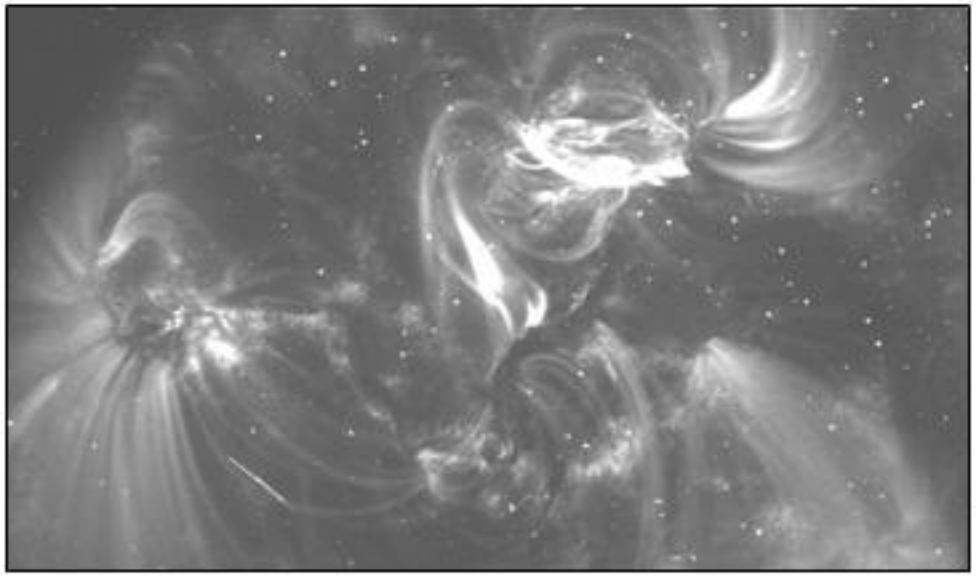
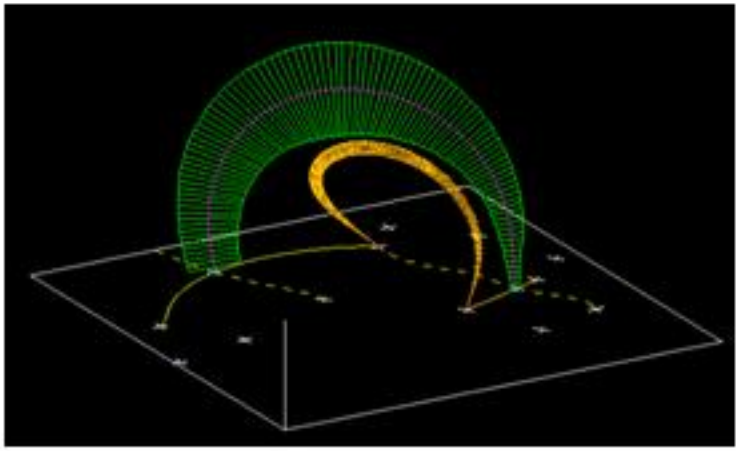
Coronal loops formed by separator reconnection:

The birth & life of AR9574





Dana Longcope

Montana State University

Aug 16, 2004

Collaborators:

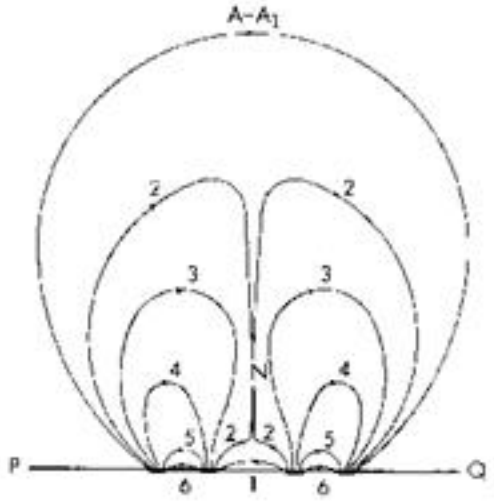
- Jonathan Cirtain
- Dave McKenzie
- Jason Scott

} MSU

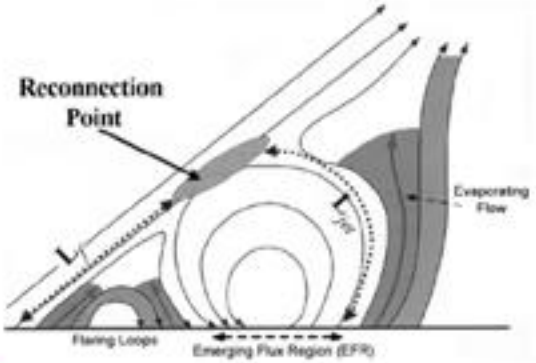
Support:

- NASA grant NAG5-10489
- Isaac Newton Institute, Cambridge

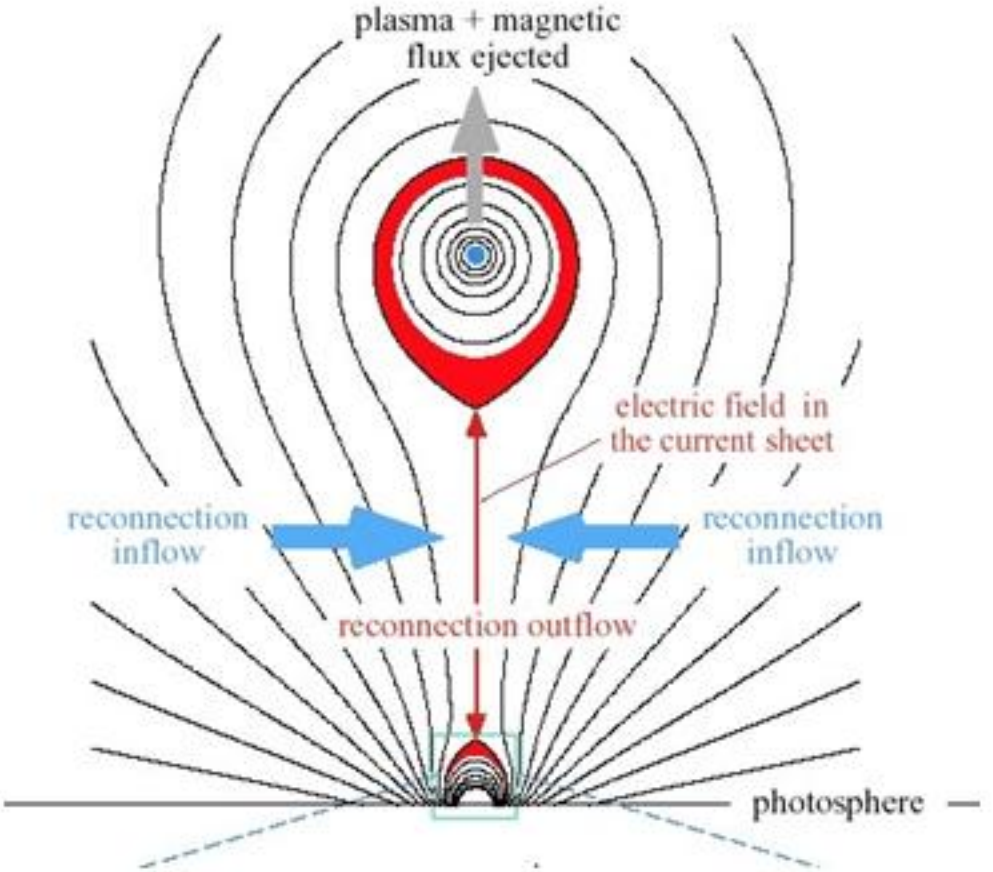
Observations of Reconnection



Flare (Sweet)



Jet (Shimojo & Shibata)



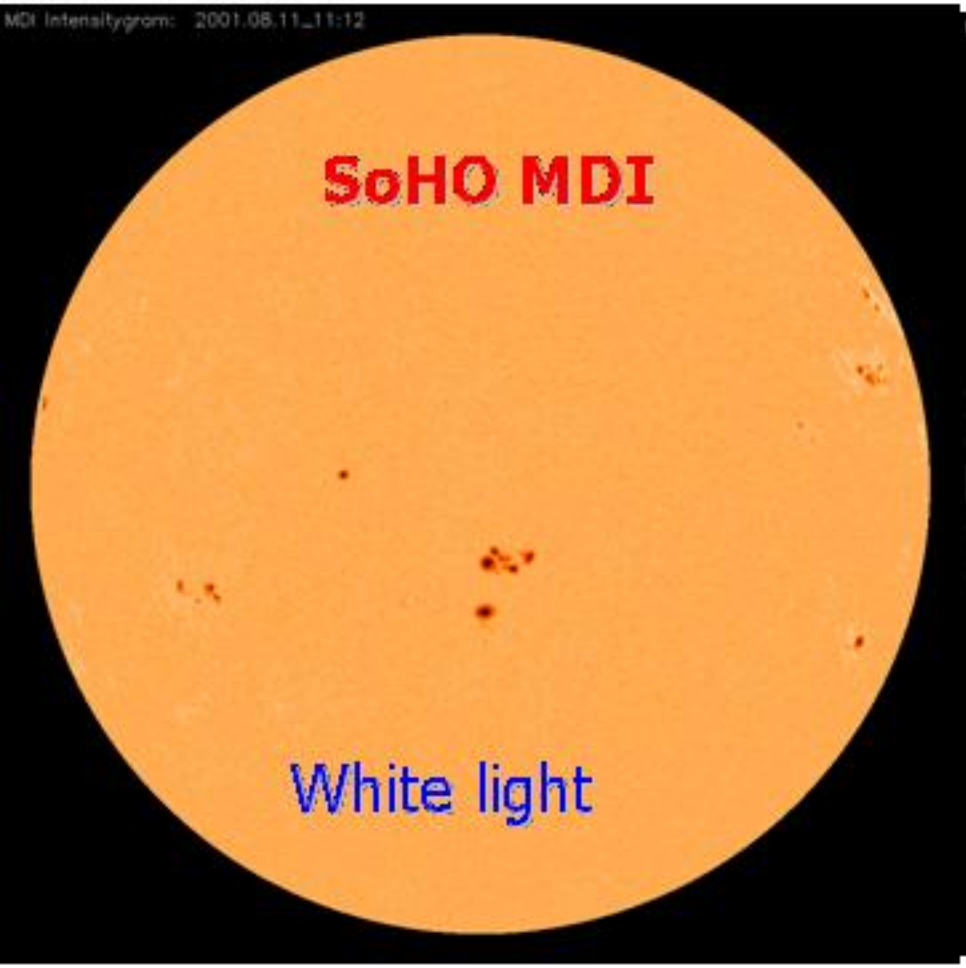
CME (Lin & Forbes)

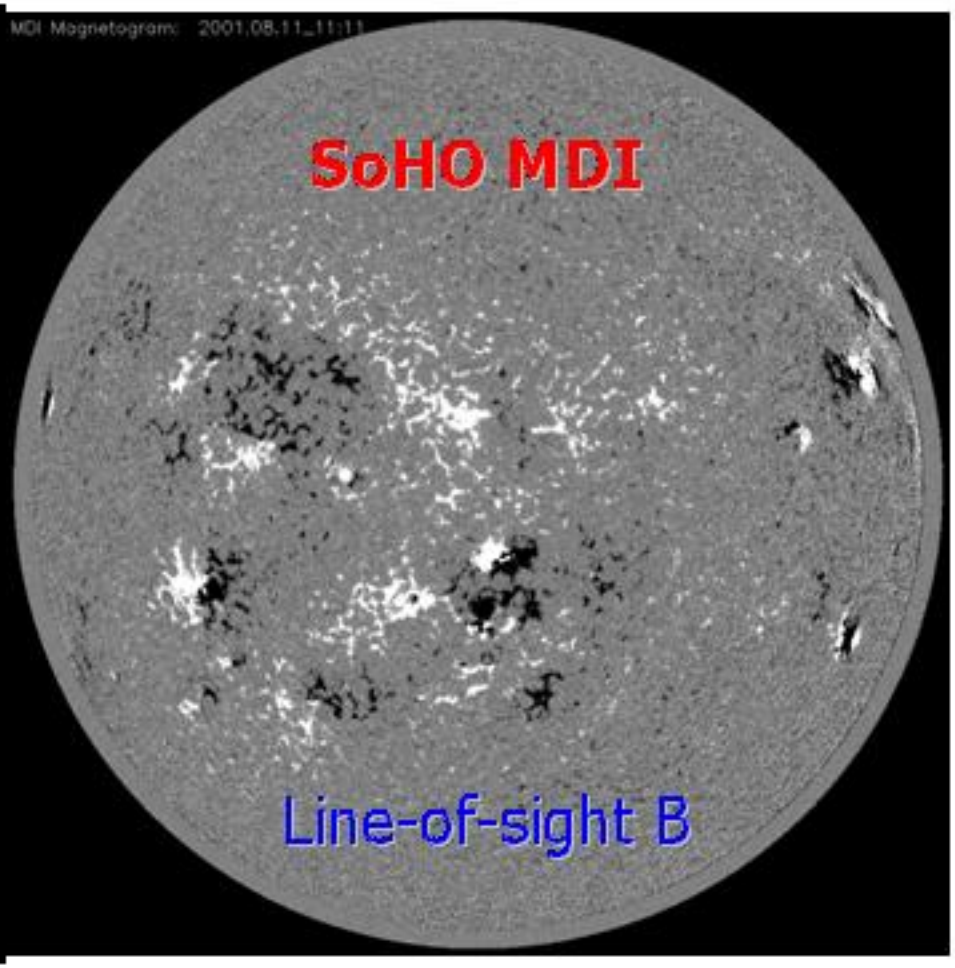
Flux Emergence:
A new setting for studying reconnection

Outline

- What happened in Aug. 2001
- Cataloging interconnections
- Making a magnetic model
- Interp'ing data w.r.t. the model
- What does it tell us about reconnection

