

Modeling and Measuring the Flux Reconnected by the Two-ribbon Flare on 2004-11-07

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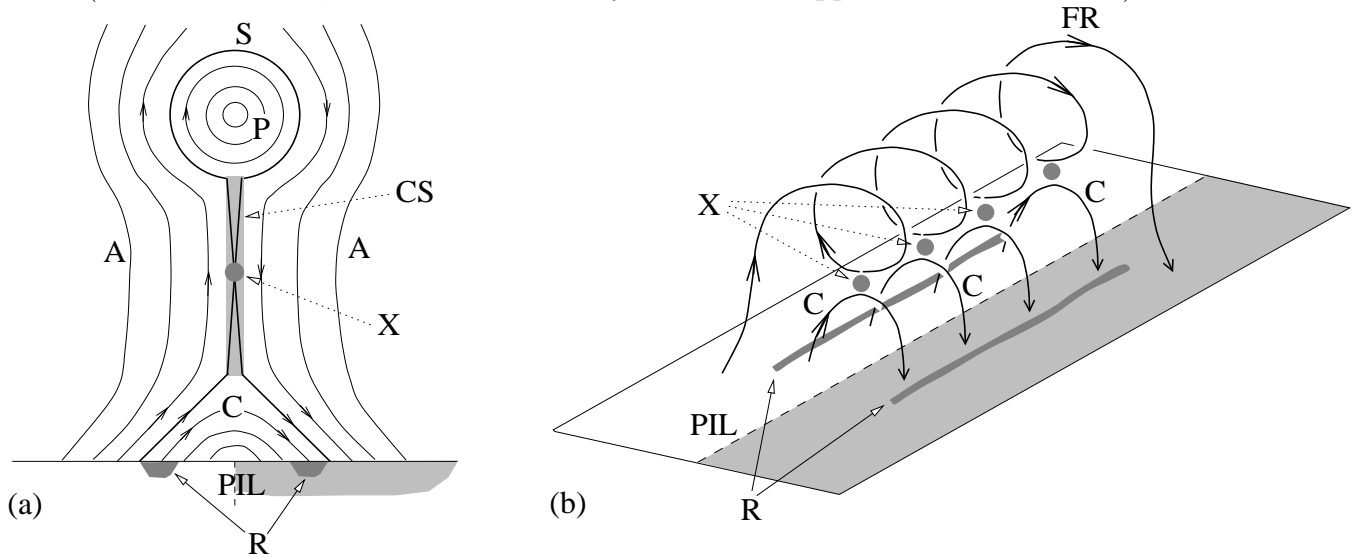
- I. Two Ribbon Flares
- II. Magnetic Model for AR 10696
- III. The Flare and its 2 Ribbons
- IV. Quantifying the Reconnected Flux
- V. Energy/Helicity Storage & Release
- VI. Flare Energetics
- VII. Flux Rope Creation

† Work supported by NASA grant NAG5-10489

I. Two ribbon flares

- Classical (2d) CSHKP model — (a)

(Carmichael 1964; Sturrock 1968; Hirayama 1974; Kopp and Pneuman 1976)



- 3d generalization (b) — (Gosling 1990; Gosling *et al.* 1995)

- Recon'n flux: magnetic flux swept by flare ribbons (R)

(Forbes & Priest 1984; Poletto & Kopp 1986; Fletcher *et al.* 2001; Qiu *et al.* 2002)

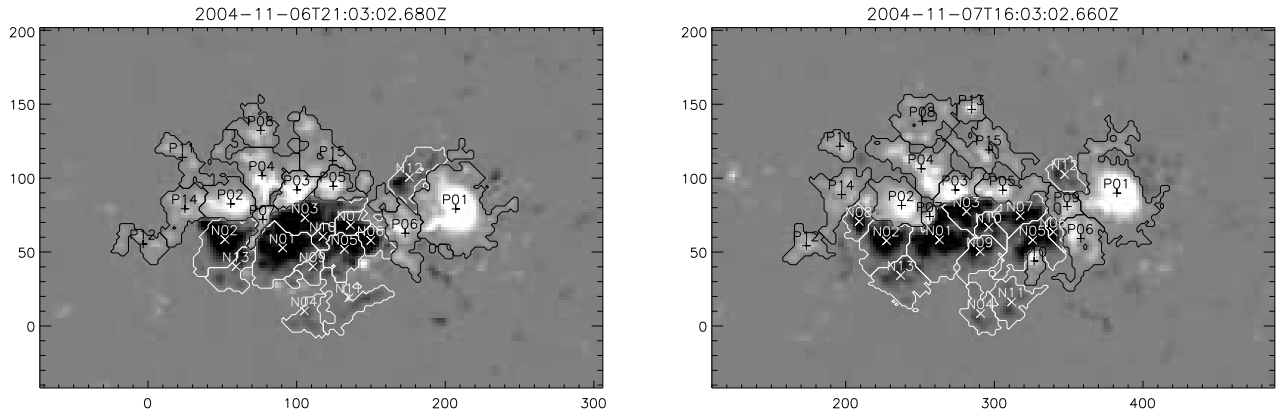
- Ejected flux rope (FR) → Magnetic Cloud (MC) at 1 AU

(Burlaga *et al.* 1981; Lepping *et al.* 1990)

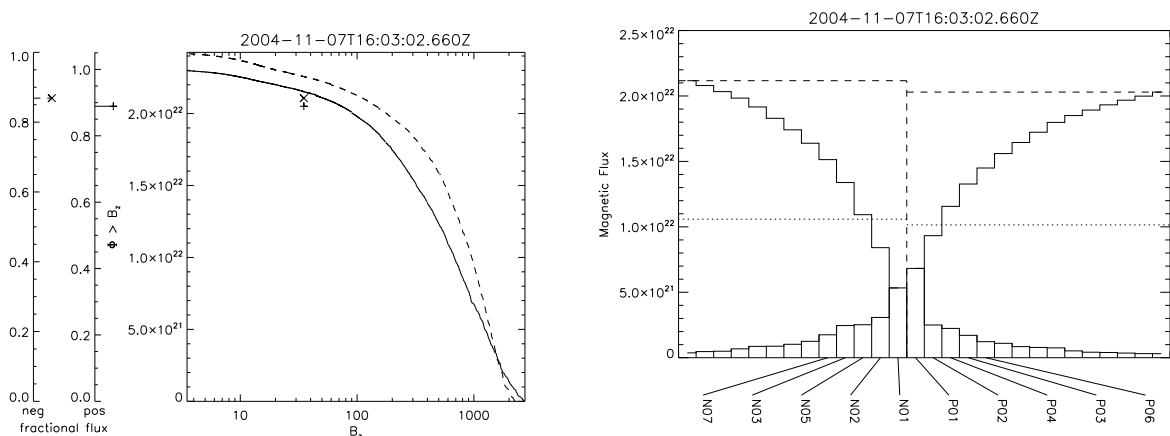
Outstanding Questions/Challenges

- ★ Predicting ribbon flux from photospheric shear
- ★ Predicting energy storage/release from photospheric shear
- ★ Relating ribbon flux to MC flux (Leamon *et al.* 2004)
- ★ How many sites (X) reconnect — in what order?
- ★ Why do ribbon features move || to ribbon? (Fletcher *et al.* 2004)

