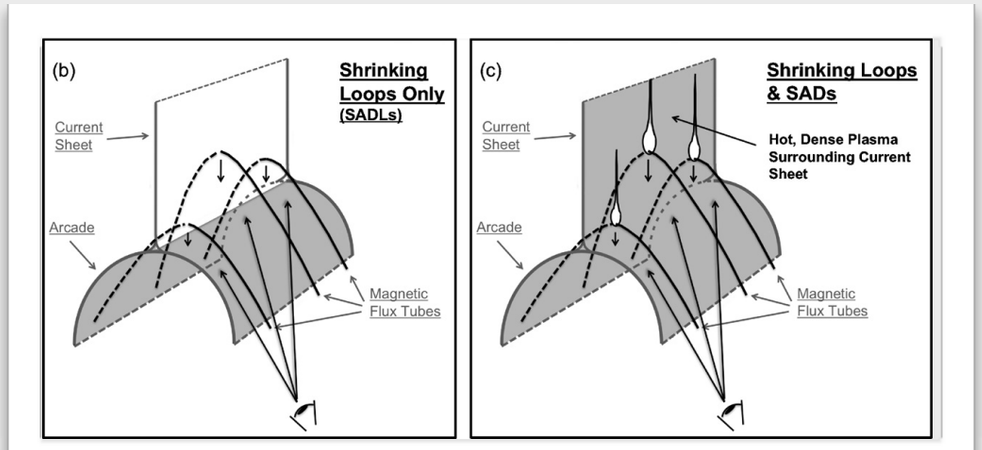
- Speeds & decelerations

- Hot fan: current sheet sheath

Revised Model



Savage et al. 2012



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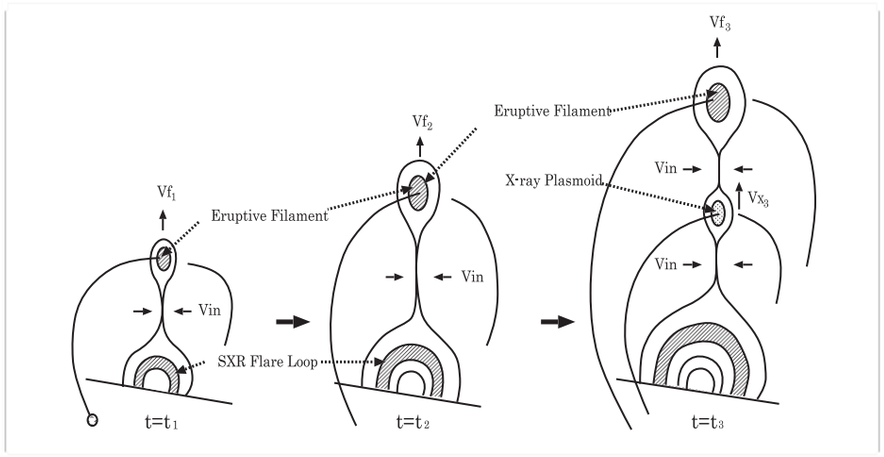
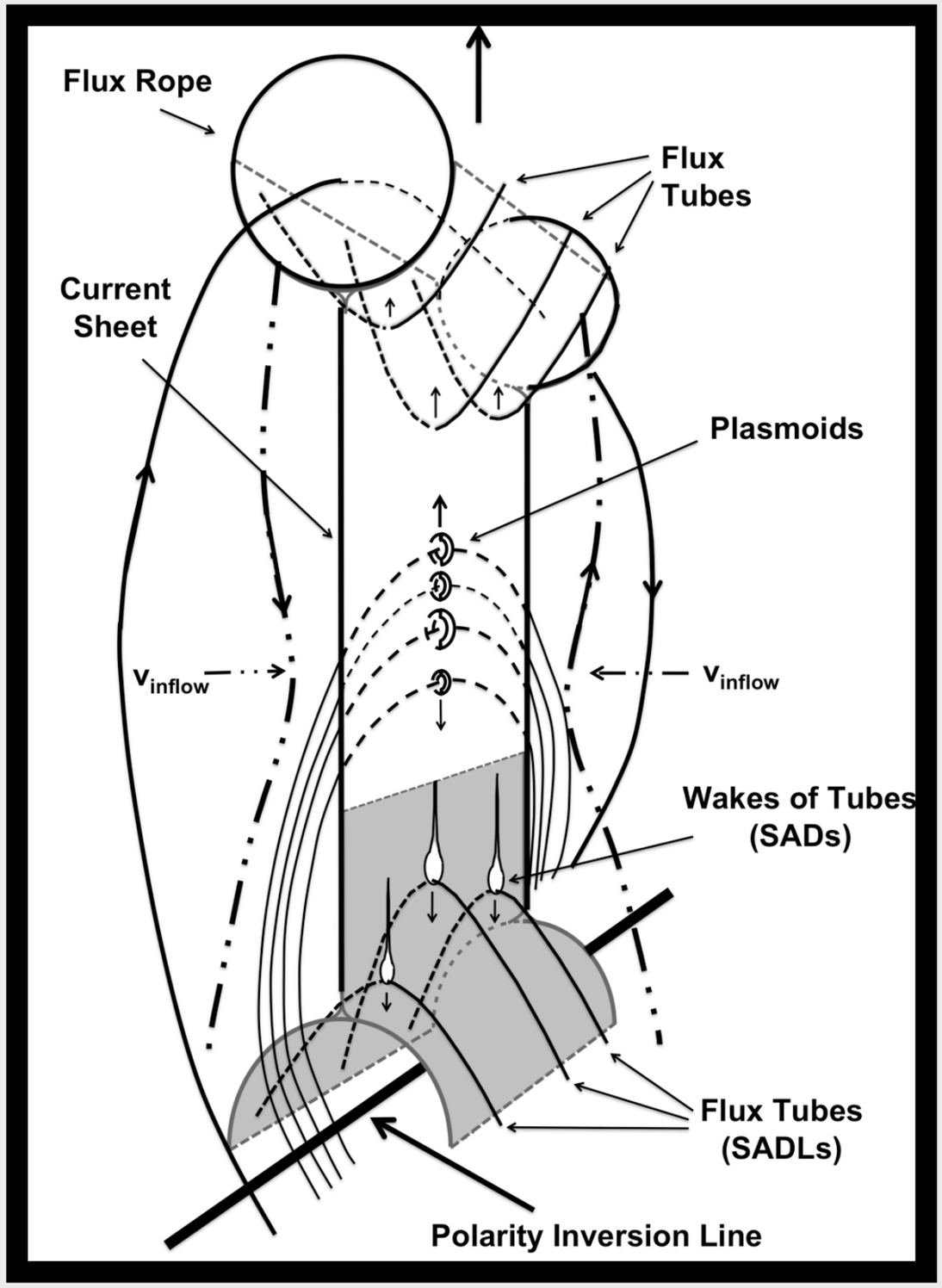