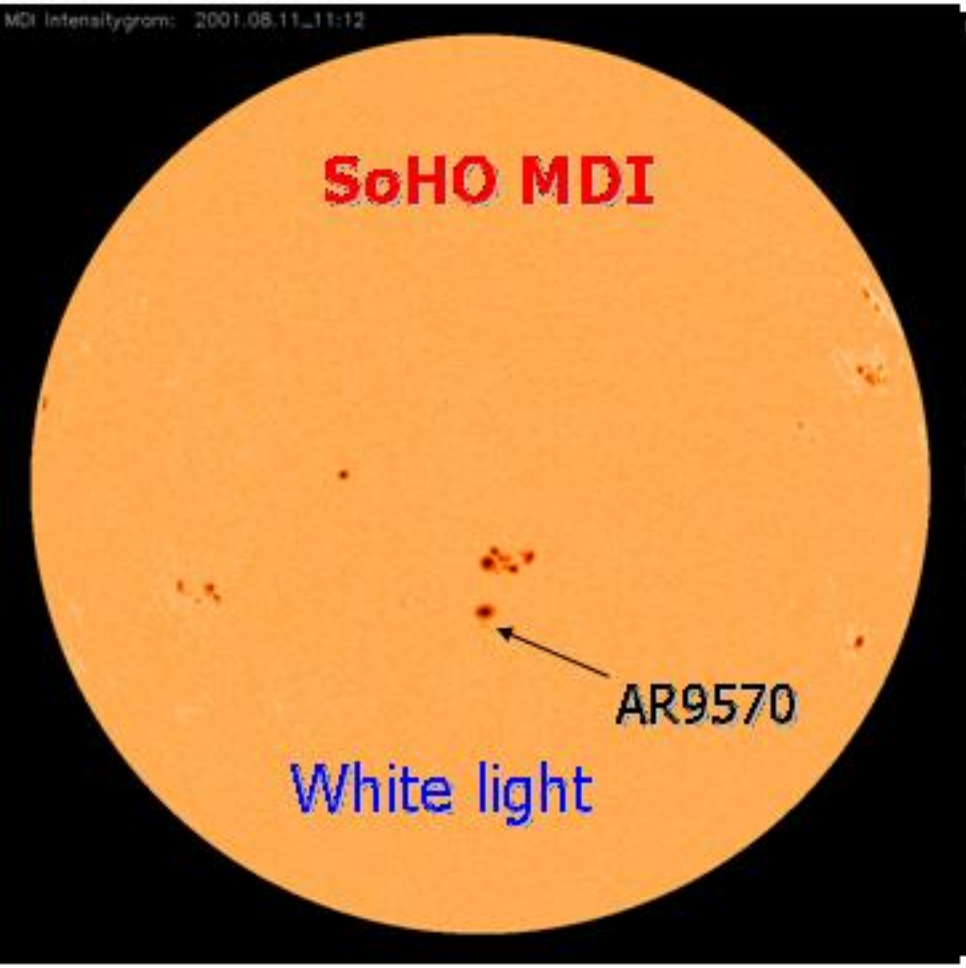
Case study: AR 9574

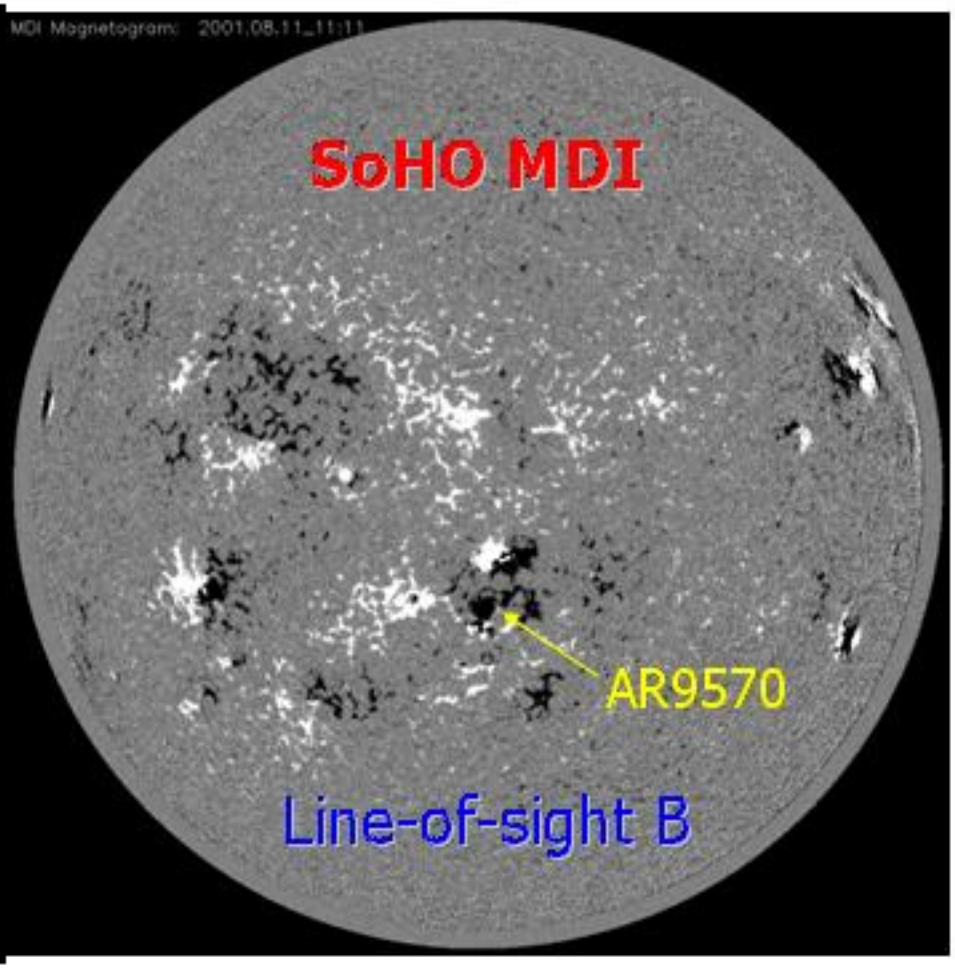




2001 Aug 11, 11:15 UT

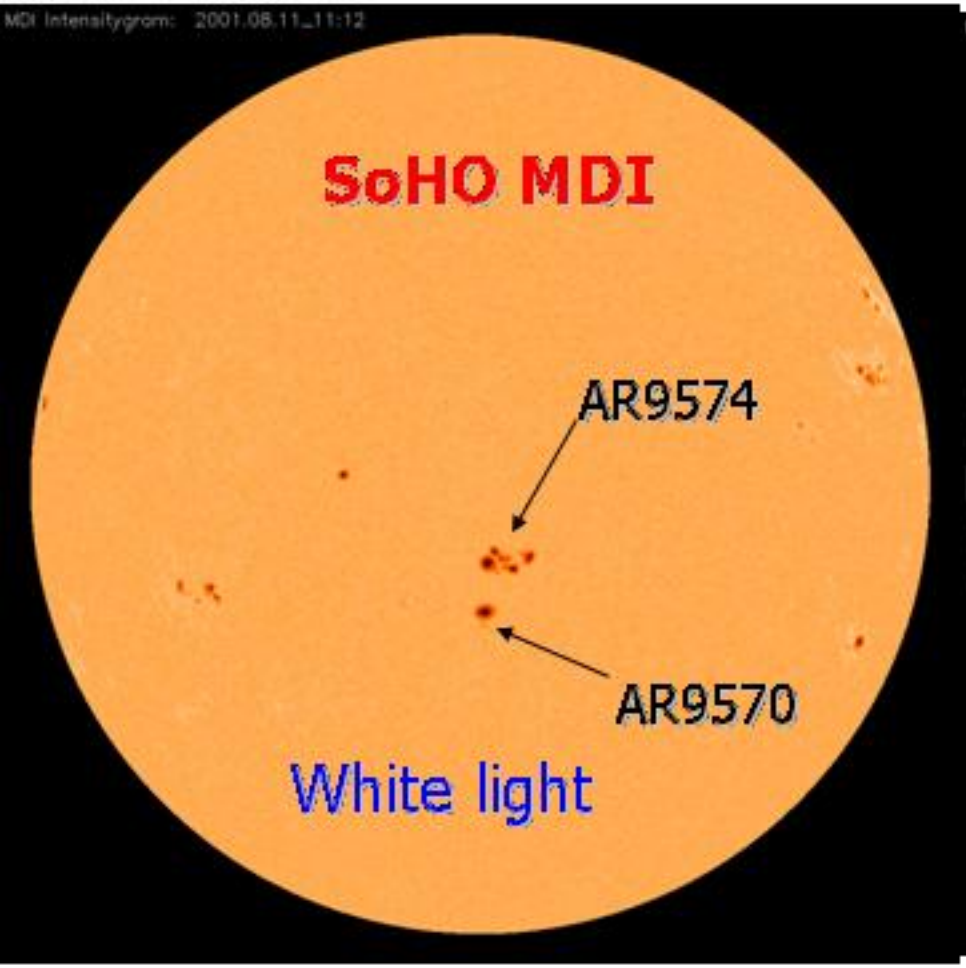
Case study: AR 9574

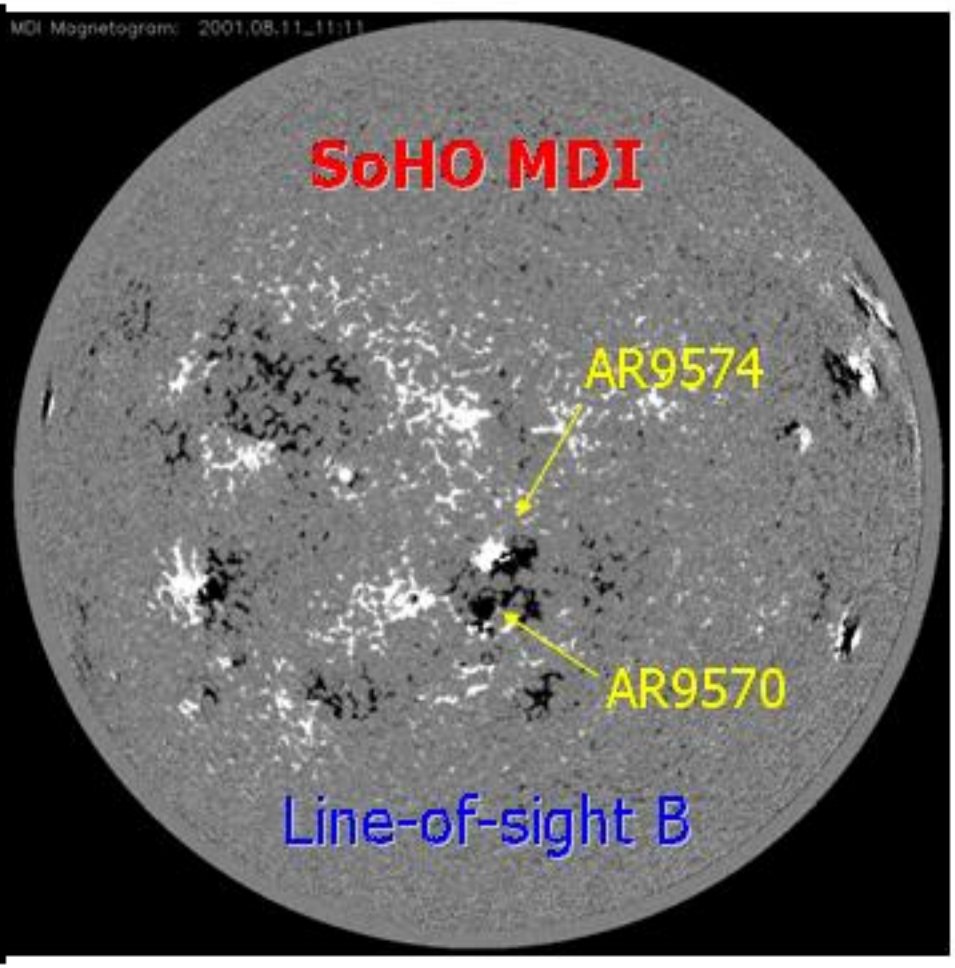




2001 Aug 11, 11:15 UT

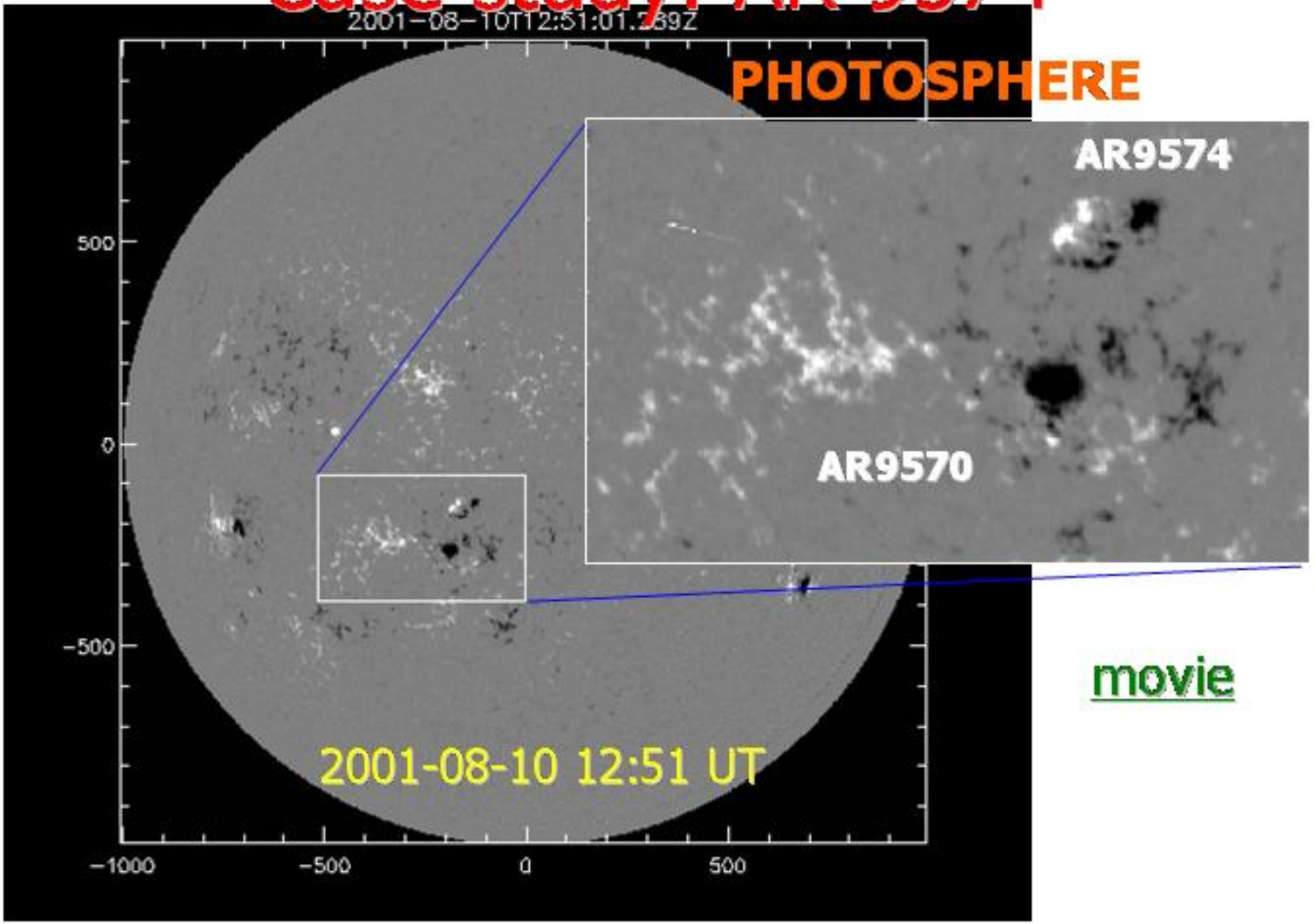
Case study: AR 9574





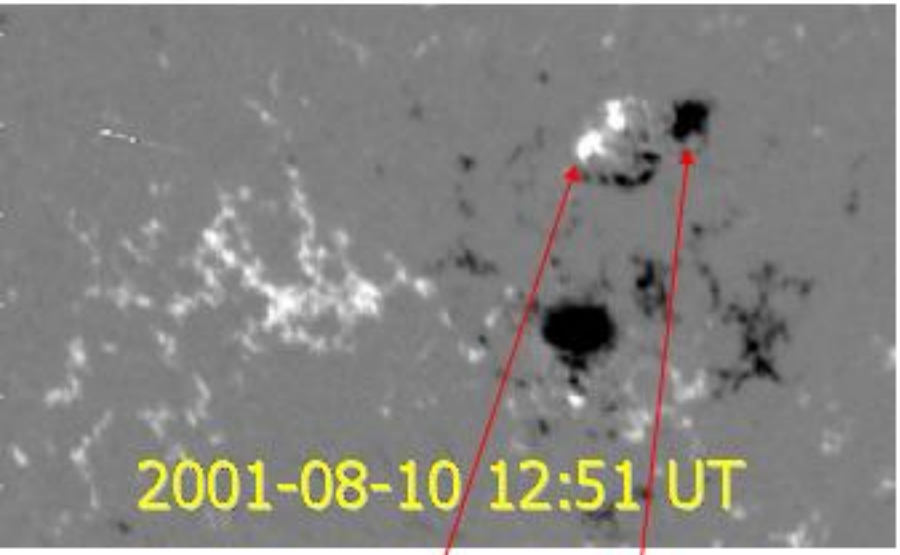
2001 Aug 11, 11:15 UT

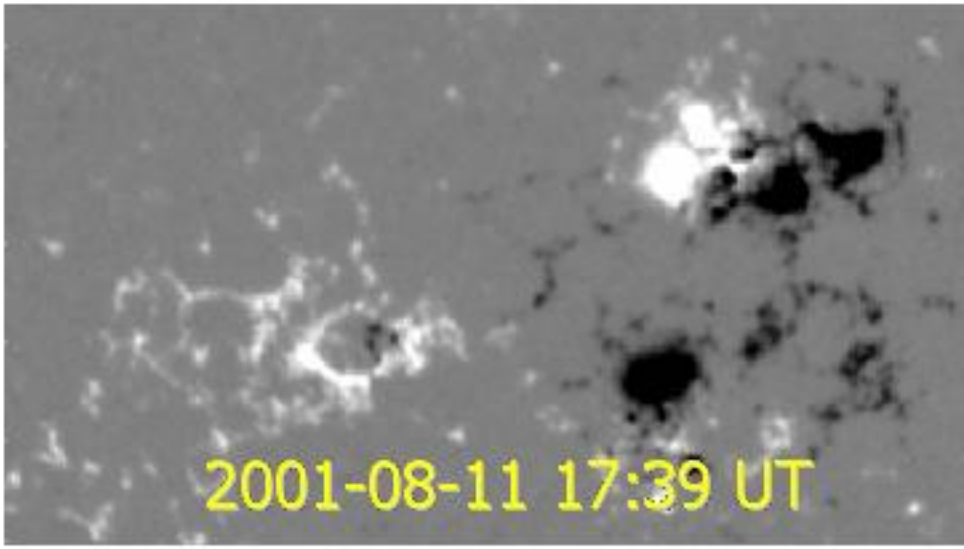
Case study: AR 9574

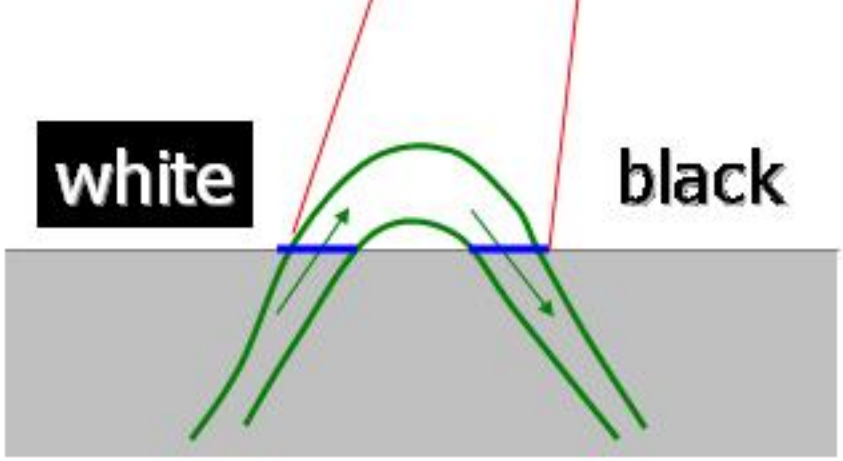


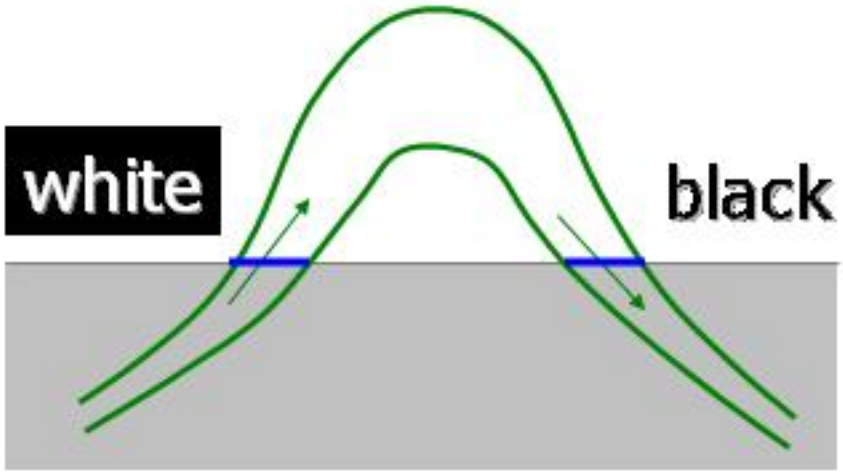
