Evidence in White Light of Post-CME Current Sheets – Mostly Observational

David Webb

ISR, Boston College

OUTLINE

- Review previous results of SMM & LASCO WL rays trailing CMEs
  - Lifetimes, lengths (heights) of ray
  - Comparison with Lin & Forbes model
- SOHO-era/ISSI/CFA work
  - LASCO/UVCS Catalog
  - Near-Surface Topology & Evolution
  - Density & widths as f(height, time), height evolution of CS & X-point, inflows, speed of blobs - above & below X-point
  - Compare models (numerical - MHD & analytical) with observations
  - Steady vs bursty reconnection in CS
- Future Work

Review of *Webb et al., 2003* Study of SMM Post-CME Rays

- **Background**

  Webb, Burkepile, Forbes, & Riley, JGR, 108-A12 (2003)
  IP Magnetic Flux Buildup Problem
  Observational Evidence of Reconnection/Disconnection
  Eruptive Flare Models & Current Sheet Development:
  - Basic CSHKP model
  - Developed by, e.g., *Lin & Forbes (JGR, 2000)*

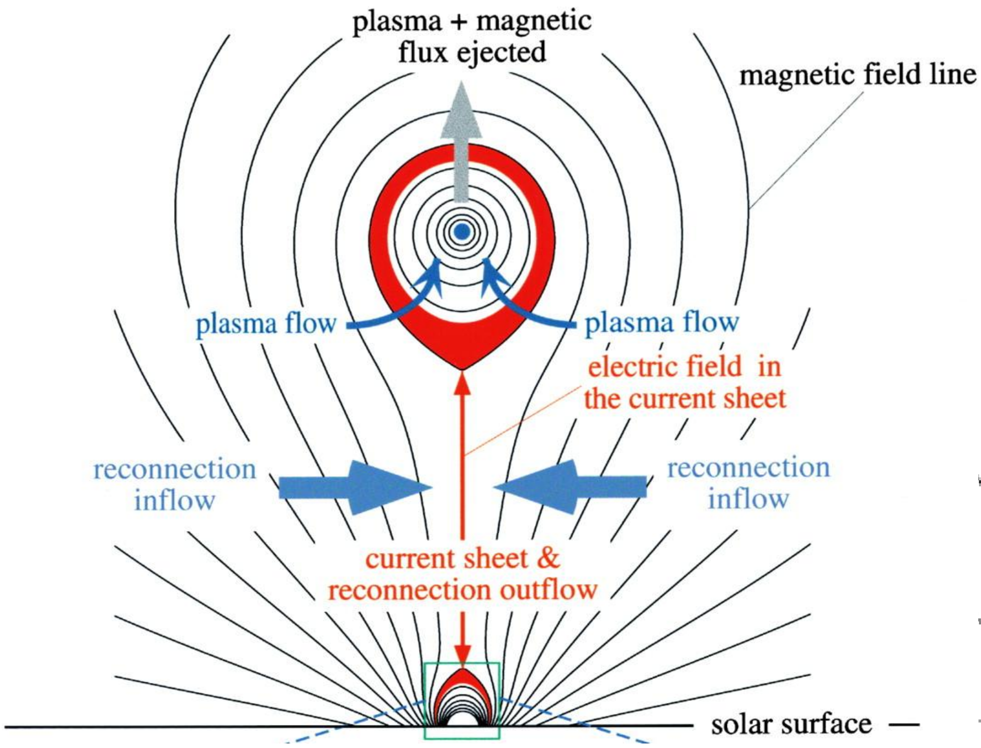
- **Approach**

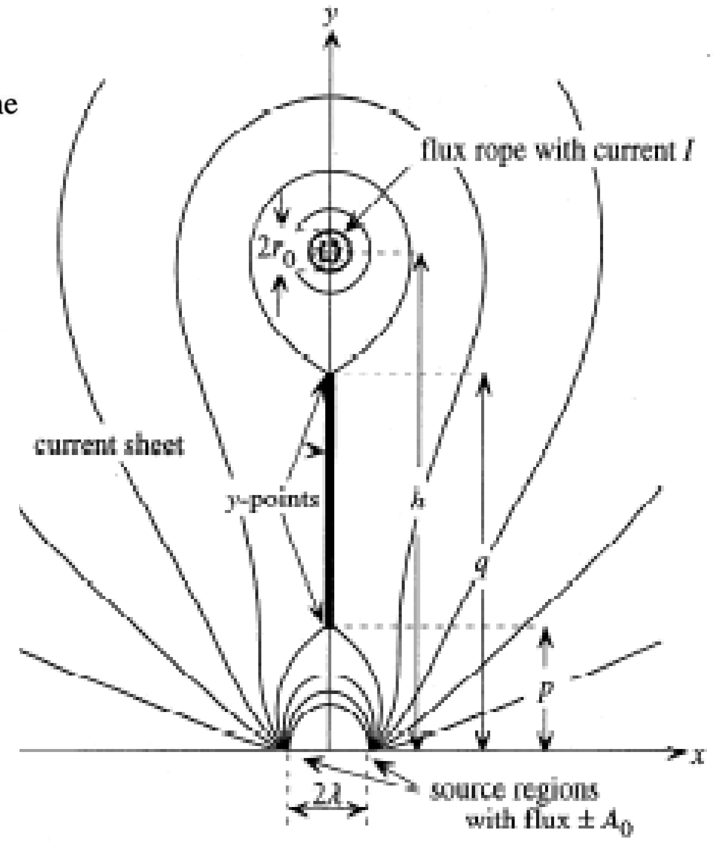
  Measure Rays Trailing SMM Concave-Outward CMEs
  Test the Hypothesis that Rays are Current Sheets due to Reconnection following CME/Flux Ropes

- **Results**

  Measured Parameters of Transient Rays
  Compare with Model Predictions

Parameters that can be Measured in White Light Observations to Test the Lin & Forbes Model