Ohyama & Shibata 2008



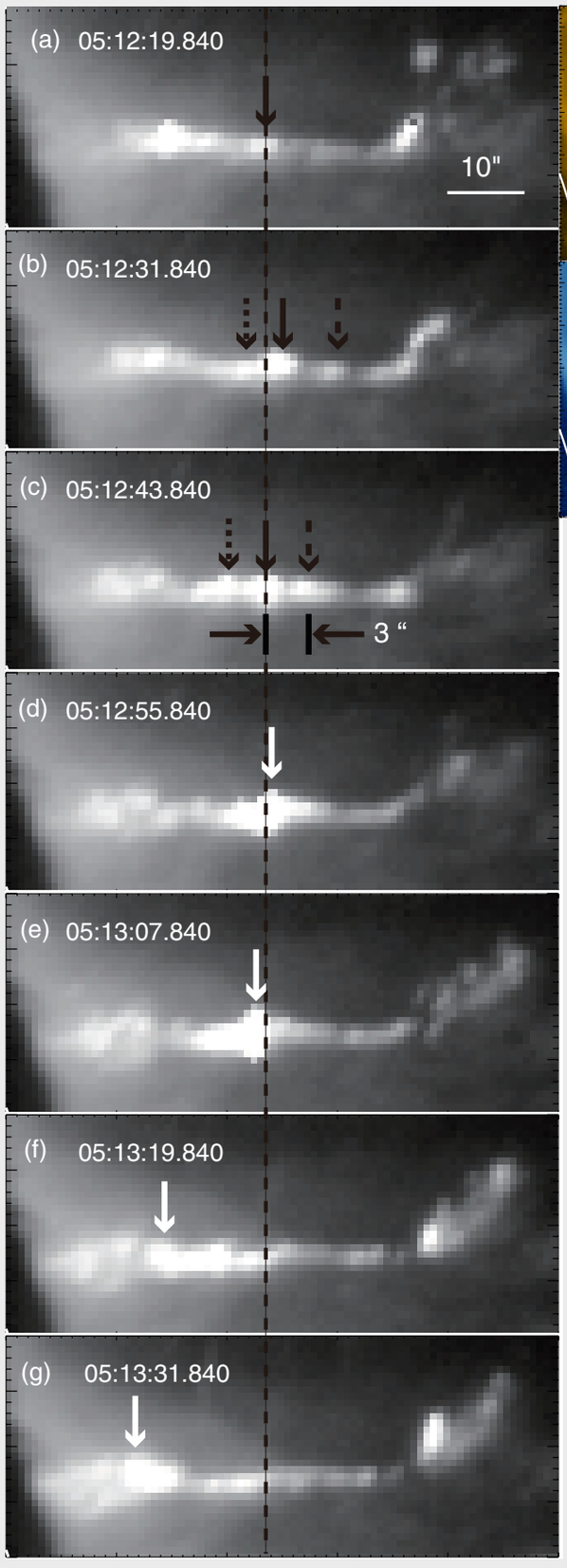
Savage et al. 2012

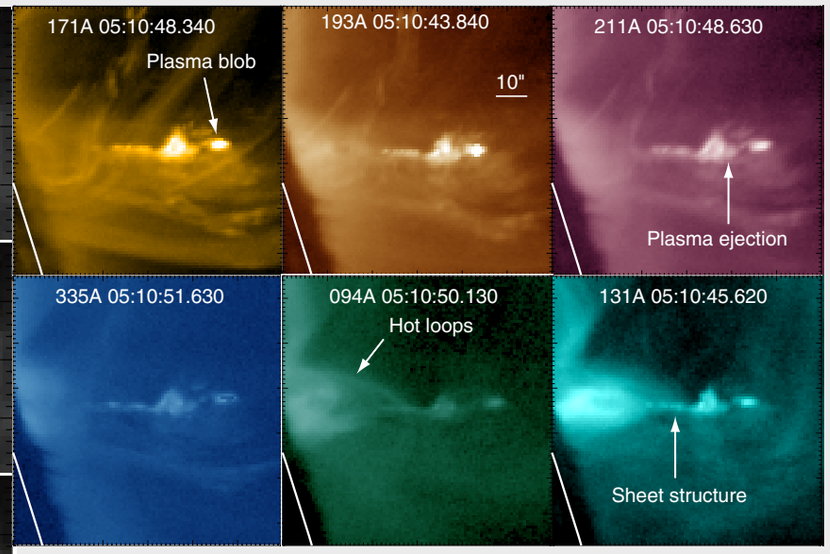
!

SADs != “Plasmoids”

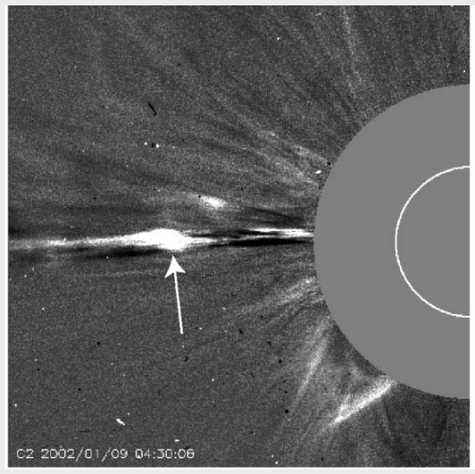
Plasmoid Observations

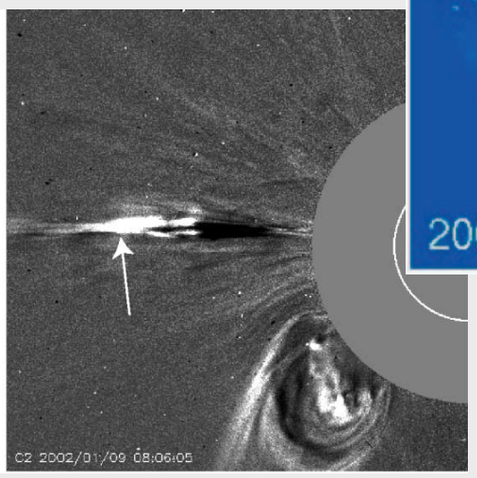
- "section of plasma having a characteristic shape"
- "coherent structure of plasma and B fields"
- often referred to as "magnetic bubbles."