movie

The emergence process

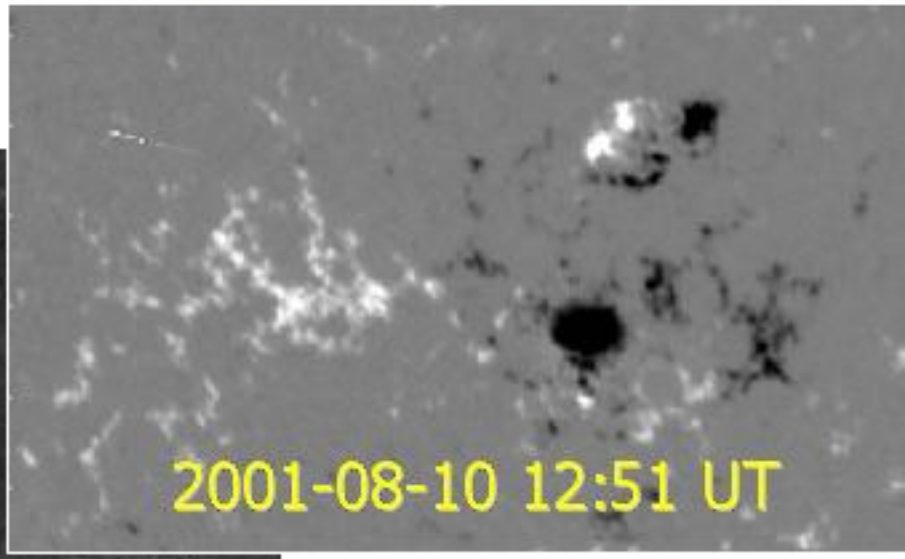


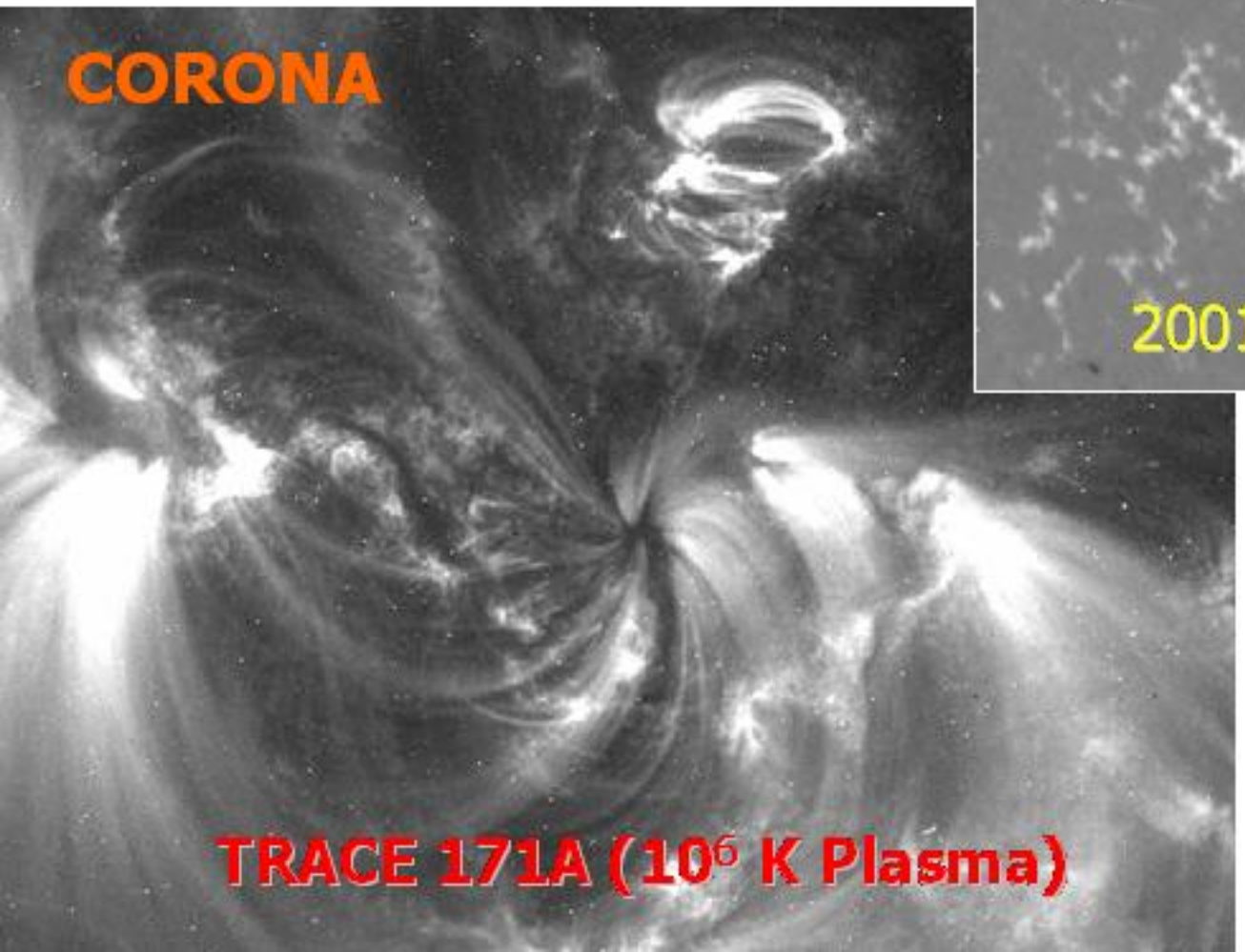






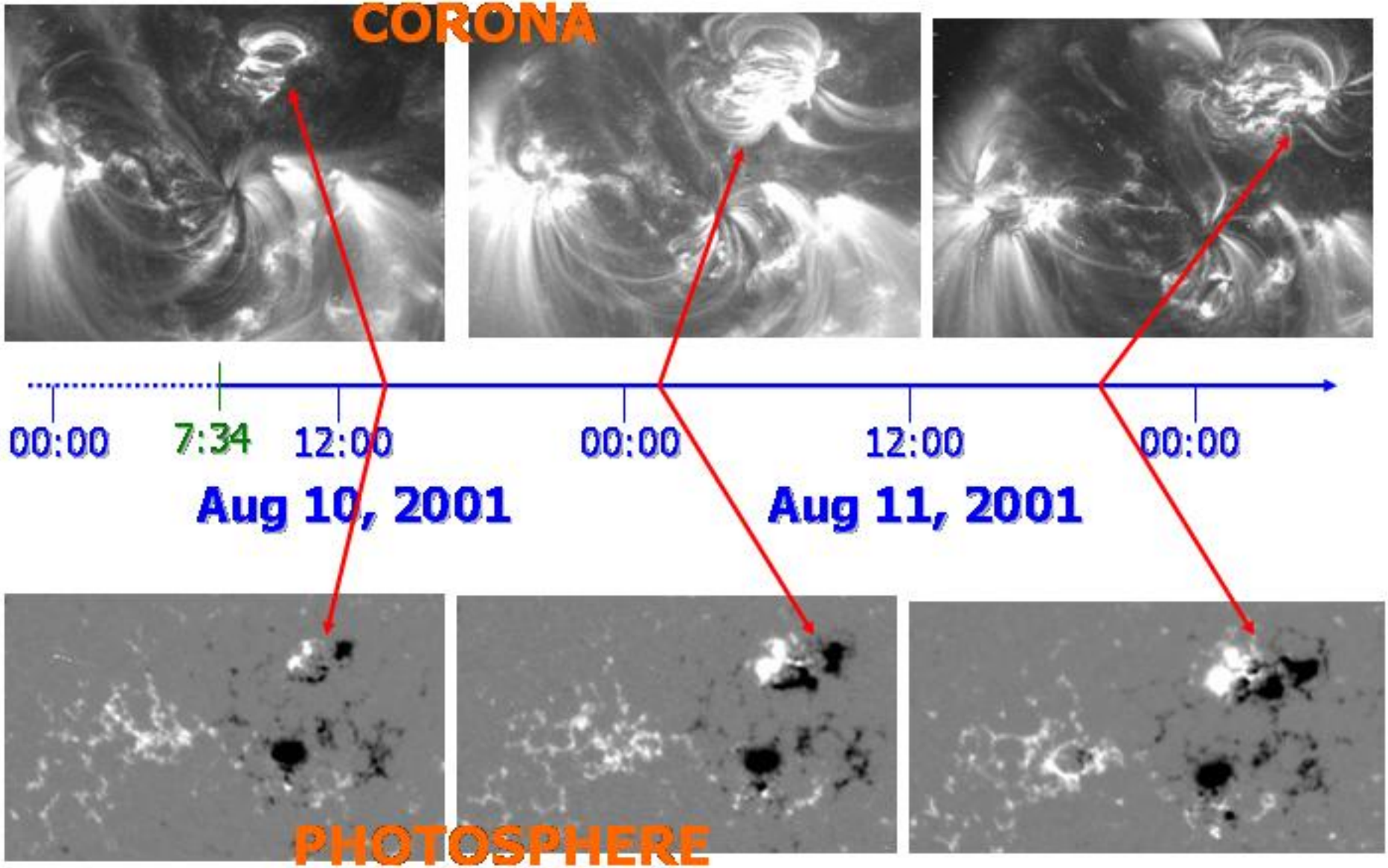
Case study: AR 9574



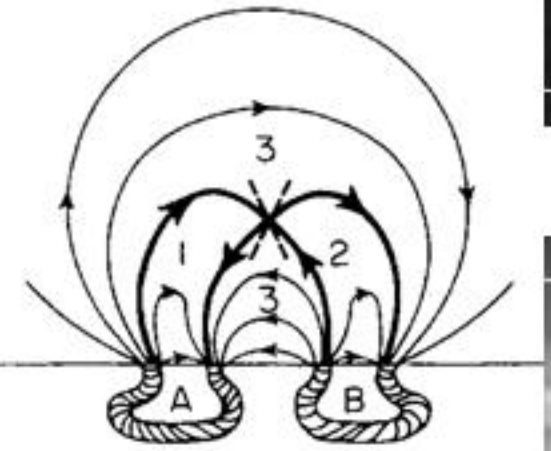


movie

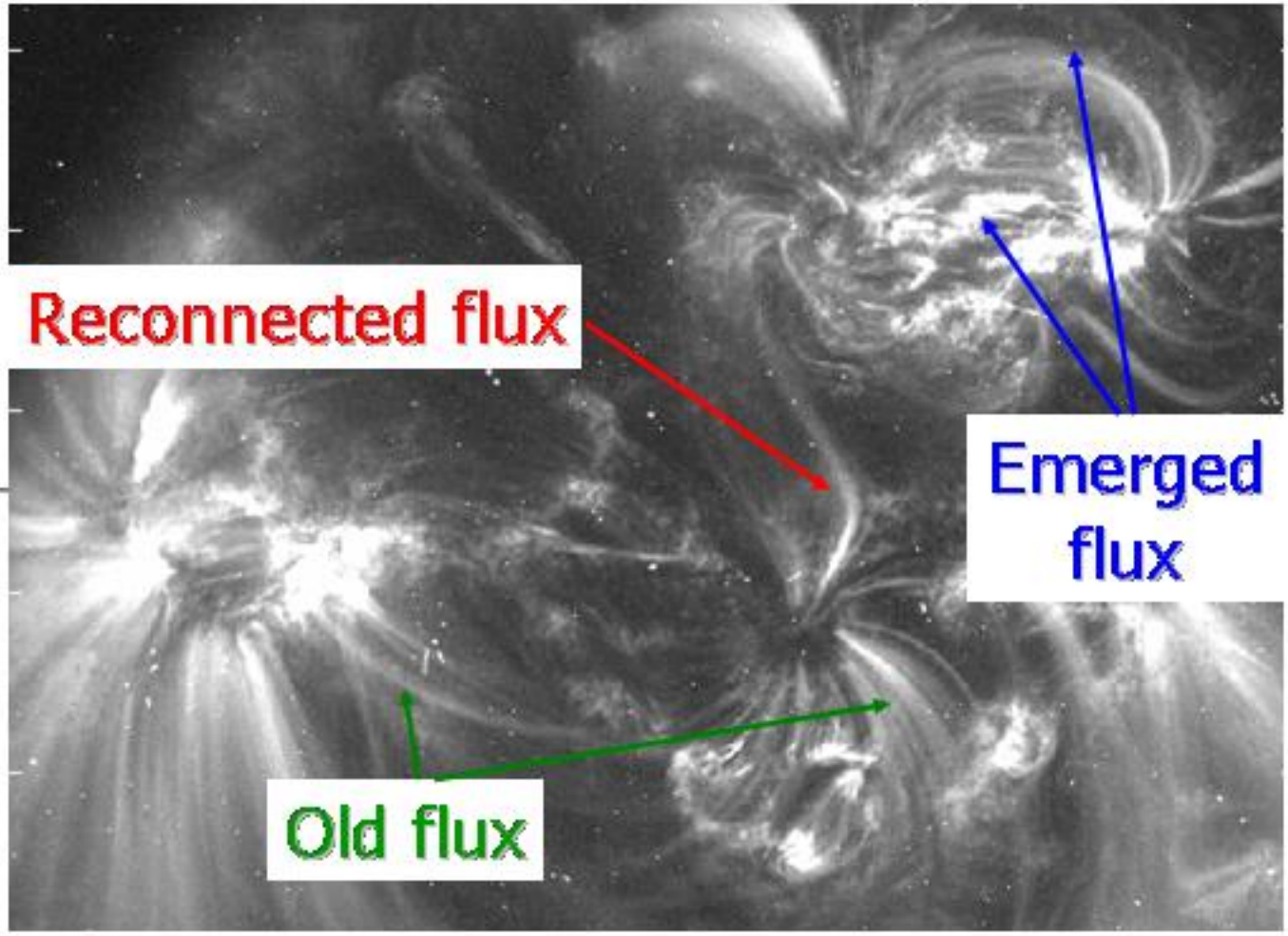
Timeline of emergence



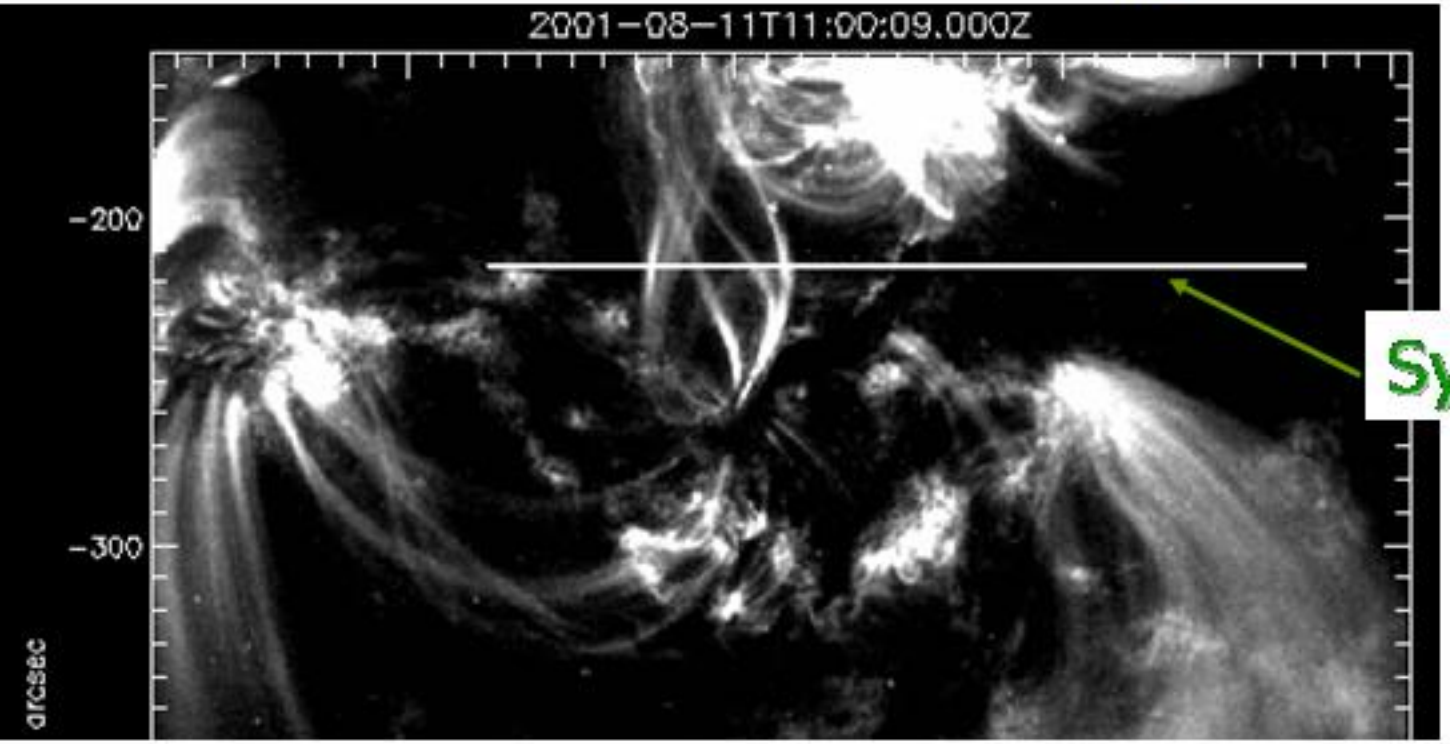
Why this is reconnection



Baum &
Bratenahl
1976



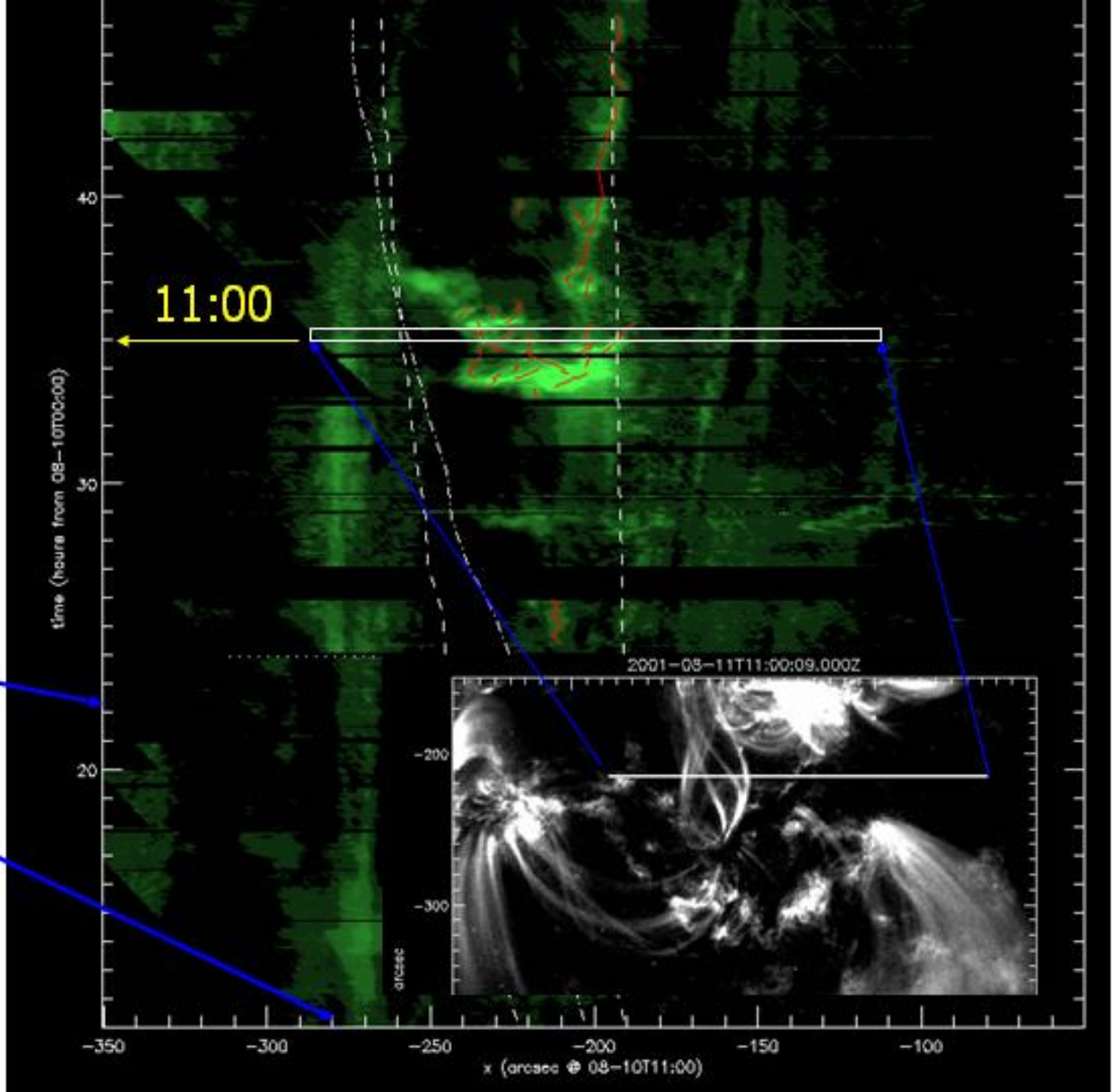
Interconnecting loops:
A catalog



Synthetic slit

TRACE 171 images:

5139 images @ 28 sec
7:00 Aug10 – 23:59 Aug11
BG subtracted



Stack slit pixels…

Time after 00:00 Aug10

Position @ 11:00 Aug10

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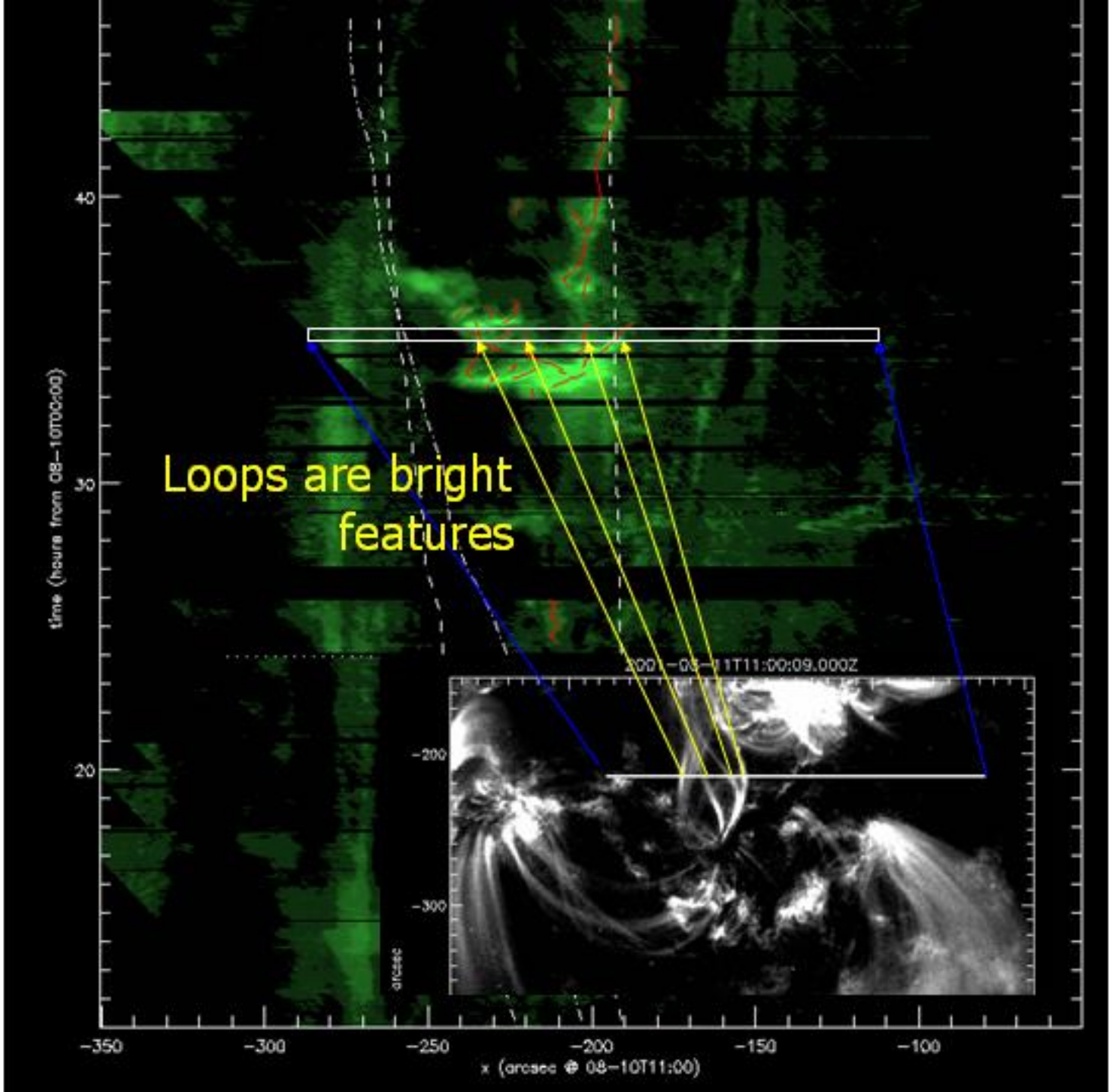
Loops are bright features
time (hours from 08-10T00:00)
40
30
20
-350
-300
-250
-200
-150
-100
x (arcsec @ 08-10T11:00)
-200
-300
arcsec

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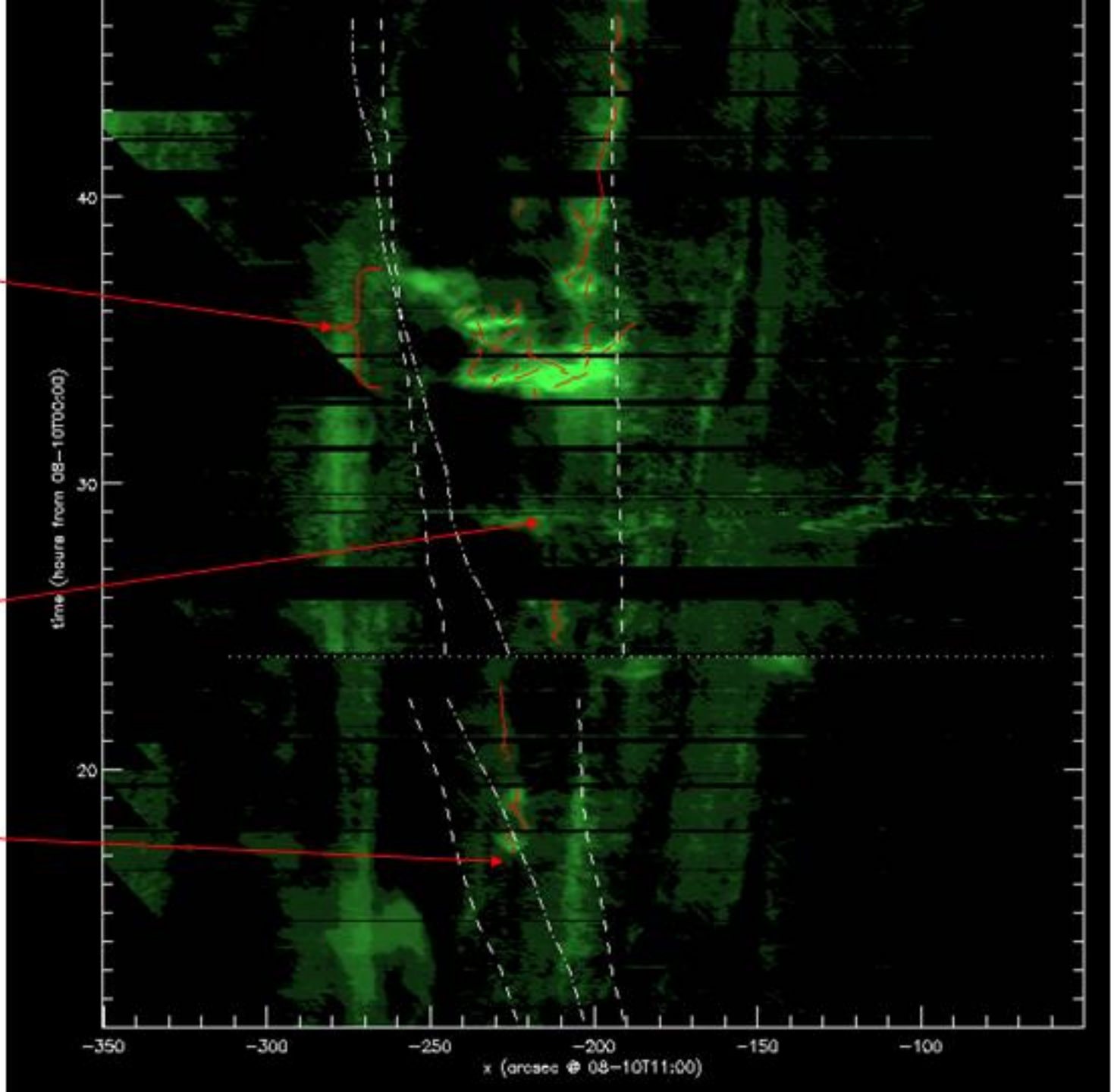
Lots of loops: ~9:00 → 14:00
Gen'l bright'g
1st loop: 12:36
time (hours from 08-10T00:00)
40
30
20
-350
-300
-250
-200
-150
-100
x (arcsec @ 08-10T11:00)

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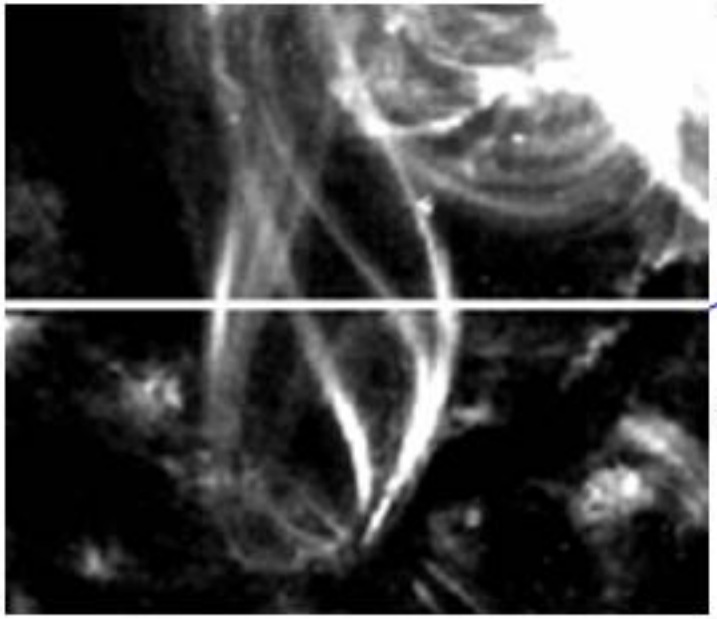
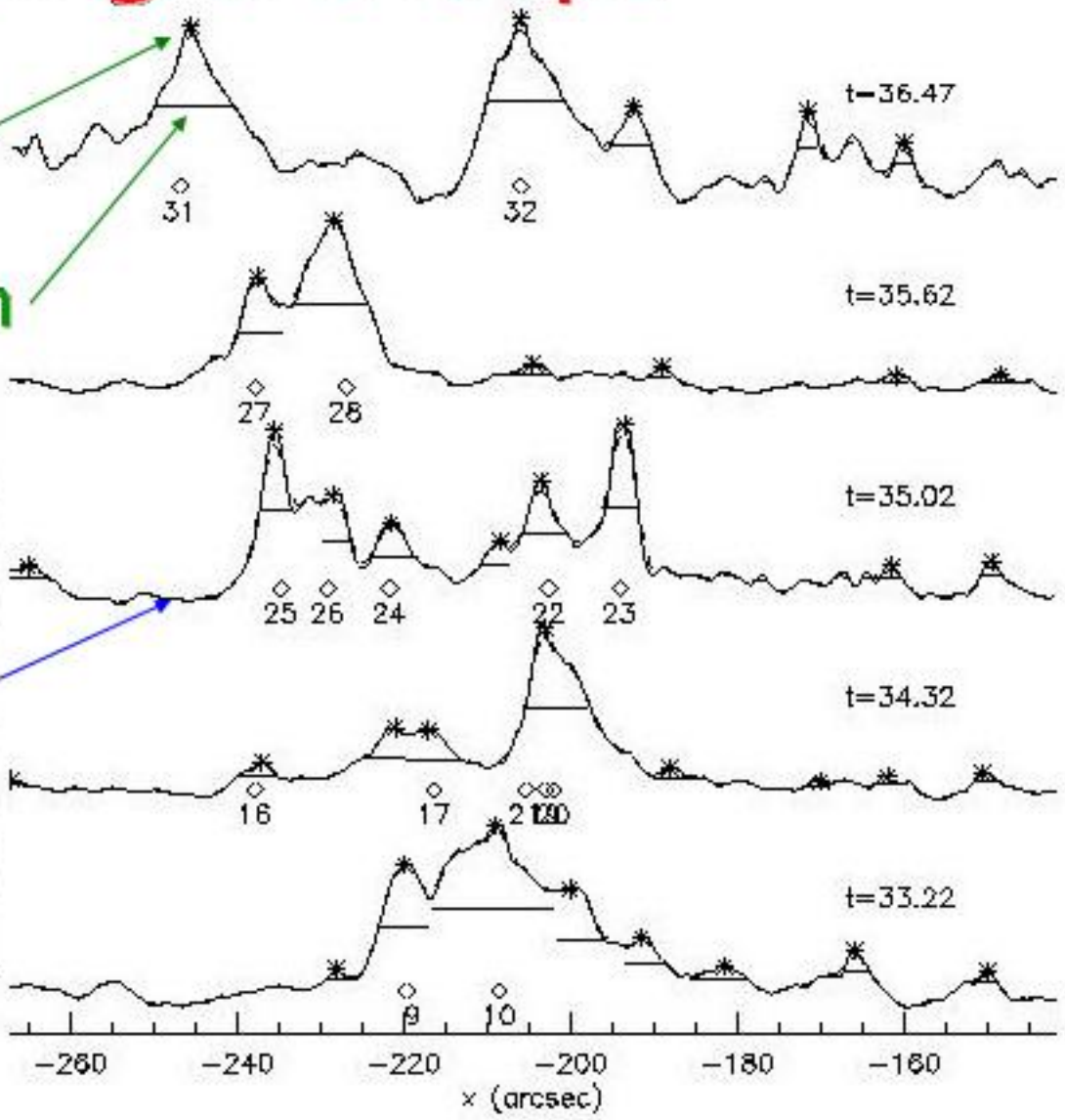
Finding the loops

- Identify peaks in slit-intensity
- **loop** = fw @ hm





Finding the loops

- Identify peaks in slit-intensity
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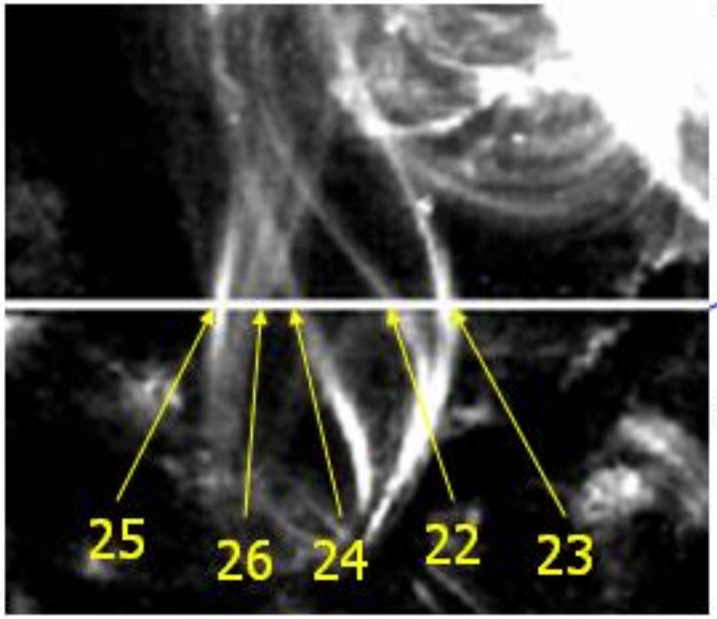
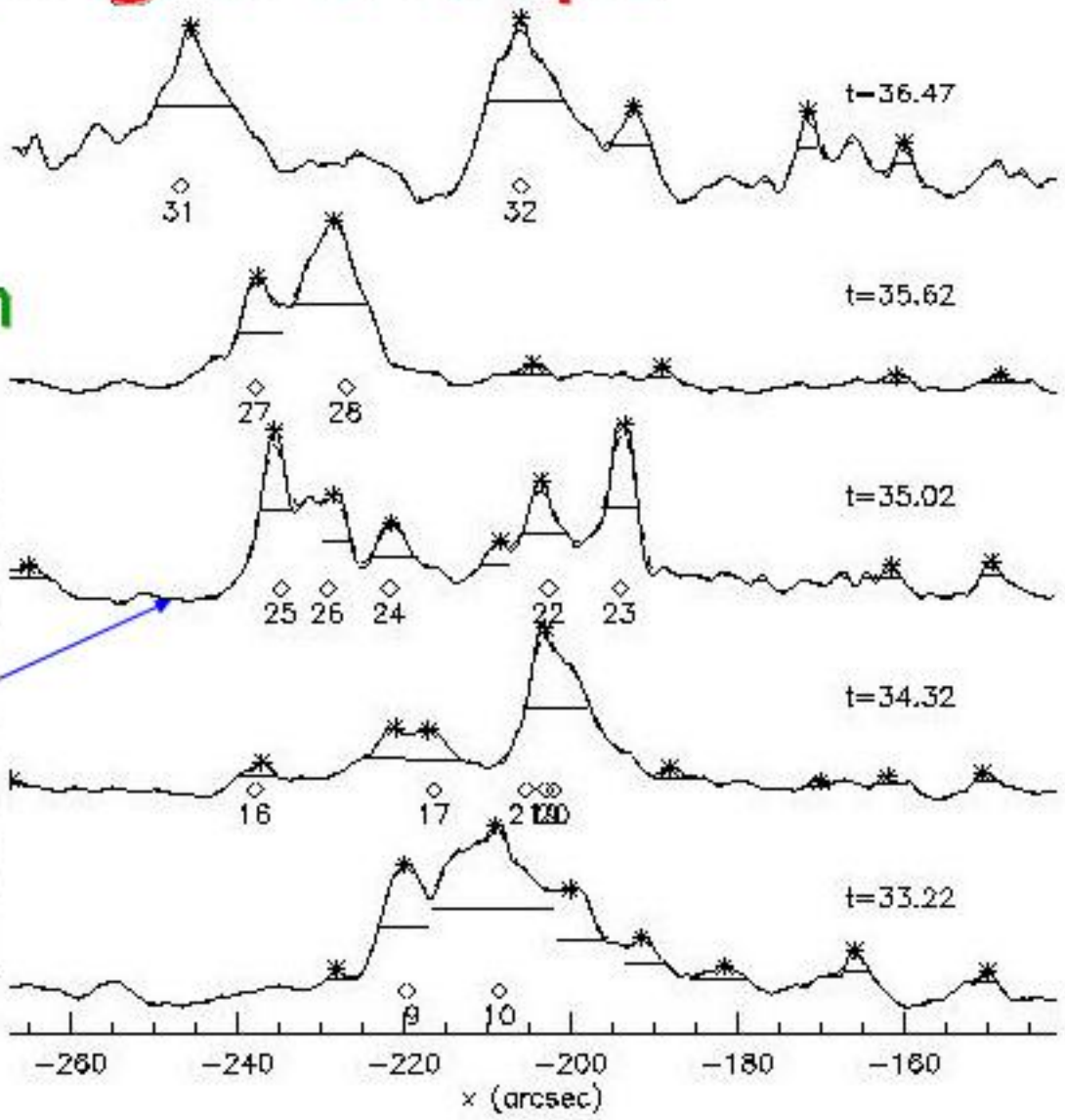
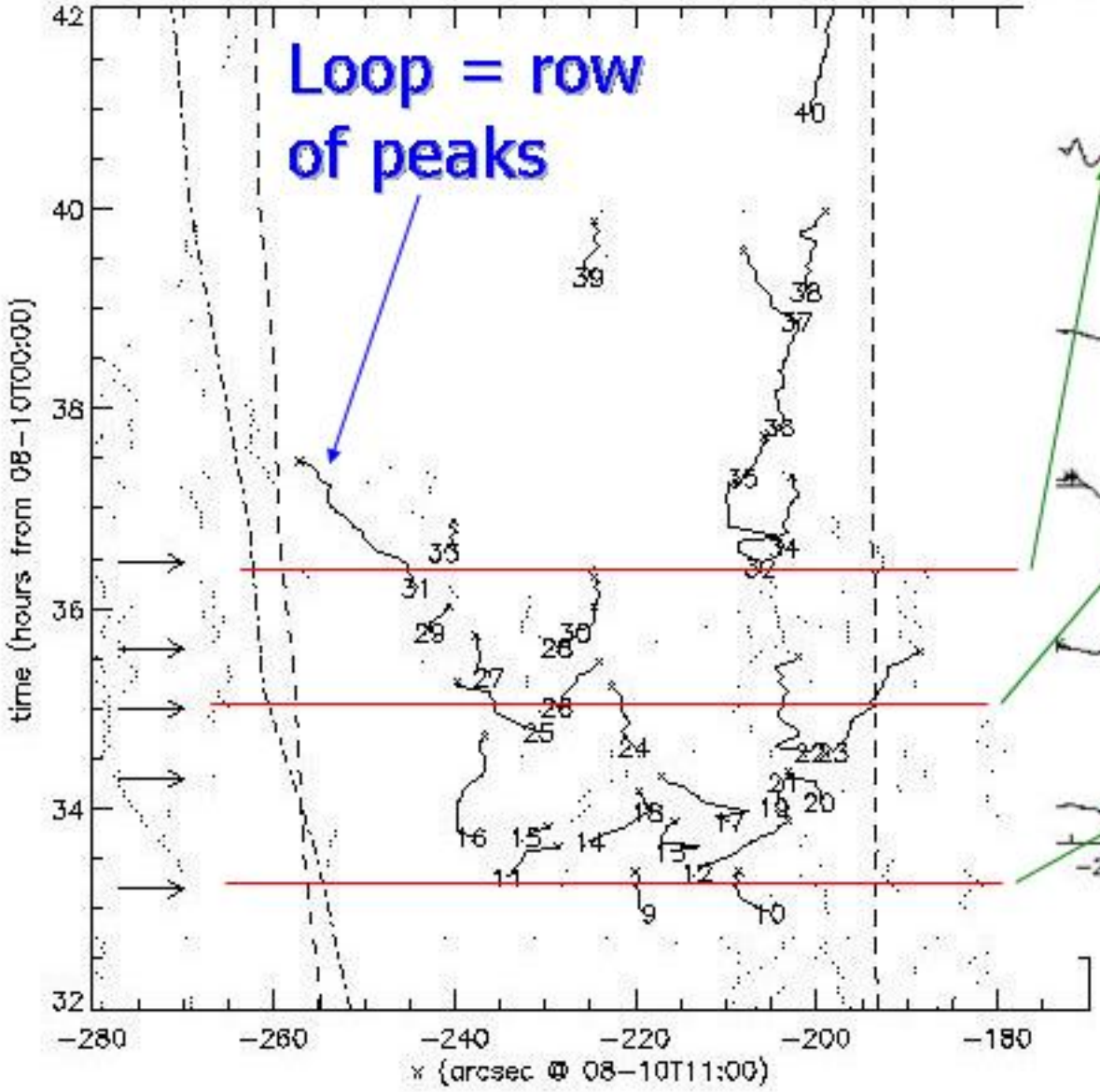
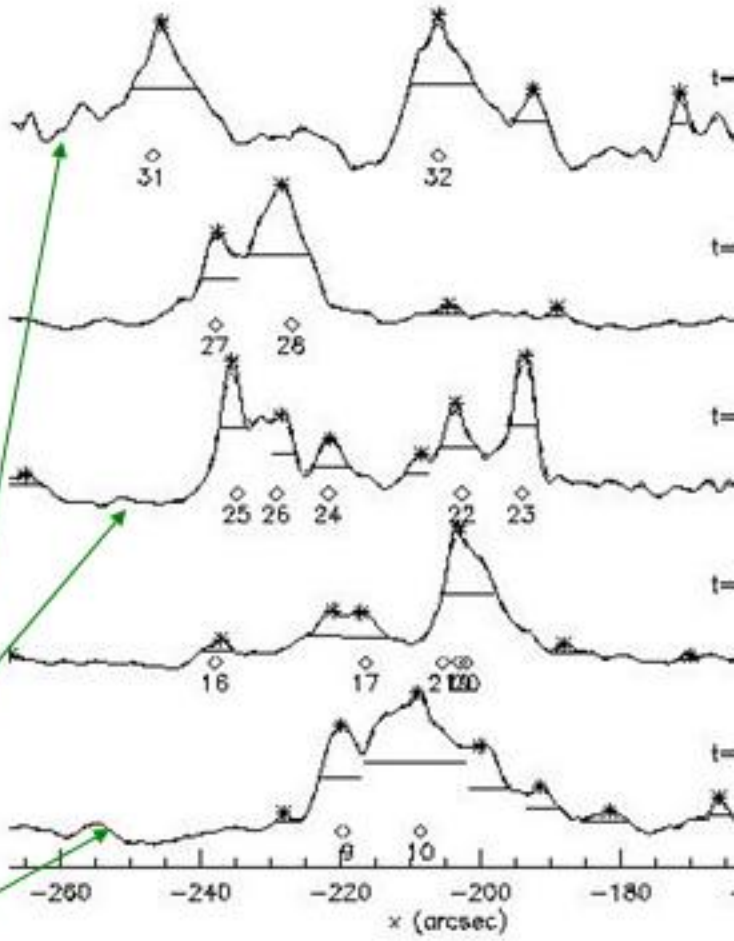