II. The Magnetic Model of AR 10696



- 40 Hourly MDI FD magnetograms (Scherrer *et al.* 1995)
- $\times 1.56$ calibration factor (Berger & Lites 2003)
- P-spheric \mathbf{v} from LCT (November & Simon 1988)
- Partition into unipolar regions (Barnes *et al.* 2005; Longcope *et al.* 2006)
 - $B_z > 35$ G; Label downhill from local maxes
 - Merge saddles < 300 G or $\Phi < 7.6 \times 10^{19}$ Mx
 - Label regions from reference advected with \mathbf{v}



Histograms summarizing the mask (left) and partitioning (right)

LEFT: pos/neg = solid/dashed; +/× amount in partition

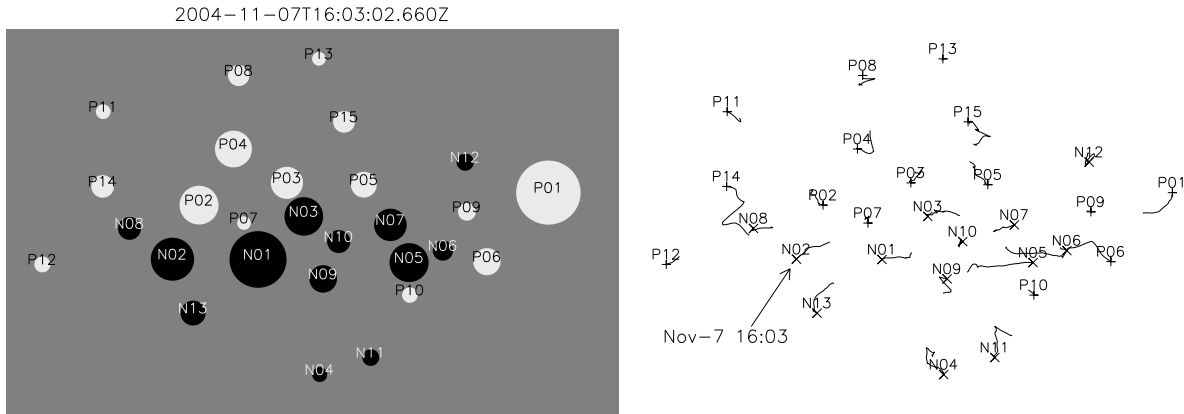
RIGHT: Bars: flux in regions; stair-steps: cummulative flux

Magnetic Model (cont'd)

- Characterize region \mathcal{R}_a by net flux & centroid

$$\Phi_a = \int_{\mathcal{R}_a} B_z(x, y) dx dy \quad , \quad \bar{\mathbf{x}}_a = \frac{1}{\Phi_a} \int_{\mathcal{R}_a} \mathbf{x} B_z(x, y) dx dy \quad .$$

- Project onto co-rotating tangent plane (correct Φ_a for LOS)
- Φ_a s change very little \implies simplify by making them const.
- Smooth $\bar{\mathbf{x}}_a(t)$ (five-hour box-car) — reduce centroiding noise



Fluxes & centroids (left); centroid trajectories (right)

Helicity Injection

$$\Delta H / \Phi^2 = -1/3 \text{ turn}$$

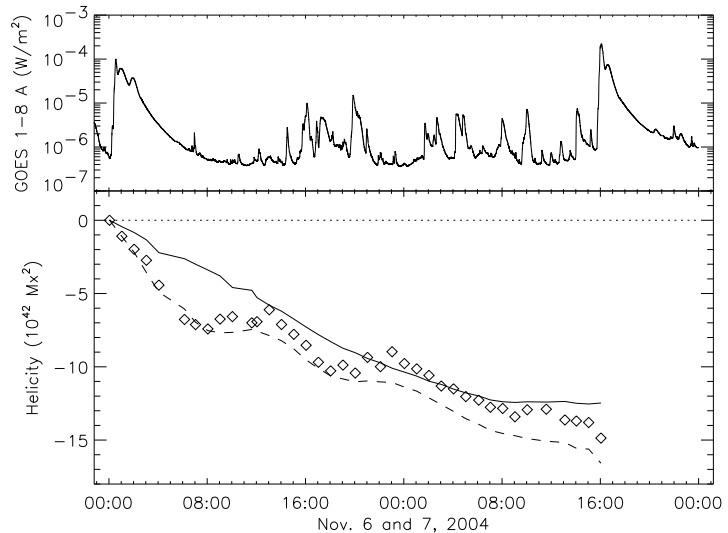
Full fields B_z & \mathbf{v} :

$$\dot{H} = -2 \int (\mathbf{v} \cdot \mathbf{A}_P) B_z dx dy$$

Centroids only:

$$\dot{H}_{\text{br}} = -\frac{1}{2\pi} \sum_a \sum_{b \neq a} \Phi_a \Phi_b \frac{d\theta_{ab}}{dt}$$

$$\tan \theta_{ab} = \frac{\bar{y}_b - \bar{y}_a}{\bar{x}_b - \bar{x}_a}$$

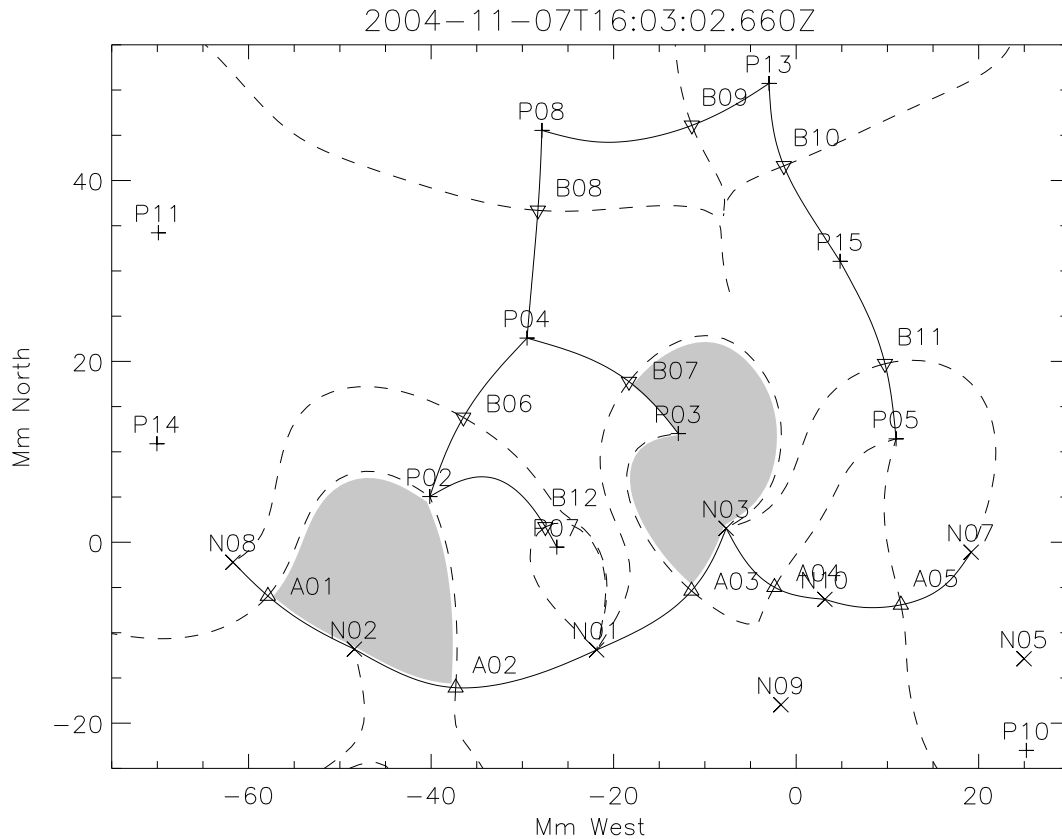


The Coronal Field: Connectivity

- Field lines $Pa \rightarrow Nb$: Domain $Pa-Nb$ a.k.a. a/b
- Total flux in domain:

$$\int \mathbf{B} \cdot d\mathbf{a} = \psi_{a/b}$$

- For potential (vacuum) field: $\psi_{a/b} = \psi_{a/b}^{(v)}$
- Footprint (below) outlines domains at $z = 0$



- +s, & -s: centroids; \triangle s & ∇ s: null points
- Dashed lines: separatrices; solid lines: spines
- Shaded domains: $P02-N02$ and $P03-N03$

A Sheared Arcade?

