Cross-scale Observational Signatures of Magnetic Reconnection

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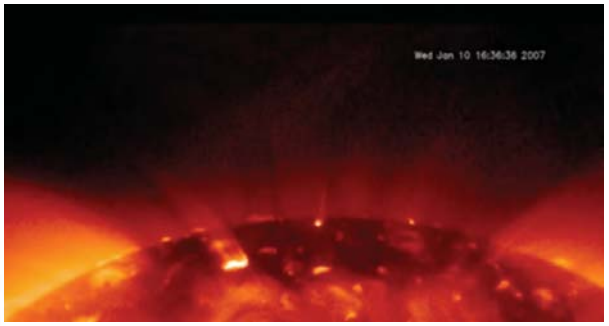
Variety of Signatures

Solar, Non-laboratory

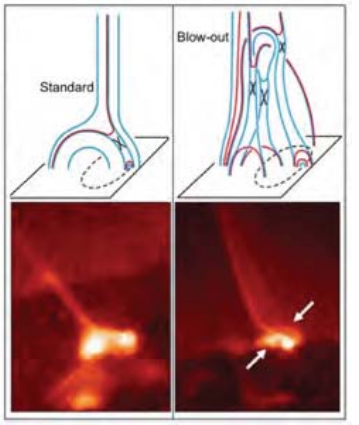
…to name just a few

Example observations of reconnection

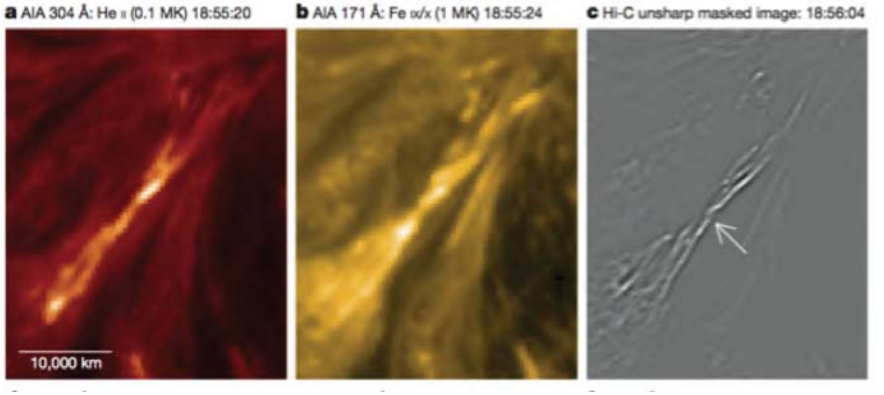
- Polar regions teeming with jets
- Field line unbraiding suggested by the Hi-C sounding rocket observations (193 A)
- Field line spreading
- Flare initiation, etc.



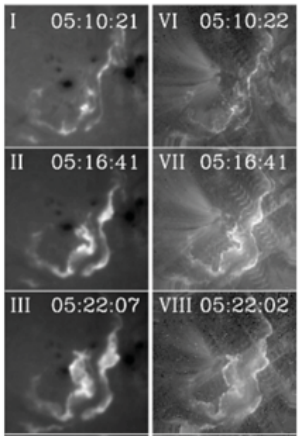
Cirtain et al 2007



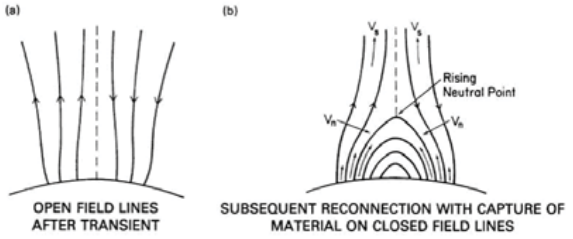
Moore et al 2011; Shimojo et al 1996



Cirtain et al 2013



Asai et al 2003



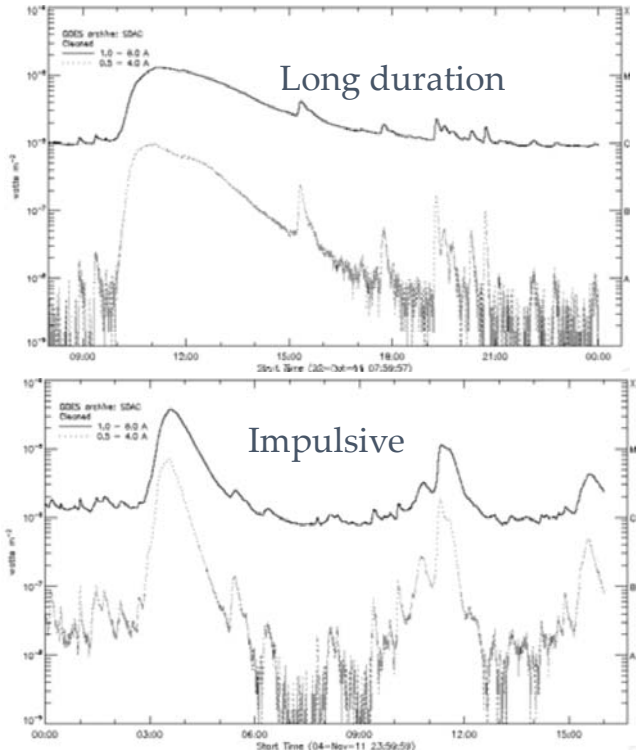
Kopp & Pneuman 1976

Current Sheet Reconnection

…during long duration solar flaring events

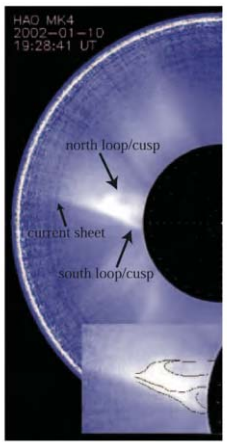
Long Duration Events

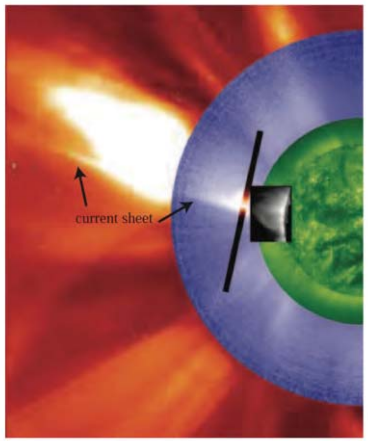
- Energy released for many hours
- CMEs
- Development of current sheets & supra-arcade fans

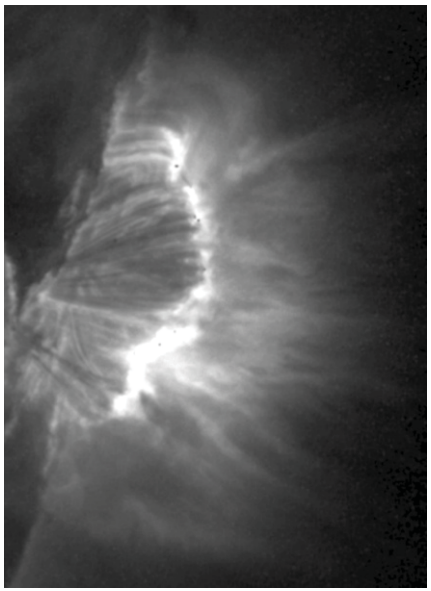


Example GOES Lightcurves

Ko et al 2003



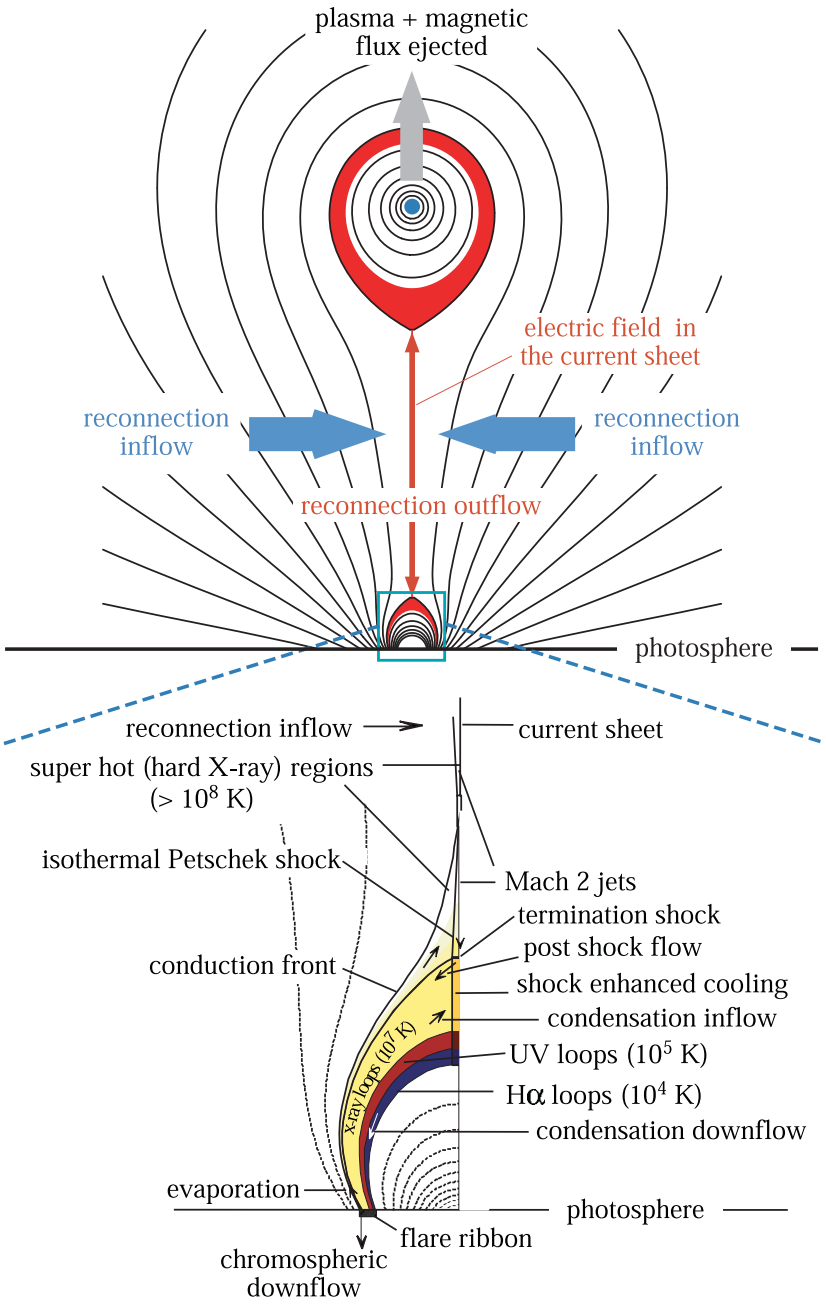




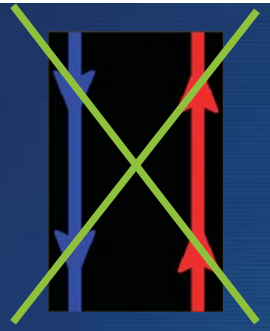
Savage & McKenzie 2011

Theory

- Basic 2D ReX
- Magnetic Islands
  - Enablers or Comparable Outputs?
- CSHKP model, updated

