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

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**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

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 and Forbes, JGR (2000)
L&F Model Current Sheet Evolution for a Set of Parameters $\Rightarrow M_A = 0.1$
CME of November 20-21, 1988

+ 1.5 hr

+ 10 hr

+ 18 hr

00 hr.
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° (2.2Rs)
  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 Rs  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

Ha limb
PICS

He 10830A
CHIP

2490 km/s!
Determining p and q for Sept. 2005 CS

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

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/s²
- 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
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

Inflow velocities 10 – 105 km/s at 1.7 Rs
Inflow Velocity – White Light

Inflow speed: \( v \sim 15\text{–}25 \text{ km/s } (3.5 R_s) \)

[Later: 25\text{–}30 \text{ km/s driven by a disturbance from a distant CME}]

\textit{Vrsnak et al., A&A, 499, 905, 2009}
Comparison of Models (CS characterized by Petshe-like reconnection geometry with diffusion region located at heliocentric distance $R_{DR}$) & Observations (excess density; Vršnak et al.)

$$y = 7 \times 10^8 x^{-3.6}$$

$R^2 = 0.9961$

LASCO mass maps (avg)

CS model results

for $R_0=1.1, 1.3, 1.5$

model corona

**UVCS:**

- corona
  - Bemporad et al. (2006)

**LASCO:**


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*polarization brightness, ray*

*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 $\lambda$)

• 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 $\lambda$)
  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

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
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 $v \sim 400$ km/s at $3 R_s$, $M_A = 0.1$

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

18 March 1999 – Yokoyama et al. (2001) event
EIT inflow/CME/FR/broad ray(?)

void

X-point

plasmoid
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