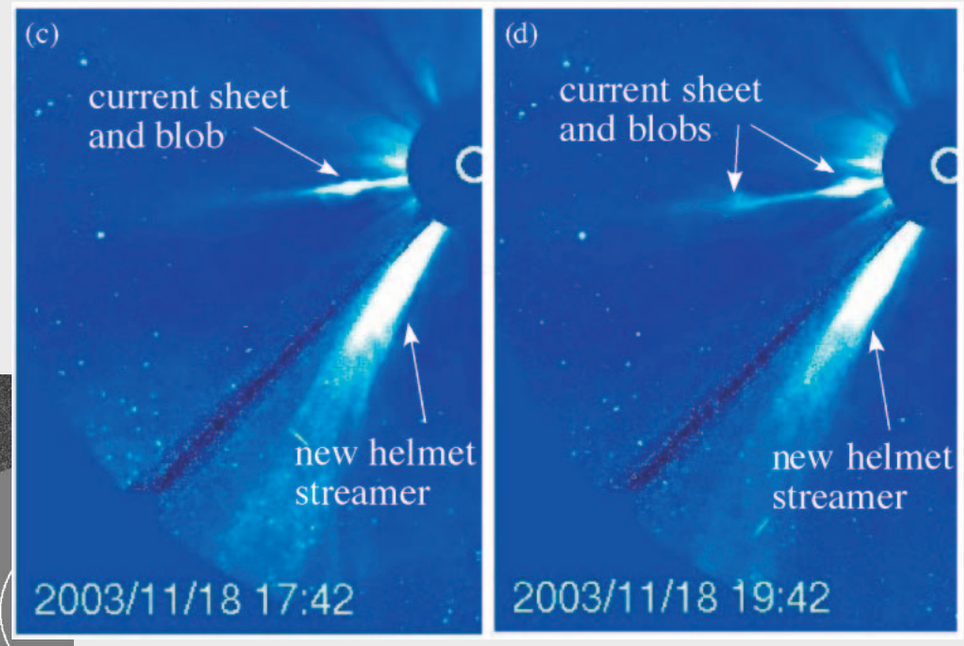


Takasao et al. 2012

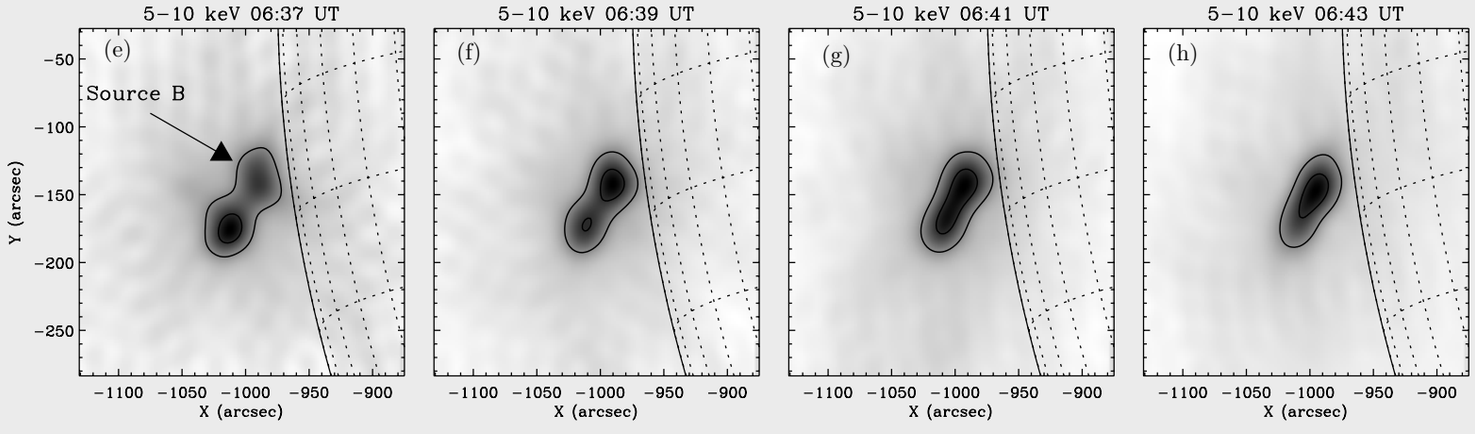




Ko et al. 2003



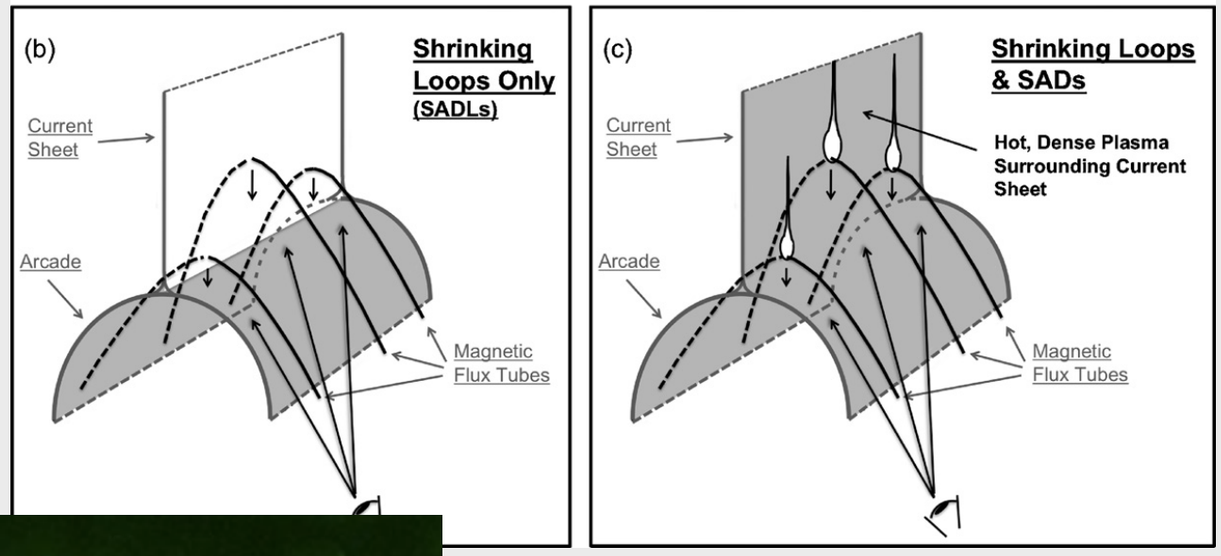
Lin et al. 2004



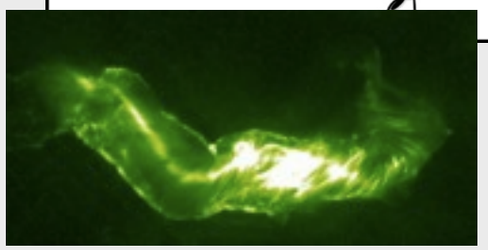
Milligan 2010

Plasmoids versus Down (& Up) Flows

Savage et al. 2012



~~Plasmoids~~