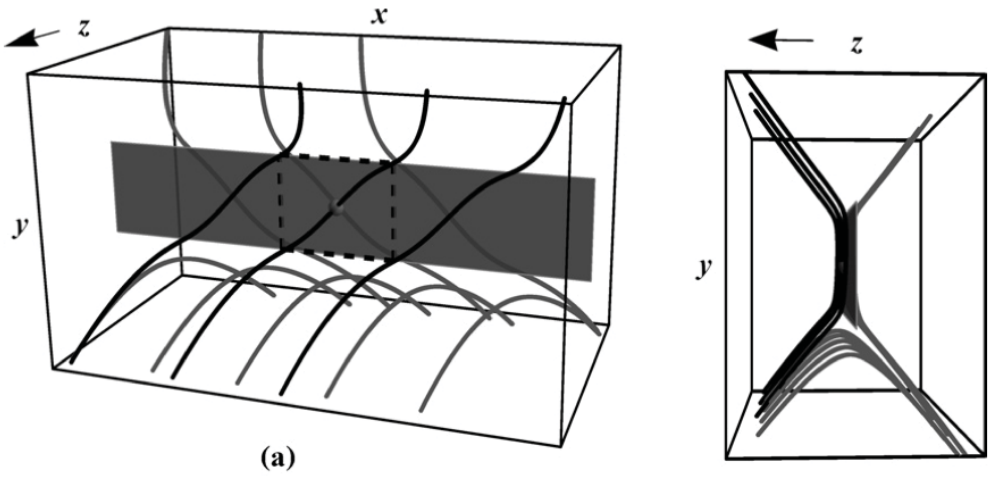


Lin & Forbes 00, Forbes & Acton 96, Ko et al 03

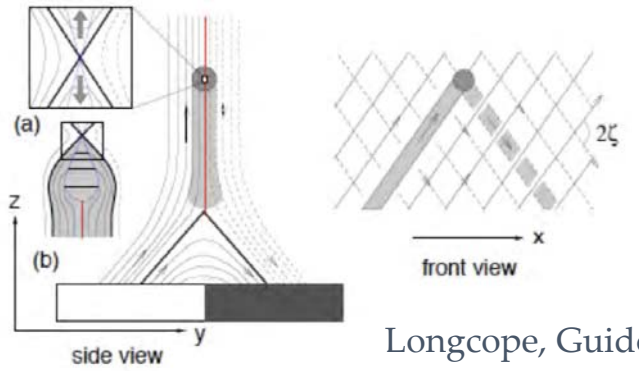


Theory

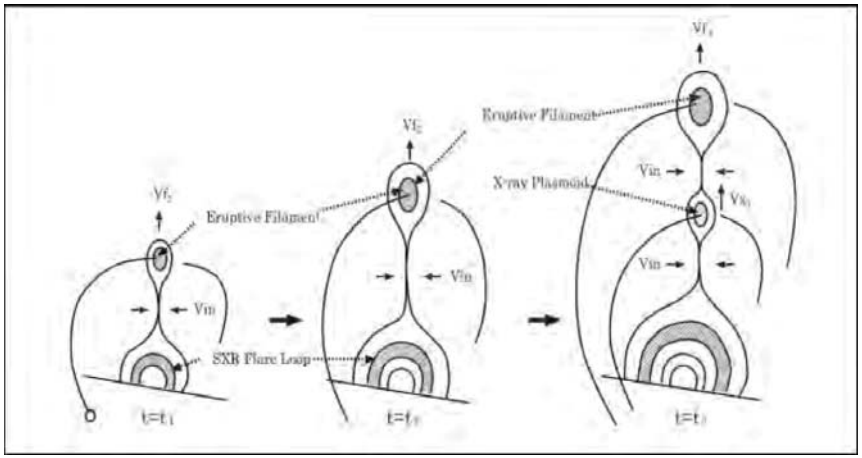
- Basic 2D ReX
- Magnetic Islands
  - Enablers or Comparable Outputs?
- CSHKP model, updated
- 3D ReX for fast reconnection and plasmoids



Guidoni & Longcope 2010



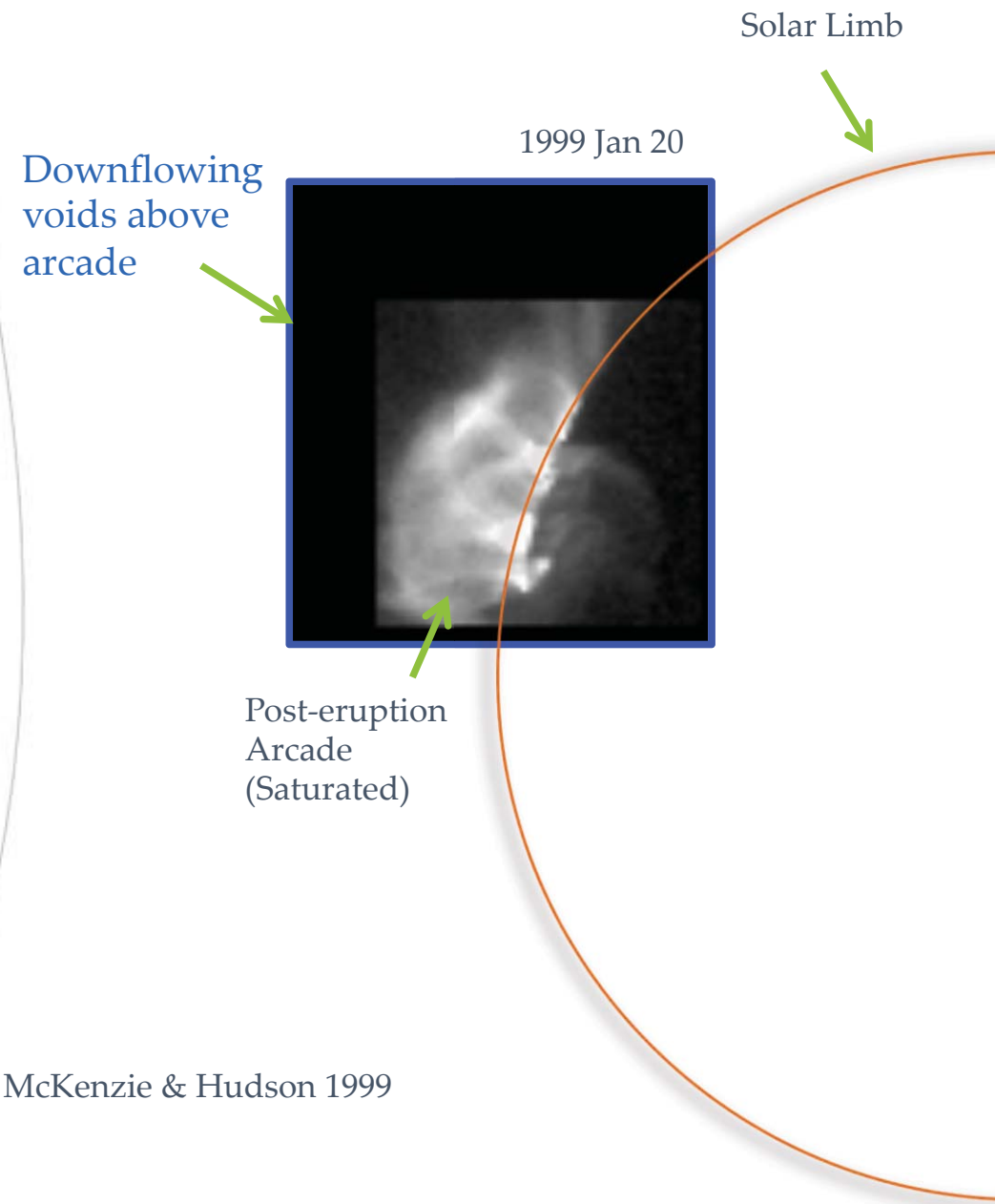
Longcope, Guidoni, & Linton 2009



Ohyama & Shibata 2008

SXT

- First observation of downflowing voids above developing post-eruption arcades

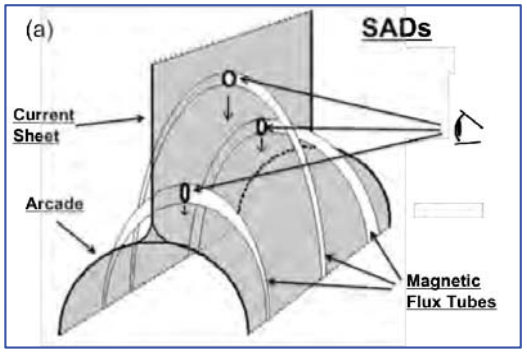


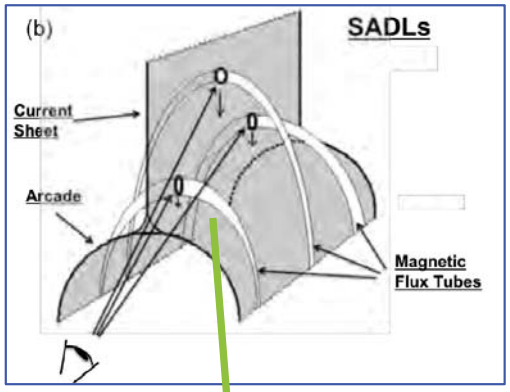
McKenzie & Hudson 1999

SADs / SADLs

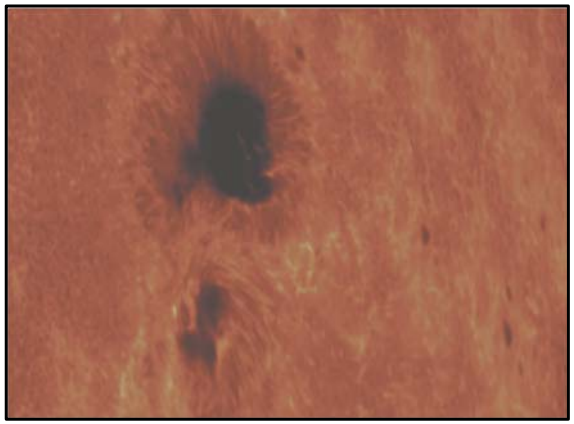
- Teardrop shaped voids flowing sunwards through the voids
- Cross-sections of retracting flux tubes
  - reconnection outflows