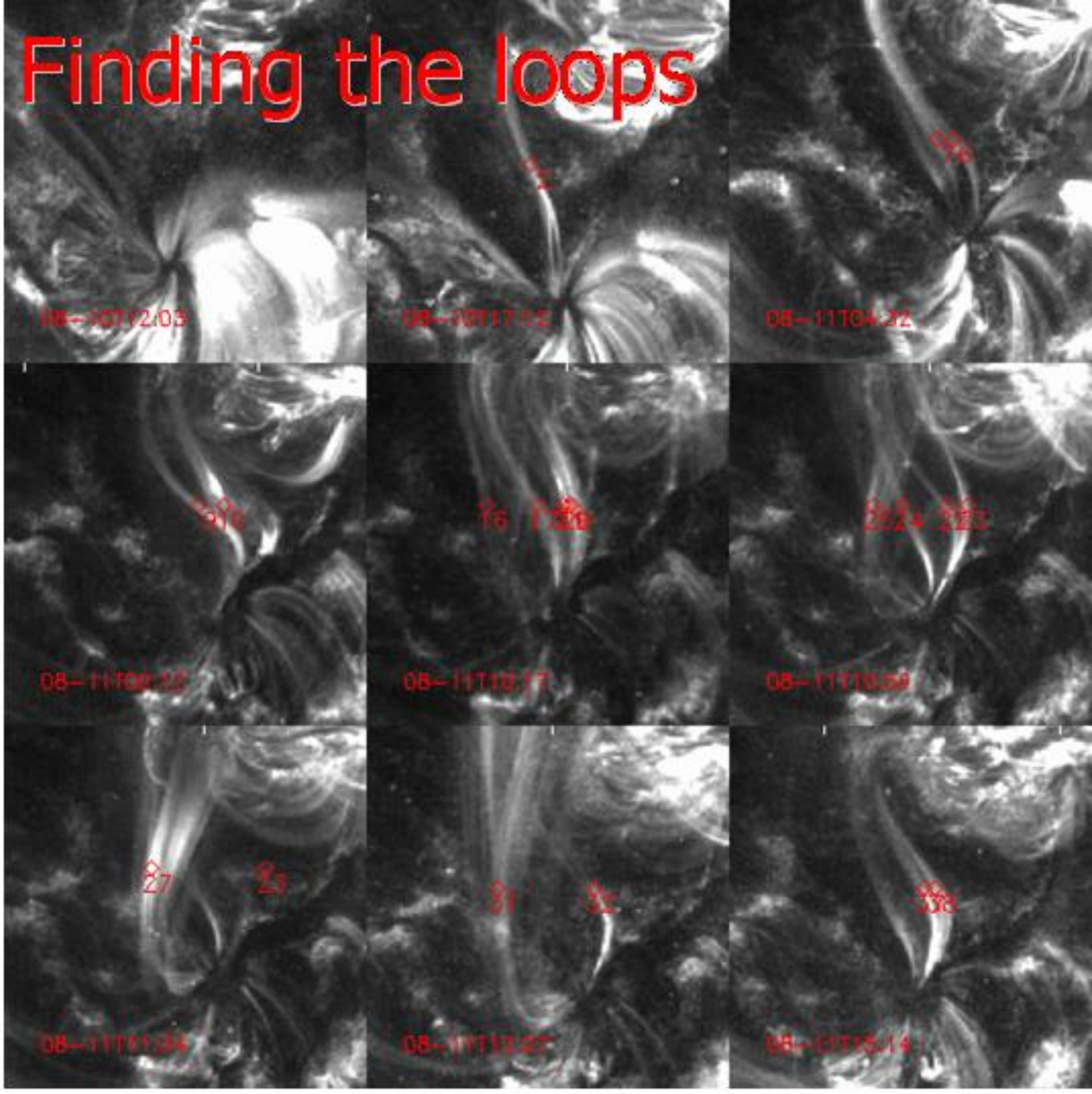
Finding the loops





Show peaks *vs.* time

Finding the loops



Verify spatial correspond-ence w/ intercon'ing loops

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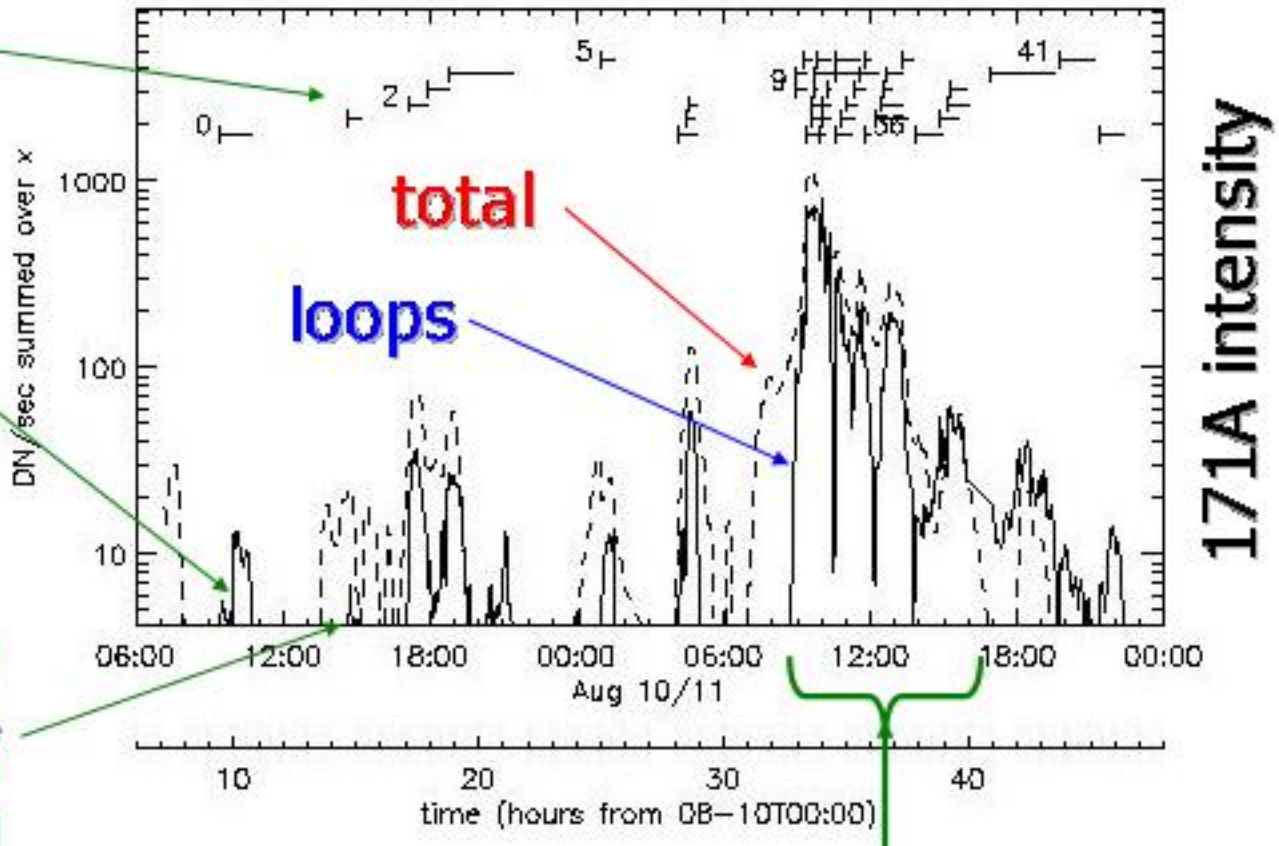
Interconnecting loops:
A catalog