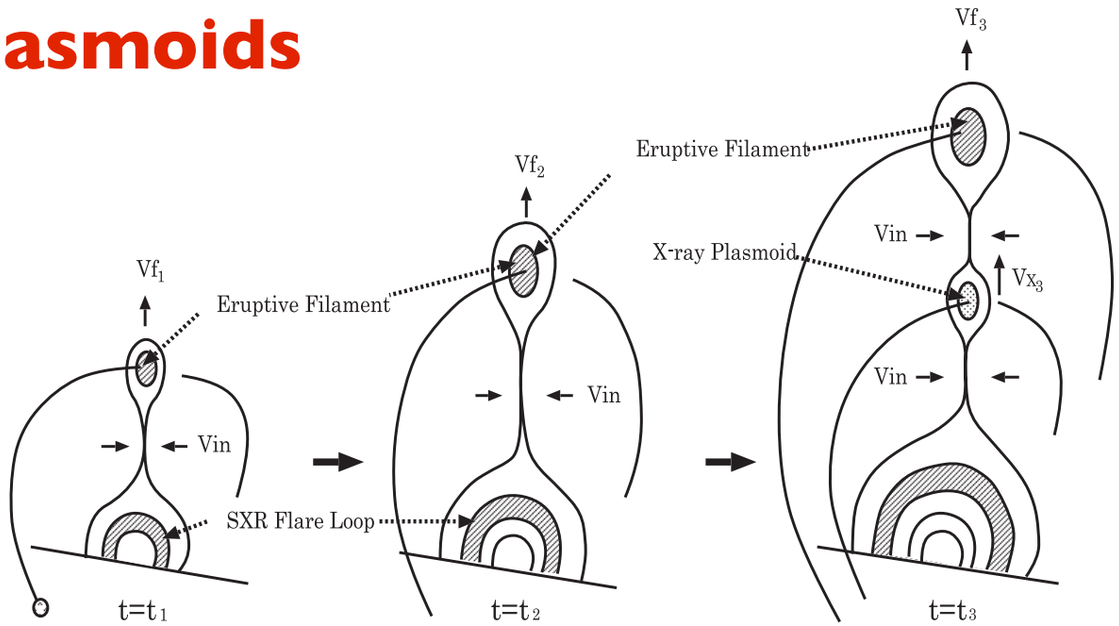


Rarefied; Decrease in size; Footpoints *across* PIL

Plasmoids

Daughton et al. 2012

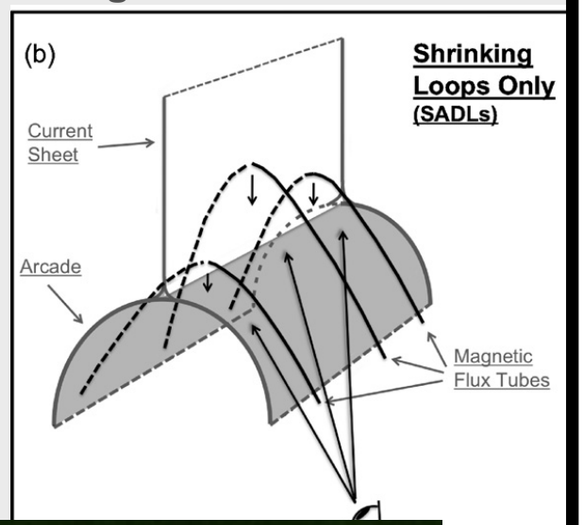
Plasmoids

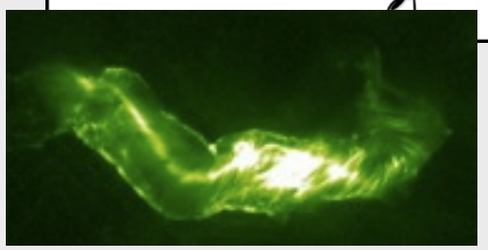


Ohyama & Shibata 2008

Plasmoids ve

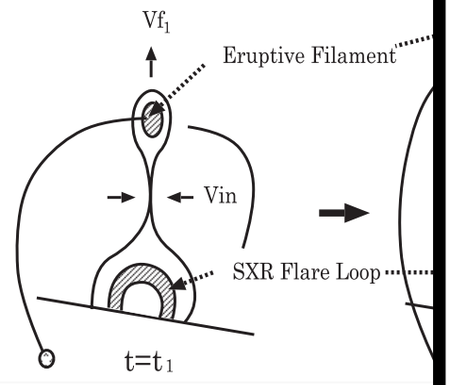