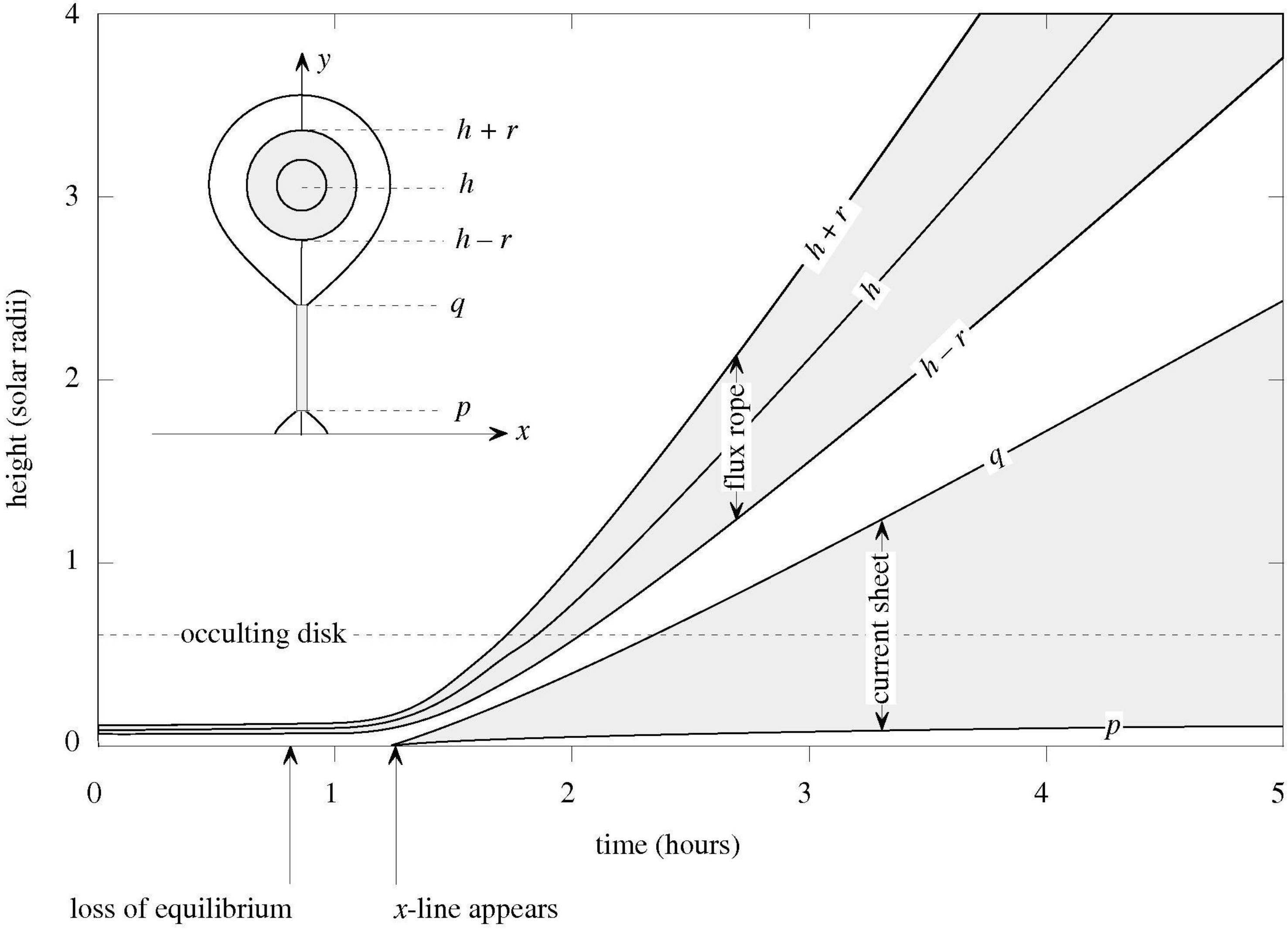


Current sheet length = q – p

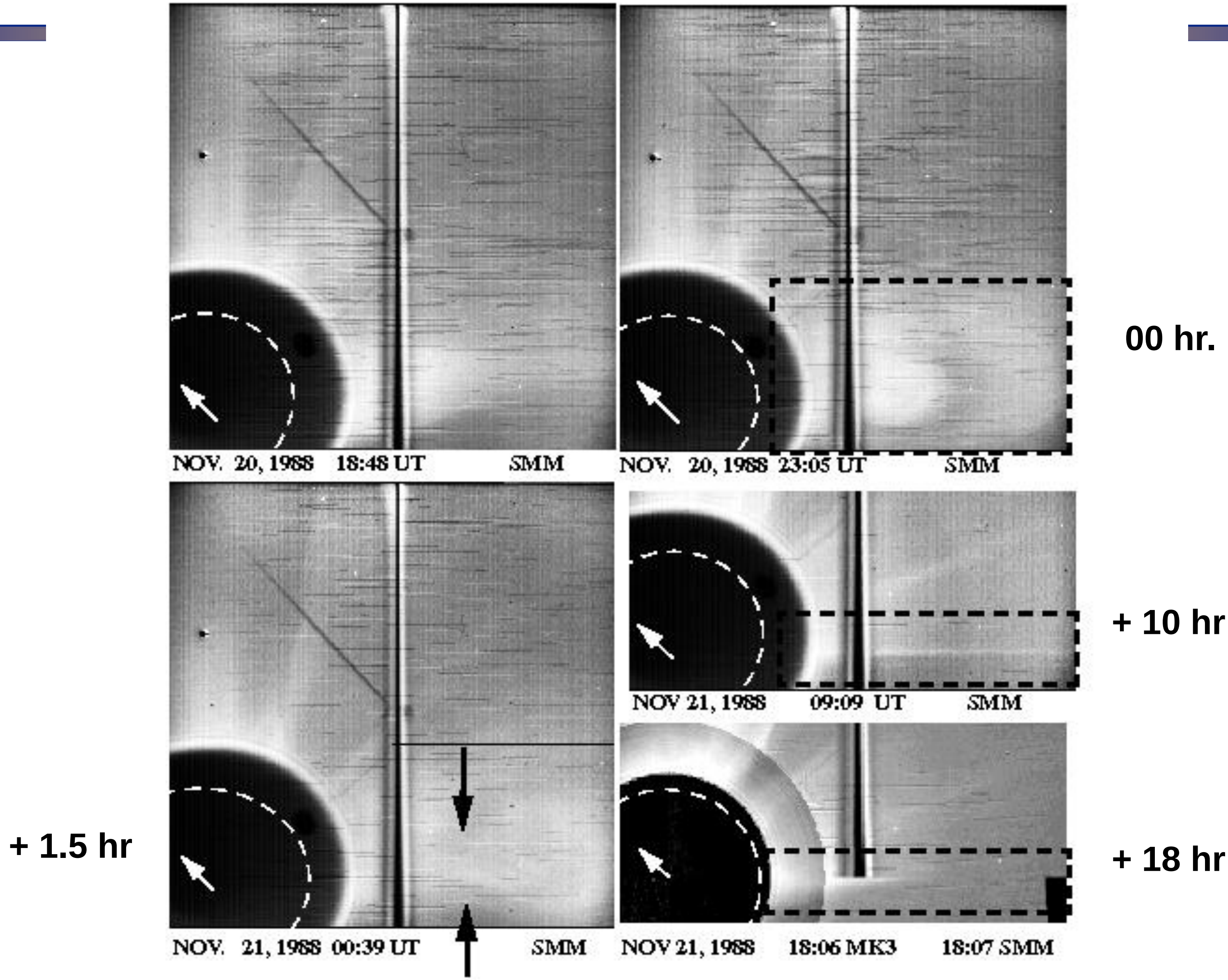
Lin et al., ApJ, 2004

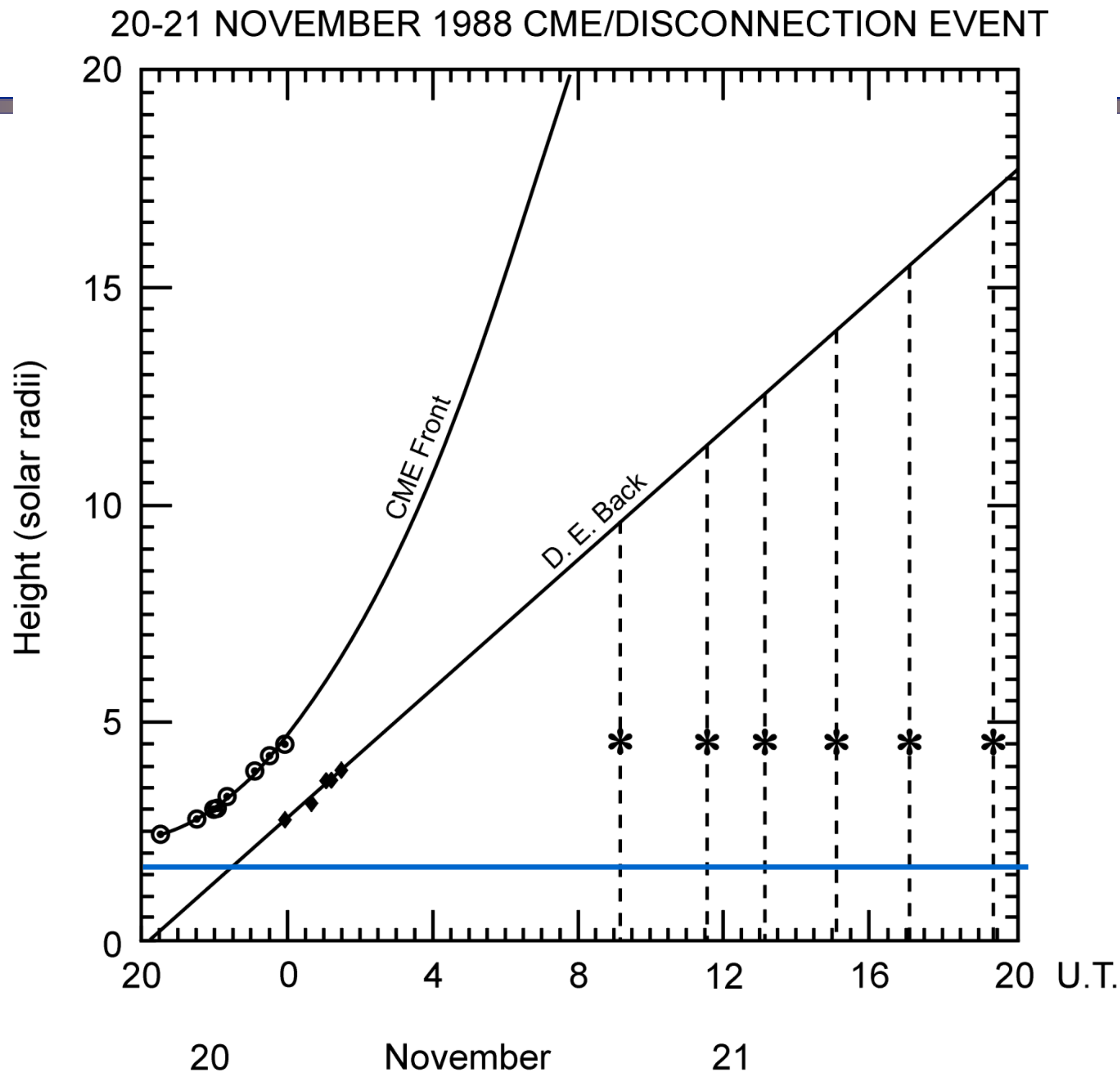
Lin and Forbes, JGR (2000)

L&F Model Current Sheet Evolution for a Set of Parameters → M_A = 0.1



CME of November 20-21, 1988




20-21 NOVEMBER 1988 CME/DISCONNECTION EVENT
Height (solar radii)
CME Front
D. E. Back
20
15
10
5
0
20
0
4
8
12
16
20
U.T.
20
November
21

Summary of SMM WL Rays Study

- **Previous Study Using SMM C/P Obs., 1984-1989:**
  ~10% of SMM CMEs followed by evidence of disconnection
  ***Half* (26) of these C-O events had new, transient, late rays**
- **Analysis of Transient Rays to Test Hypothesis → Rays are Current Sheets**
  Widths = 2.5° (2.2R_S)
  CME & ray axes offset by ~9°
  Most rays coaxial with C-O & non-radial (equatorward)
- **Ray Lifetimes: ~8 hr.**
  Δt, Back of C-O to onset of ray: 3.8 hr.
  Δt, Back of C-O to end of ray: >11.6 hr.
- **Ray Lengths: 3.25 to >11.3 R_S Large Range**
- **Comparison w/ Lin & Forbes Model:**
  Widths consistent with narrow, dense CSs
  Lengths generally consistent, *but*
  H, t evolution of base and top of CS did not agree

WHAT NEXT?

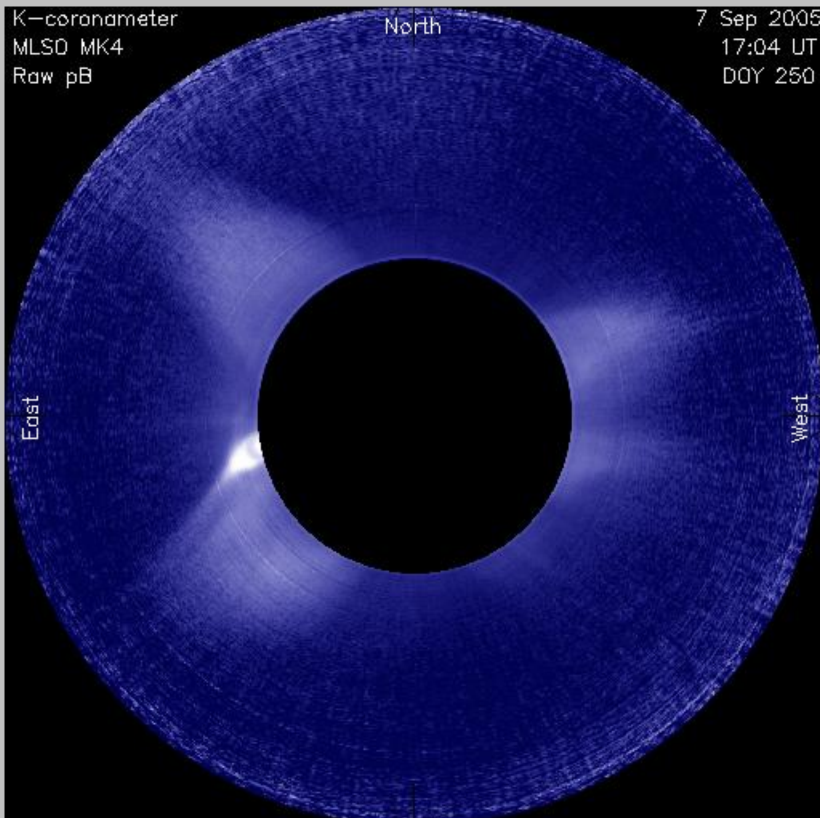
- **Study SOHO-era Data**

  - **Examine near-surface topology & evolution**
  - **Evolution from surface to 30 R_S**
    - ***Source region (EIT, TRACE, Hα, Hinode, etc.)***
    - ***Arcade development (MLSO, EIT, X-ray)***
  - **Use ray light curves to compare w/ kinematics, energy, etc. in models**