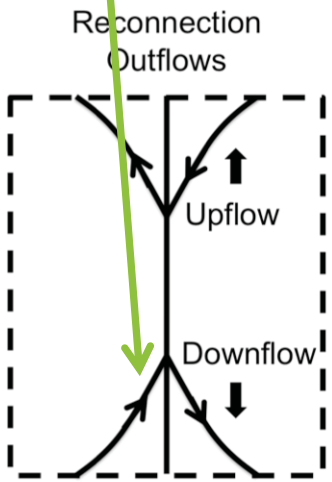
Long-standing Interpretation





McKenzie & Hudson 1999
McKenzie & Savage 2009



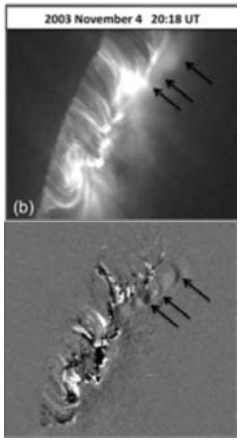


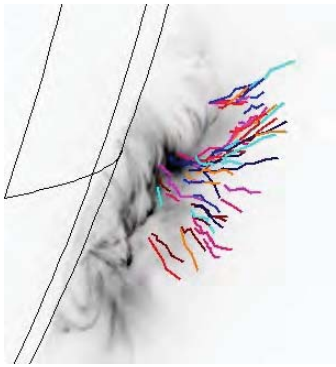
Observed across the spectrum

- X-class flares
- Voids
- Loops
- Disconnection Event
- "Plasmoids" & outflows
- Many hours after initiation in LASCO

Sadpoles
(not tadpoles)

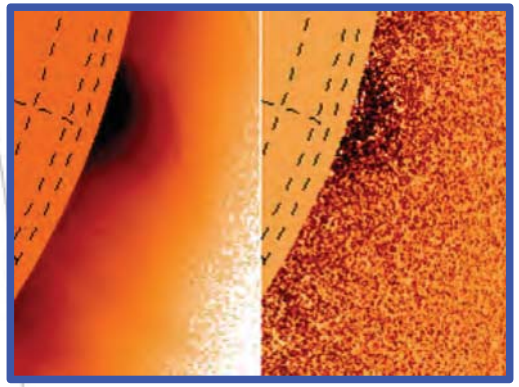
What's the [X-]point?

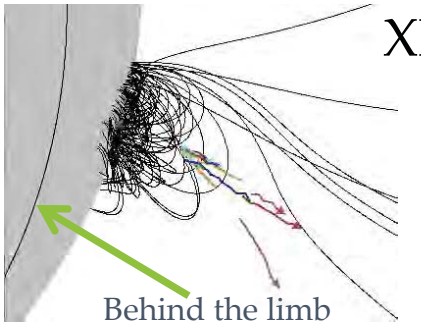




TRACE

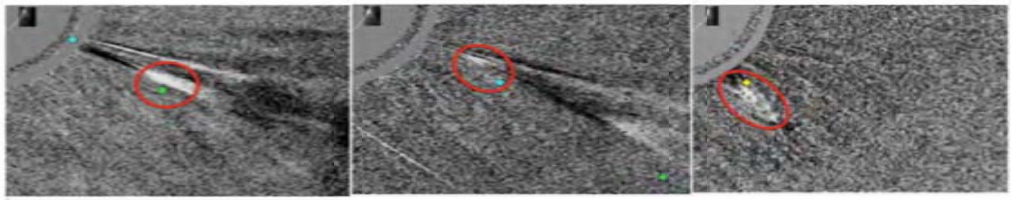
McKenzie & Savage 2009

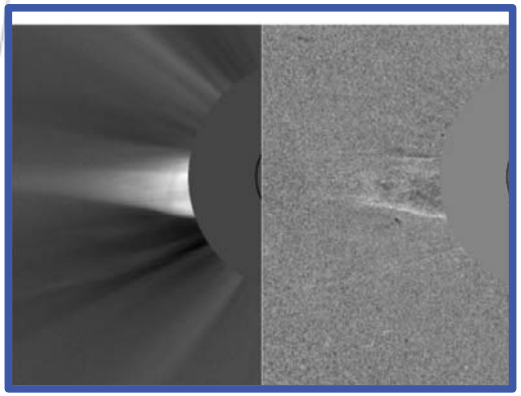




XRT

Savage et al. 2010



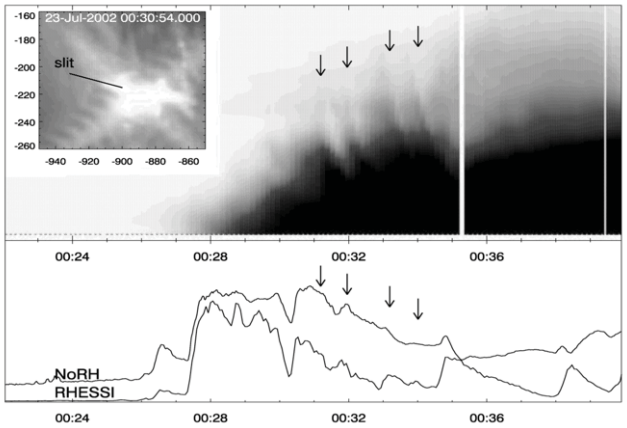


LASCO

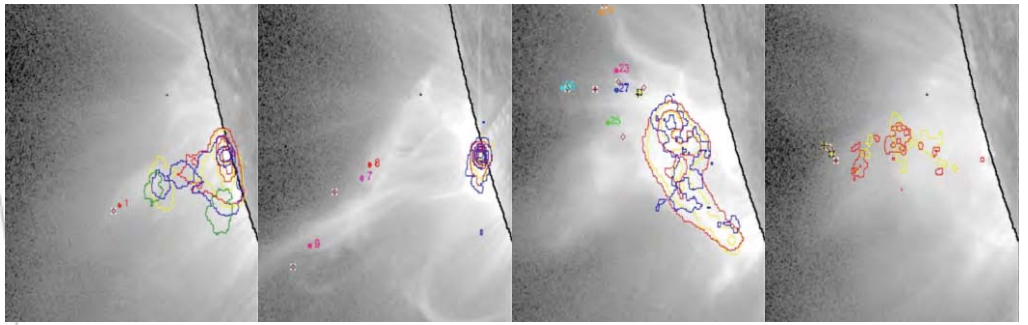
Observed across the spectrum

- Particle acceleration to footpoints (HXRs)
- Hot thermal plasma temporally and spatially associated with downflows
- Radio termination shocks
  - Nonthermal & coherent

RHESSI

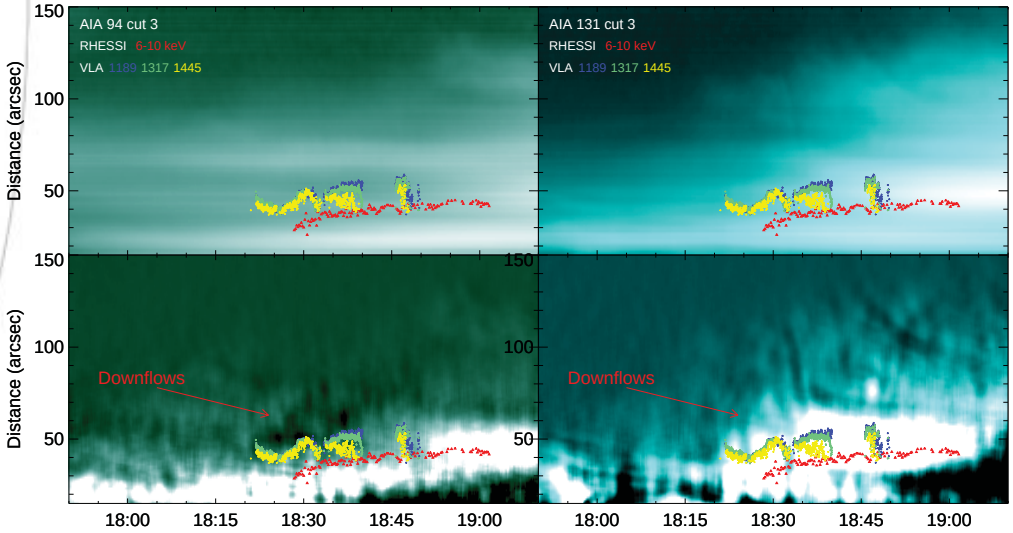


Asai et al 2004



Savage – 2010 Nov 3 flare

VLA

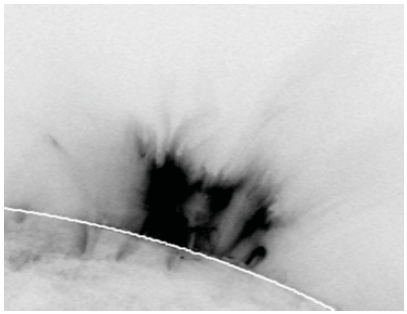


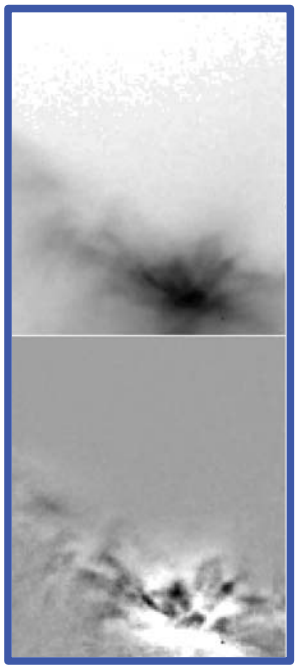
Chen et al. 2014 – 2012 Mar 3 flare, courtesy of T. Bastian