43 loops identified

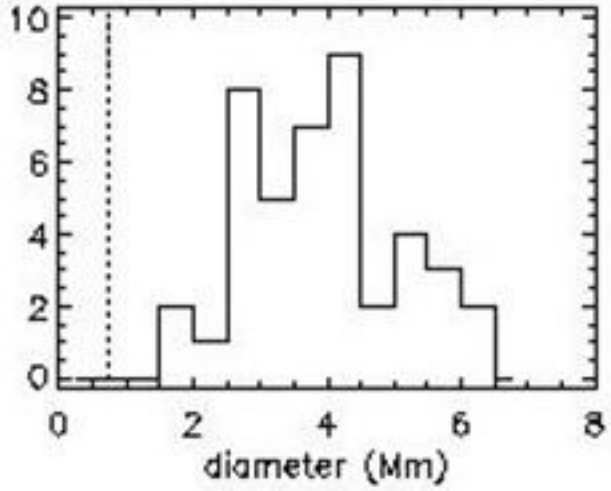
1st loop: (probably) interconnects

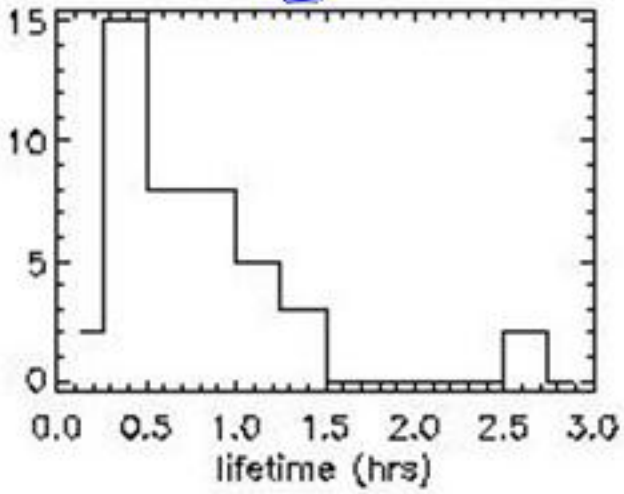
1st loop: definitely interconnecting



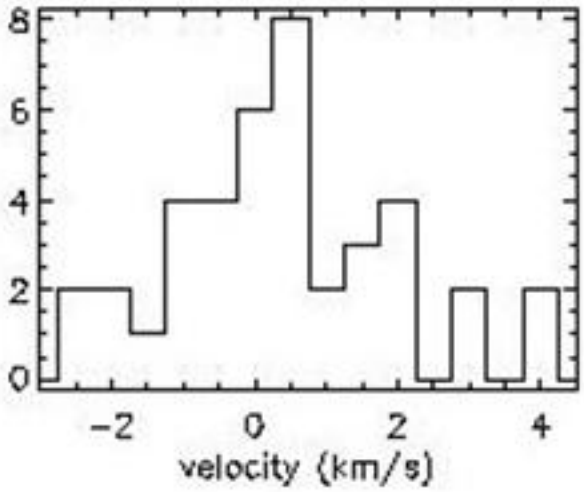
loop flurry ~9:00

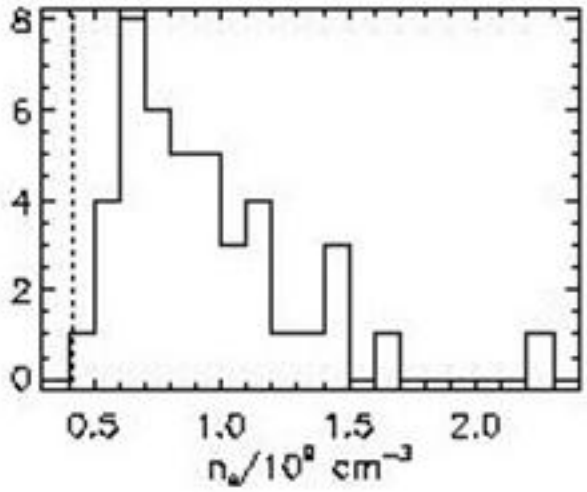
Interconnecting loops:
A catalog





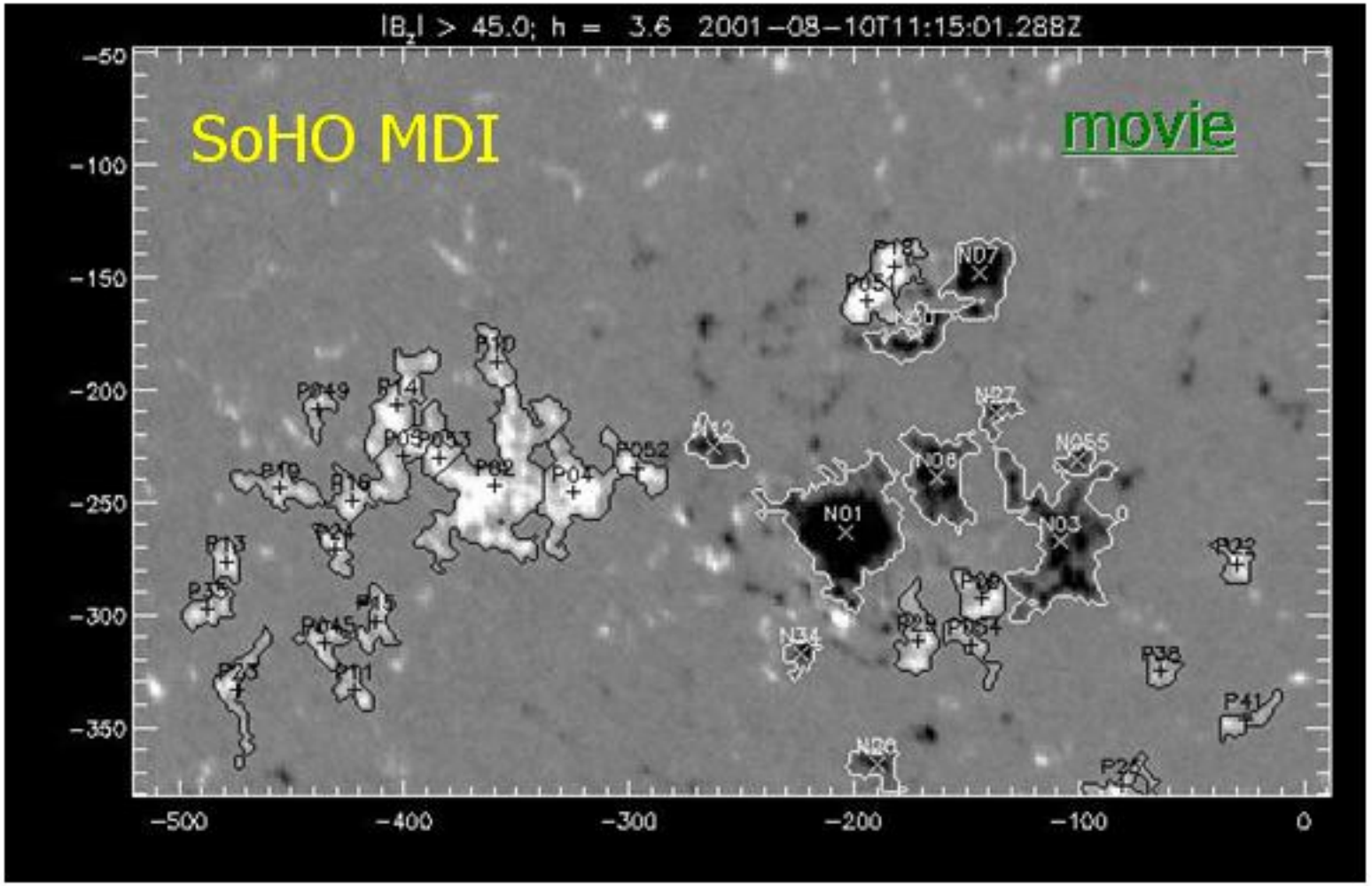
properties of all 43 loops





density lower bound

Magnetic Model



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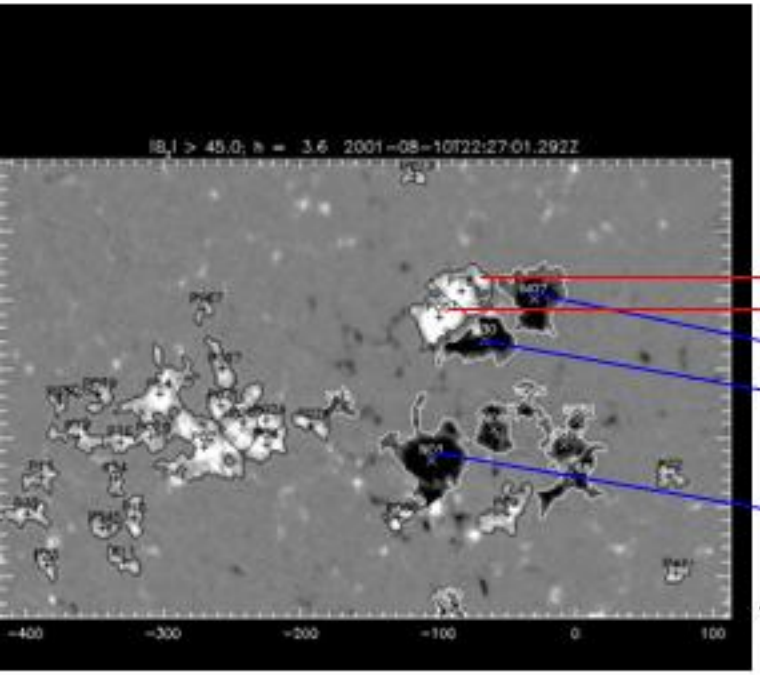
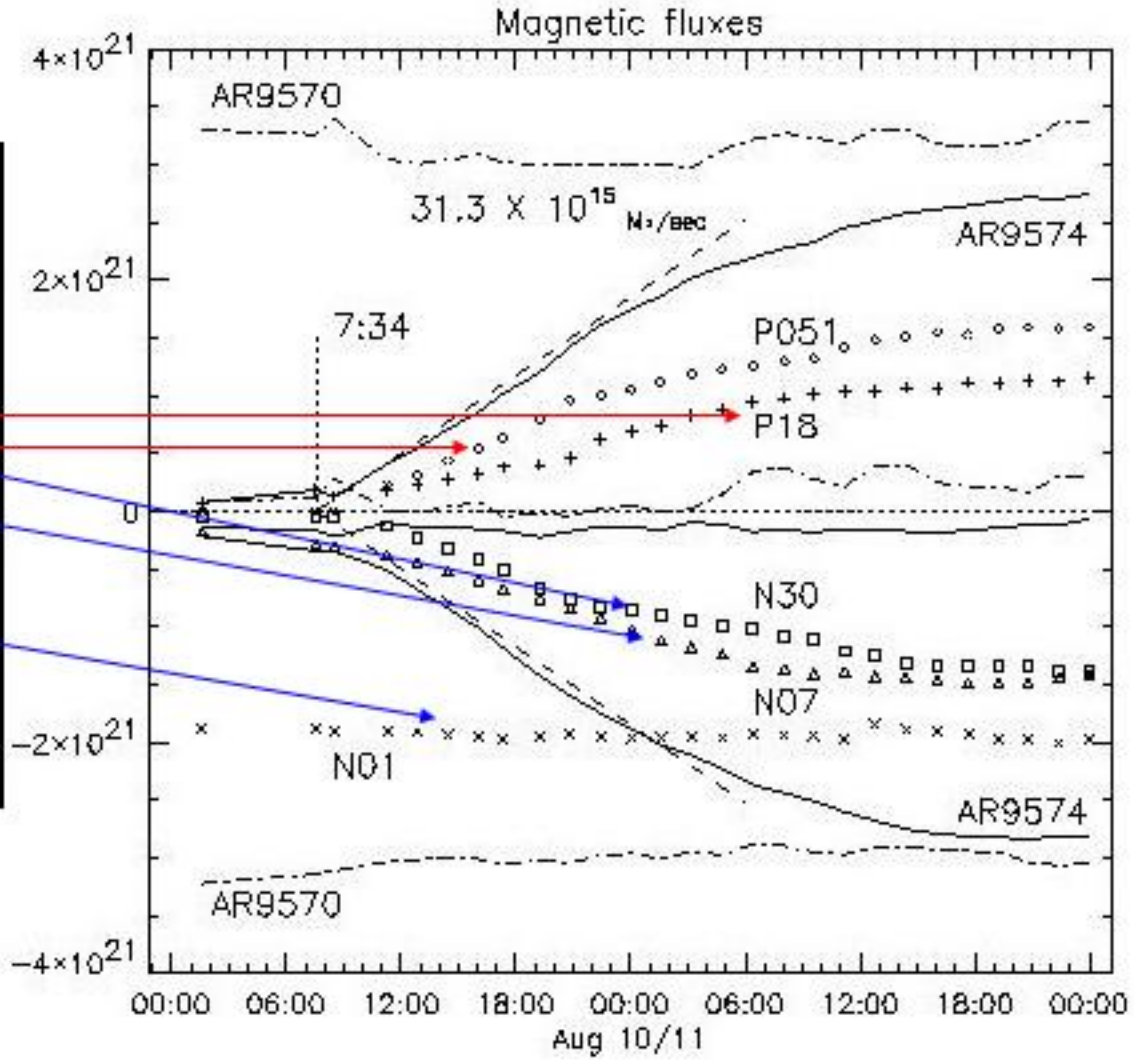
Identify distinct regions with $|B_z| > 45$ G

Magnetic evolution





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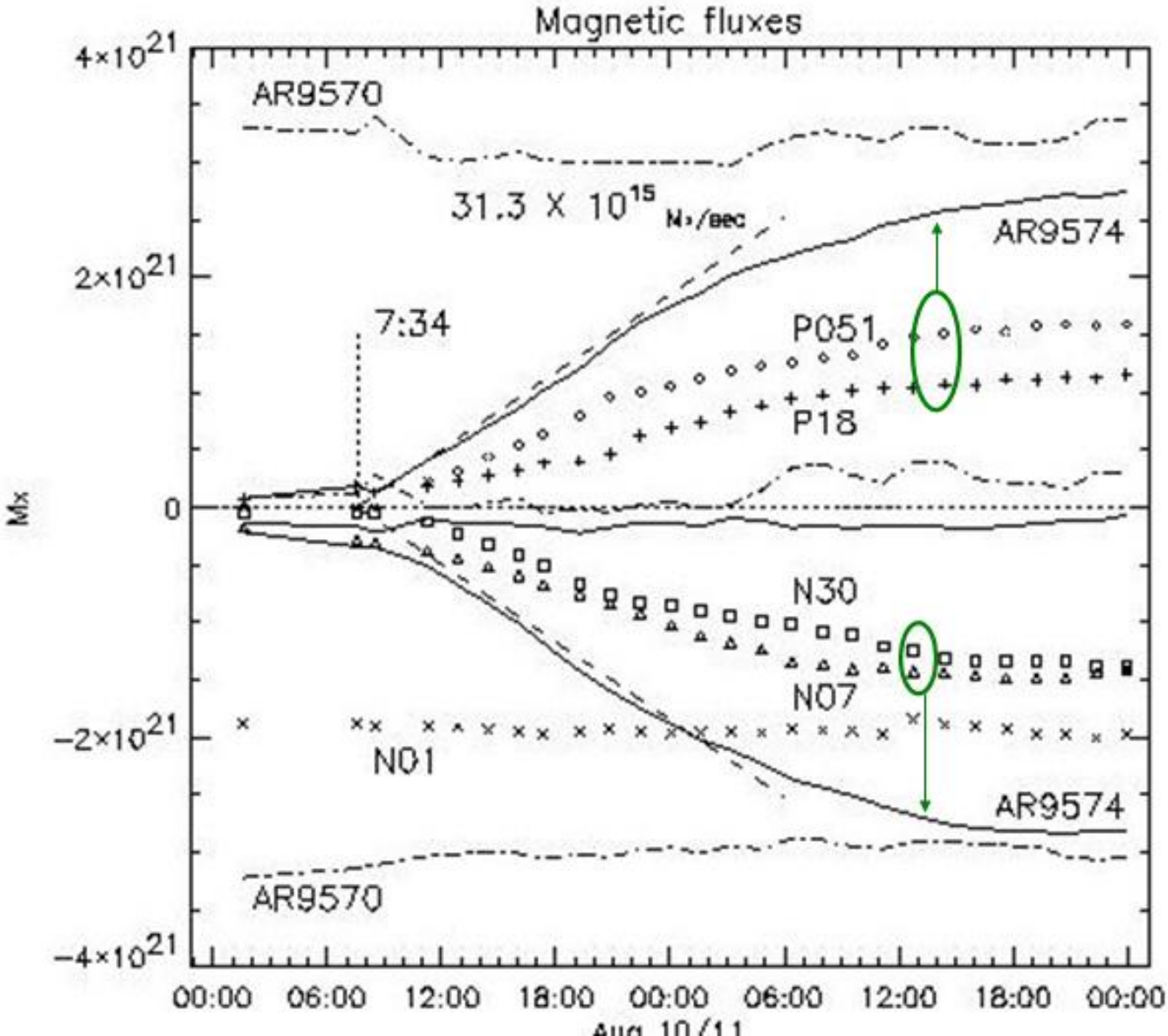
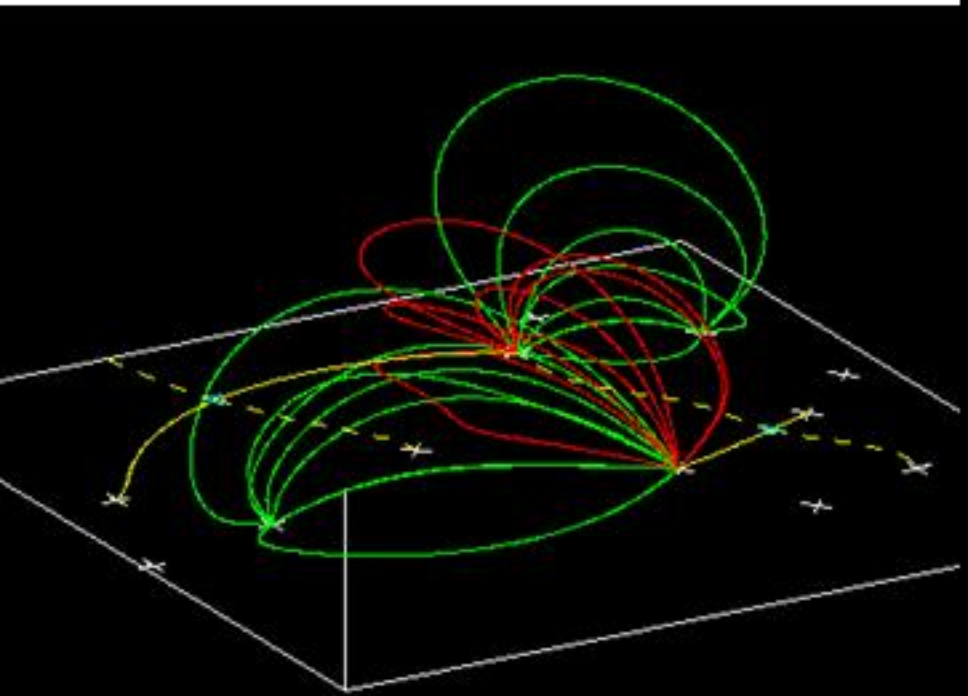
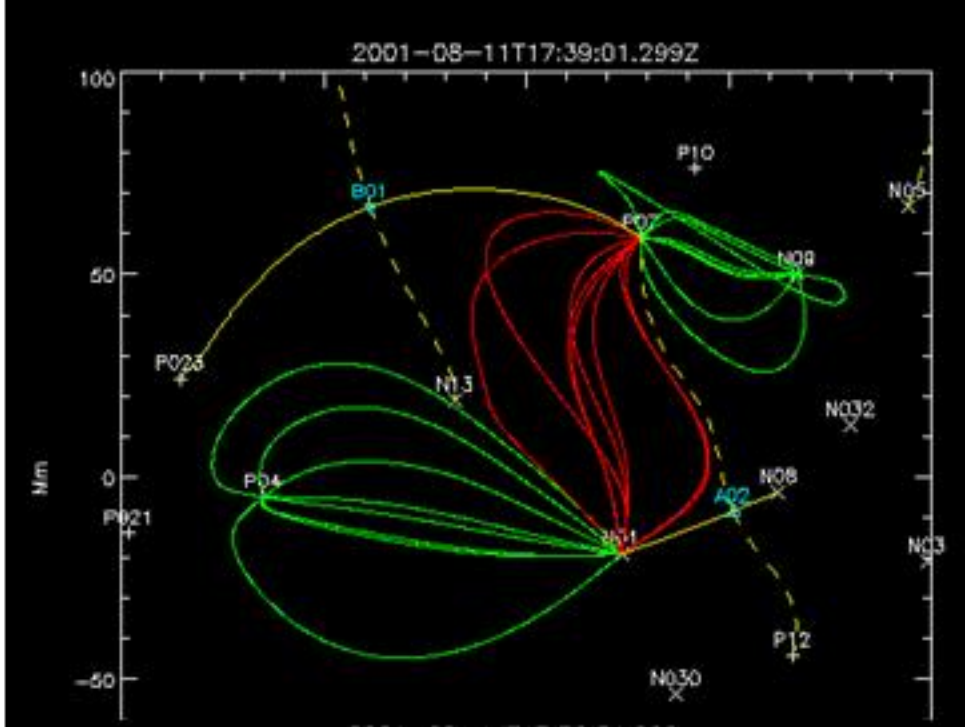

Magnetic fluxes
4×10^21
2×10^21
0
−2×10^21
−4×10^21
Mx
AR9570
31.3 X 10^15 Mx/sec
AR9574
7:34
P051
P18
N30
N07
N01
AR9574
AR9570
00:00
06:00
12:00
18:00
00:00
06:00
12:00
18:00
00:00
Aug 10/11