- Begin after M-flare Nov-6 00:11
- End before X2 flare Nov-7 15:42
- Sources move
 - ⇒ potential field changes
 - ⇒ connections $\psi_{a/b}^{(v)}$ change

	N01	N02	N03	N07	N10	Φ_a
P01	0.73 + 0.64 1.37	0.00 + 0.05 0.05	0.09 - 0.09 0.00	0.72 + 0.09 0.81	0.68 - 0.34 0.34	6.82
P02	0.03 + 1.01 1.04	2.15 - 0.77 1.38	-	-	-	2.50
P03	0.95 - 0.84 0.12	-	0.67 + 0.90 1.57	-	0.04 - 0.04 0.00	1.71
P04	1.85 - 0.36 1.49	0.21 + 0.18 0.40	0.03 + 0.27 0.30	-	0.12 - 0.12 0.00	2.24
P05	-	-	1.08 - 0.88 0.20	0.02 + 0.58 0.61	0.00 + 0.30 0.30	1.10
P15	0.00 + 0.00 0.00	0.00 + 0.00 0.00	0.60 - 0.24 0.36	0.18 + 0.00 0.18	0.02 + 0.23 0.25	0.78
Φ_b	5.33	3.08	2.46	1.75	0.88	

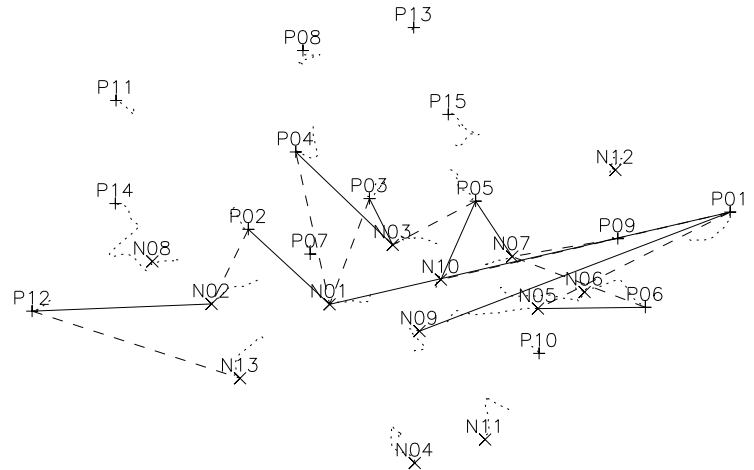
Domain fluxes $\psi_{a/b}^{(v)}$ and their changes $\Delta\psi_{a/b}^{(v)}$ in units of 10^{21} Mx. Each entry gives the fluxes at $t_1 = \text{Nov-6 00:03}$ (upper left) and $t_2 = \text{Nov-7 16:03}$ (lower right) and the net change (center); a dash indicates that no connection exists between those sources.

		N03			
		$\psi_{5/3}^{(v)}(t_1)$			$\Delta\psi_{5/3}^{(v)}$
P05		1.08	-0.88	0.20	$\psi_{5/3}^{(v)}(t_2)$

Clockwise shearing:

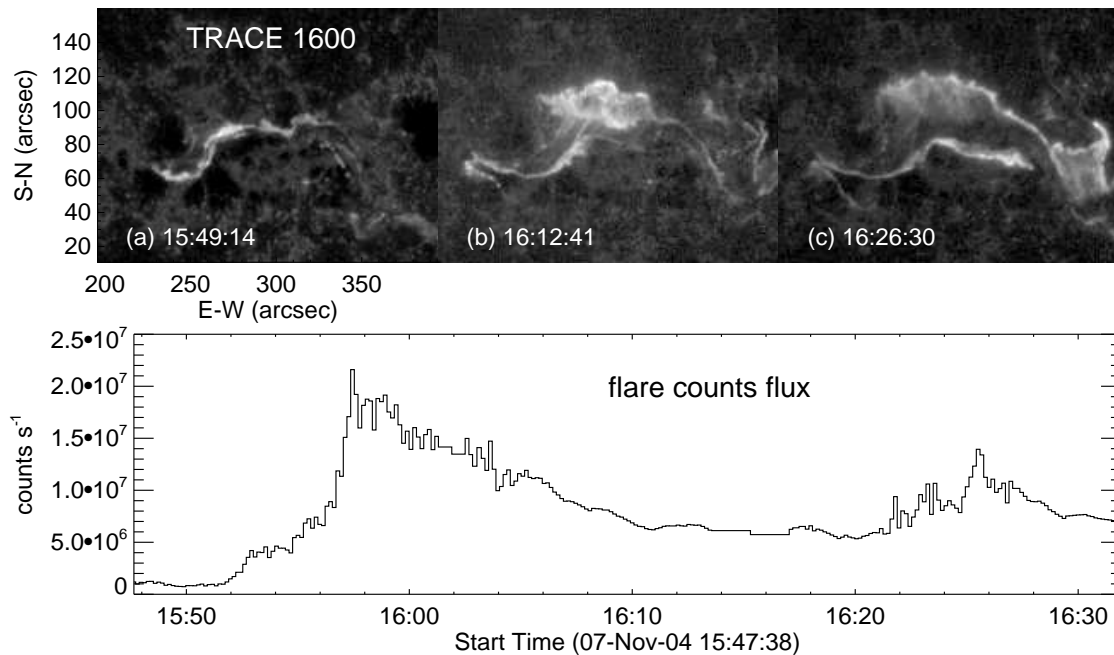
$$\dot{\theta}_{+-} < 0 \implies \dot{H} < 0$$

- 've sources break connections
- Eastward ($\Delta\psi^{(v)} < 0$ dashed)
- form new connections
- Westward ($\Delta\psi^{(v)} > 0$ solid)