AIA

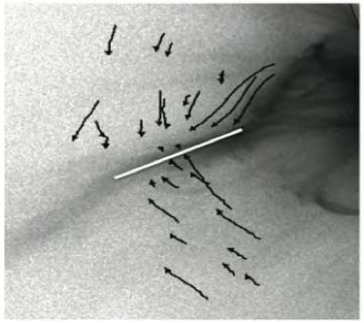
- Inflows & Outflows
- SADs & SADLs

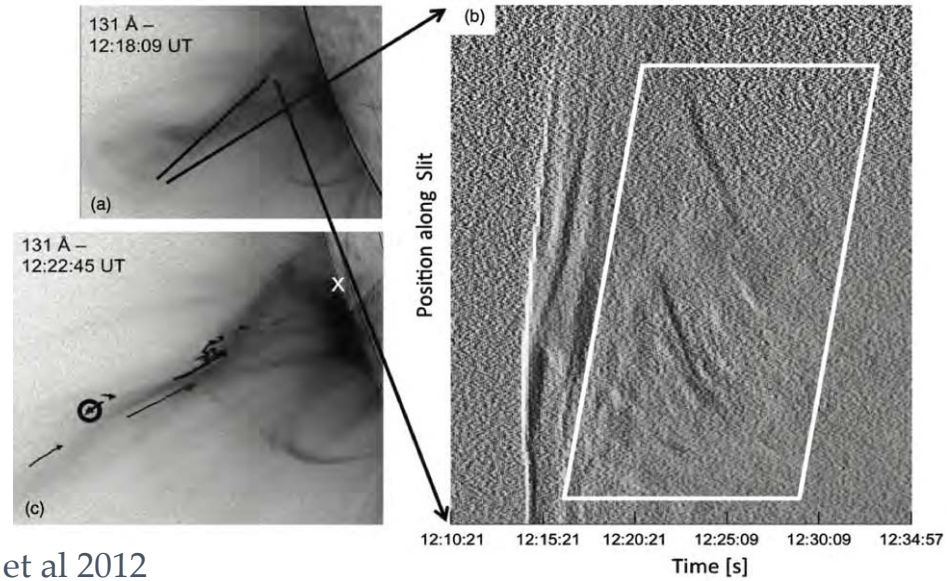
2011 May 9





2010 Nov 3

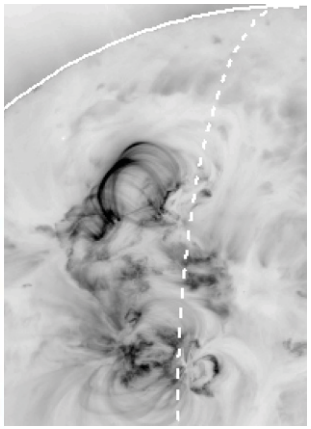


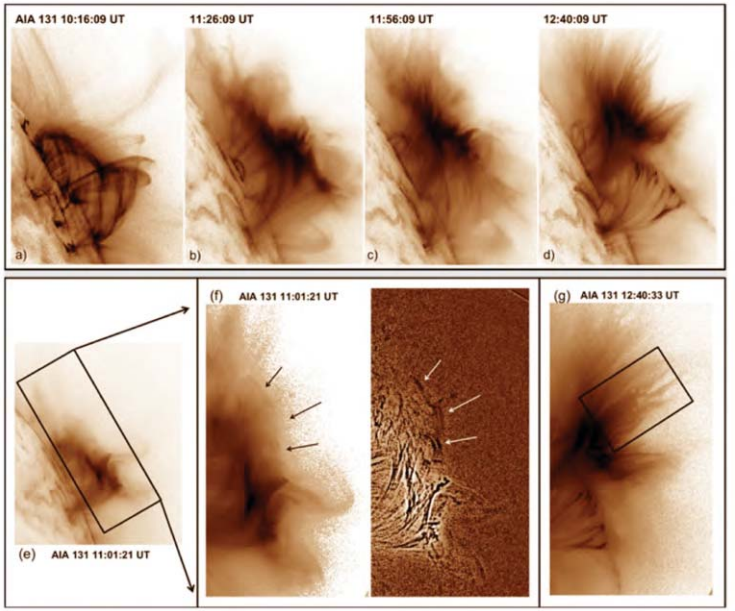


Savage et al 2012

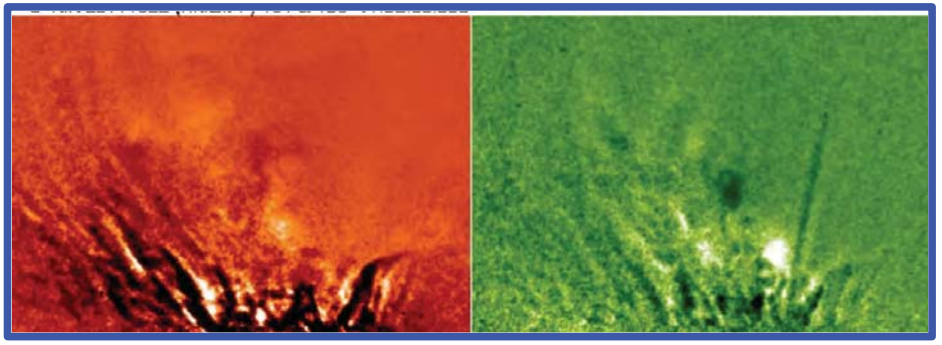
AIA

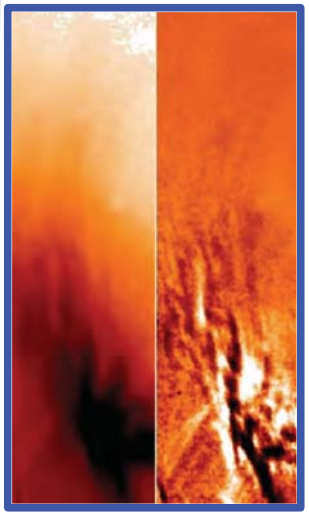
- Paradigm shift
  - Flare defying geometrical argument
  - Voids in current sheet behind thin retracting flux tubes vs. Cross-sections

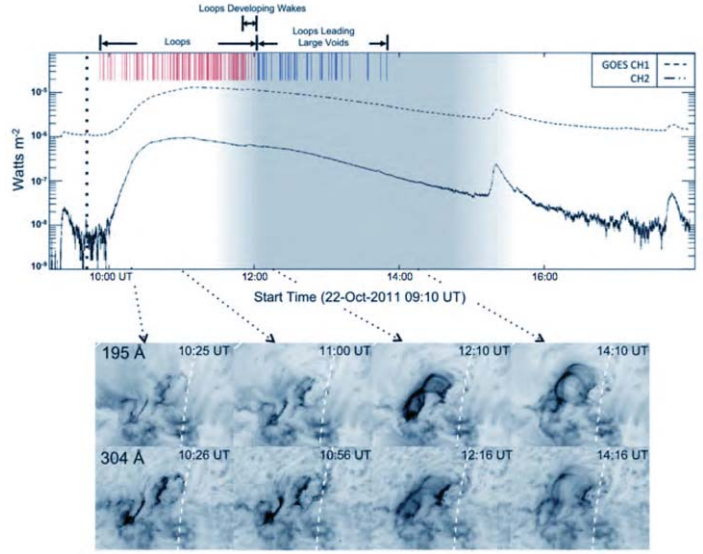




2011 Oct 22

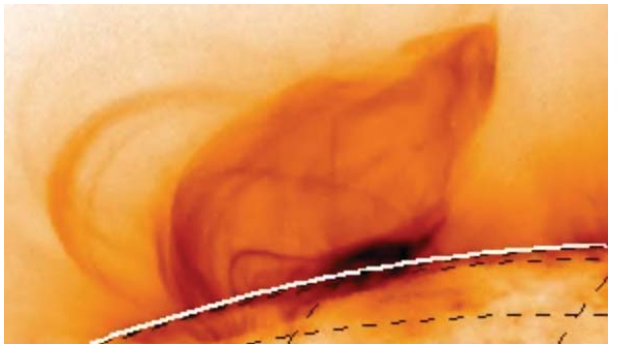




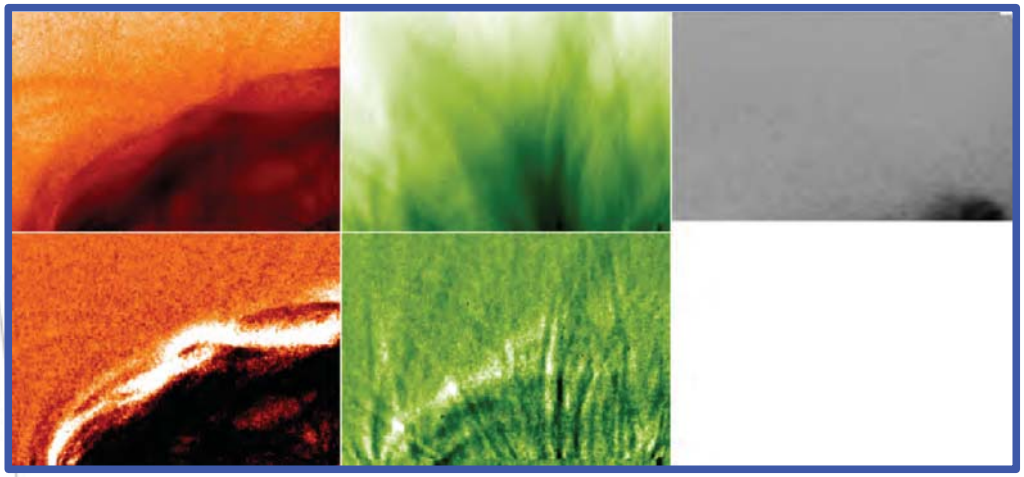


AIA

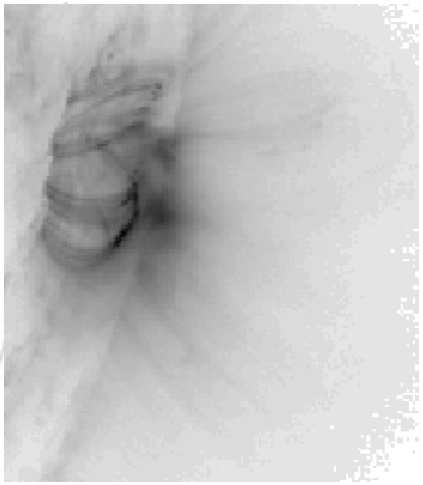
- Paradigm shift
  - Flare defying geometrical argument
  - Voids in current sheet behind thin retracting flux tubes vs. Cross-sections
  - Mounting observational evidence