- **ISSI Workshop, CFA & Beyond**

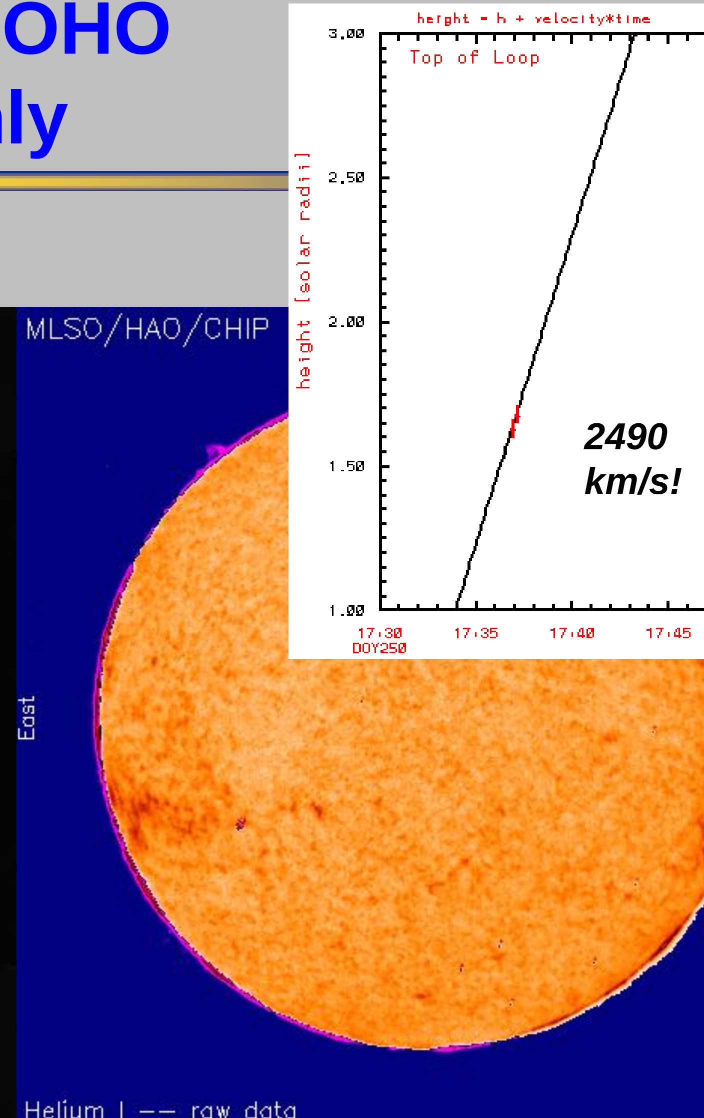
  - **Origin & evolution of CSs & associated eruptive events from surface through interplanetary space;**
    - ***Goal: Develop an empirical description***
    - ***What do we need?***
    - ***Ne & widths as f(height, time), height evolution of CS & X-point, inflows, speed of blobs - above & below X-point***
  - **Compare models (numerical- MHD & analytical) with observations**
  - **Identify the CS heating source**
  - **CSs in flares & relation to CMEs**
  - **Steady vs bursty reconnection in CS?**
  - **Is CS broadening and/or the plasma blobs due to tearing mode turbulence or Petschek-type reconnection, or both vs time?**

Examples: 7 Sept. 2005 → No SOHO Data; MLSO Observations only



MK4 pB Corona

Hα limb
PICS

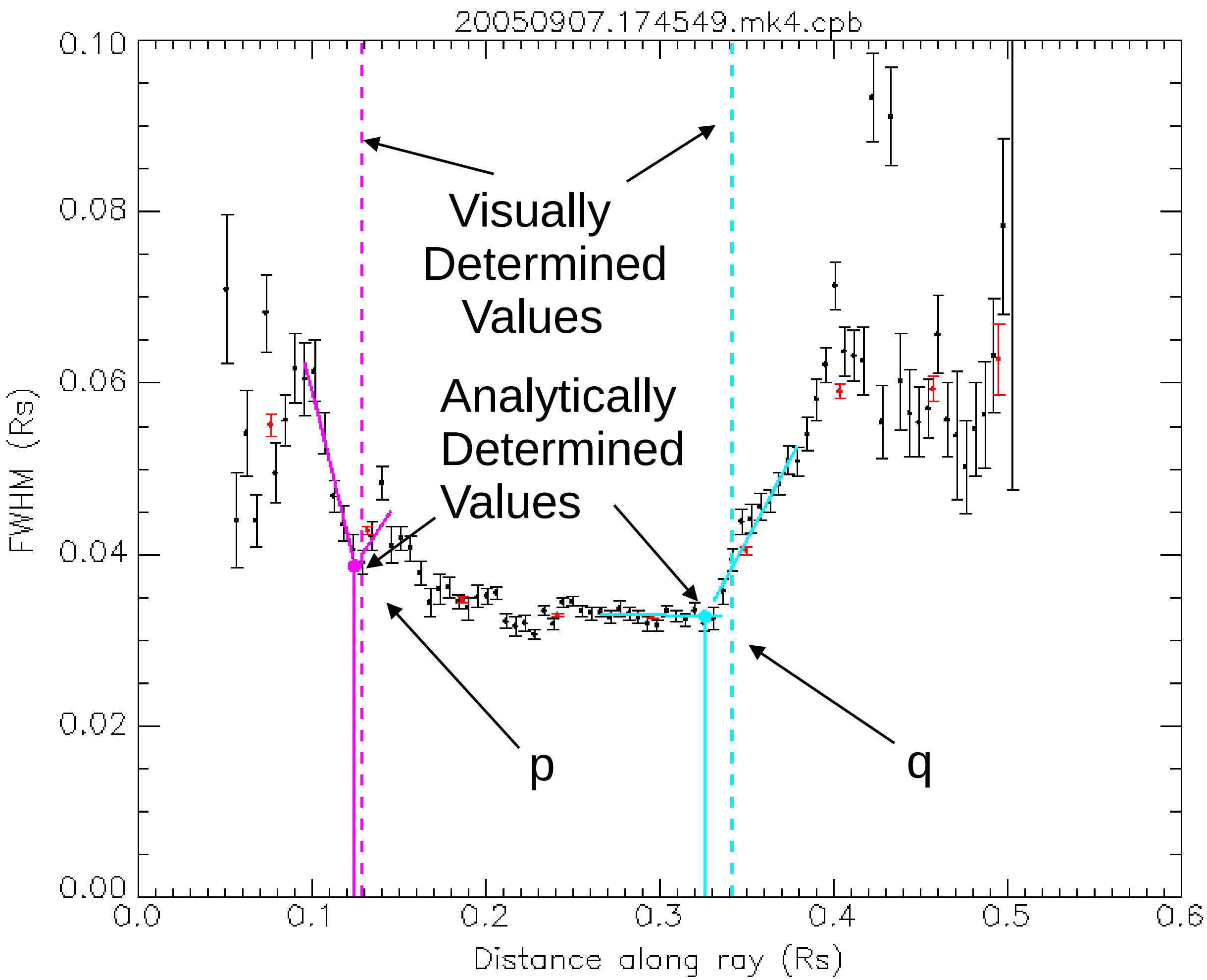


He 10830A
CHIP

Determining p and q for Sept. 2005 CS

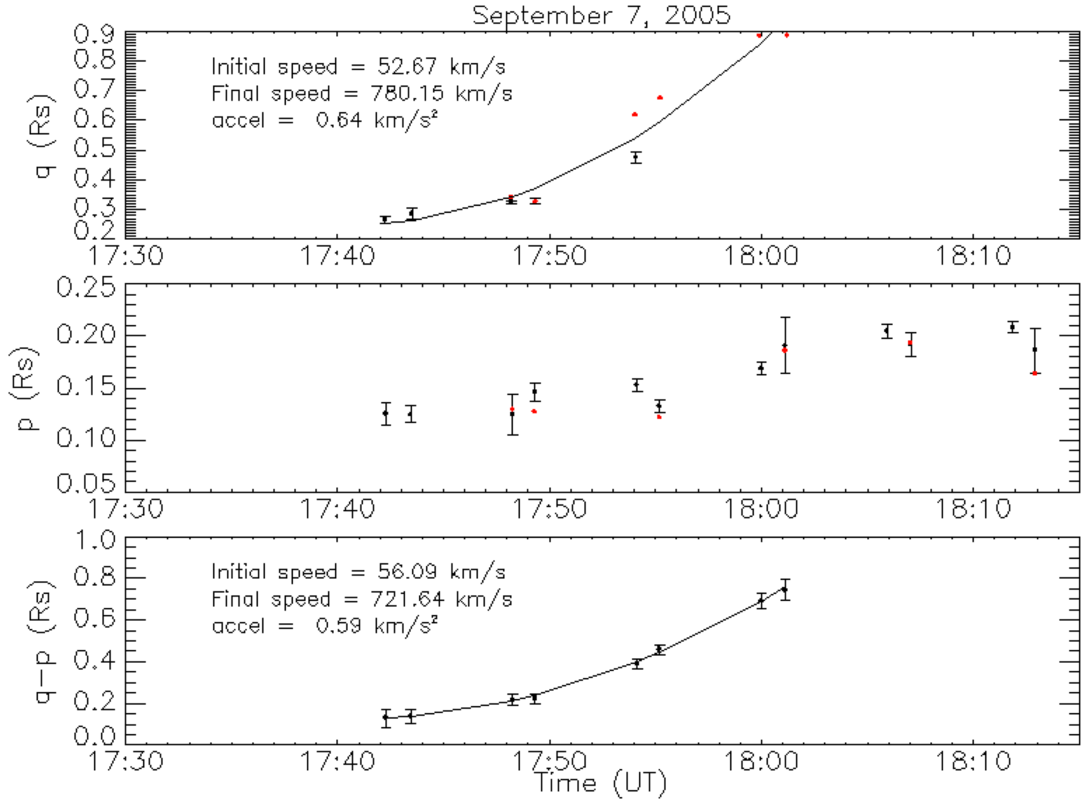
First time → determine extent of CS from top of arcade to base of flux rope

Black points: Data
Red points: Average over 10 bins



Procedure for determining p and q analytically: Fit data to lines near inflection points. The intersection of the lines is taken to be p or q.