Savage et al. 2012





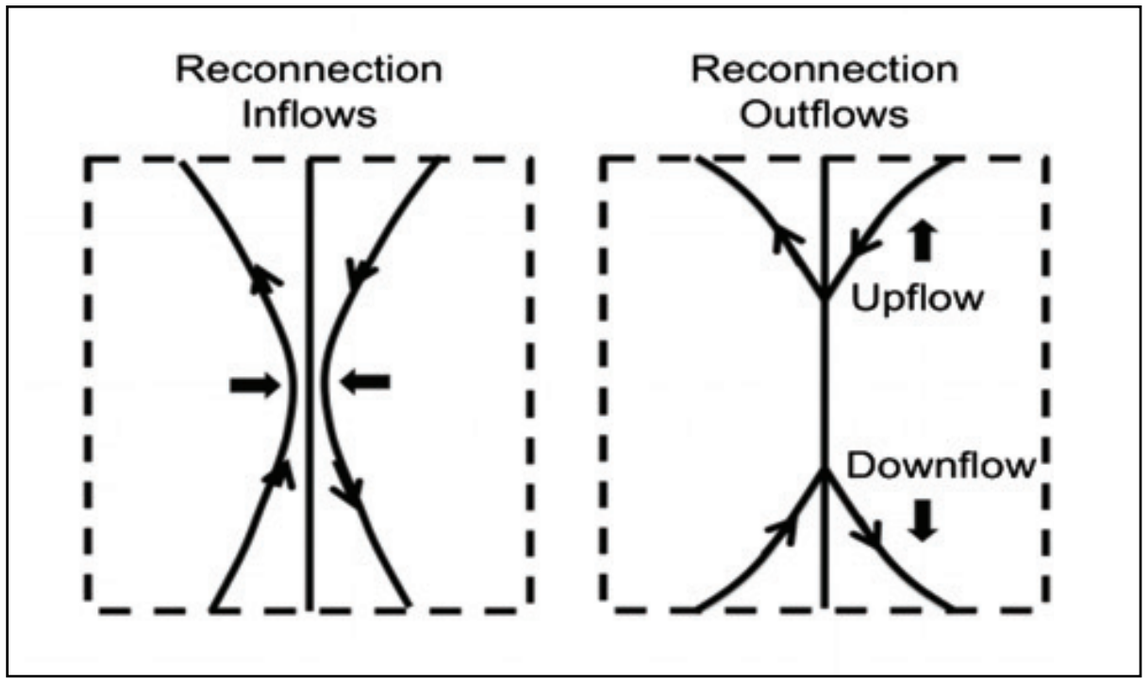
Rare

Plasmoids



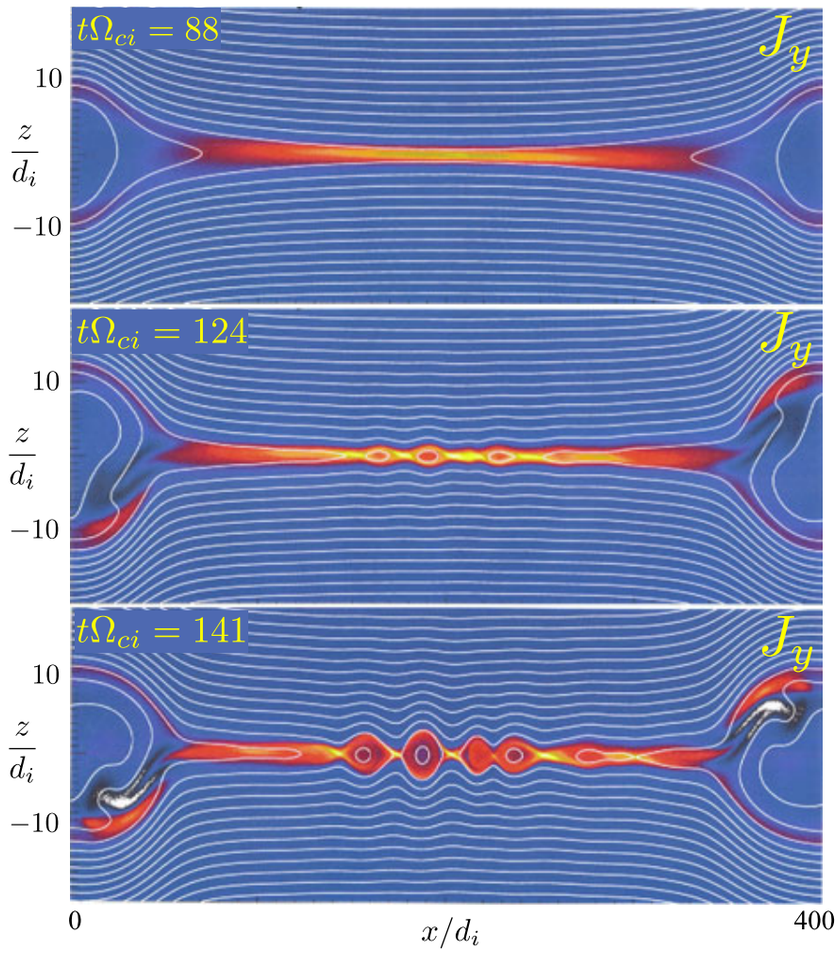
Ohyama & Shibata 2008

SADs / Shrinking Loops



Savage et al. 2012

Plasmoids

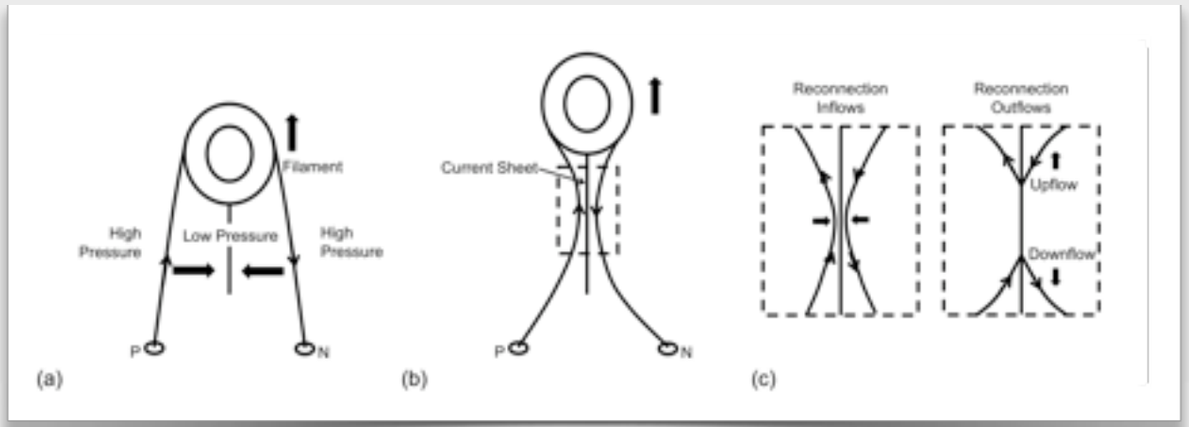


Daughton et al. 2012

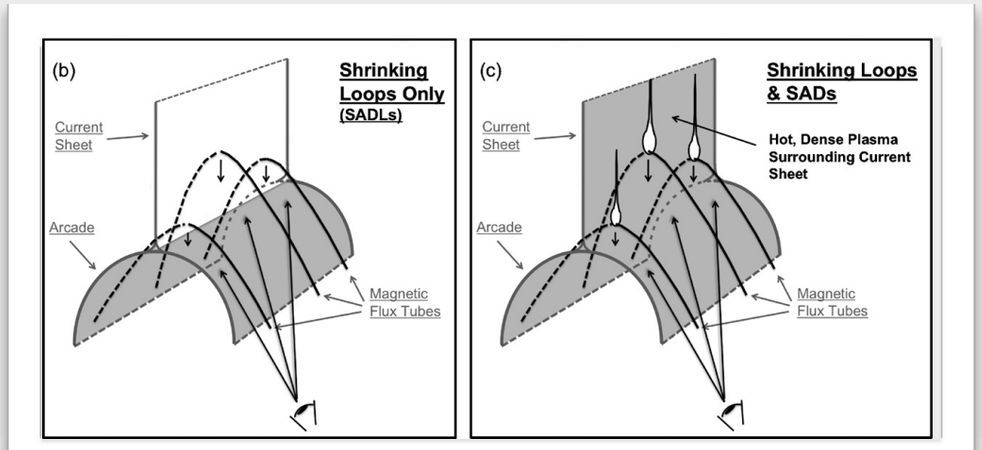