III. The Flare and its 2 Ribbons

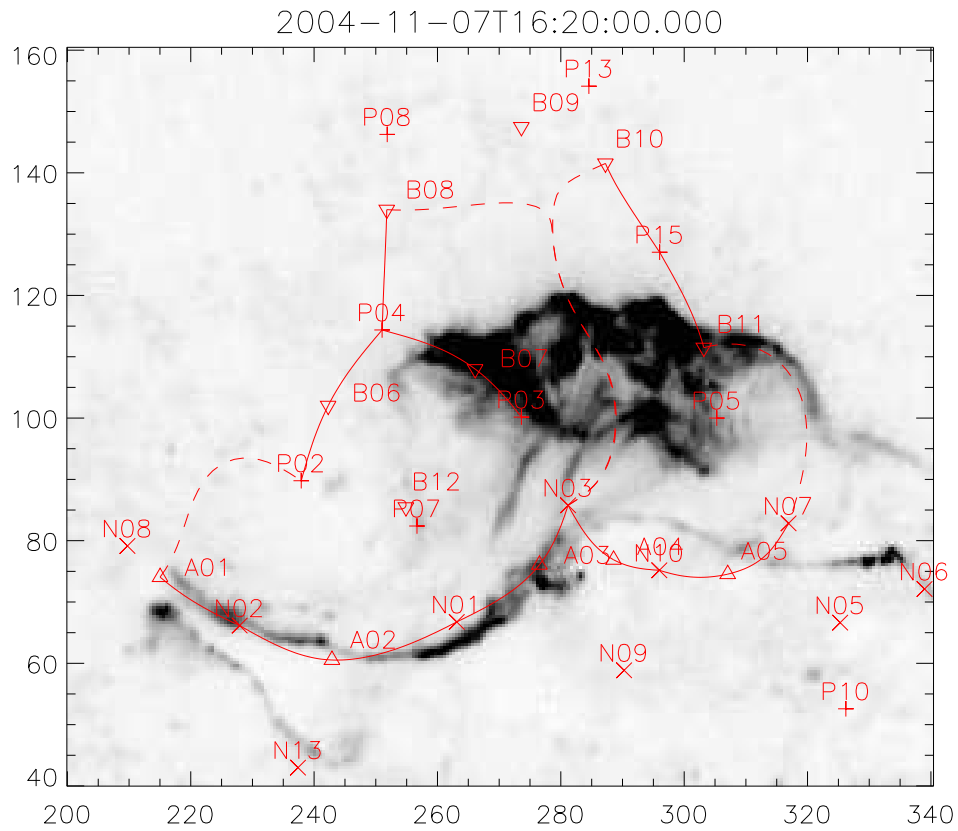
- GOES class X2 flare: Nov-7 15:42
- Ribbons observed in 1600 Å by TRACE (Handy *et al.* 1999)
- 15:36 – 16:40 at cadence of 2–4 seconds
- Sequence co-aligned to reference via cross-correlation to non-flaring reference region \implies sub-pixel accuracy



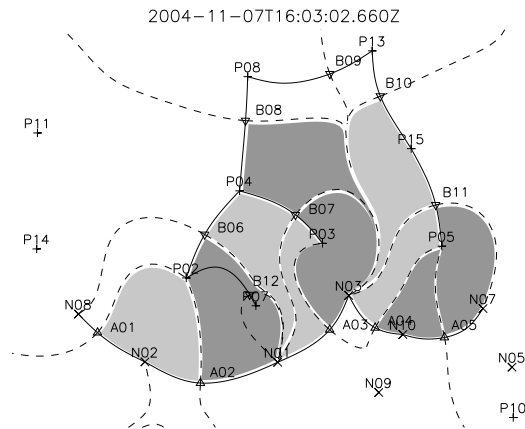
- 2 flare phases in total count rate (bottom)

The Ribbons

- Superpose footprint (red) on 1600 Å image (reverse grey)

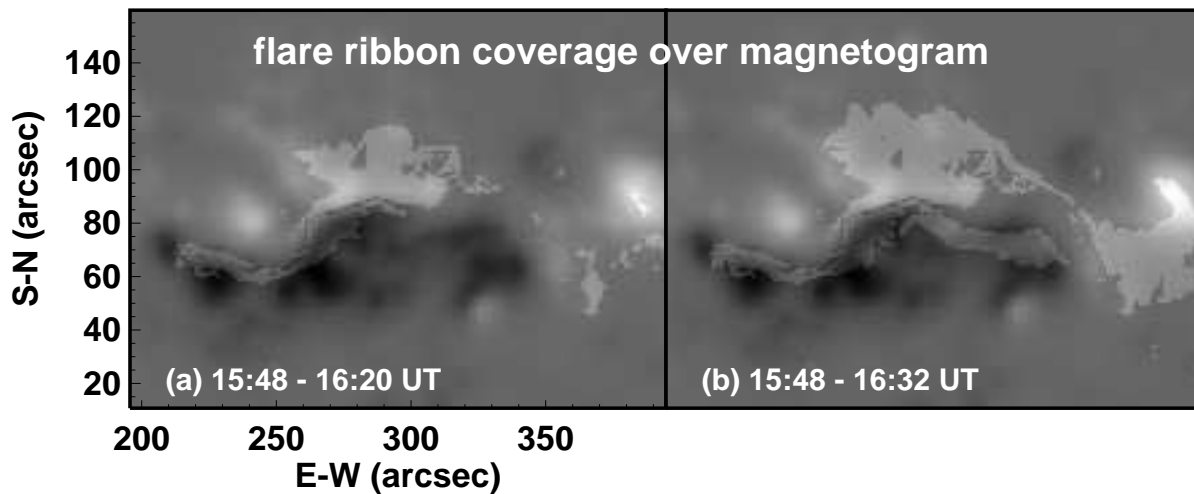


- Suggests reconnection between domains interconnecting
 Positive (North) line: $P02, P04, P07, P03, P15, P05$
 Negative (South) line: $N02, N01, N03, N10, N07$



IV. Measuring the Reconnected Flux

- 1600 Å seq. aligned to avg'd MDI m-gram centered @ 15:11
- Extrapolate m-gram (pot'l field) 2,000 km to chromosphere
- Identify “ribbon pixels” in TRACE images:
brightens* in running average of 10 1600Å frames
*: exceeds intensity threshold
- Tally flux in corresponding MDI pixels —
 Σ +’ve pixels = Ψ_+ ; Σ -’ve pixels = Ψ_-



Ribbon pixels (grey) during initial phase (left) & entire flare (right)

- Repeat, varying alignment & ribbon-intensity threshold

Initial (Eastern) phase of flare (a) reconnects

$$\Psi_+ = 2.3 \pm 0.2 \times 10^{21} \text{ Mx} \quad , \quad \Psi_- = 2.6 \pm 0.5 \times 10^{21} \text{ Mx}$$

Entire flare (b) reconnects

$$\Psi_+ = 4.8 \pm 0.3 \times 10^{21} \text{ Mx} \quad , \quad \Psi_- = 4.6 \pm 0.6 \times 10^{21} \text{ Mx}$$

Modeling the Flux Transfer

- Assume potential field after M-flare $t_1 = \text{Nov-6 00:11}$

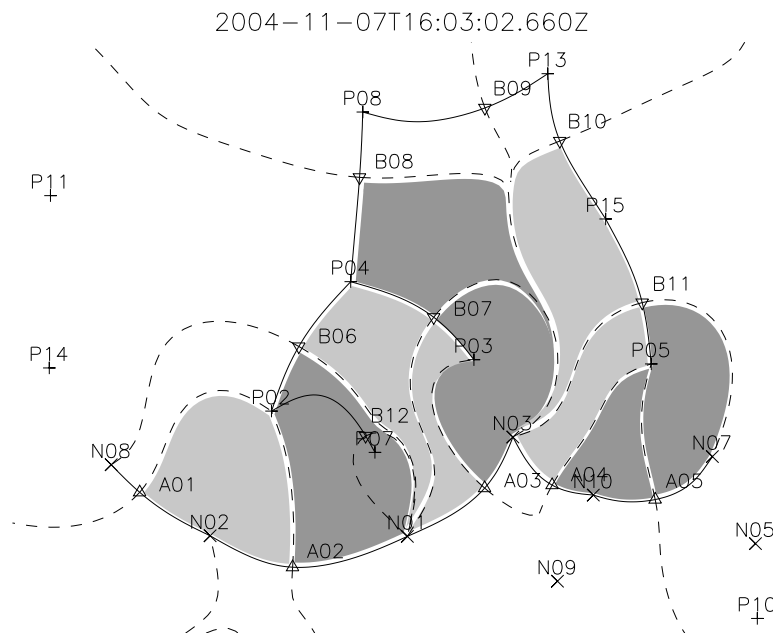
$$\psi_{a/b}(t_1) = \psi_{a/b}^{(v)}(t_1)$$