Results for Sept. 2005 CS

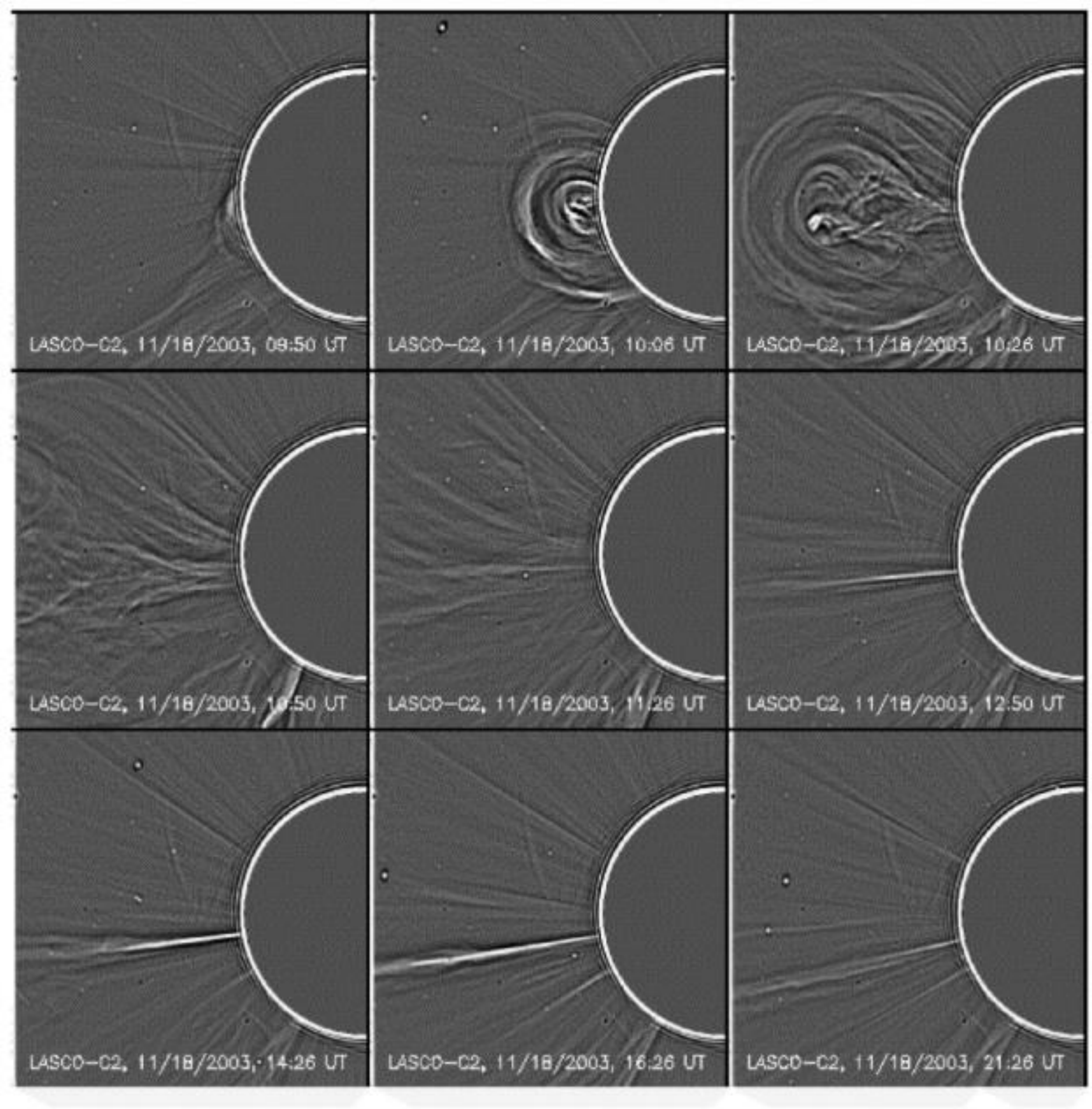


- Narrowest ray width is ~0.05 Rs (37,000 km)
- No evidence for outward motion of the X-point, or diffusion region.
- Motion of CS top (q) is meas. from 0.27 – 0.89 Rs and fit with a polynomial with final speed 780 km/s and acceleration of 0.64 km/s^2
- Over this same time period the CS length (q - p) grows from 0.13 – 0.74 Rs; avg. growth rate = 377 km/s

• **Future Work:**
- Derive densities distributions of ray
- Compare ray kinematic & mass characteristics with other studies and reconnection models

Bursty Reconnection in Current Sheet: 18-20 Nov 2003 Event

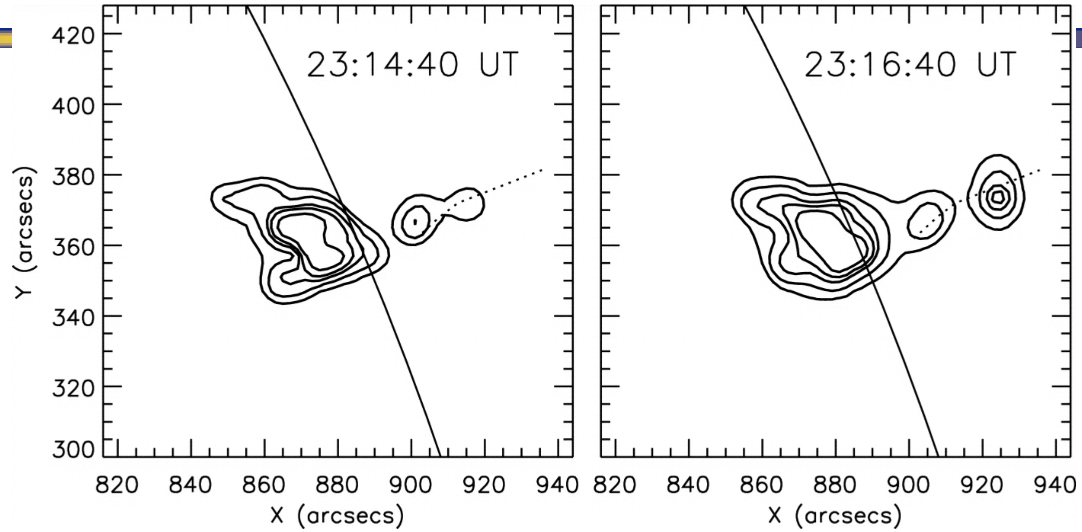
Very fast CME/FR/ray *(Lin et al., ApJ, 2005)*



RHESSI X-ray Coronal Sources & Current Sheets

RHESSI observation of 15 April 2002 flare

Work by Holman, Sui, Dennis, etc.

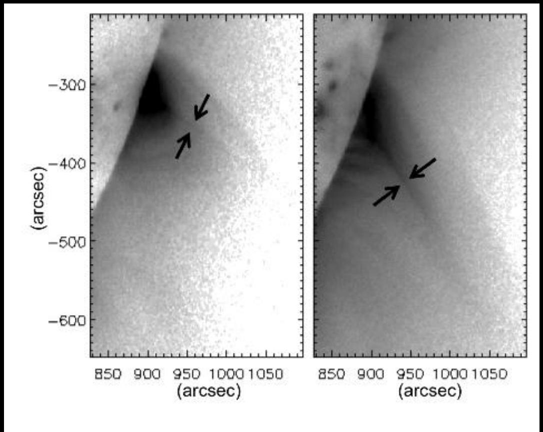


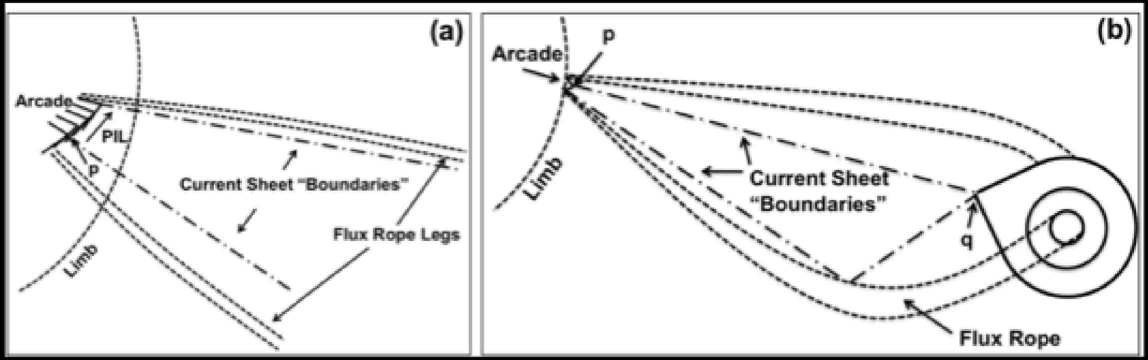
List of events that “show a compact X-ray source above the top of a roughly vertical current sheet in which magnetic reconnection was occurring”:

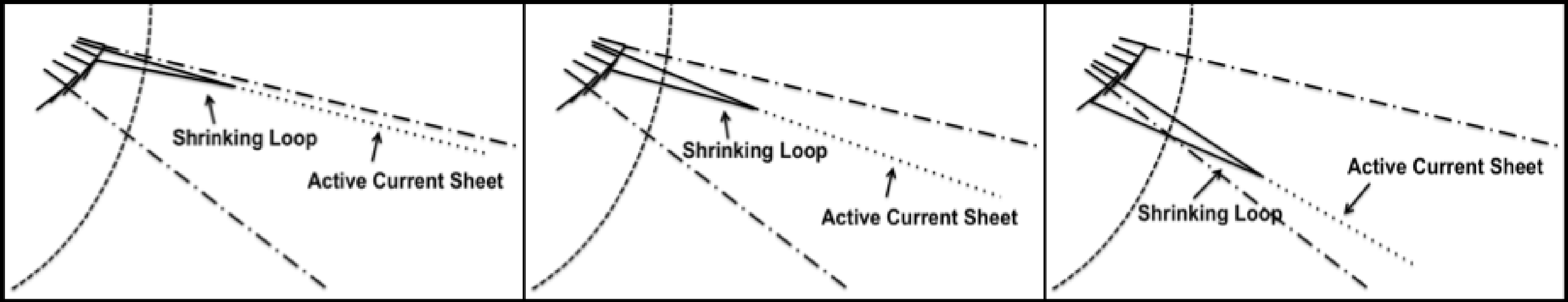
- **2002 Feb 20**
- **2002 Apr 14-15**
- **2002 Apr 15**
- **2002 Apr 16**
- **2002 Jun 2**
- **2003 Nov 3**

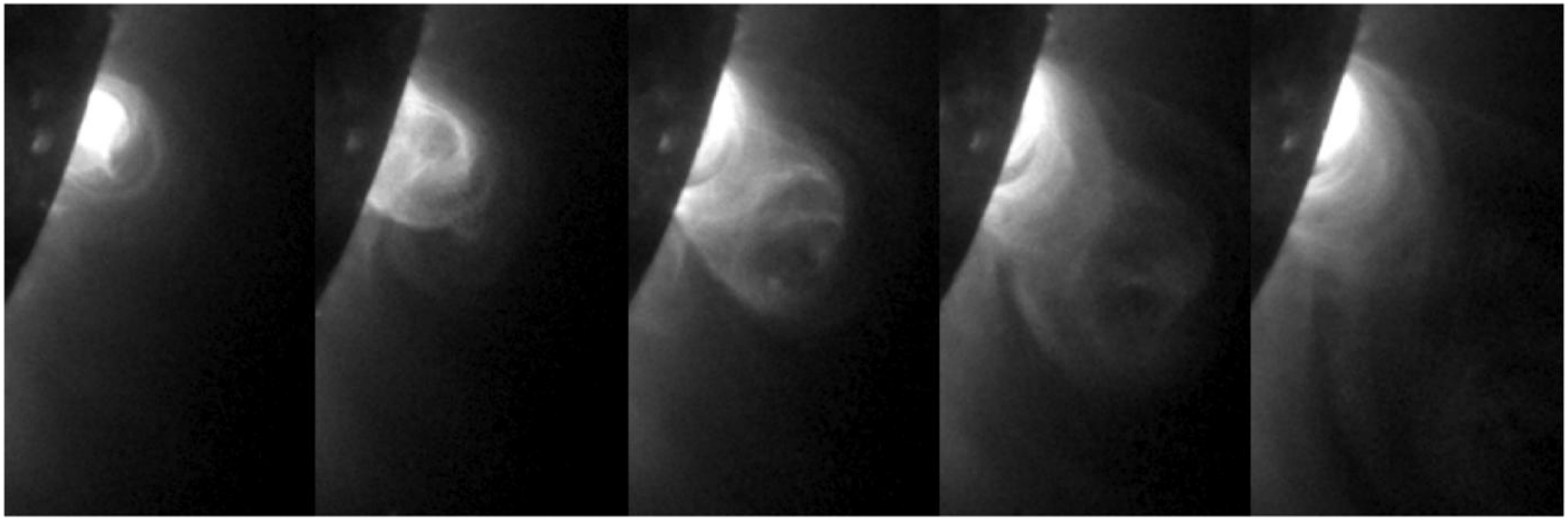
Check for associated CMEs and UVCS data

First Clear View of CS Formation in Low Corona – Hinode XRT; 9 April 2008

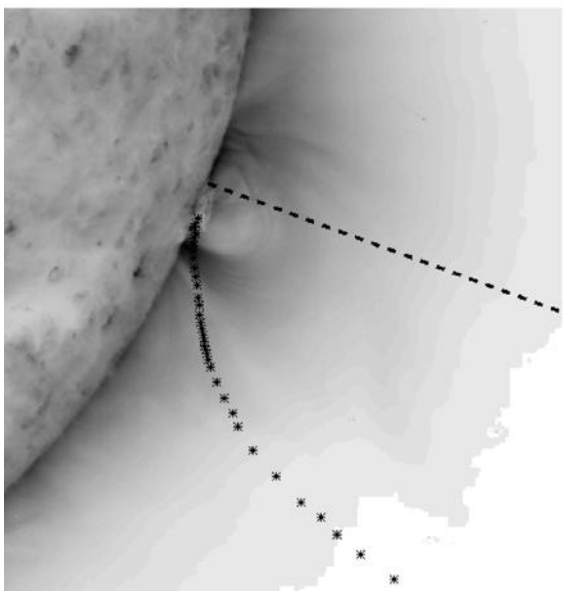




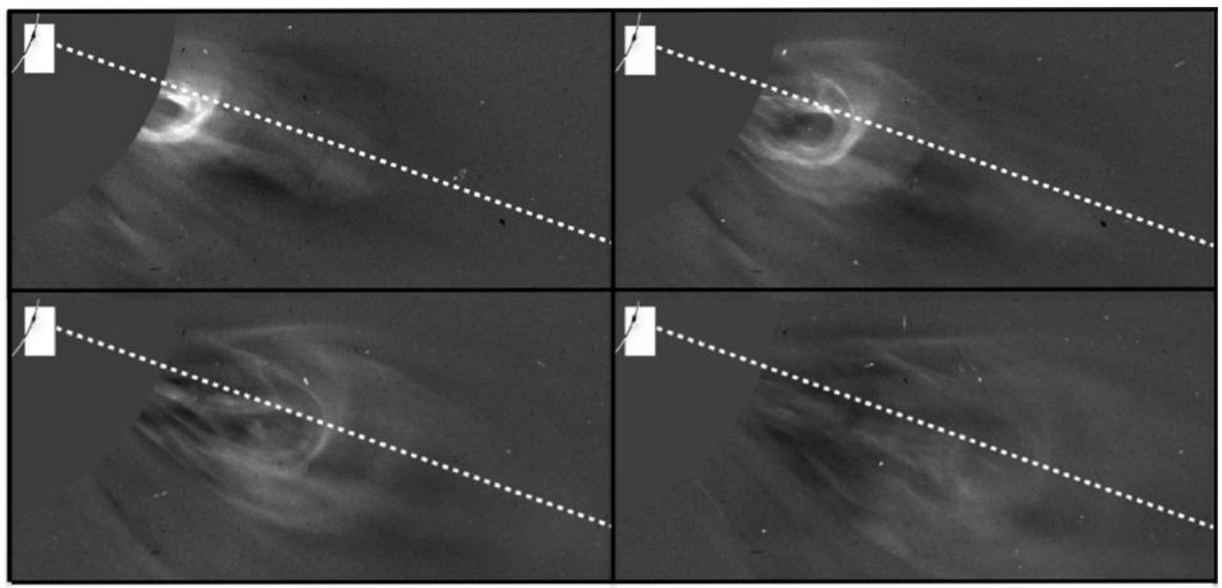




“Cartwheel” CME observed by XRT → 09:16 to 10:11 UT

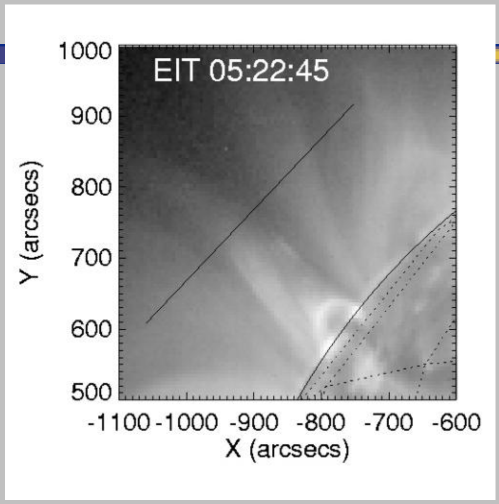


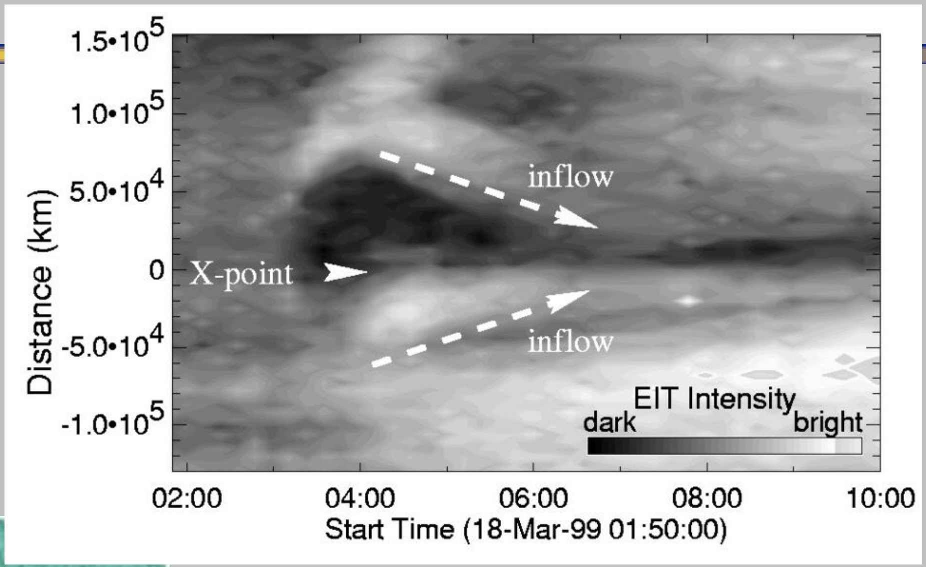
Filament eruption in STEREO EUVI-A. Dashed line → radial direction from AR. Curved path → trajectory of fil.