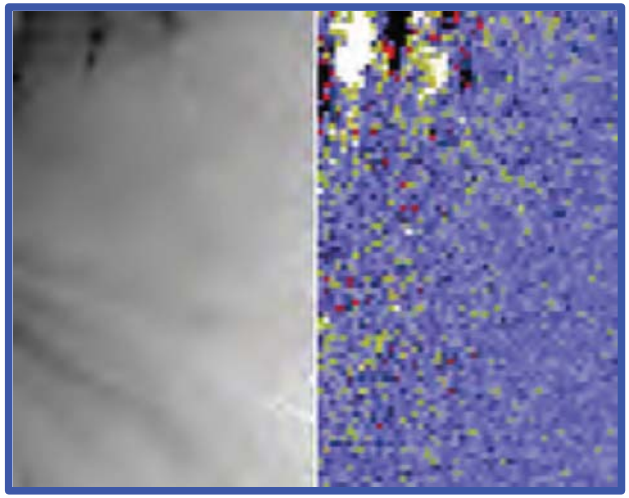


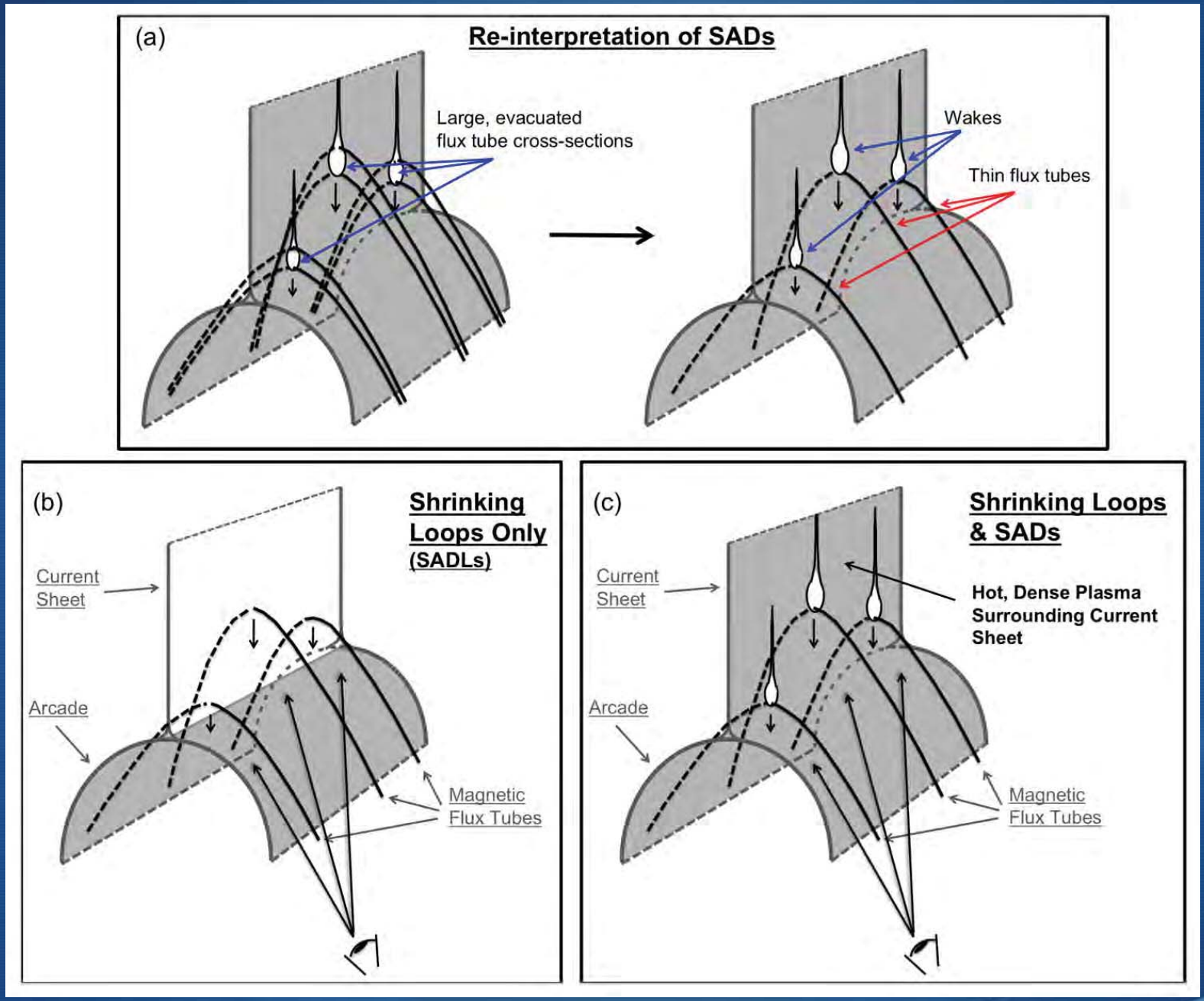
2012 Jan 27



2014 Feb 20





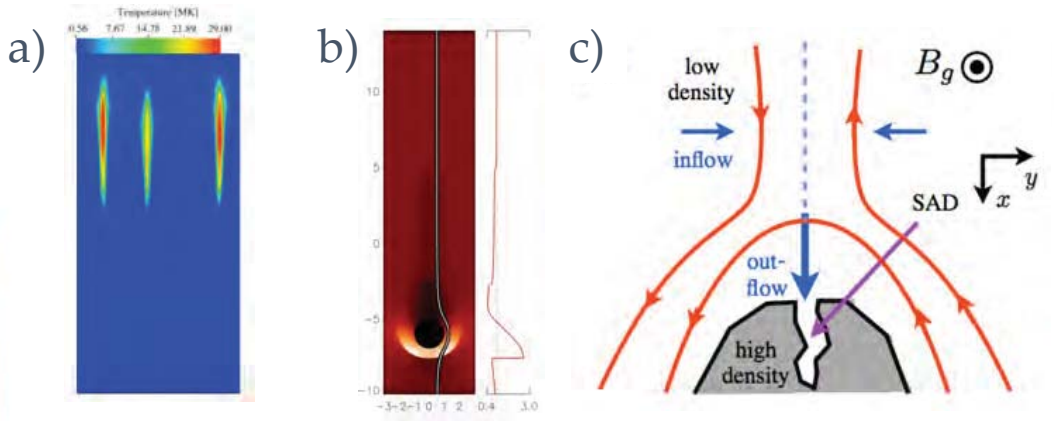


Savage, McKenzie, Reeves 2012

Models

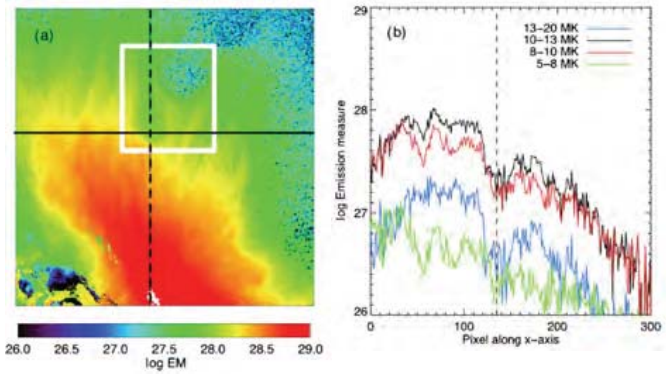
Temperature Discriminant

- a) Cecere et al 2012
  - Pressure pulse + MHD wave (T >> fan)
- b) Scott et al 2013
  - Peristaltic pumping (T ~< fan)
- c) Cassak et al 2013
  - ReX outflows (T ~< fan)