- Fluxes do not change thereafter: $\psi_{a/b}(t) = \psi_{a/b}^{(v)}(t_1)$
- Build up discrepancy from pot'l field

$$\Delta\psi_{a/b} = \psi_{a/b} - \psi_{a/b}^{(v)}(t) = -\Delta\psi_{a/b}^{(v)} \neq 0$$

- Discrepancies in intra-ribbon domains:

$\Delta\psi_{a/b}$	N02	N01	N03	N10	N07	Σ
P02	0.77	-1.01	-	-	-	-0.24
P07	0.10	-0.09	-	-	-	0.01
P04	-0.18	0.36	-0.27	0.12	-	0.03
P03	-	0.84	-0.90	0.04	-	-0.02
P15	-0.00	-0.00	0.24	-0.23	-0.00	0.00
P05	-	-	0.88	-0.30	-0.58	0.00
Σ	0.69	0.10	-0.04	-0.37	-0.59	



Light: $\Delta\psi_{a/b} > 0$; Dark: $\Delta\psi_{a/b} < 0$

- Complete relaxation:* $\psi_{a/b} \rightarrow \psi_{a/b}^{(v)}$ ($\Delta\psi_{a/b} \rightarrow 0$)
- Transfer flux across separators \implies reconnection
 - ↑: X-fer **in** to make $\psi_{a/b} \uparrow$ (when $\Delta\psi_{a/b} < 0$)
 - ↓: X-fer **out** to make $\psi_{a/b} \downarrow$ (when $\Delta\psi_{a/b} > 0$)
- Would require total x-fer of:

$$\Delta\Psi_{\downarrow} = \sum_{\Delta\psi>0} \Delta\psi_{a/b} = 3.36 \times 10^{21} \text{ Mx} ,$$

$$\Delta\Psi_{\uparrow} = \sum_{\Delta\psi<0} |\Delta\psi_{a/b}| = 3.57 \times 10^{21} \text{ Mx} .$$

$\Delta\psi_{a/b}$	N02	N01	N03	N10	N07	Φ_a
P02	0.77	-1.01	-	-	-	2.50
P07	0.10	-0.09	-	-	-	0.31
P04	-0.18	0.36	-0.27	0.12	-	2.24
P03	-	0.84	-0.90	0.04	-	1.71
P15	-0.00	-0.00	0.24	-0.23	-0.00	0.78
P05	-	-	0.88	-0.30	-0.58	1.10
Φ_b	3.08	5.33	2.46	0.88	1.75	

- Compare to
 - Total of fluxes in affected sources

$$\sum_{+} \Phi_a = 8.3 \times 10^{21} \text{ Mx} , \quad \sum_{-} \Phi_b = 13.5 \times 10^{21} \text{ Mx}$$

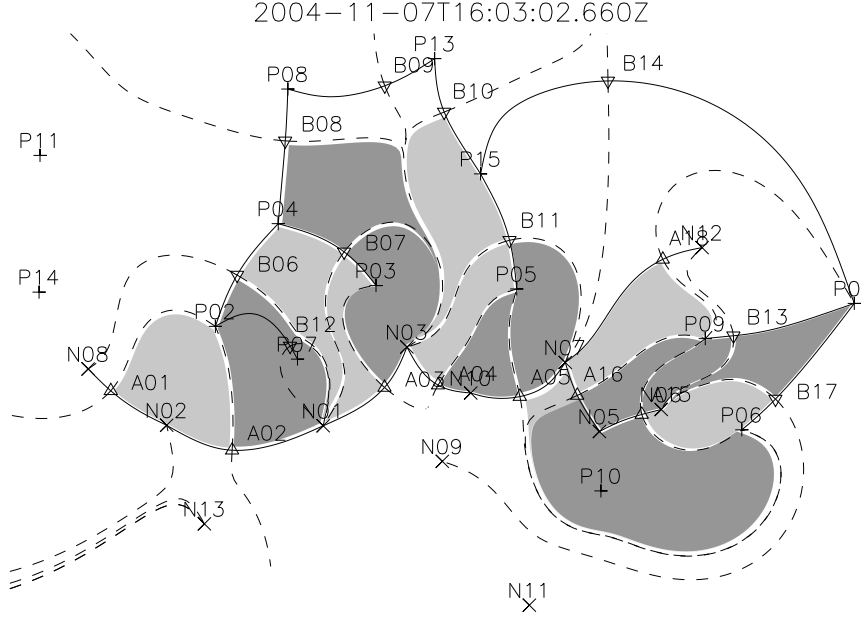
- Observed ribbon fluxes in intitial phase

$$\Psi_{+} = 2.3 \pm 0.2 \times 10^{21} \text{ Mx} , \quad \Psi_{-} = 2.6 \pm 0.5 \times 10^{21} \text{ Mx} .$$

- * Incomplete relaxation $\implies \Psi_{\pm} < \Delta\Psi_{\downarrow}$ — as observed

Flux Transfer in the Full Flare

Include Western sources: $P01$, $P06$, $P09$, $N05$, $N06$



$\Delta\psi_{a/b}$	N02	N01	N03	N10	N07	N05	N06	Σ
P02	0.77	-1.01	-	-	-	-	-	-0.24
P07	0.10	-0.09	-	-	-	-	-	0.01
P04	-0.18	0.36	-0.27	0.12	-	-	-	0.03
P03	-	0.84	-0.90	0.04	-	-	-	-0.02
P15	-0.00	-0.00	0.24	-0.23	-0.00	-	-	0.00
P05	-	-	0.88	-0.30	-0.58	-	-	0.00
P01	-0.05	-0.64	0.09	0.34	-0.09	0.85	-0.07	0.42
P06	-	-	-	0.00	0.34	-0.55	0.21	-0.00
P09	-	-	-	-	0.33	-0.18	-0.15	-0.00
Σ	0.63	-0.54	0.05	-0.03	-0.01	0.12	-0.01	

$$\Delta\Psi_{\downarrow} = 5.52 \times 10^{21} \text{ Mx} \quad , \quad \Delta\Psi_{\uparrow} = 5.32 \times 10^{21} \text{ Mx} \quad .$$

Observed ribbon fluxes for entire flare

$$\Psi_{+} = 4.6 \times 10^{21} \text{ Mx} \quad , \quad \Psi_{-} = 4.5 \times 10^{21} \text{ Mx} \quad .$$

Once again $\Psi_{\pm} < \Delta\Psi_{\uparrow}$ — incomplete relaxation (?)