Plasmoids

Daughton et al. 2012

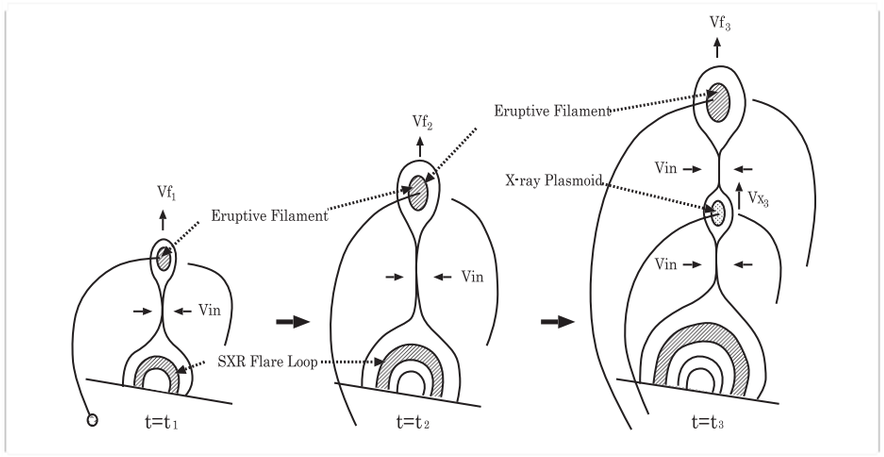
Revised Model



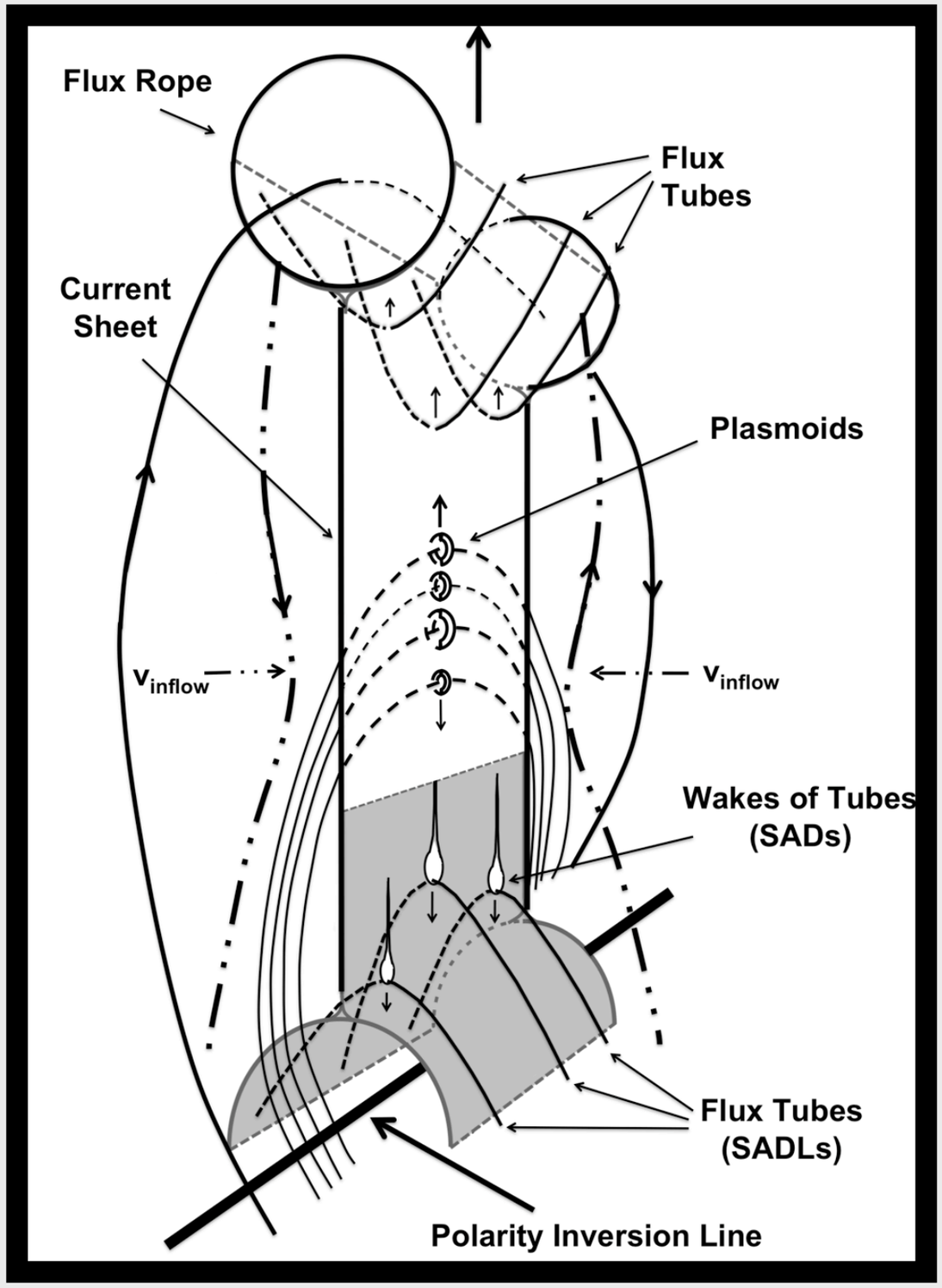
Savage et al. 2012



Savage, McKenzie, Reeves 2012

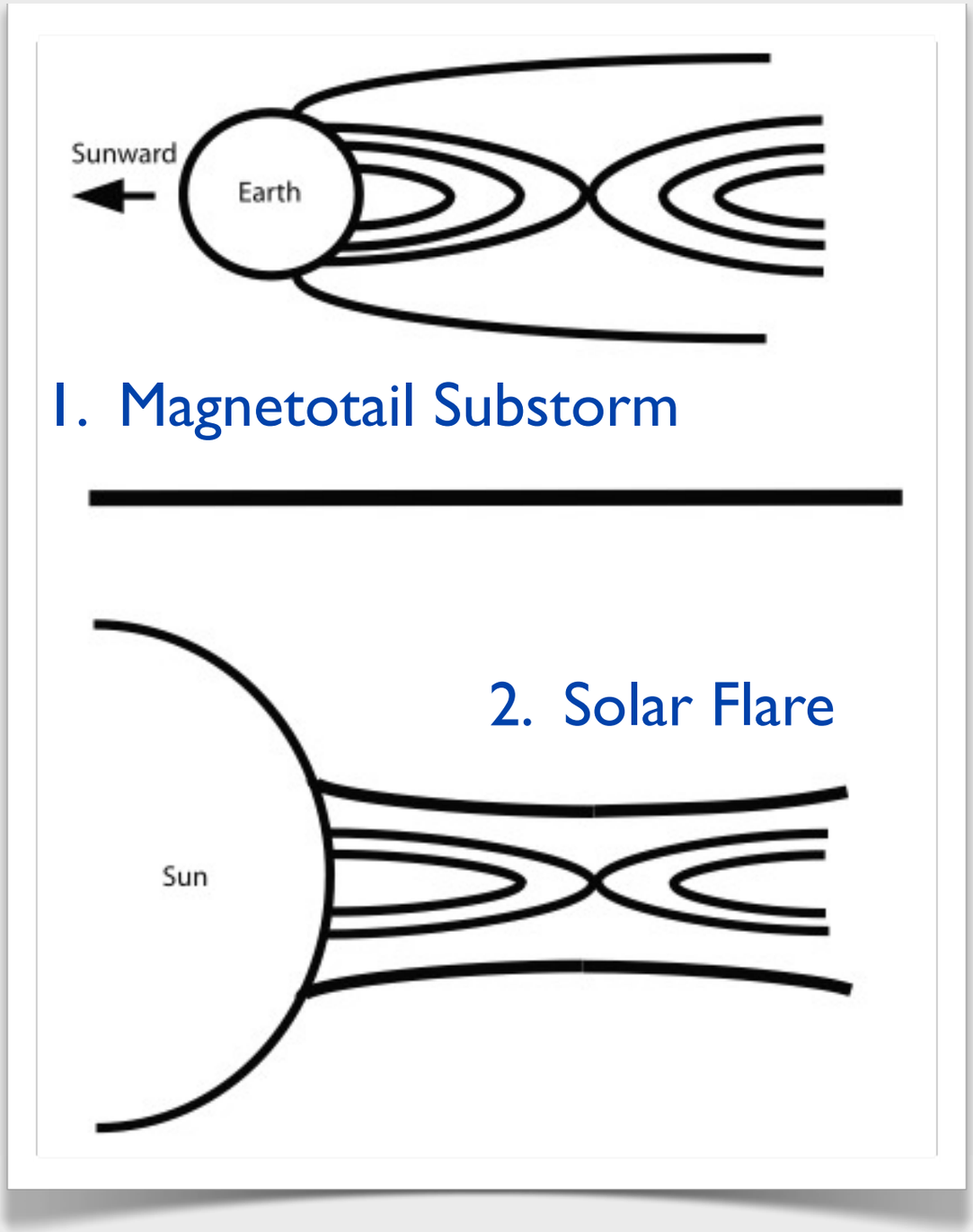


Ohyama & Shibata 2008



Savage et al. 2012

Compare with Magnetotail Observations?