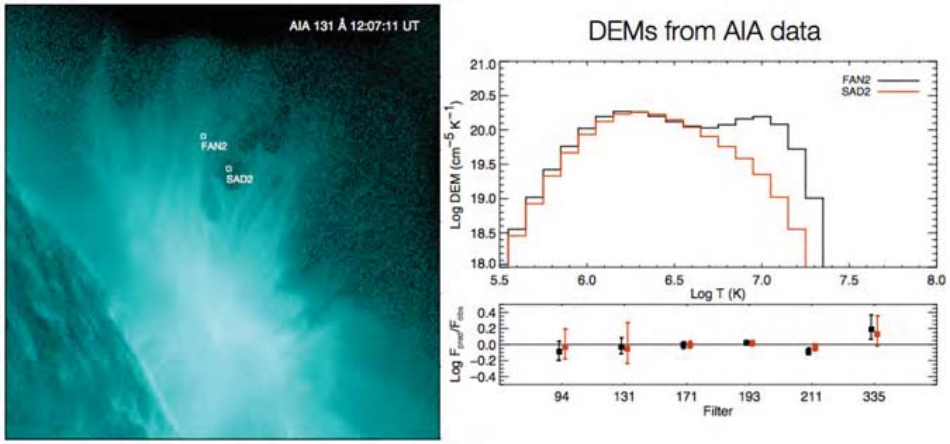


Adapted from Reeves et al Hinode 7 presentation

OBSERVED TEMPERATURE AND DENSITY ALWAYS LOWER THAN FAN

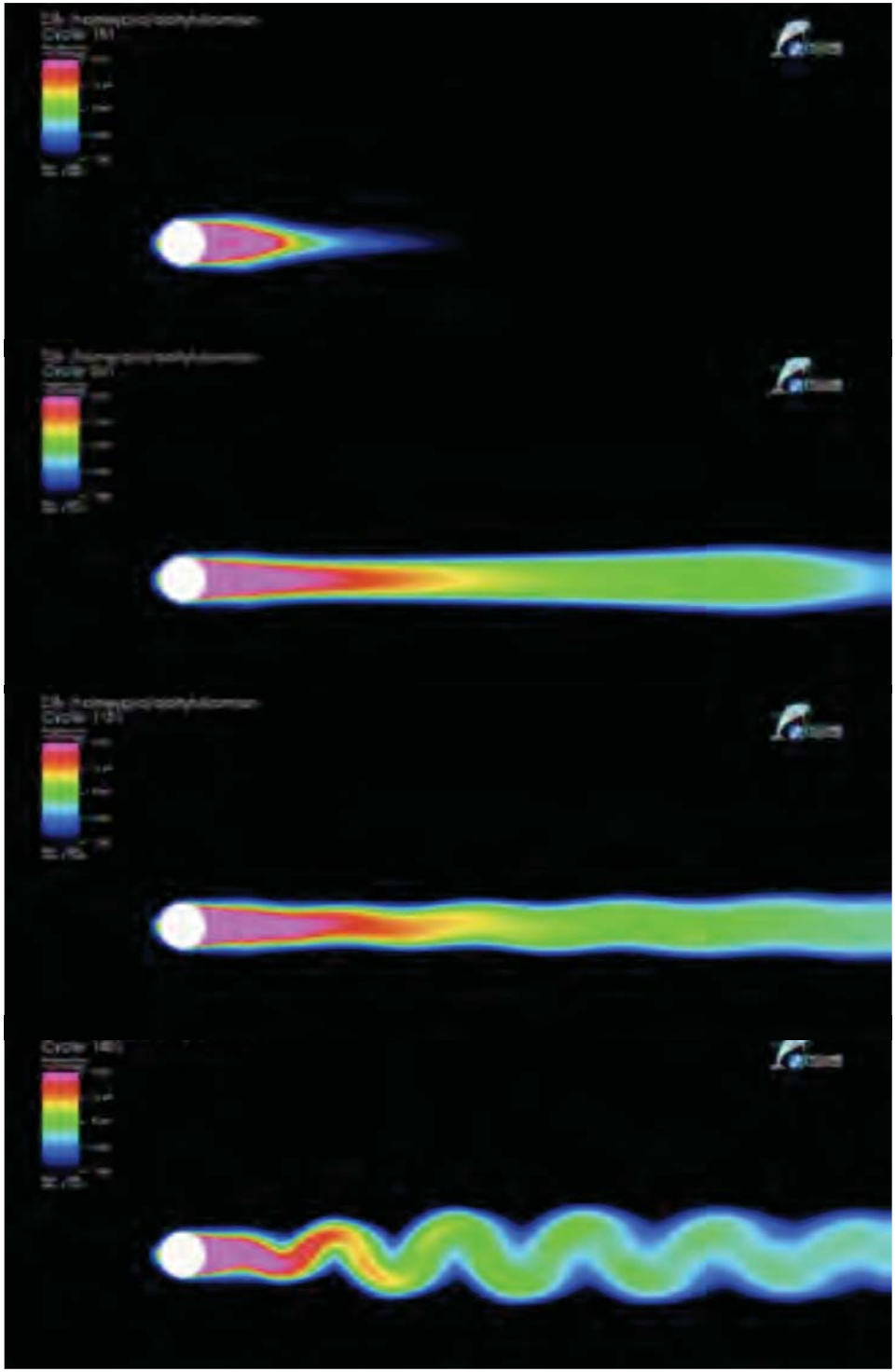


Savage, McKenzie, & Reeves 2012



Von Karman vortex street

- Perhaps something simple like some nice fluid dynamics?
  - ….only for describing the voids and tails