V. Energy/Helicity Storage & Release

Minimum Current Corona: constrain domain fluxes

- Minimize magnetic energy

$$W = \frac{1}{8\pi} \int |\mathbf{B}|^2 d\mathbf{x}$$

- Constrain all domain fluxes $\psi_{a/b}$
- Equivalent to constraining fluxes through separators, ψ_i
- Equivalent to fixing discrepancies $\Delta\psi_i \equiv \psi_i - \psi_i^{(v)}$
- Minimum = FCE*: $\nabla \times \mathbf{B} = 0$ except for ...
- ... Singular current ribbons along separators
- Estimate current I_i on each separator

$$\Delta\psi_i \simeq I_i L_i \ln(e I_i^* / |I_i|) + \sum_{j \neq i} M_{ij} I_j$$

L_i = length of (pot'l-field) separator

I_i^* = mean \perp magnetic shear about (pot'l-field) separator

M_{ij} = mutual inductance

- Free energy stored (prior to flux x-fer)

$$\Delta W \simeq \sum_i \frac{1}{2} L_i I_i^2 \ln(e^{1/2} I_i^* / |I_i|) + \sum_i \sum_{j \neq i} \frac{1}{2} M_{ij} I_i I_j$$

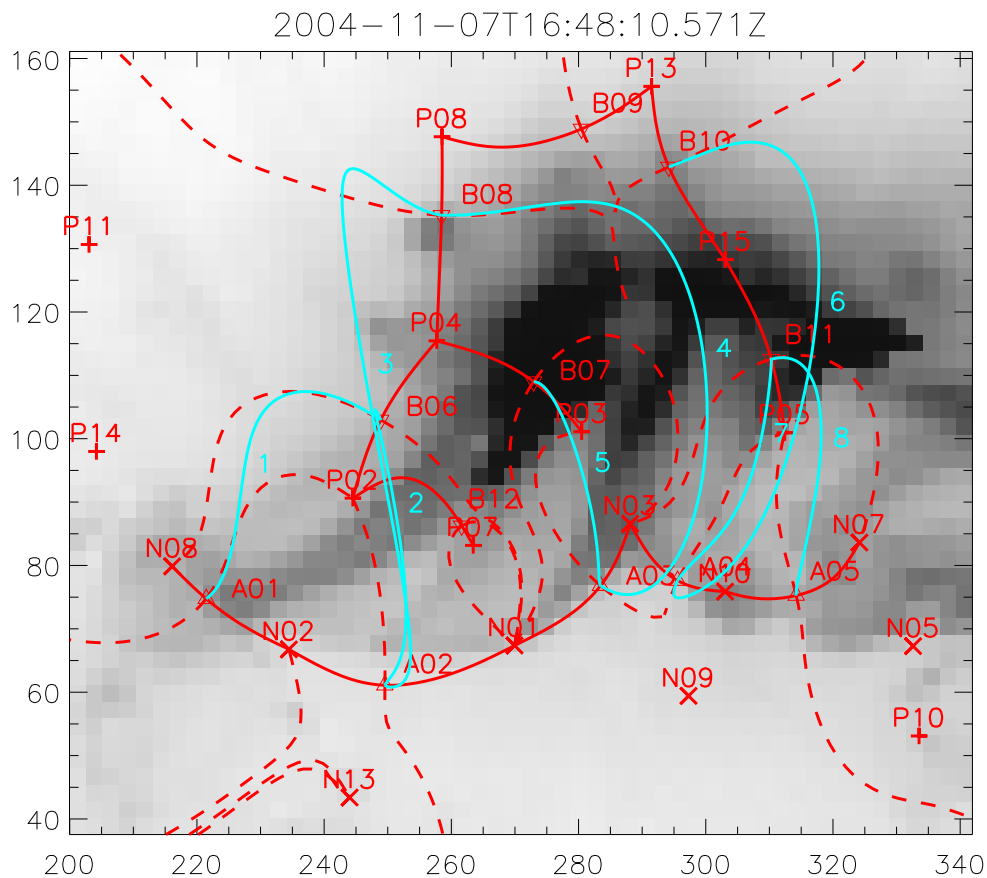
- Helicity of non-potential field (mutual helicity)

$$H \simeq \sum_i I_i \oint_{C_i} \mathbf{Z} \cdot d\mathbf{l} = \sum_i H_i$$

$\nabla \times \mathbf{Z} = \mathbf{A}_P$ and $\nabla \times \mathbf{A}_P = \mathbf{B}_P$ potential field

* Flux Constrained Equilibrium (Longcope 2001)

Separators of intra-ribbon domains



EIT 195Å image (inverse gray scale) w/ footprint (red) & separators (cyan)

i	nulls		encloses	L_i Mm	z_{\max} Mm	$\Delta\psi_i$ 10^{21} Mx	I_i GAmps	ΔW_i 10^{30} ergs	H_i 10^{42} Mx ²
	-	+							
1	A01	B06	P02-N08	43.9	8.7	-0.23	-24.2	0.06	-0.05
2	A02	B06	P02-N01	55.0	18.6	-1.01	-465.4	17.79	-2.92
3	A02	B08	P04-N02*	127.3	42.6	-0.79	2.7	0.00	0.04
4	A03	B08	P04-N03*	91.2	28.7	-1.11	-65.4	0.73	-0.72
5	A03	B07	P03-N01	35.3	10.8	-0.84	-562.6	14.98	-2.29
6	A04	B10	P15-N03*	97.2	32.3	-1.13	-97.7	1.45	-1.17
7	A04	B11	P05-N03	36.1	9.8	-0.88	-948.4	29.06	-3.16
8	A05	B11	P05-N10*	39.0	11.7	-0.59	57.3	0.31	0.19
total						-6.57		64.38	-10.09

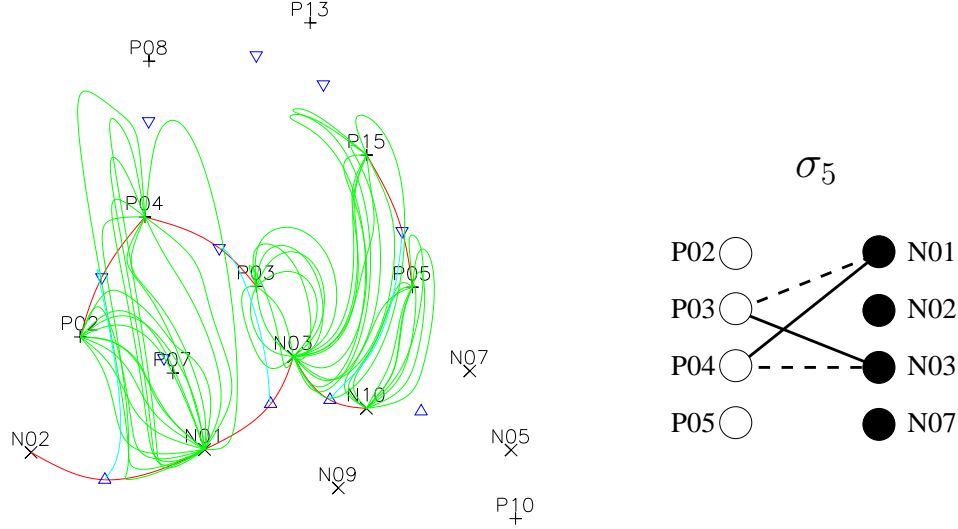
Including Mutual Inductances

$$\Delta W = 8.2 \times 10^{31} \text{ ergs} = 0.06 W_{\text{pot}}$$

* One of several domains enclosed by separator

VI. Flare Energetics

- Most significant* separators: σ_2, σ_5 & σ_7
- Each reconn'n: 2 **donor** domains \rightarrow 2 **recipient** domains



- Energy ΔW_i deposited into recipient domains — 50:50
- Each domain: volume $V_{a/b}$ and mean field line length, $\langle L \rangle$
- Assume e^- accel. efficiency of 50% (guess)
- Flare volume $V_f =$ smaller of $V_{a/b}$ or frac. w/ recon'd flux
- Use Warren & Antiochos (2004) peak GOES fluxes:

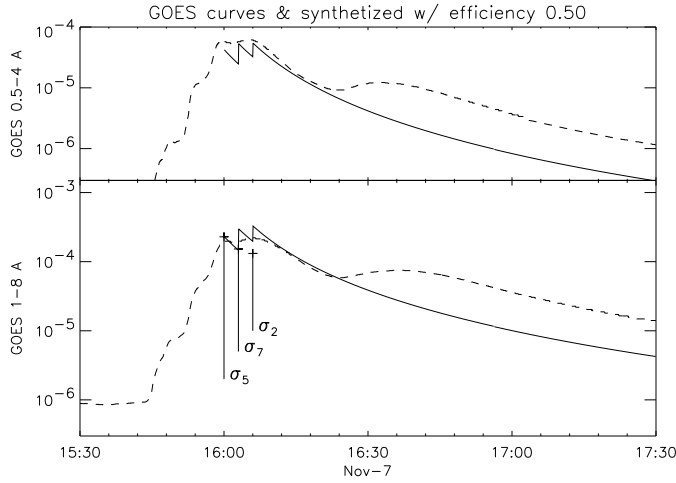
$$F_{1-8} = 3.7 \times 10^{-35} \left(\frac{EL}{V} \right)^{1.75} \frac{V}{L^2}, \quad F_{0.5-4} = 4.4 \times 10^{-42} \left(\frac{EL}{V} \right)^{2.24} \frac{V}{L^2}$$

i	recipient domain	ψ_i 10^{21} Mx	$\psi_{a/b}^{(v)}$	$\langle L \rangle$ Mm	$V_{a/b}$ 10^{27} cm ³	V_f	E_d 10^{30} erg	E_f	F_{1-8} 10^{-6} W/m ²	$F_{0.5-4}$
2	P02-N01	1.01	1.05	33.8	4.27	4.12	4.45	4.45	127.9	22.0
2	P04-N02	1.01	0.37	87.9	30.29	30.29	4.45	1.61	3.8	0.2
5	P04-N01	0.84	1.53	64.2	46.27	25.34	3.74	3.74	20.6	1.8
5	P03-N03	0.84	1.58	20.9	3.18	1.69	3.74	3.74	208.3	40.3
7	N10-P05	0.88	0.31	25.9	1.26	1.26	7.26	2.53	123.7	25.3
7	P15-N03	0.88	0.33	53.4	8.45	8.45	7.26	2.76	29.0	3.5
	total				93.72	71.14	30.92	18.84	513.4	93.2

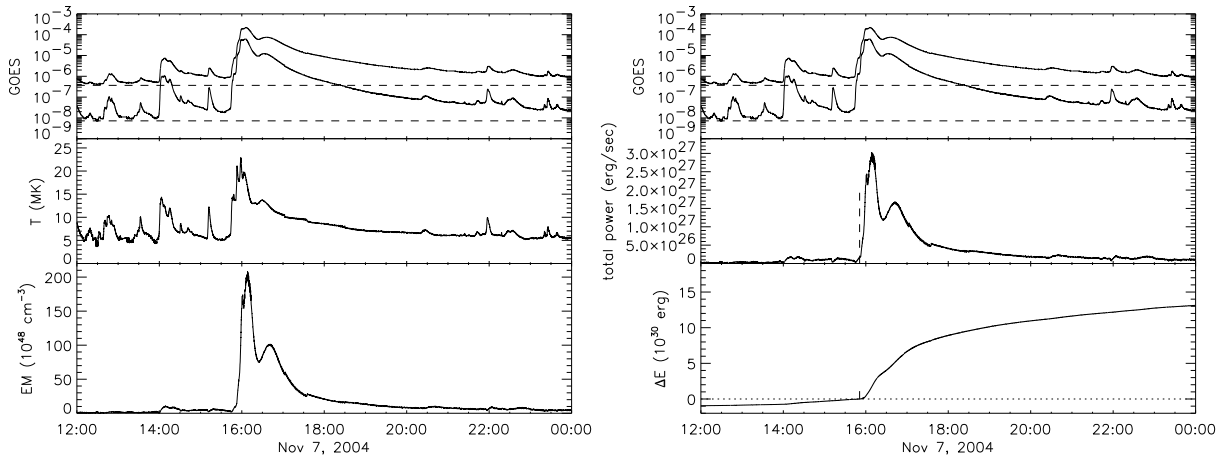
* Largest stored energy ΔW_i — released by reconnection

Flare Energetics (cont'd)

- Synthesize GOES light-curves from peaks: F_{1-8} & $F_{0.5-4}$
 - empirical decay curve: $\sim (t - t_0)^{-p}$
 - stagger reconnection episodes by 3 minutes.



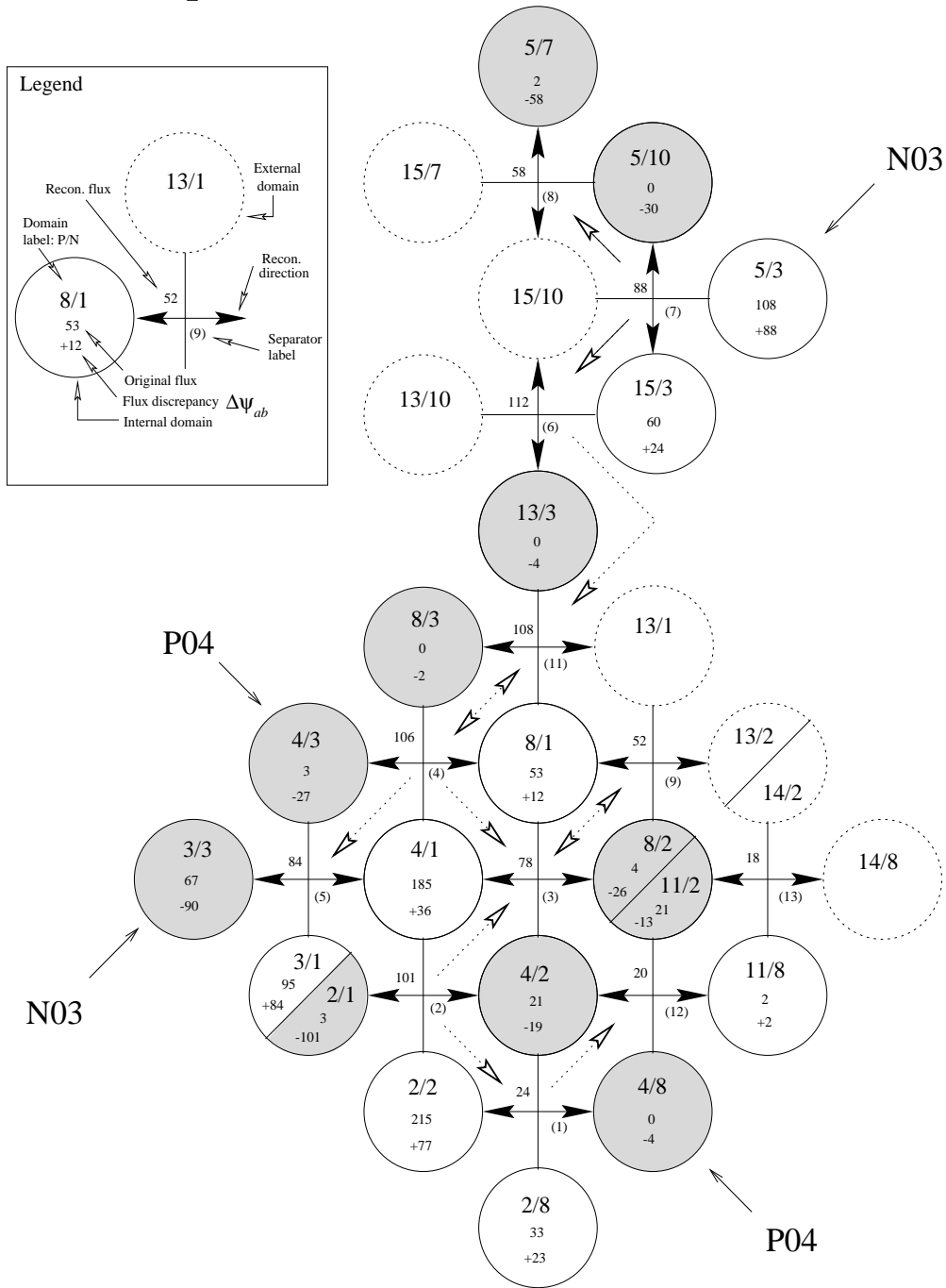
- GOES data alone $\implies \Delta E_{\text{rad}} \simeq 1.5 \times 10^{31}$ ergs