LASCO C2 images showing CME path beyond ~2.5 R. Dashed line → radial direction AR. XRT FOV shown in upper left corner of each image.

Measured Inflow Velocities – EUV

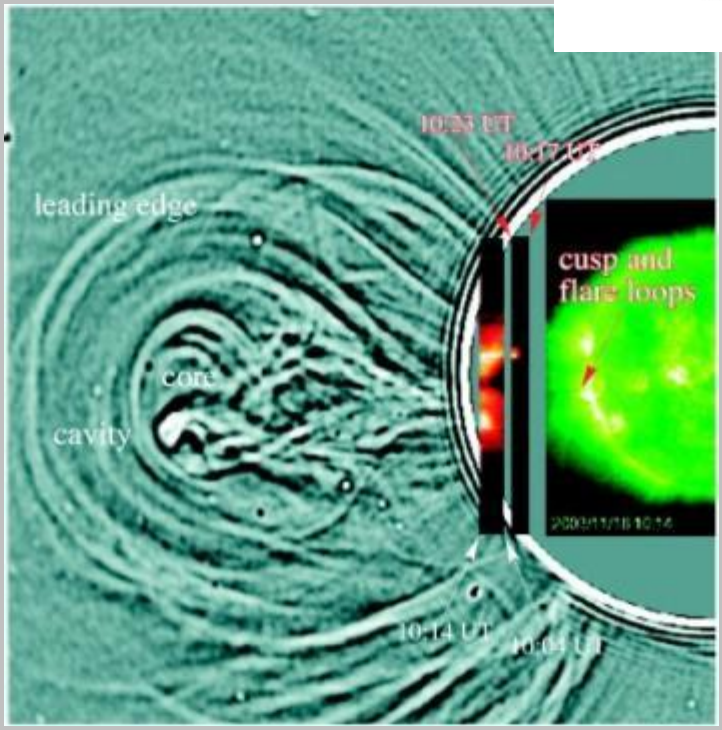




18 March 1999 – *Yokoyama et al. (2001)*

Time variation of EIT intensity across X-point region → line in left panel.

Inflow velocity ~5 km/sec at ~120,000 km

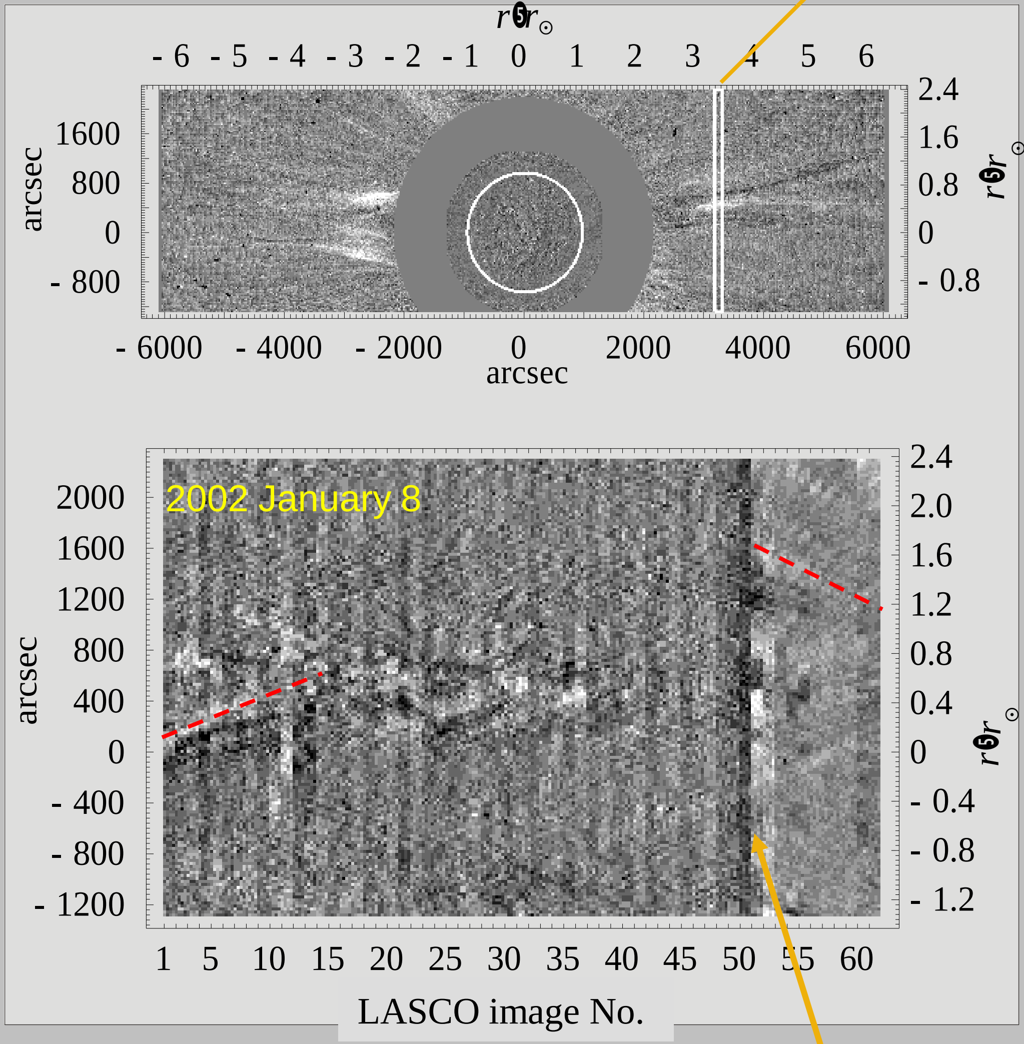


18 November 2003 Event
EIT – UVCS Lyα – LASCO
Lin et al., ApJ (2003)

Inflow velocities 10 – 105 km/s at 1.7 Rs

Inflow Velocity – White Light

cut used for the stackplot



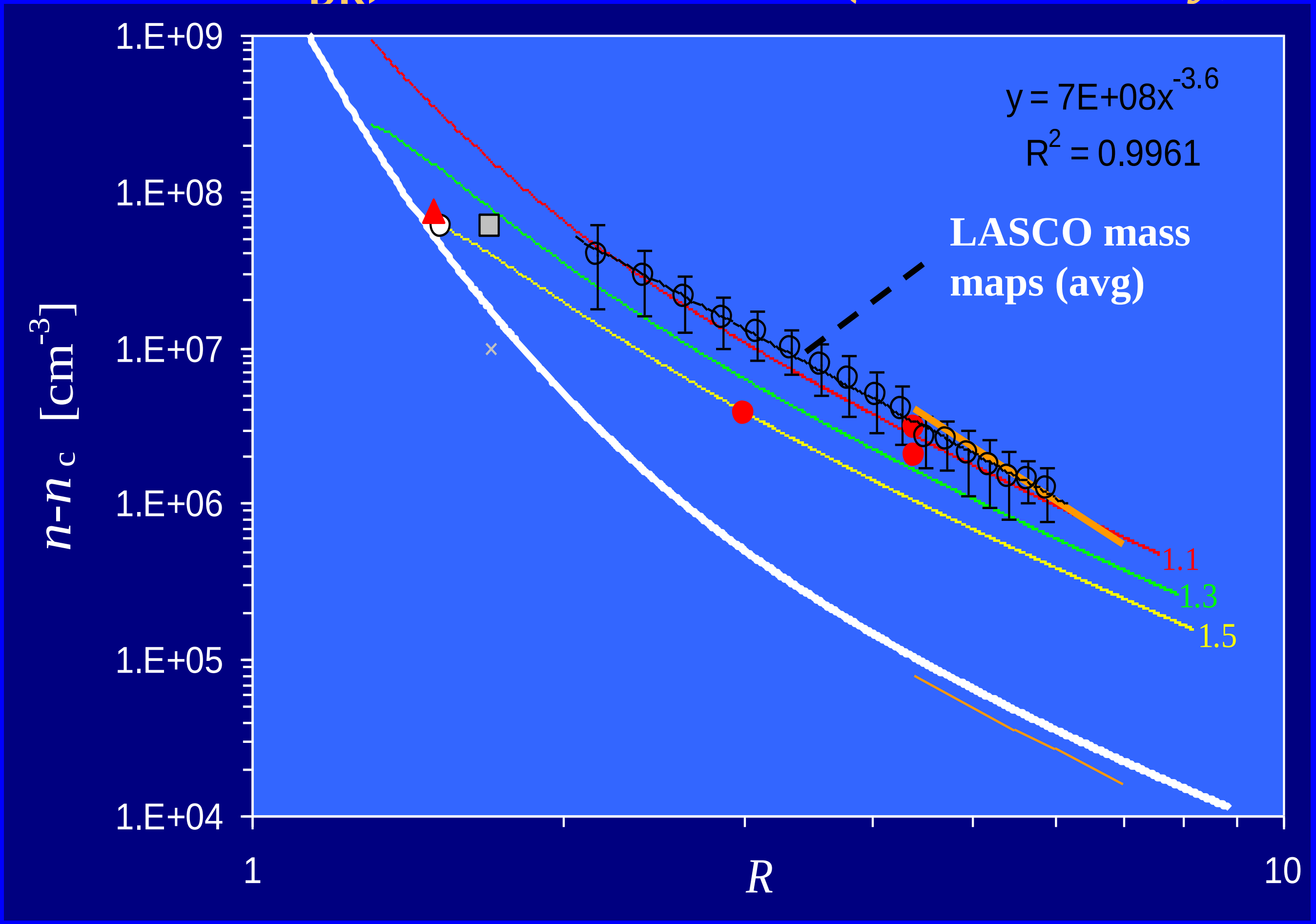
Inflow speed:
v ~ 15-25 km/s (3.5 R_s)

[Later: 25-30 km/s
driven by a disturbance
from a distant CME]

Vrsnak et al., A&A, 499, 905, 2009

disturbance from a distant CME

Comparison of Models (CS characterized by Petshek-like reconnection geometry with diffusion region located at heliocentric distance R_{DR}) & Observations *(excess density; Vrsnak et al.)*