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

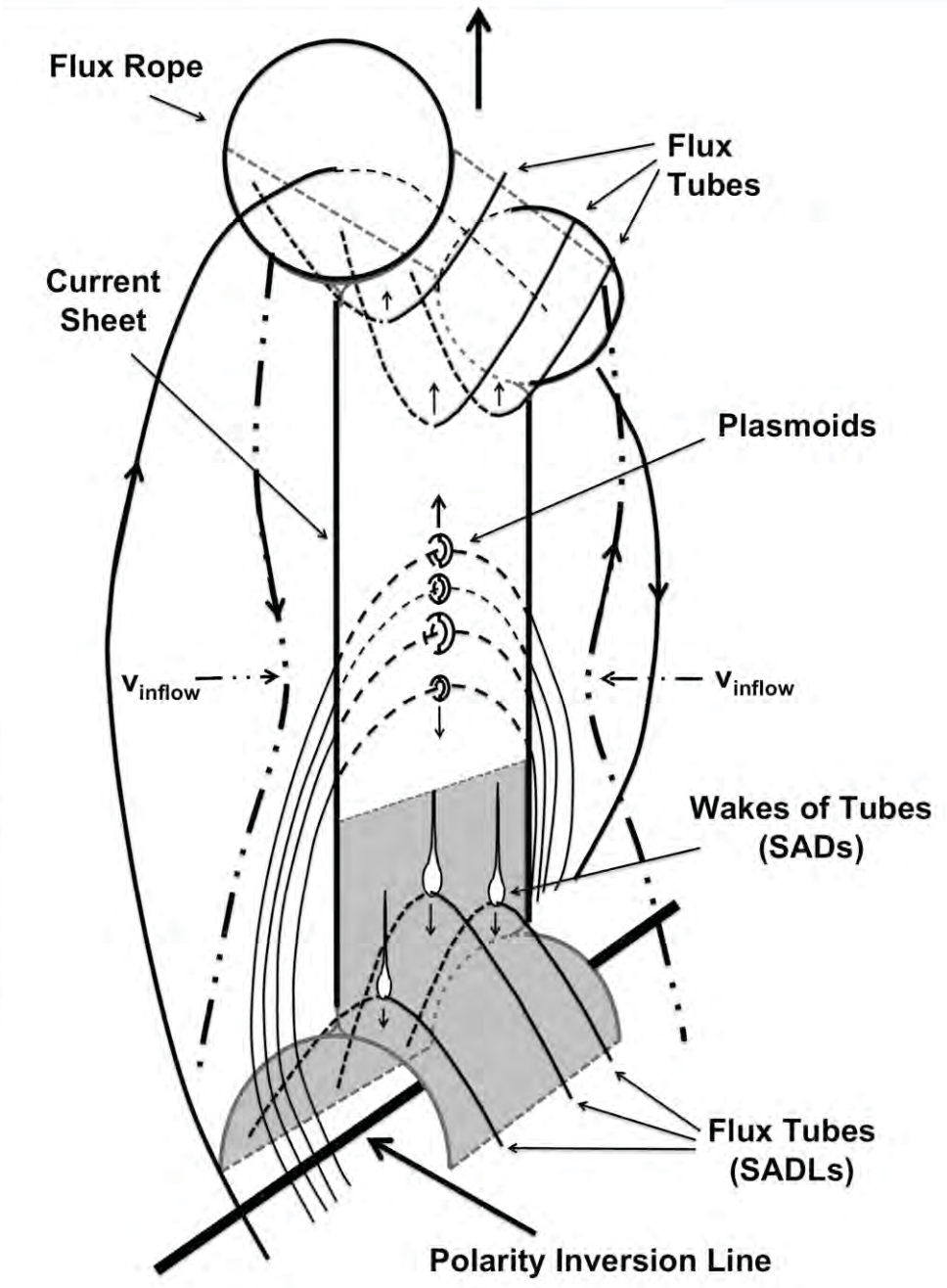
Putting it all together

…or at least starting to

Theory

- Plasmoids ≠ SADs

Nishizuka & Shibata 2013, Nishida et al 2013



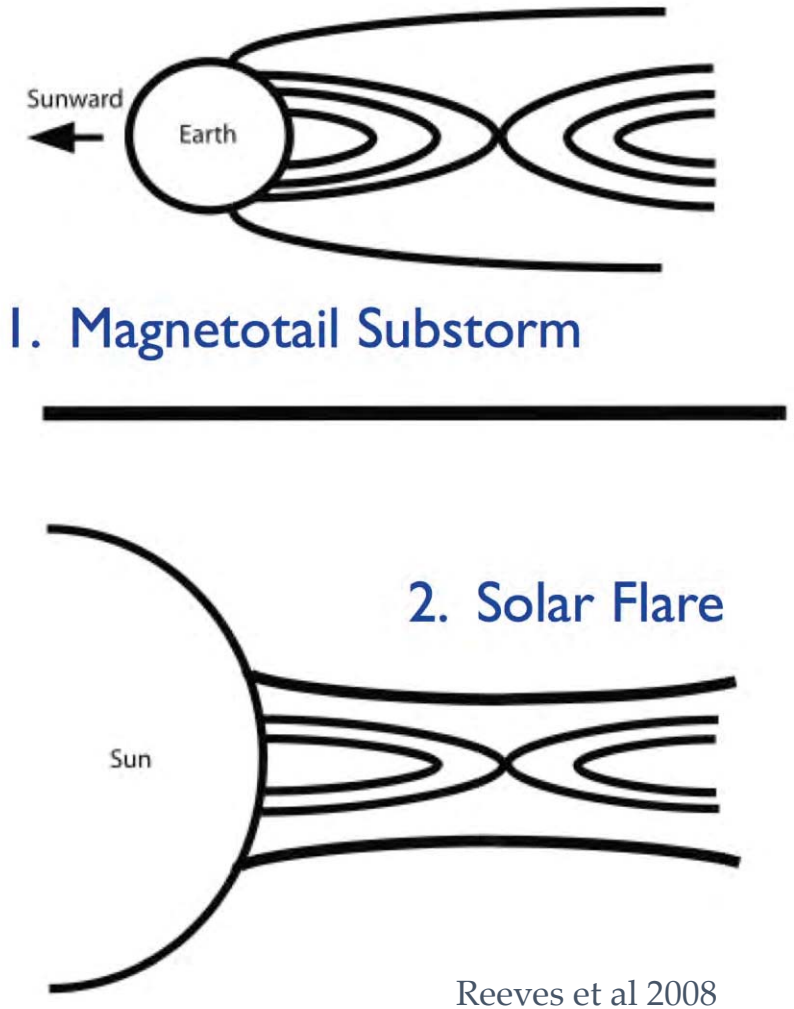
Savage et al 2012

Closer to Earth

ReX counterparts in the magnetotail

Magnetotail ReX

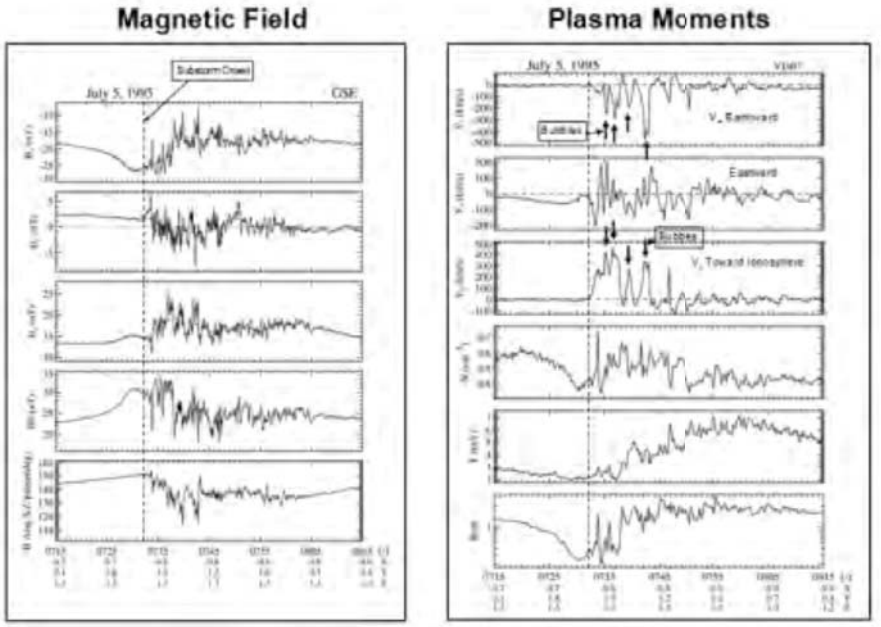
- Similar outputs
  - Accelerations & speeds
  - Double footpoint ribbons from electron acceleration
    - G: Aurora ribbons in dense ionosphere
    - S: Flare ribbons from chromospheric evaporation / ablation



Reeves et al 2008

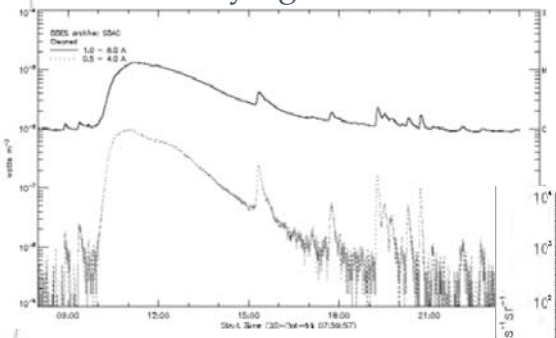
Magnetotail ReX

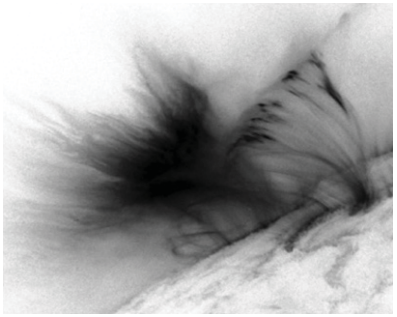
- Competing notation
  - G: Dipolarization
  - S: Field line shrinkage
- Complementary measurement regimes
  - G: In situ B field & plasma parameters
  - S: Global context



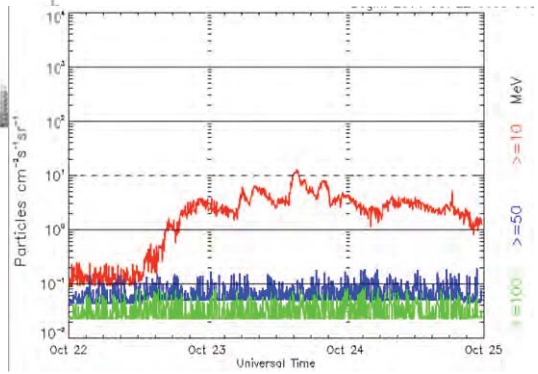
Wolf et al 2006

GOES X-ray light curve



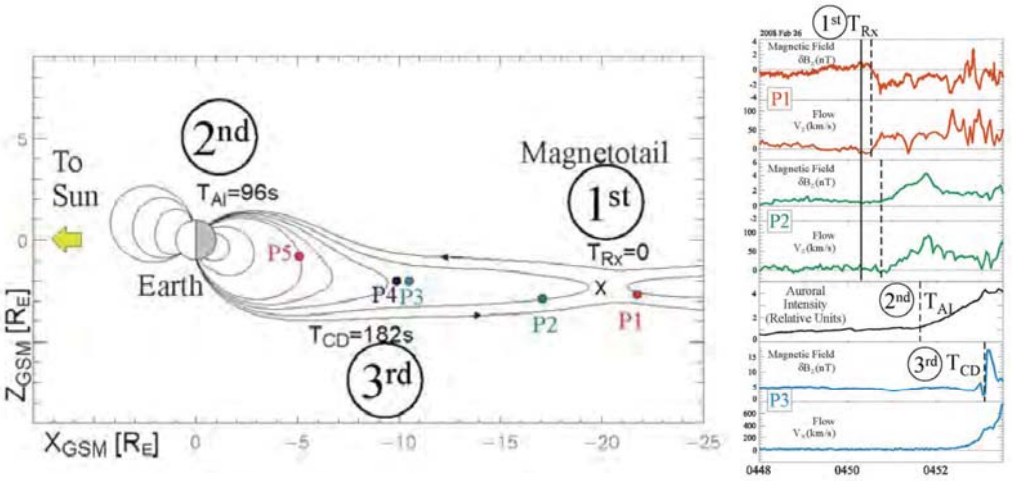


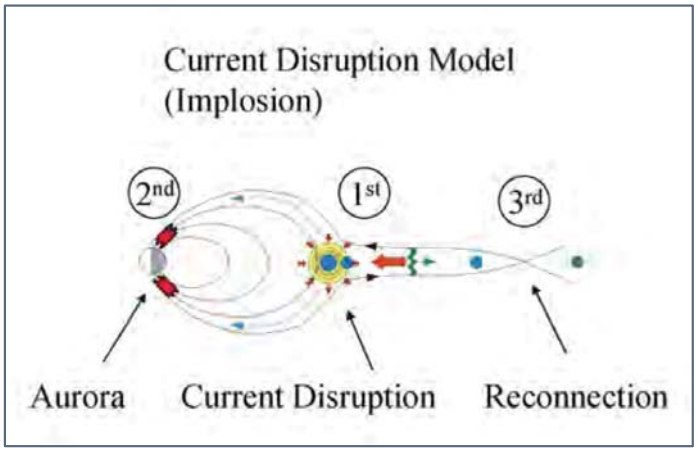
GOES Proton Flux



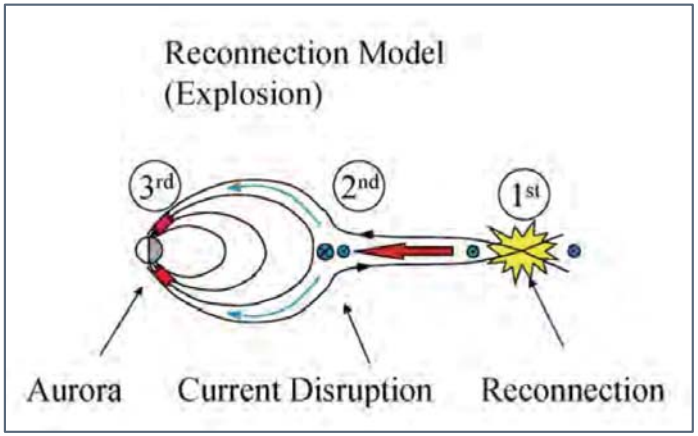
THEMIS

- 5 → 3 spacecraft
  - B, E, ϱ, …





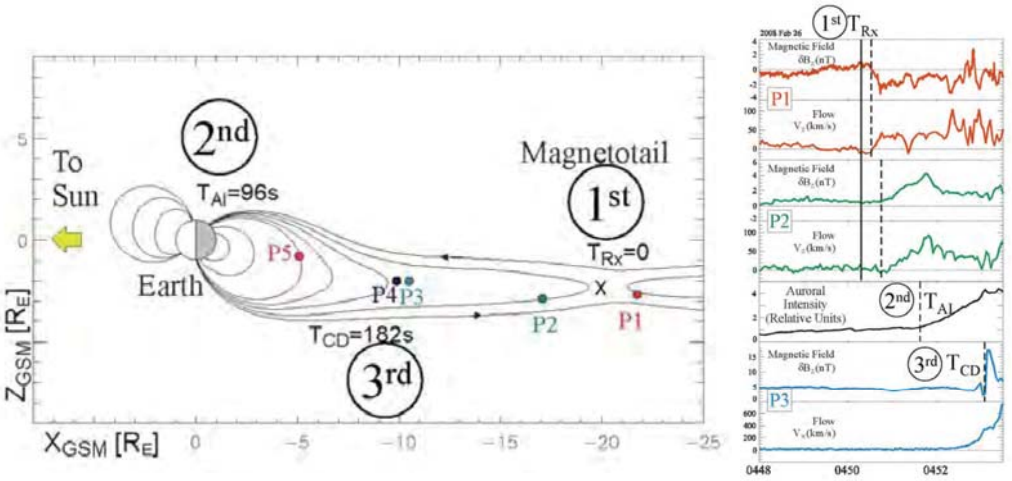
vs.