- 3rd estimate from GOES data:

- $EM = 2 \times 10^{50} \text{ cm}^{-3}$ $V_f = 7 \times 10^{28} \text{ cm}^3$ (recip. domains)
 $\implies n_e = 5 \times 10^{10} \text{ cm}^{-3}$
- $T = 20 \text{ MK} \implies E_{\text{th}} = 3n_e k_b T V_f = 3 \times 10^{31} \text{ ergs}$

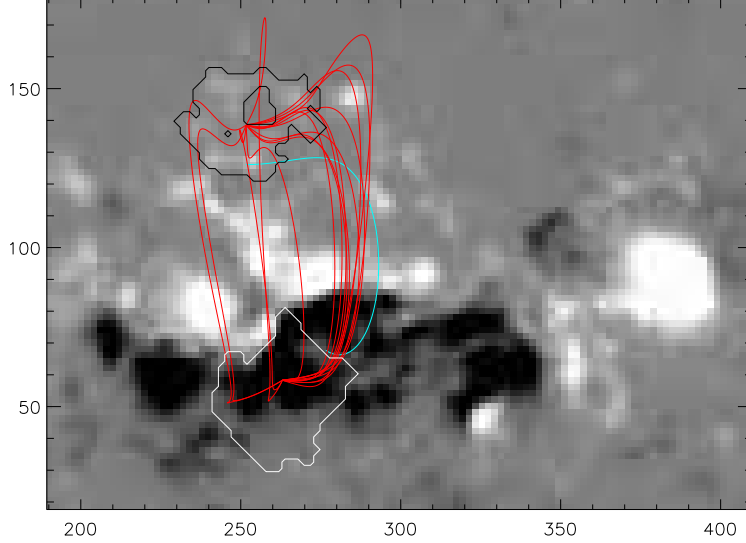
VII. Flux Rope Creation



- Bubbles = domains; vertices = separators (\rightarrow to recipient)
- Fluxes listed inside in 10^{19} Mx — see key
- Some domains share a bubble — divided by diagonals
- Shaded domains: $\Delta\psi_{a/b} < 0$
- Dashed outline: domain outside ribbons

Sequence of cascading reconnection

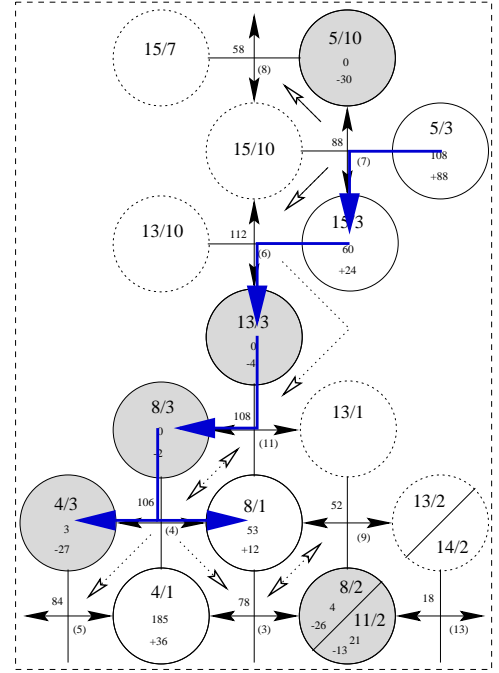
- Cascade: recipient from σ_i is donor for σ_j
- Separator sequence: $\sigma_7 \rightarrow \sigma_6 \rightarrow \sigma_{11} \rightarrow \sigma_4$
- First donors: 15/10 and 5/3 — $\Delta\psi_{5/3} = +0.88 \times 10^{21} \text{ Mx}$



Red: 8/1 field lines

Cyan: separator σ_4

Regions: P08 (black) N01 (white)



- Ends transferring $\Delta\psi_4 = 1.06 \times 10^{21} \text{ Mx}$.
- Final recipient: P08–N01 (shown) $\psi_{8/1} = 10^{21} \text{ Mx}$
- Observed: MC (Nov-9 20:30) w/ $\Phi_{MC} = 0.72 \times 10^{21} \text{ Mx}$
(Longcope, Beveridge, Qiu, Ravindra, Barnes & Dasso, 2007)
- Mutual helicity (H_i) \implies self helicity of recipient domains

$$\Delta H = \frac{1}{2}(H_7 + H_6 + H_{11} + H_4) = -2.7 \times 10^{42} \text{ Mx}^2$$

- $\Delta H/\Phi^2 = -2.7 = \#$ of RH turns in flux rope
- Observed MC: $H = -11 \times 10^{42} \text{ Mx}^2$ (assuming 2 AU rope length)

Summary: Build-up & flare fits quantitative CSHKP model

- Shearing: $\Delta H = -14 \times 10^{42} \text{ Mx}^2$
 $\Delta H/\Phi^2 = -1/3 = \text{avg. \# of RH turns in AR}$
- Energy storage: $\Delta W = 8 \times 10^{31} \text{ ergs} = 0.06 W_{\text{pot}}$ —
consistent w/ 2d arcade sheared by $\text{atan}(1/3) = 18^\circ$
(Klimchuk *et al.* 1988; Mikic *et al.* 1988; Choe & Cheng 2000)
GOES light-curves suggest $\sim 3 \times 10^{31} \text{ ergs}$ released
- **MODEL:** Relaxation to pot'l field requires reconnection:
 - $\Delta\Psi_{\downarrow} \simeq 3.5 \times 10^{21} \text{ Mx}$ — initial phase
 - $\Delta\Psi_{\downarrow} \simeq 5.4 \times 10^{21} \text{ Mx}$ — total
- **OBSERVATION:** Fluxes swept by 1600Å flare ribbons:
 - $\Psi_{\pm} \simeq 2.4 \times 10^{21} \text{ Mx}$ — initial phase
 - $\Psi_{\pm} \sim 4.5 \times 10^{21} \text{ Mx}$ — total
- ★ **COMPARISON:** $\Psi_{\pm} < \Delta\Psi_{\downarrow} \iff$ incomplete relaxation
- Sequence of recon'n produces flux rope (*P08–N01*)
with $\Phi_{\text{ft}} = 1.1 \times 10^{21} \text{ Mx}$ – c.f. $\Phi_{MC} = 0.7 \times 10^{21} \text{ Mx}$
- 4 reconnections \implies – 2.7 twists in flux rope:
 $H_{\text{ft}} = -2.7 \times 10^{42} \text{ Mx}^2$ – c.f. $H_{MC} = -11 \times 10^{42} \text{ Mx}^2$
(subsequent reconnection after flare?)

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Thanks to: Louise Harra, Sergio Dasso