CS model results for R_0=1.1, 1.3, 1.5

model corona

UVCS:

Ciaravella et al., ApJ 575, 1116 (2002)

Ko et al., ApJ 594, 1068 (2003)

Bemporad et al., ApJ 638, 1110 (2006)

x corona Bemporad et al. (2006)

LASCO:

Ko et al., ApJ 594, 1068 (2003)

polarization brightness, ray
Poletto et al., Ann. Geophys., in press (2008)

polarization brightness, corona
Poletto et al. (2008)

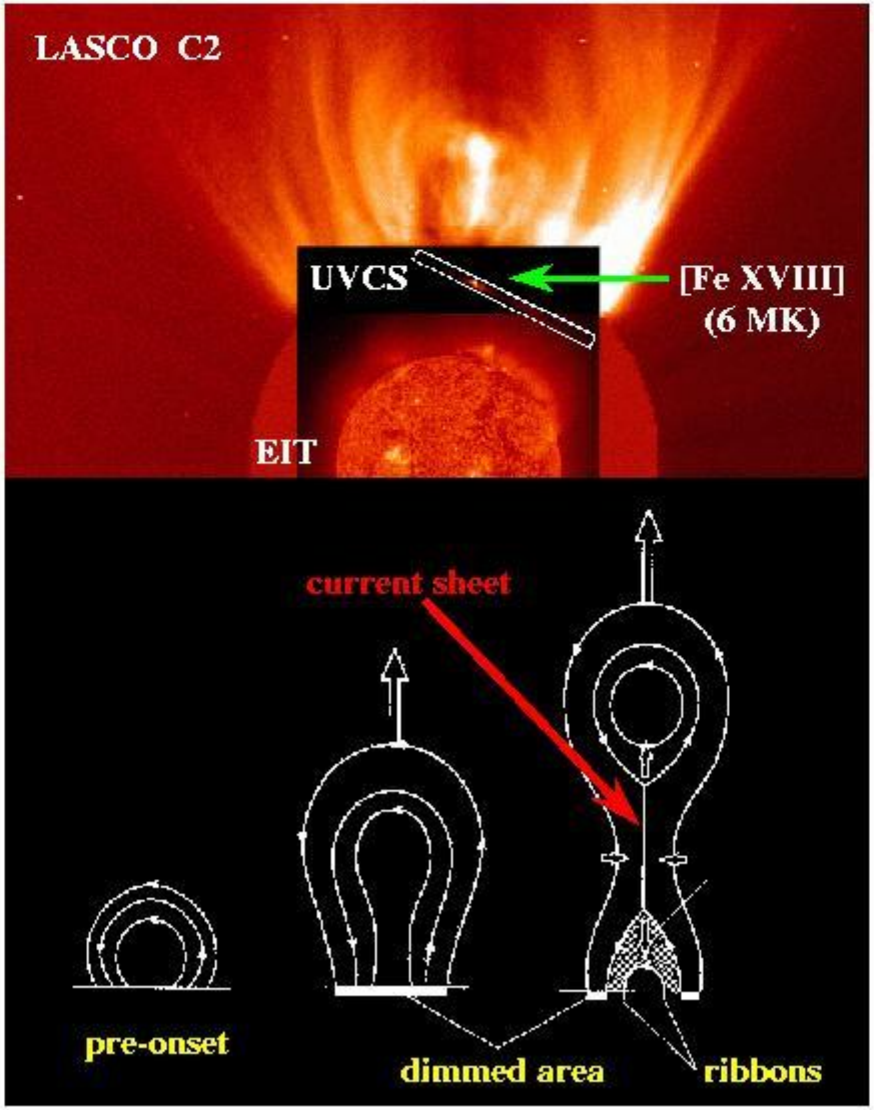
Summary: Comparison of Models & Observations

- Very good match model/obs. of $n(R)$ slopes (independent of the assumed column-length λ)
- Various types of observations (e.g., mass-maps, UVCS, PB...) give similar results
- Observed inflow speed and ray morphology consistent with Petschek-like reconnection geometry
- Problems:

  a) Unknown LOS-depth (column-length λ)
  b) Unknown diffusion region height R_0

23 March 1998 – 'Light-bulb CME'

No Trailing WL Ray but high T (Fe18) is Signature of Current Sheet



Ciaravella et al., ApJ (2002)

LASCO White Light CMEs-Rays Catalog

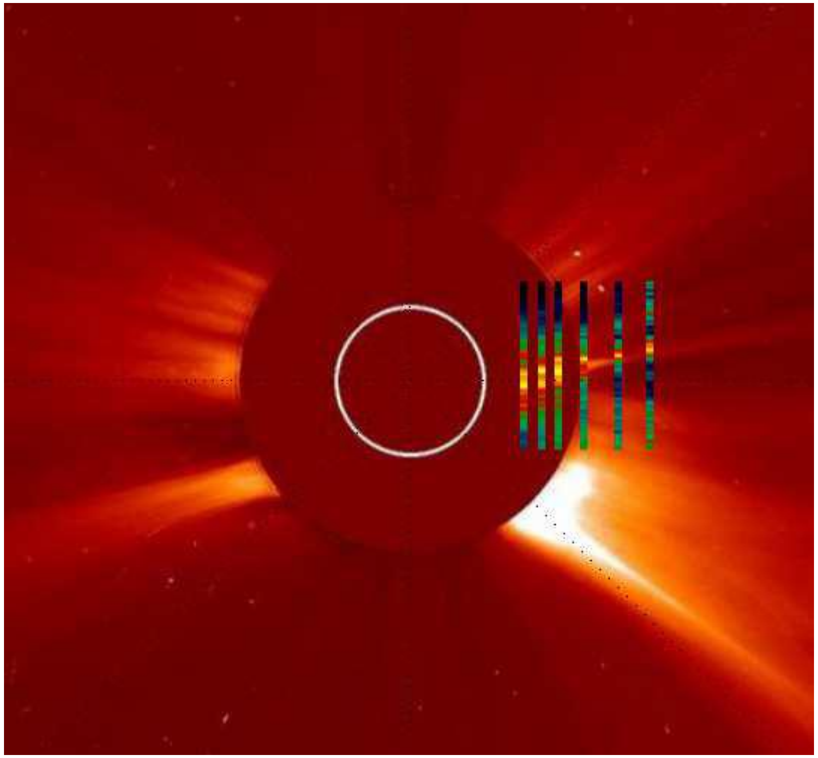
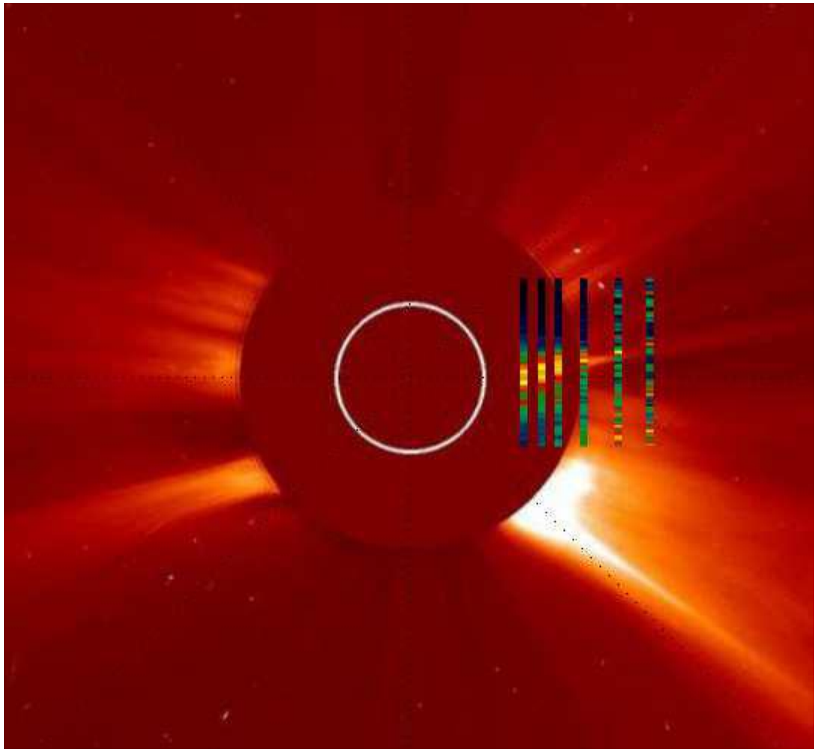
- CME speed, width; C-O; Ray; UVCS high T; Duration; Blobs; Is there a preexisting streamer?; Is a new streamer formed?
- Corresponding UVCS (A. Ciaravelli) or MLSO MK4 K-coronameter (J. Burkepile) data
  - MK4 data useful in showing the early stages of CSs
- Make width and brightness (density) measurements as f(time, height) for some of best events observed with both MLO and LASCO.

Status of Catalog

- Serendipitous events from LASCO
- J. Burkepile original list for MLSO MK3 & 4 data
- C. St. Cyr list of LASCO CMEs with C-O features: 1996- thru June 1998

- LASCO – UVCS: WL – UV Spectroscopy Study of Rays:
  - Two comprehensive surveys:
    - Solar minimum → LASCO July 1996- June 1998
    - Solar maximum → LASCO all of 2001
  - Ciaravella, Giordano & Raymond UVCS CME list through 2005

WL-UV Spectroscopy of Post CME Rays → CSs

Composite image of LASCO C2 and UVCS images for ray observed on 1998 May 22. The narrow images are O VI 1032 (left) and Si XII 520 (right) at several slit positions. UVCS slit images typical of synoptic program.