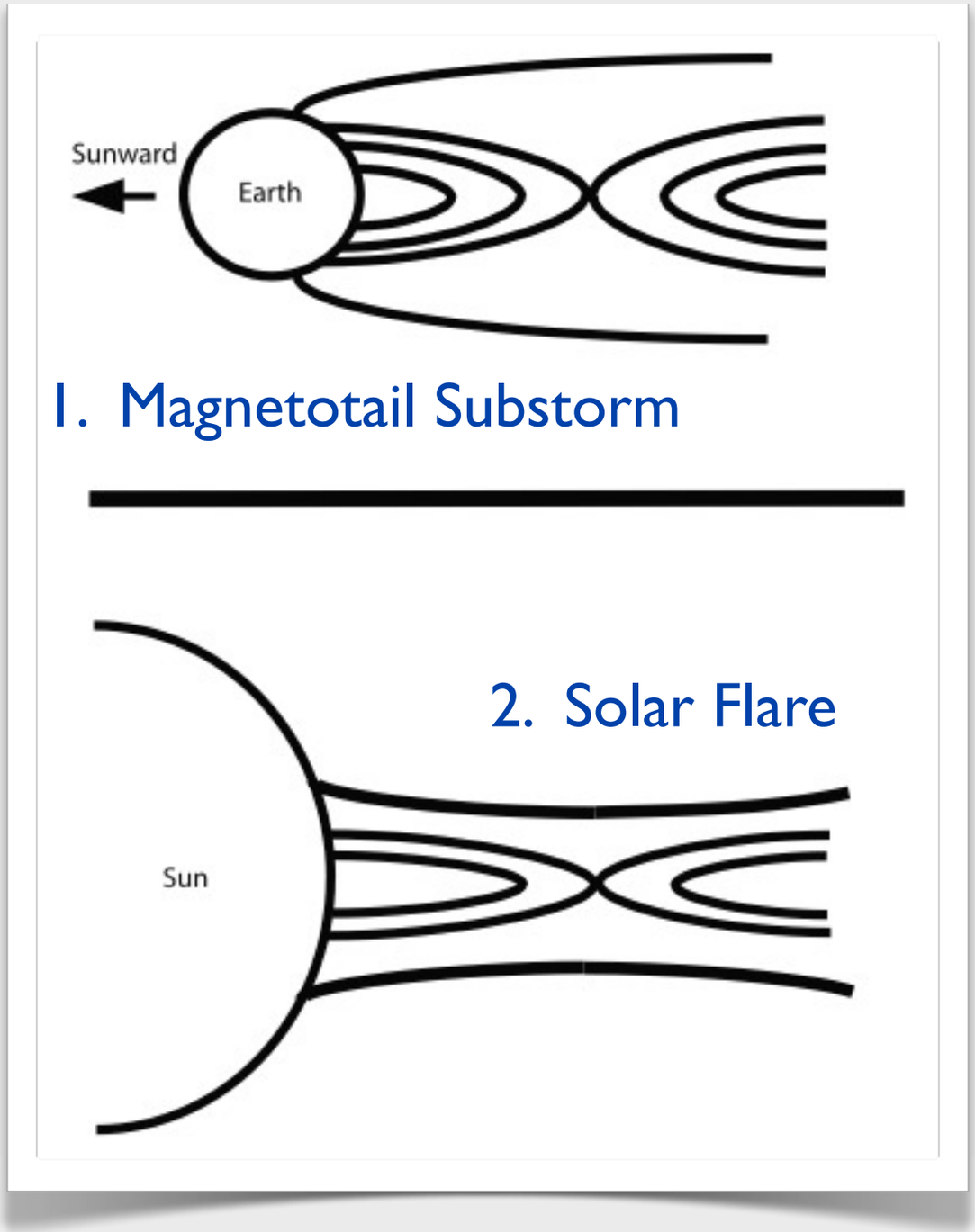


Posteruptive phenomena in coronal mass ejections and substorms: Indicators of a Universal Process?
K.K. Reeves et al. 2008, JGR, 113, A00B02

Competing notation
- 1: Dipolarization
- 2: Field Line Shrinkage

Different available measurements
- 1: In situ measurements of B fields & local plasma parameters. Inferred dipolarization.
- 2: Global context & interactions. Inferred local fields. Limited local plasma parameters. Observed shrinkage.

Compare with Magnetotail Observations?



Posteruptive phenomena in coronal mass ejections and substorms: Indicators of a Universal Process?
K.K. Reeves et al. 2008, JGR, 113, A00B02

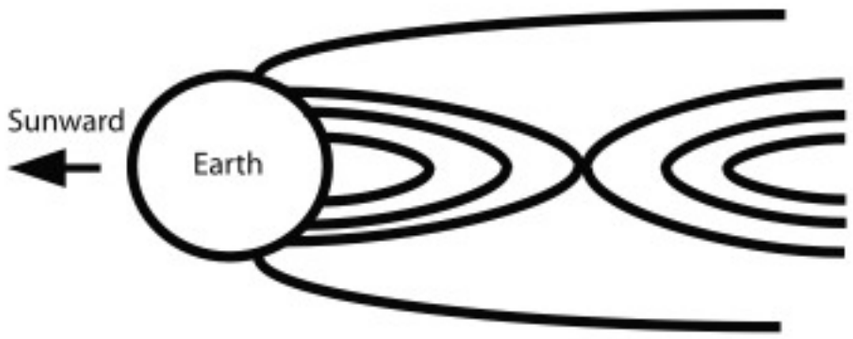
Similar speeds & decelerations (acting over different scale heights)

1: Braking from pressure gradient
2: Stop at top of arcade

Double footpoint ribbons for both from electron acceleration

1: Auroral ribbons in dense ionosphere
2: Chromospheric evaporation (ablation)

Compare with Magnetotail Observations?



1. Magnetotail Substorm

Table 1. Plasma Parameters for the Magnetosphere and the Corona

	Corona	Magnetosphere
Temperature	10^6 K	10^7 K
Density	10^{10} cm^{-3}	1 cm^{-3}
Magnetic field	10–100 G	10^{-3} G
Plasma β	0.001–0.01	1
Length scale	1000 km	1000 km
Alfvén speed	100–1000 km s^{-1}	100–1000 km s^{-1}

Posteruptive phenomena in coronal mass ejections and substorms: Indicators of a Universal Process?
K.K. Reeves et al. 2008, JGR, 113, A00B02

(1) BBFs (Bursty Bulk Flows) or DFs (Dipolarization Fronts) ?=? (2) SADs (Are DFs = global or local current sheets?)