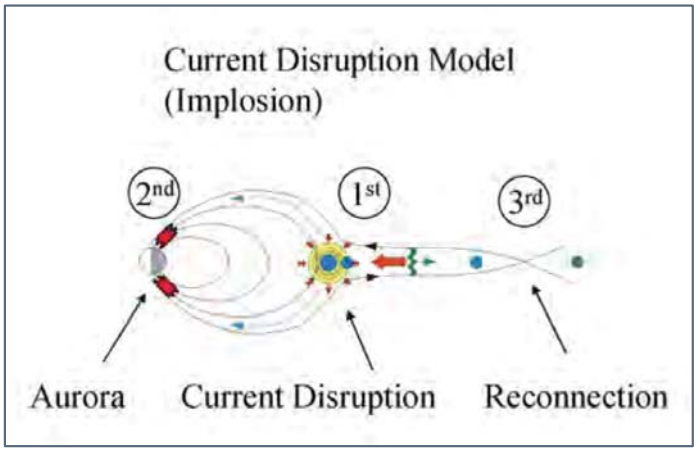


Angelopoulos et al. 2008

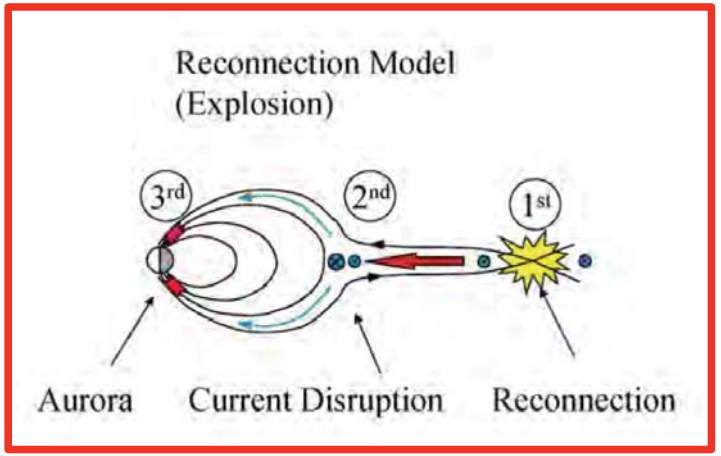
THEMIS

- 5 → 3 spacecraft
  - B, E, ϱ, …





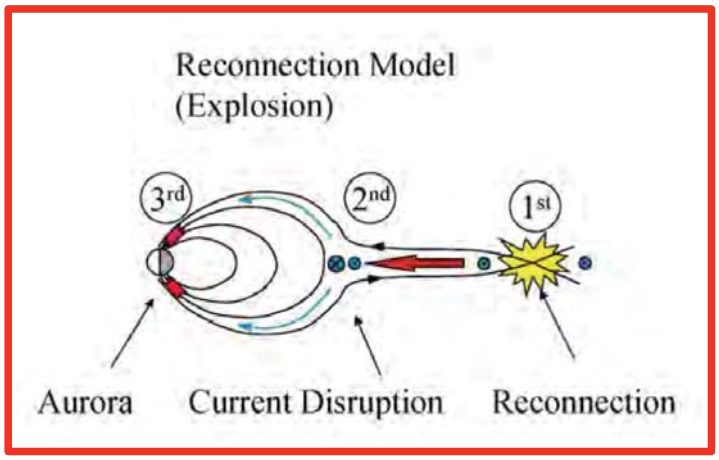
vs.



Angelopoulos et al. 2008

THEMIS

- 5 → 3 spacecraft
  - B, E, ϱ, …
- SADs, Substorms, Wedgelets
  - → Fast, patchy reconnection
- Similar Alfven speeds
  - But probably different regimes: resistive vs. collisionless



Angelopoulos et al. 2008

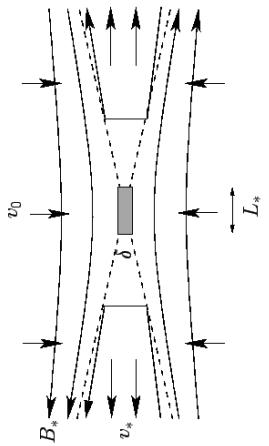
Summary of Outputs from Observational Properties

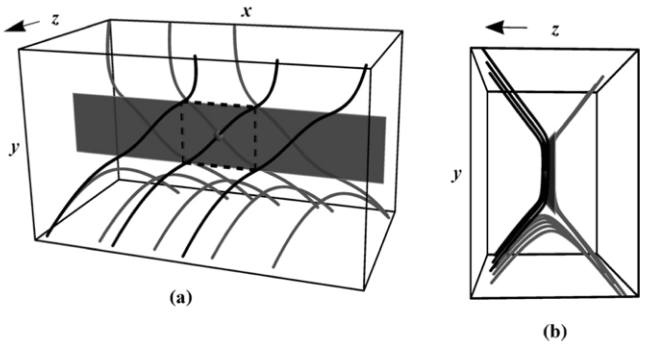
Applicable to long-duration solar flaring events

Key Extrapolated Conclusions

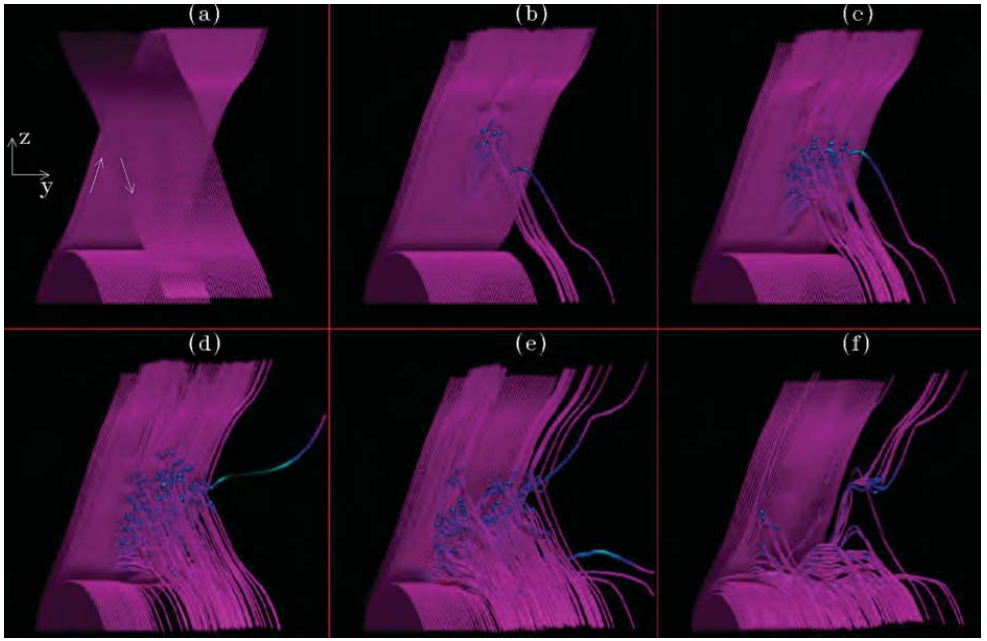
- ReX is fast in the presence of a guide field
  - Turbulence is also a helpful motivator
- ReX in wake of a CME is patchy & bursty (finite)

Petchek-type





Guidoni & Longcope 2010

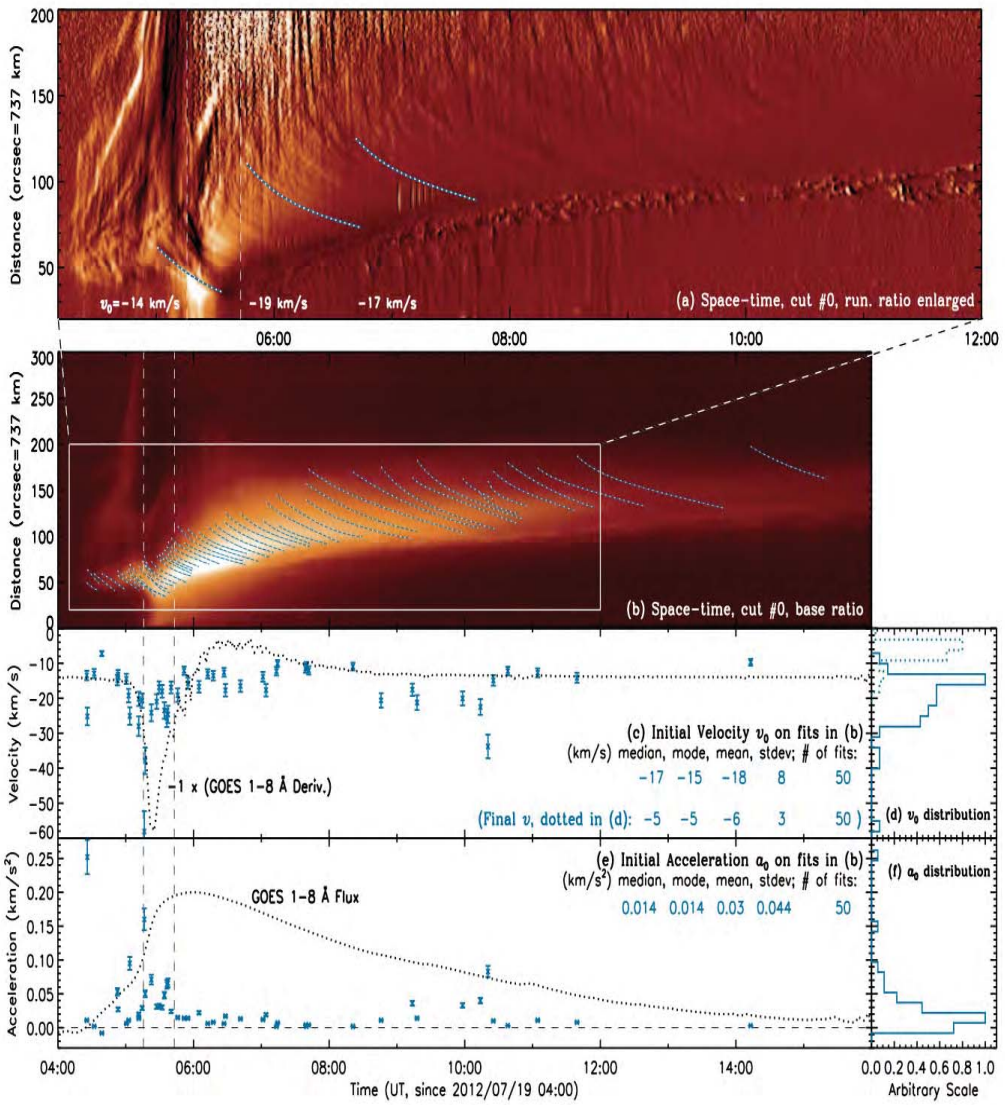


Linton & Longcope 2006

Key Extrapolated Conclusions

- Continuation of shrinking loops imparts energy into the current sheet long after the flare

$\Delta W = (B^2 A \Delta L / 8\pi) / \Delta t$
per shrinking loop



Liu et al 2013

Substorms + Solar flares

- Yes.

etc.

Substorms
+
Solar flares

- Yes.
- Potential for more complete picture of reconnection.
  - Suitable conditions?
  - How is it triggered?
    - Turbulence?
  - Etc.

etc.

Fin