LASCO - UVCS Rays; CSs Results

- **157 WL ray events selected**
  - **Mainly from minimum (74) & maximum (83) samples but also a few others**
  - **~40% had appropriate UVCS data, usually synoptic scans**
  - **Searched for coaxial, narrow, bright features in spectra**
    - **[Fe XVIII] line best signature (hot); rarely detected except during CMEs**
    - **Also H I, O VI, Si XII emission**

- **60 LASCO rays detected in UVCS spectra:**
  - **34 had no [Fe XVIII] in the spectral range**
  - **26 had [Fe XVIII] in the spectral range**
    - **10 had [Fe XVIII] , 8 of which had Si XII**
    - **16 had no [Fe XVIII] , 9 of which had Si XII**

- **18 additional CME/rays with [Fe XVIII] selected from UVCS CME catalog, 11 of which had Si XII emission**
  - **12 had WL rays**

- **So, 78 rays with WL images and UV spectra analyzed:**
  - **- Rays with [Fe XVIII] emission usually occurred during maximum**
  - **- Wide range of UV properties with no strong corr. with associated CME speed, delay time, energy or morphology.**

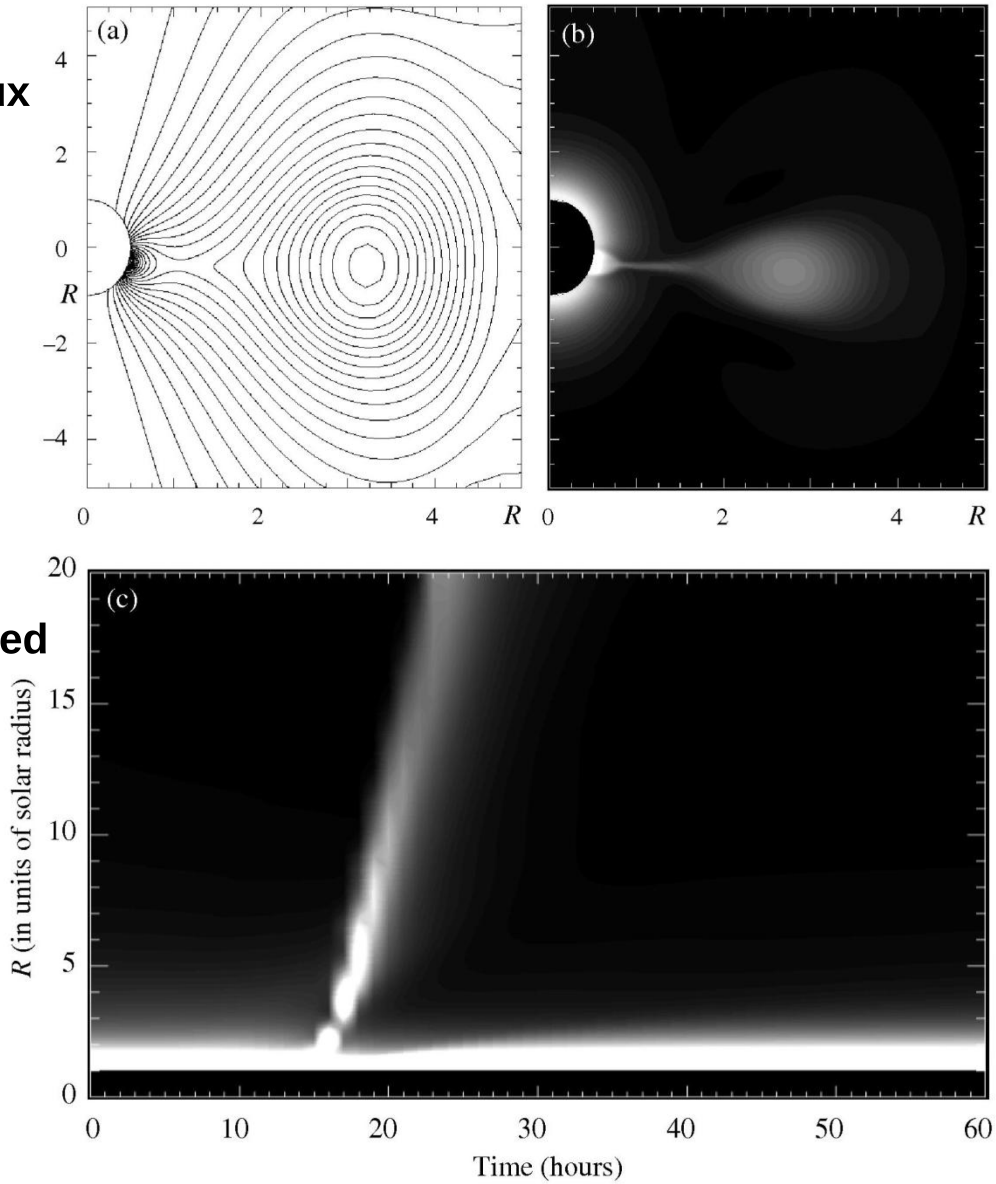
THE END

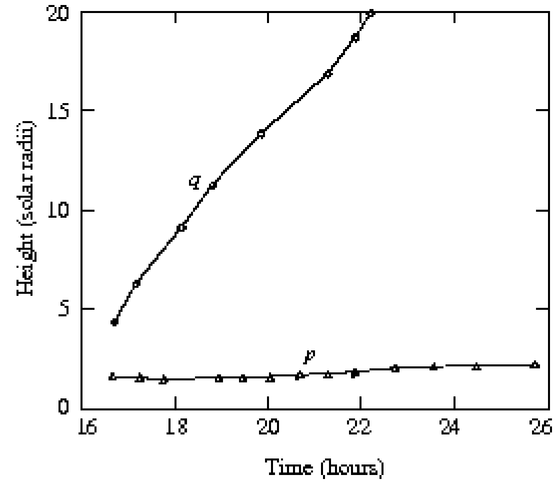
Linker et al.* model run for v~400 km/s at 3 R_s , M_A=0.1

a) Mag. flux function at 17 hr.

b) Simulated pB image at same time

c) Simulated h-t plot of pB image



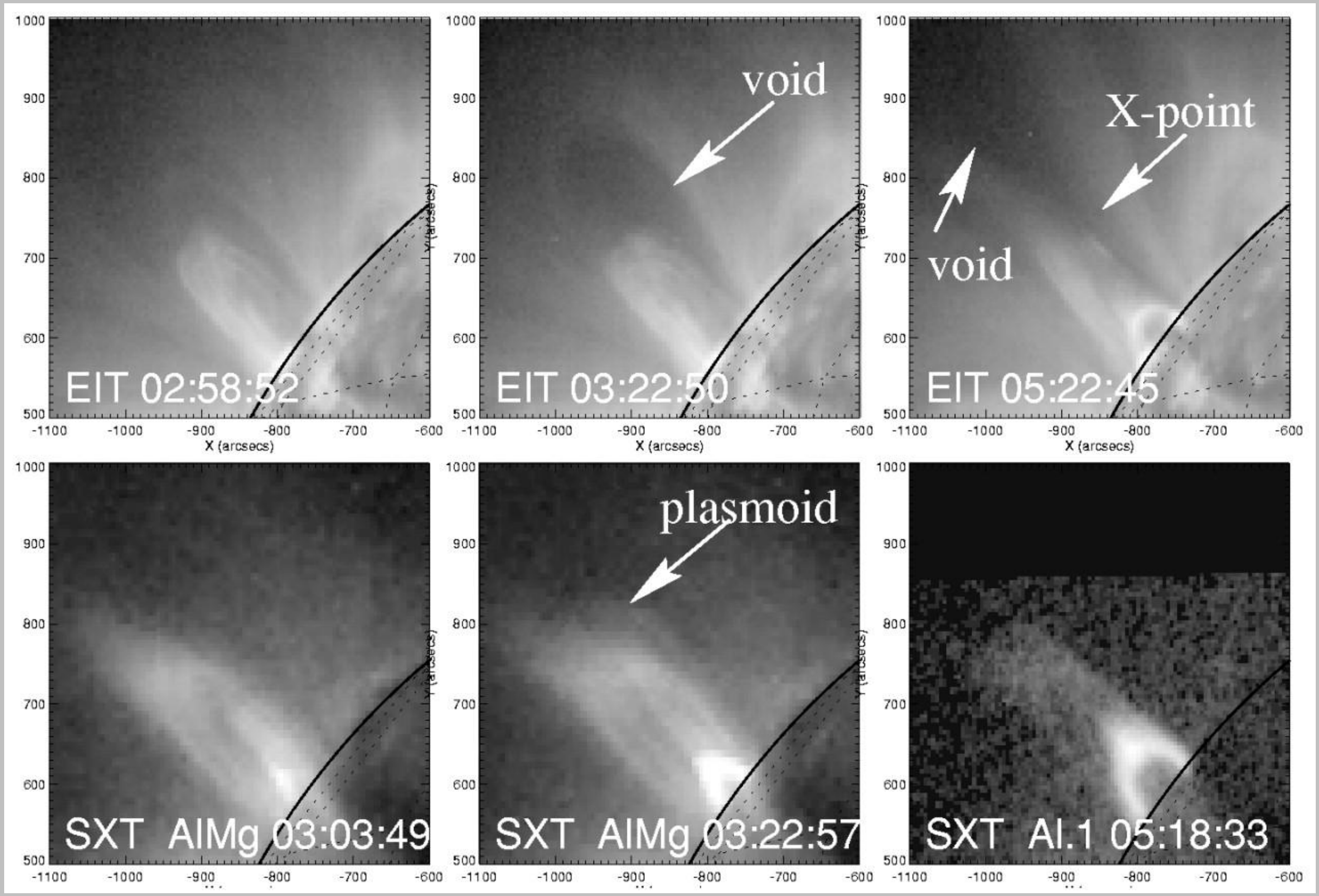


H-t plot of *q* and *p* as in L&F. Thus, *q* - *p* = length of current sheet

** Linker et al., Phys. Plas. (2003)*

18 March 1999 – Yokoyama et al. (2001) event

EIT inflow/CME/FR/broad ray(?)



A Solar Minimum Sample: 1996 - 1997

Occurrence Rates

- 224 CMEs with concave-out structure (C. St Cyr est. 40% of CMEs had C-O)
- 20% (45/224) had rays
- Suggests that ~ 10% of all CMEs have observable CSs

  - likely depends on observability factors such as how close CME/flux rope is to skyplane, tilt of CS, & background.
  - If this fraction holds during other years of cycle → rays/CSs more common feature of CMEs than thought!

Other characteristics

- CMEs (1996-1997) assoc. with the rays had wide range of speeds & widths
- Average duration of 27 rays = 17.7 hours
- Many of these CMEs were blowouts of pre-existing streamers

  - for 14 of these I could find a new streamer appearing later
  - these appeared on average ~1 day after the CME onset