1: Plasma depleted flux tubes?

2. Not quite consistent with re-interpretation of SADs

- BBFs possibly faster than SADs
- Similar size to SADs but not to loops

Both indicate patchy reconnection.

Alfvén speeds are similar in both regimes!

- Dominant factor governing reconnection processes and responses

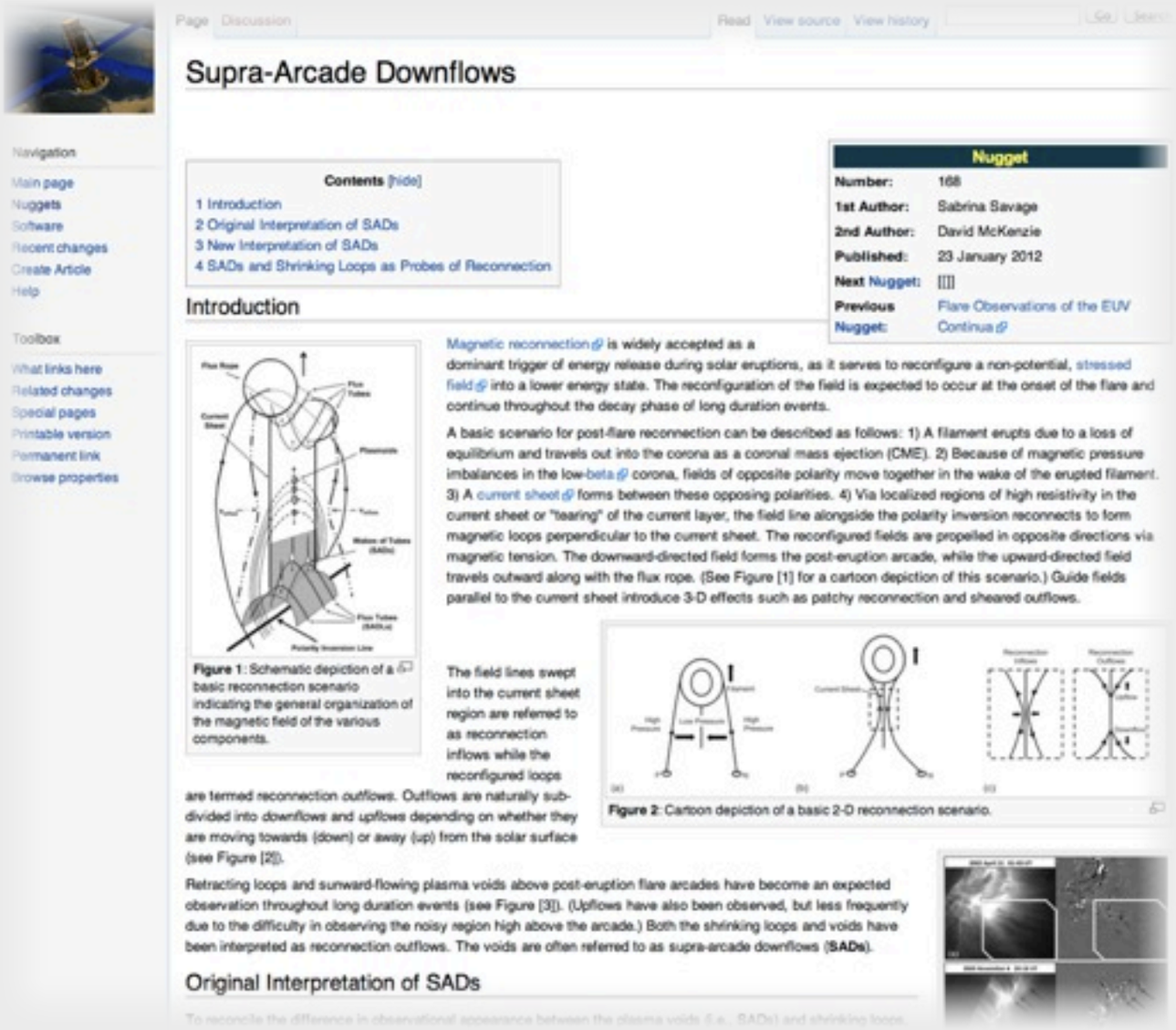
However, possibly differing reconnection scenarios per regime (resistive versus collisionless)?

References

Reeves et al. 2008
McKenzie & Savage 2009
Savage et al. 2010
McKenzie & Savage 2011
Savage, McKenzie, & Reeves 2012
Savage et al. 2012

Asai et al. 2004
Isobe et al. 2005
Sheeley, Warren, & Wang 2007
Ohyama & Shibata 2008
Warren et al. 2011
Reeves & Golub 2011
Cheng et al. 2011
Daughton et al. 2012

RHESSI NUGGET #168



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Supra-Arcade Downflows

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Number:	168
1st Author:	Sabrina Savage
2nd Author:	David McKenzie
Published:	23 January 2012
Next Nugget:	[[]]
Previous Nugget:	Flare Observations of the EUV Continua

Introduction

Magnetic reconnection is widely accepted as a dominant trigger of energy release during solar eruptions, as it serves to reconfigure a non-potential, stressed field into a lower energy state. The reconfiguration of the field is expected to occur at the onset of the flare and continue throughout the decay phase of long duration events.

A basic scenario for post-flare reconnection can be described as follows: 1) A filament erupts due to a loss of equilibrium and travels out into the corona as a coronal mass ejection (CME). 2) Because of magnetic pressure imbalances in the low-beta corona, fields of opposite polarity move together in the wake of the erupted filament. 3) A current sheet forms between these opposing polarities. 4) Via localized regions of high resistivity in the current sheet or "tearing" of the current layer, the field line alongside the polarity inversion reconnects to form magnetic loops perpendicular to the current sheet. The reconfigured fields are propelled in opposite directions via magnetic tension. The downward-directed field forms the post-eruption arcade, while the upward-directed field travels outward along with the flux rope. (See Figure [1] for a cartoon depiction of this scenario.) Guide fields parallel to the current sheet introduce 3-D effects such as patchy reconnection and sheared outflows.

Figure 1: Schematic depiction of a basic reconnection scenario indicating the general organization of the magnetic field of the various components.

The field lines swept into the current sheet region are referred to as reconnection inflows while the reconfigured loops are termed reconnection outflows. Outflows are naturally sub-divided into *downflows* and *upflows* depending on whether they are moving towards (down) or away (up) from the solar surface (see Figure [2]).

Figure 2: Cartoon depiction of a basic 2-D reconnection scenario.

Retracting loops and sunward-flowing plasma voids above post-eruption flare arcades have become an expected observation throughout long duration events (see Figure [3]). (Upflows have also been observed, but less frequently due to the difficulty in observing the noisy region high above the arcade.) Both the shrinking loops and voids have been interpreted as reconnection outflows. The voids are often referred to as supra-arcade downflows (**SADs**).

Original Interpretation of SADs