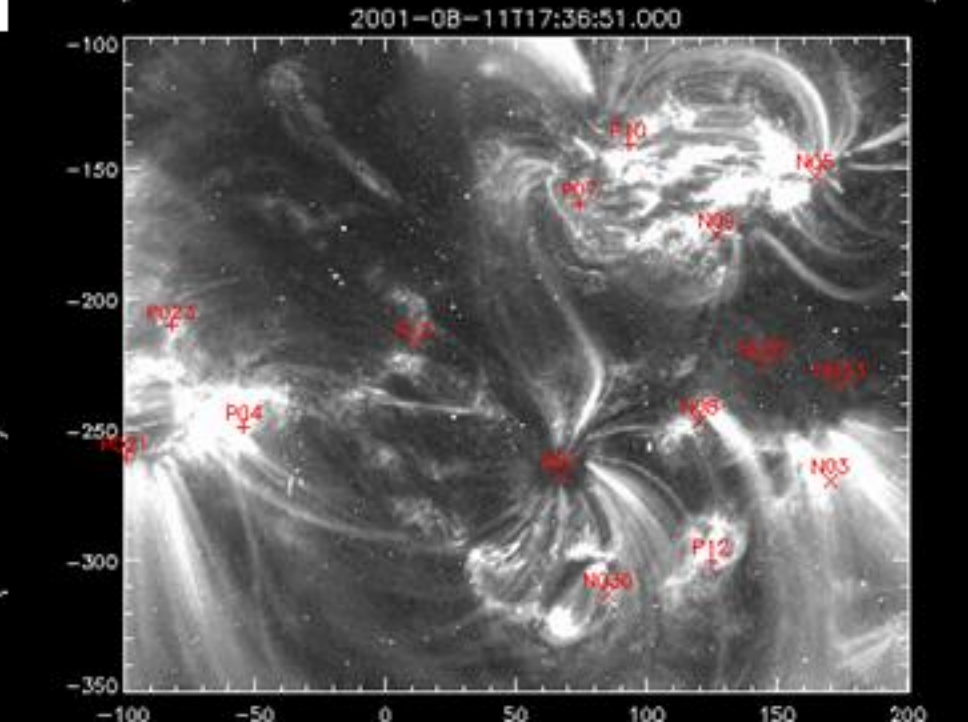
Coronal Field

State of least energy:
Potential Field

$$\nabla \times \mathbf{B} = 0$$



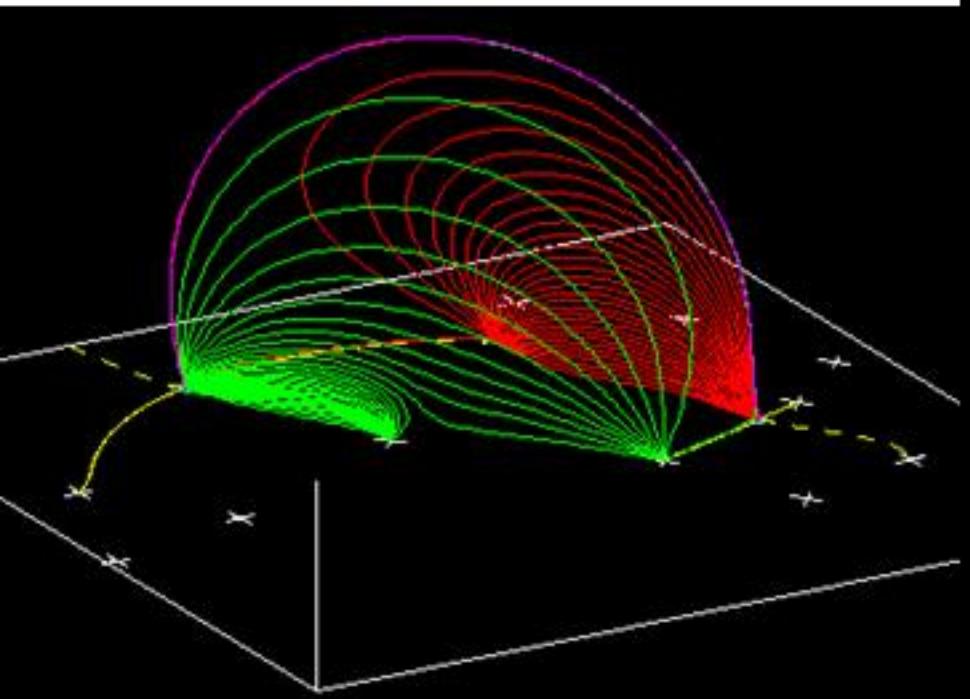


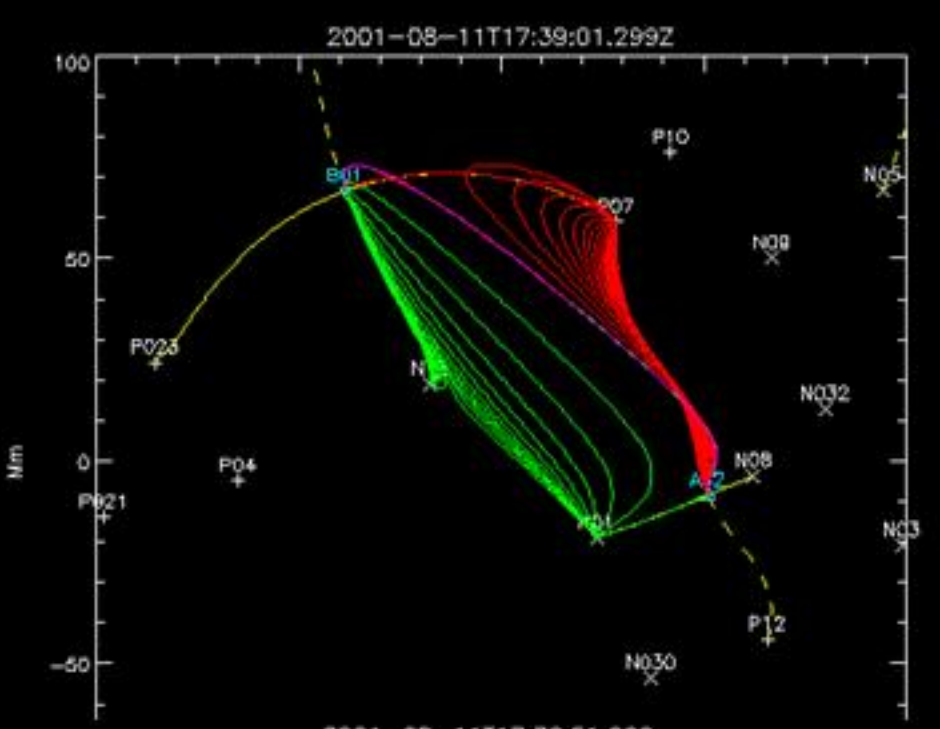


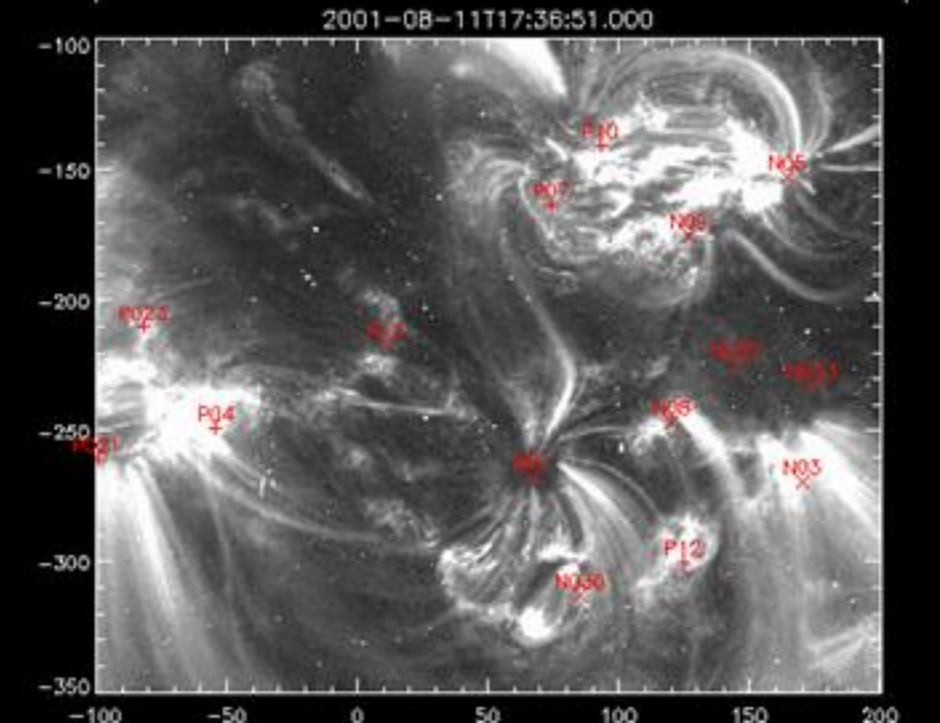
Coronal Field

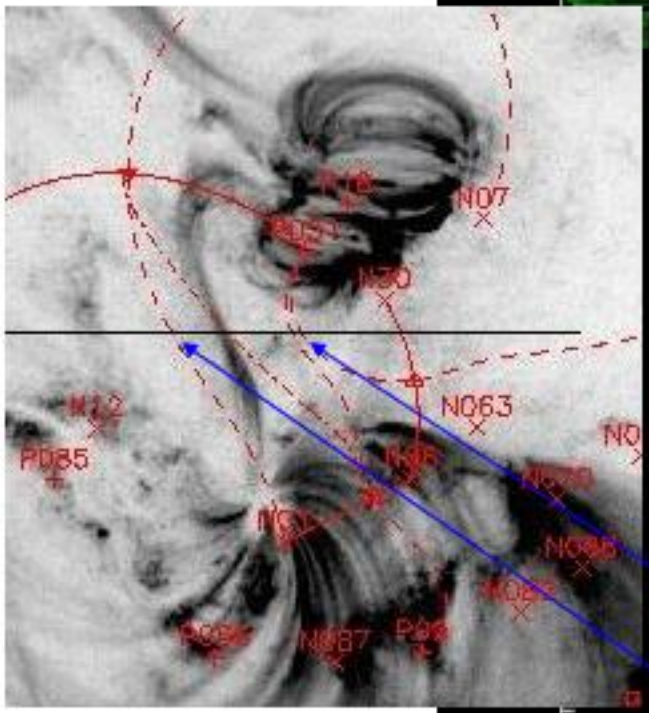
Includes connections AR9574 to AR9570 (**P051 → N01**)

...all under separatrix surface









Separatrices enclose loops

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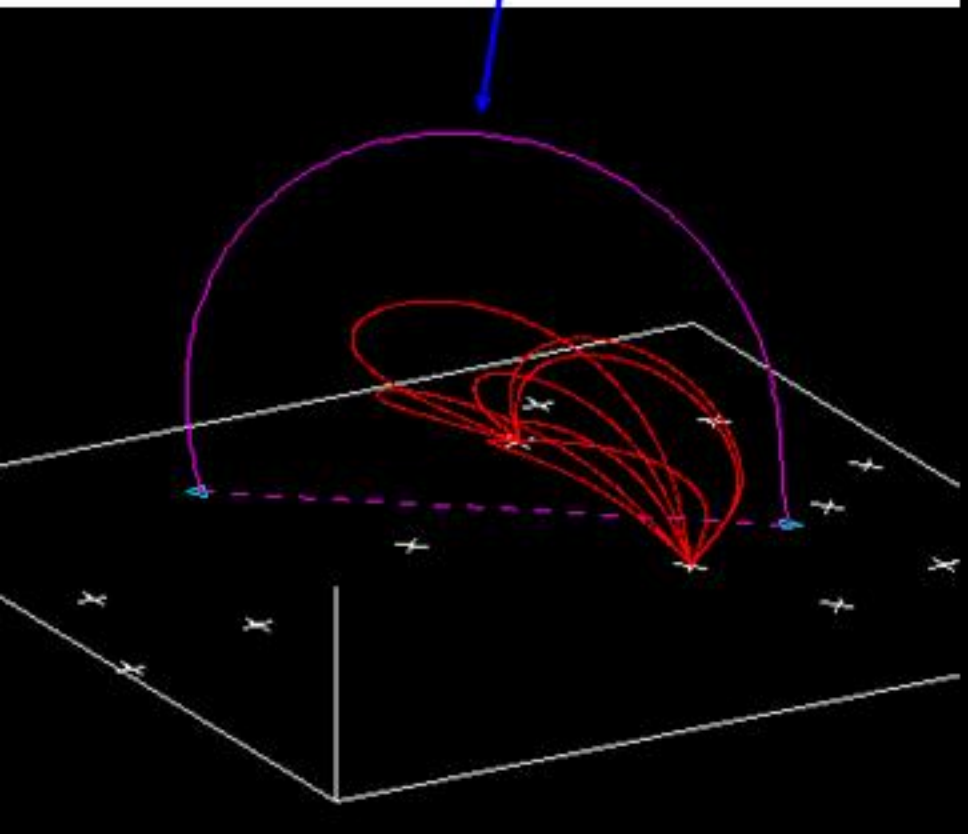
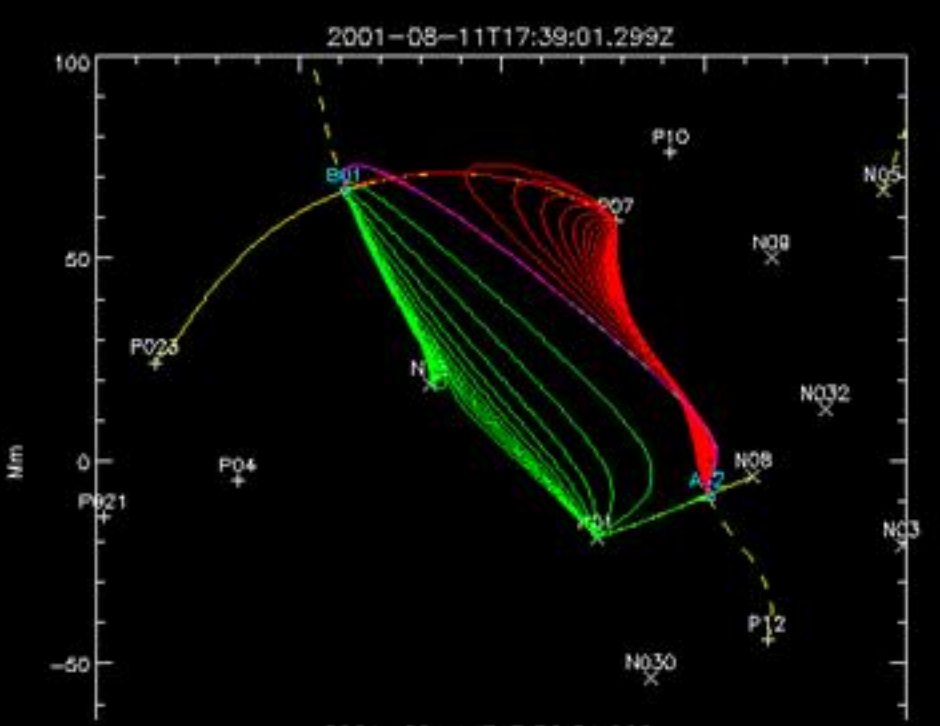
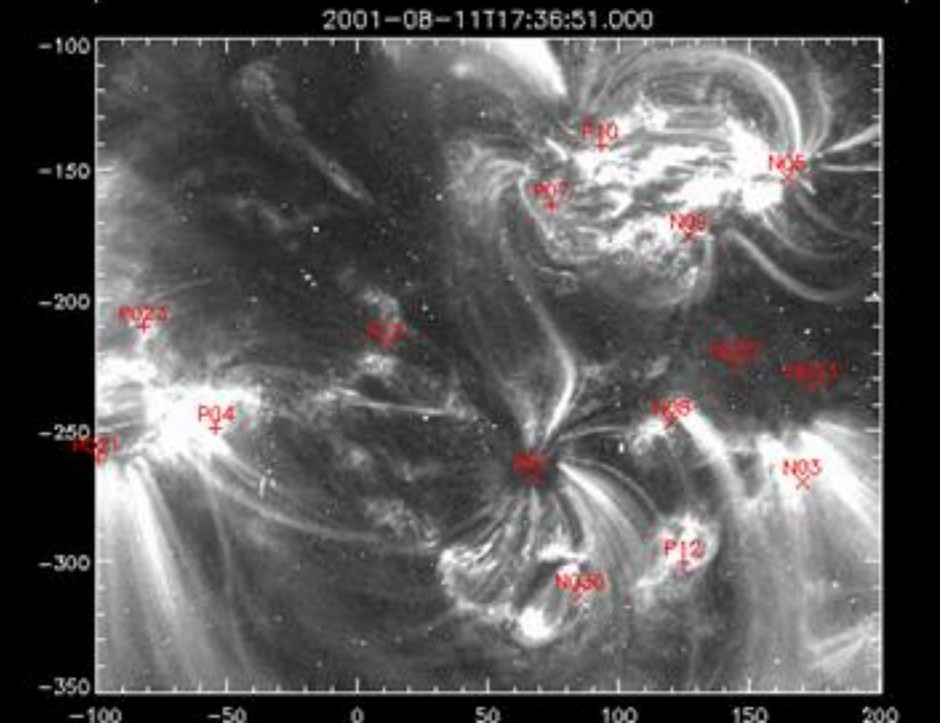
Coronal Field

Inter-connecting lines enclosed by

separator



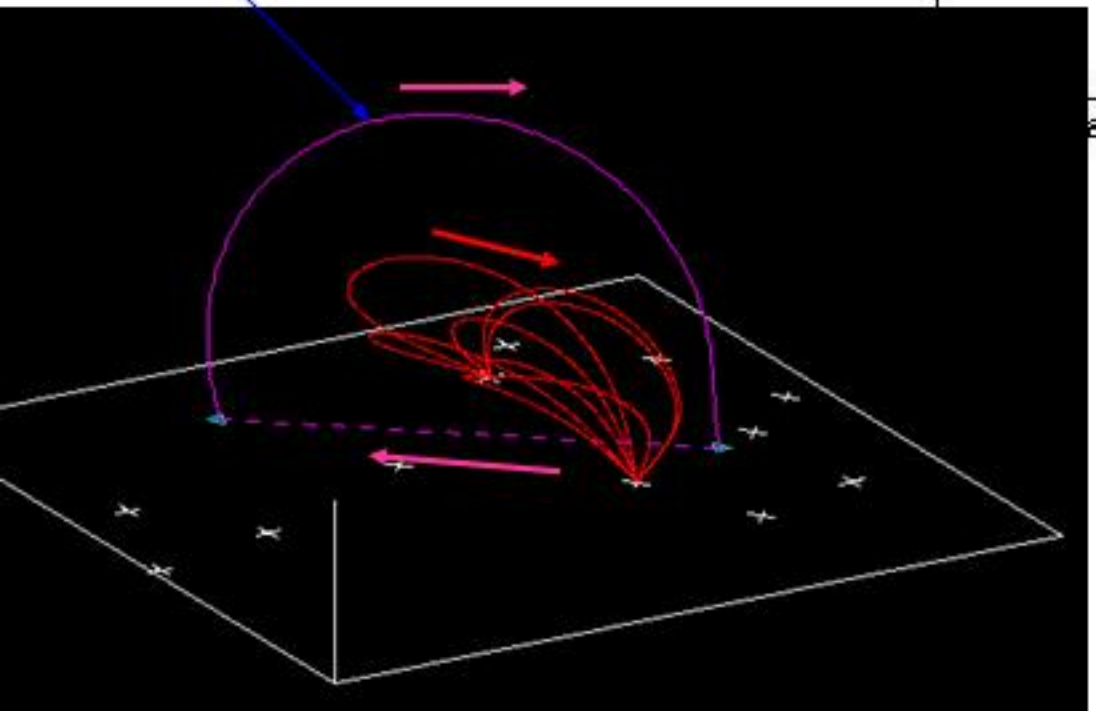


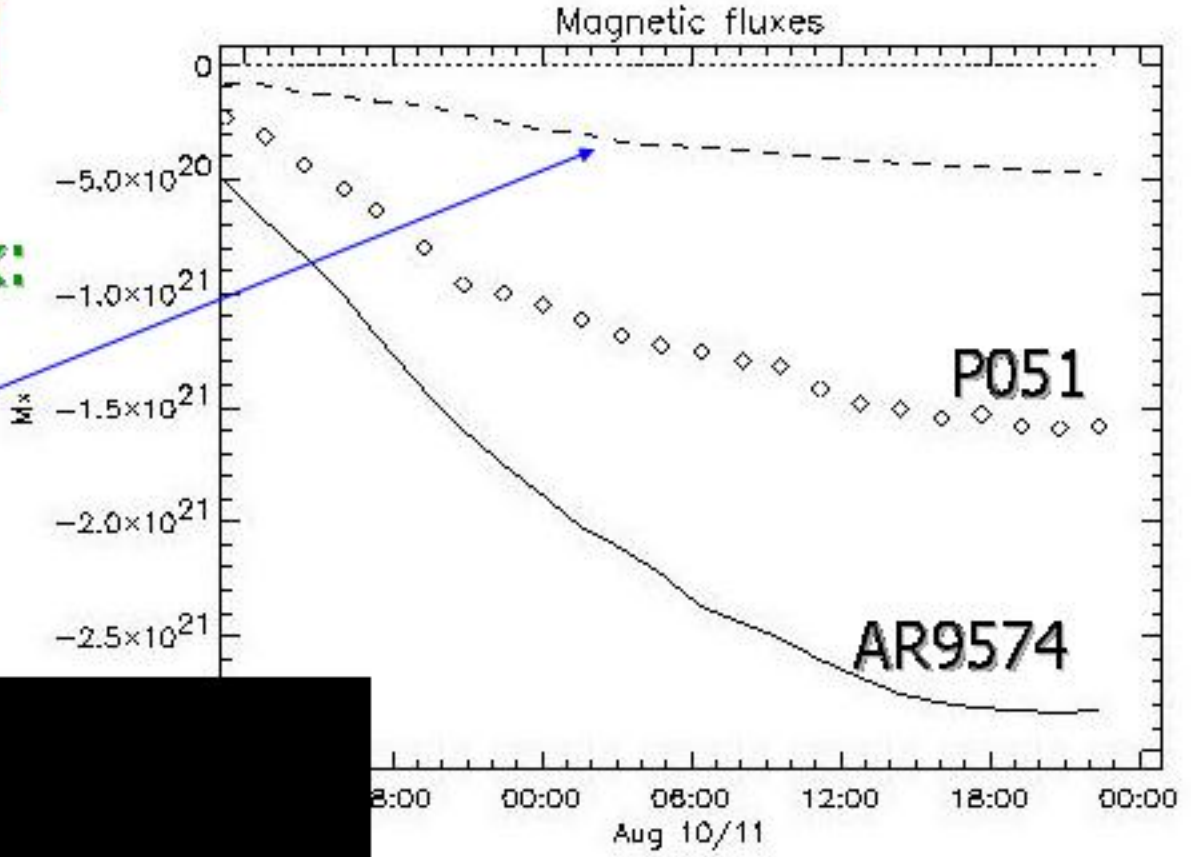


Coronal Field

Inter-connecting flux:

$$\oint_{\sigma} \mathbf{A} \cdot d\mathbf{l} = \Psi$$





Potential field:

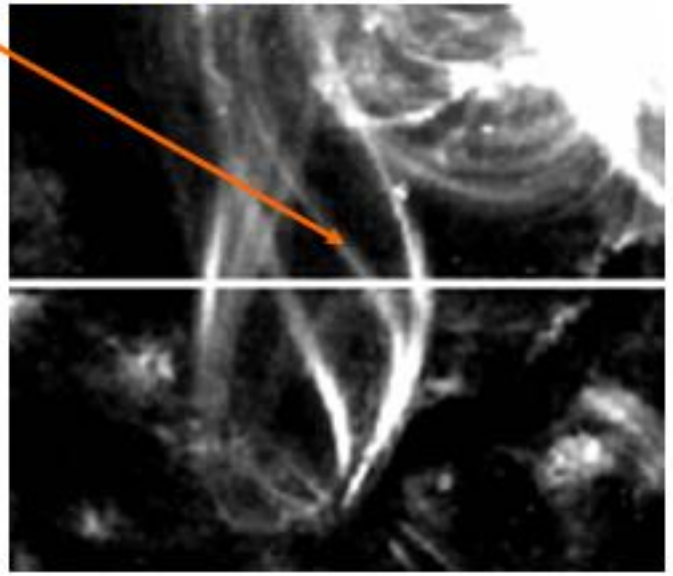
Increasing

interconnection

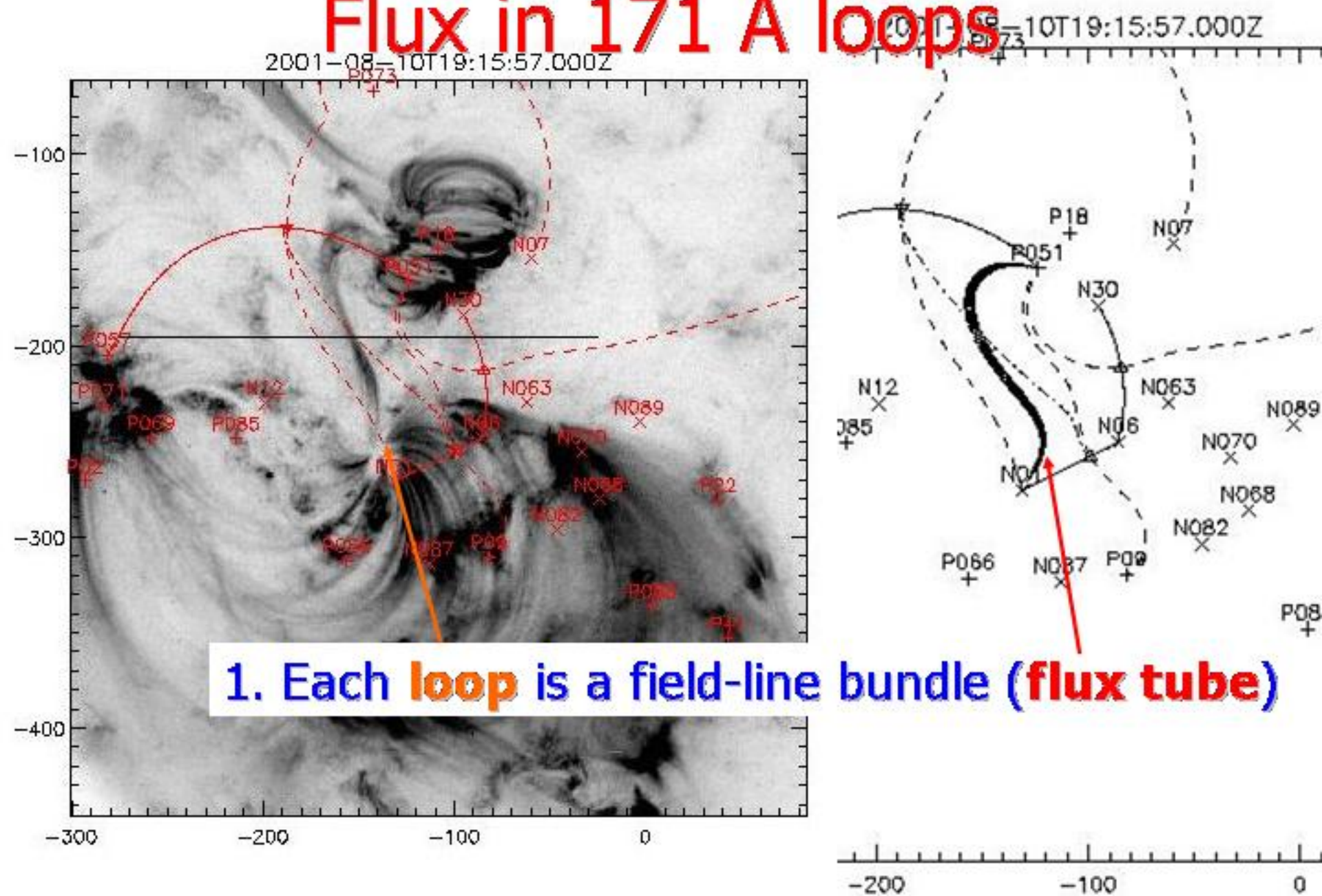
Flux in 171A loops

Assumptions

1. Each **loop** is a field-line bundle (flux tube)
2. Loops/flux tubes : ◯-section
3. Loop tracks flux tube for entire life
4. No flux tube re-appears in 171 A

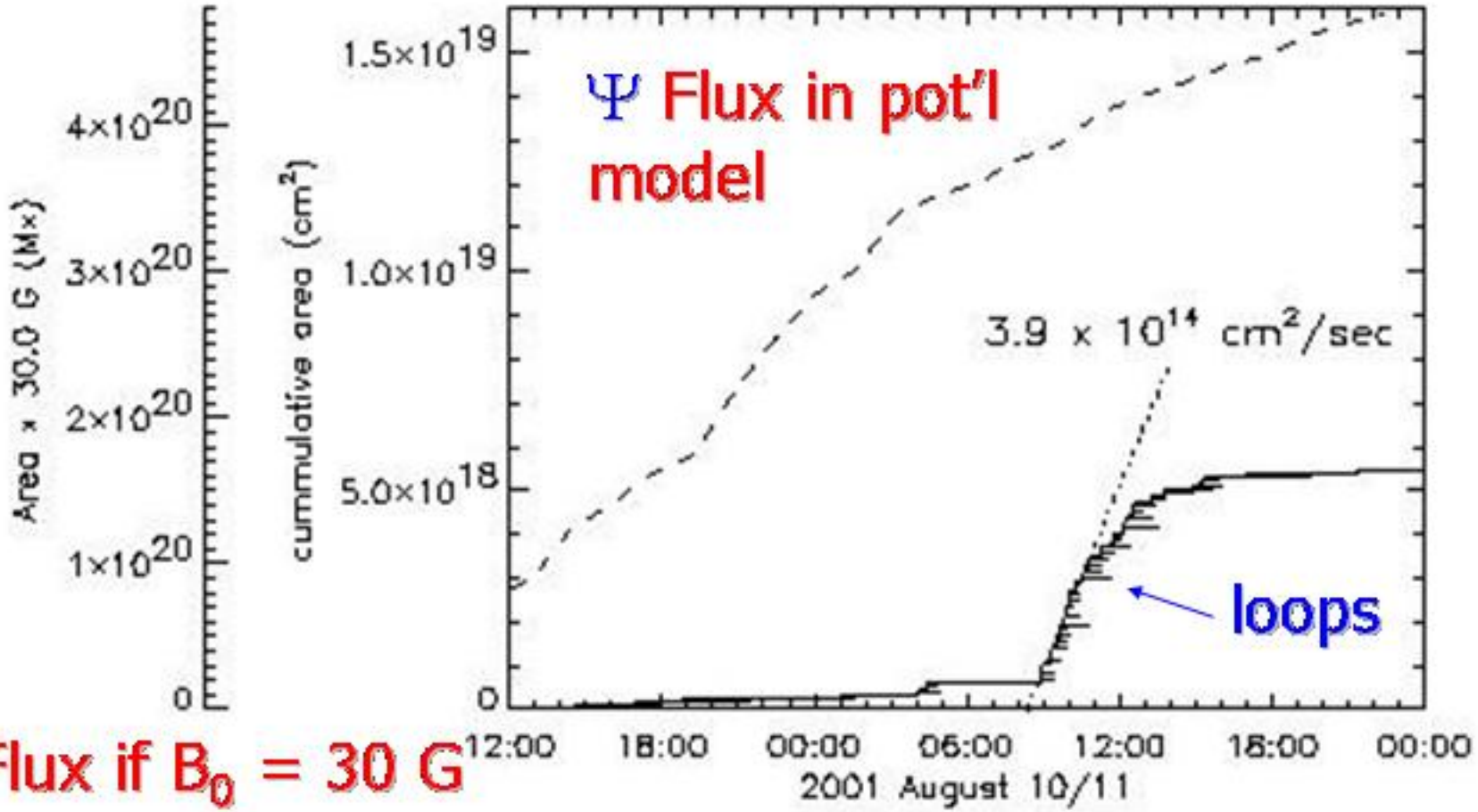


Flux in 171 A loops



1. Each **loop** is a field-line bundle (**flux tube**)

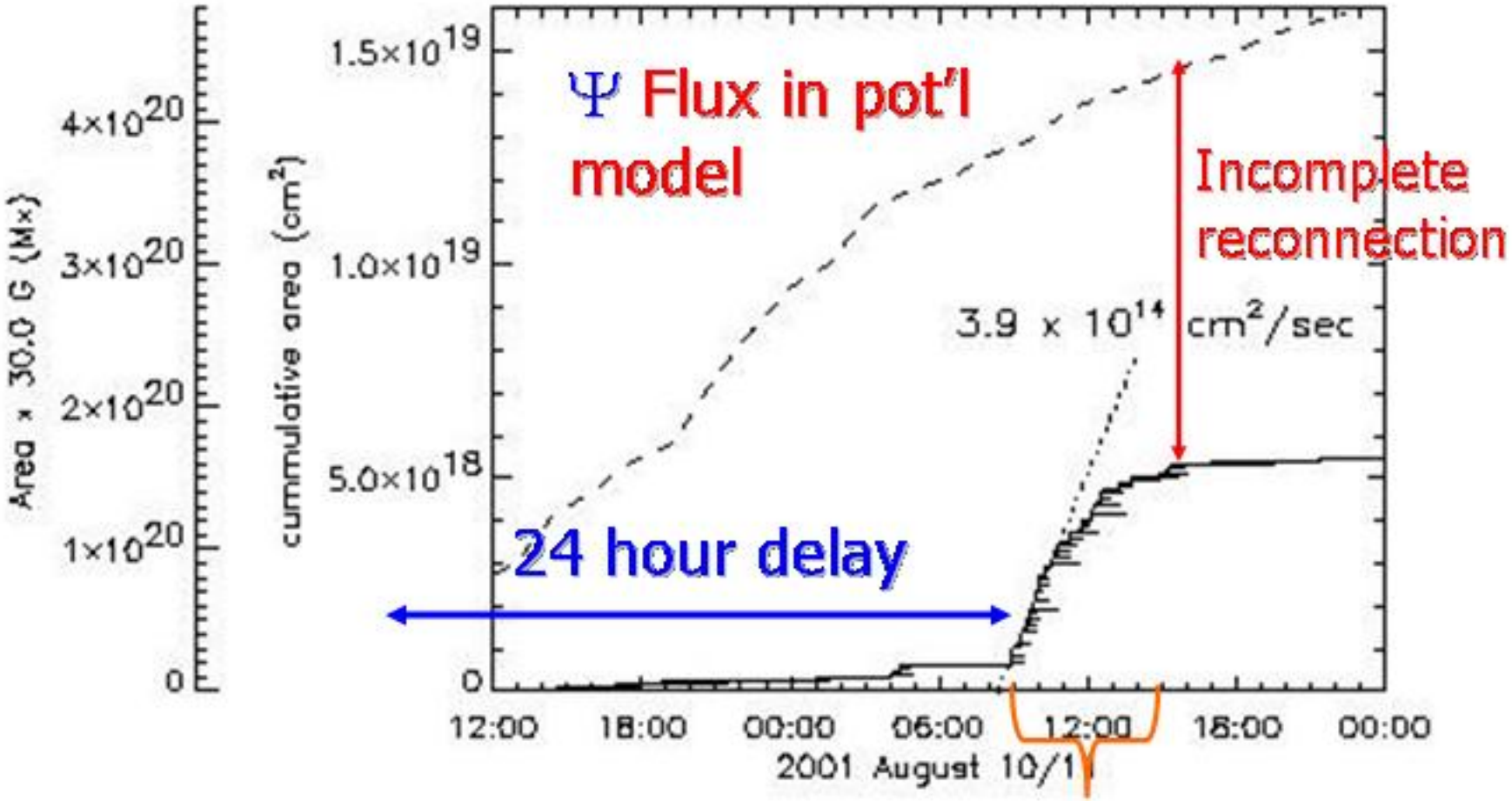
Flux in 171 A loops



Flux if B_0 = 30 G

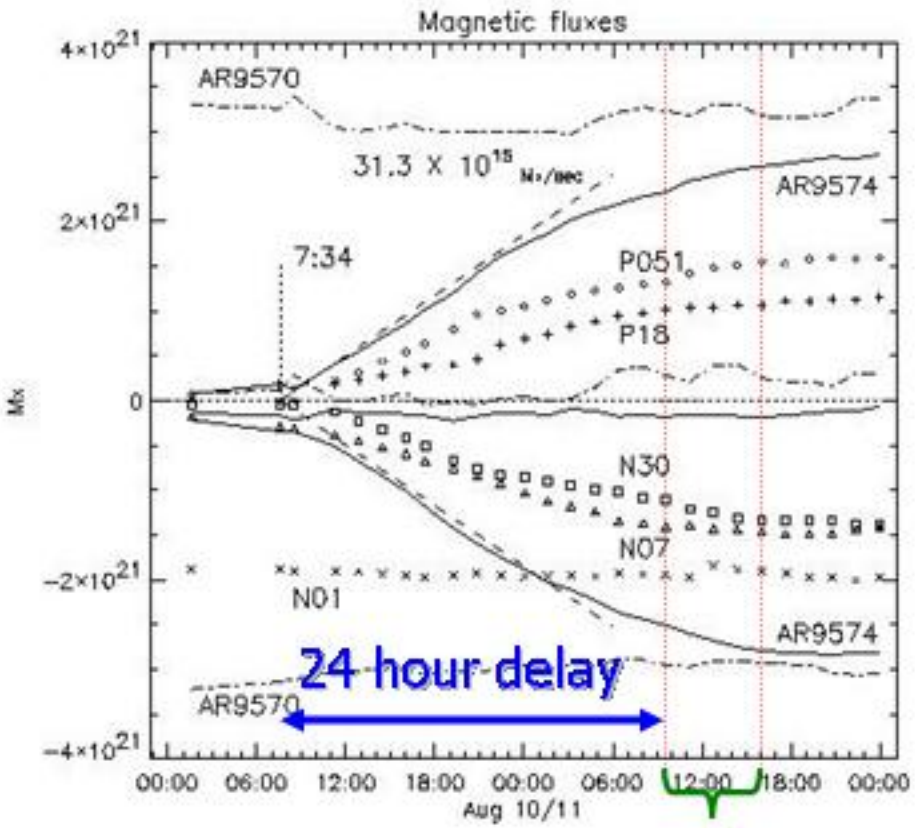
Cummulative loop areas

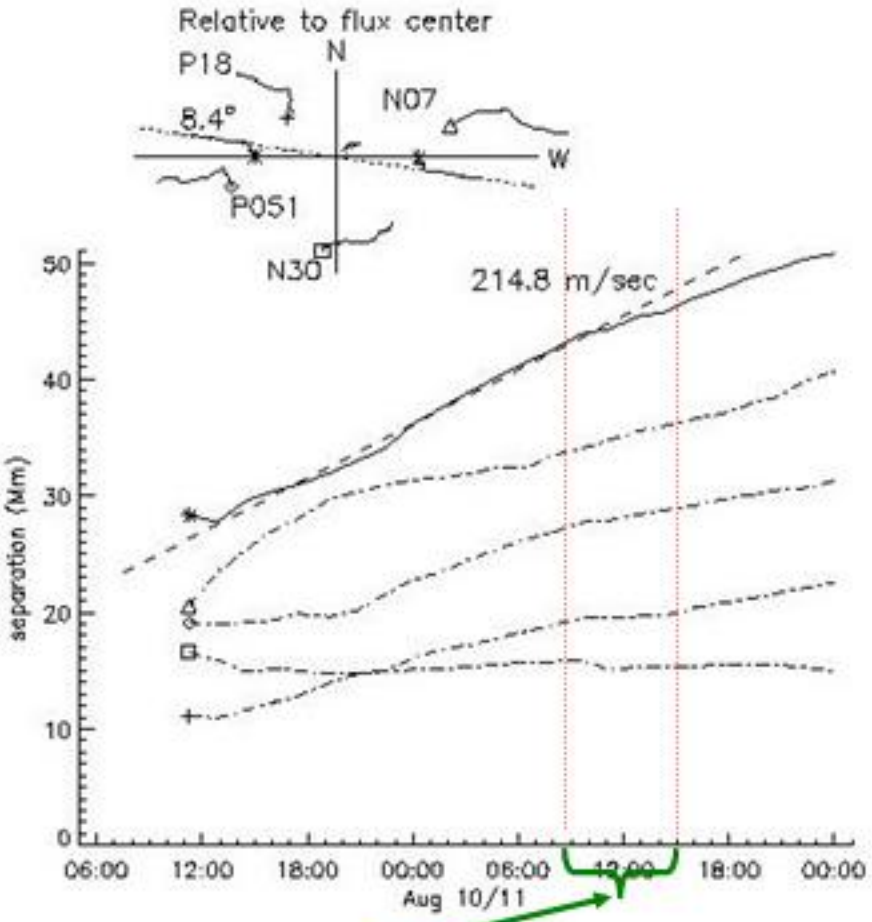
Reconnection observed



Burst of reconnection
10^{16} Mx/sec = 100 MV

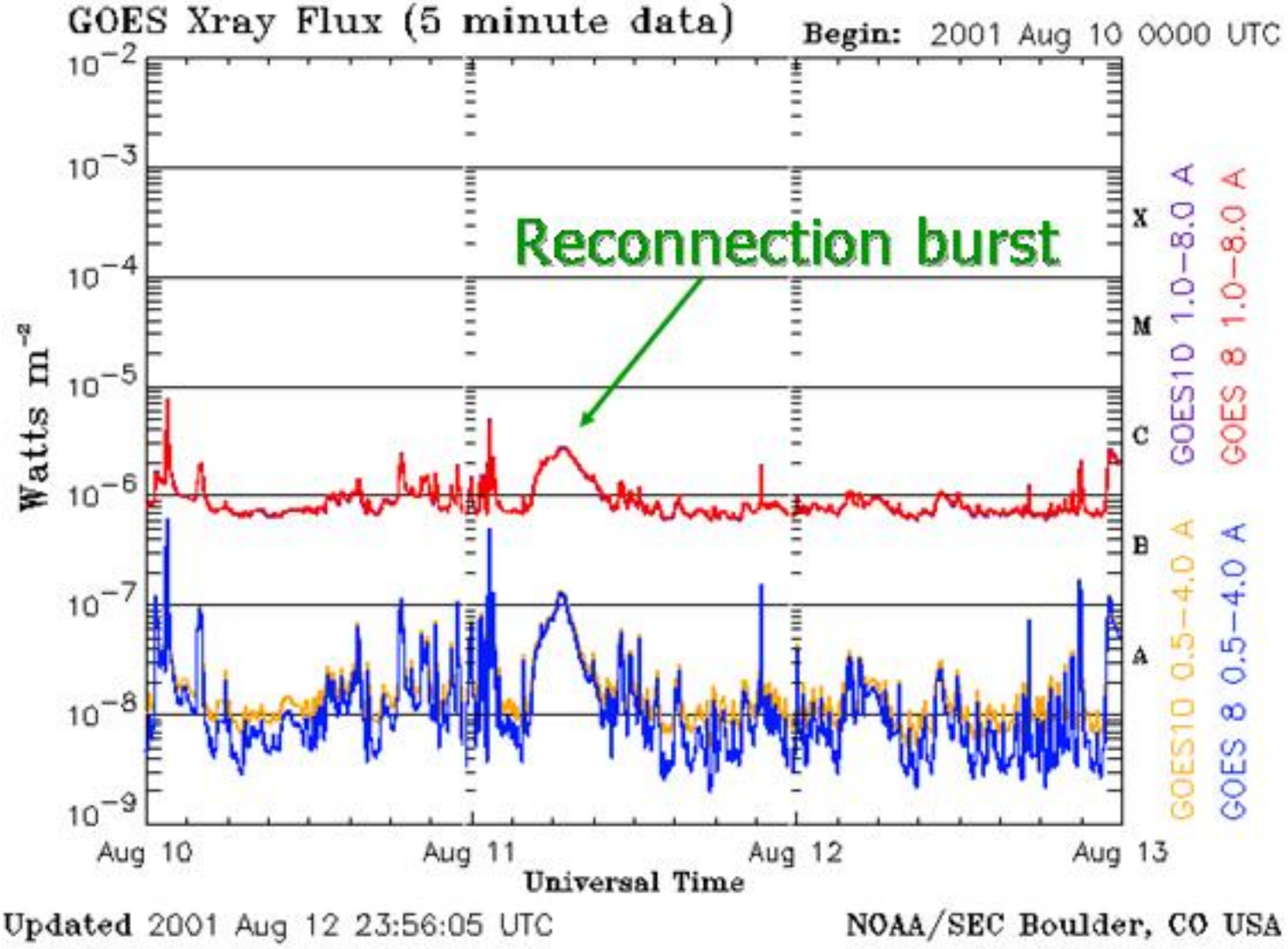
P-spheric Trigger? Response?



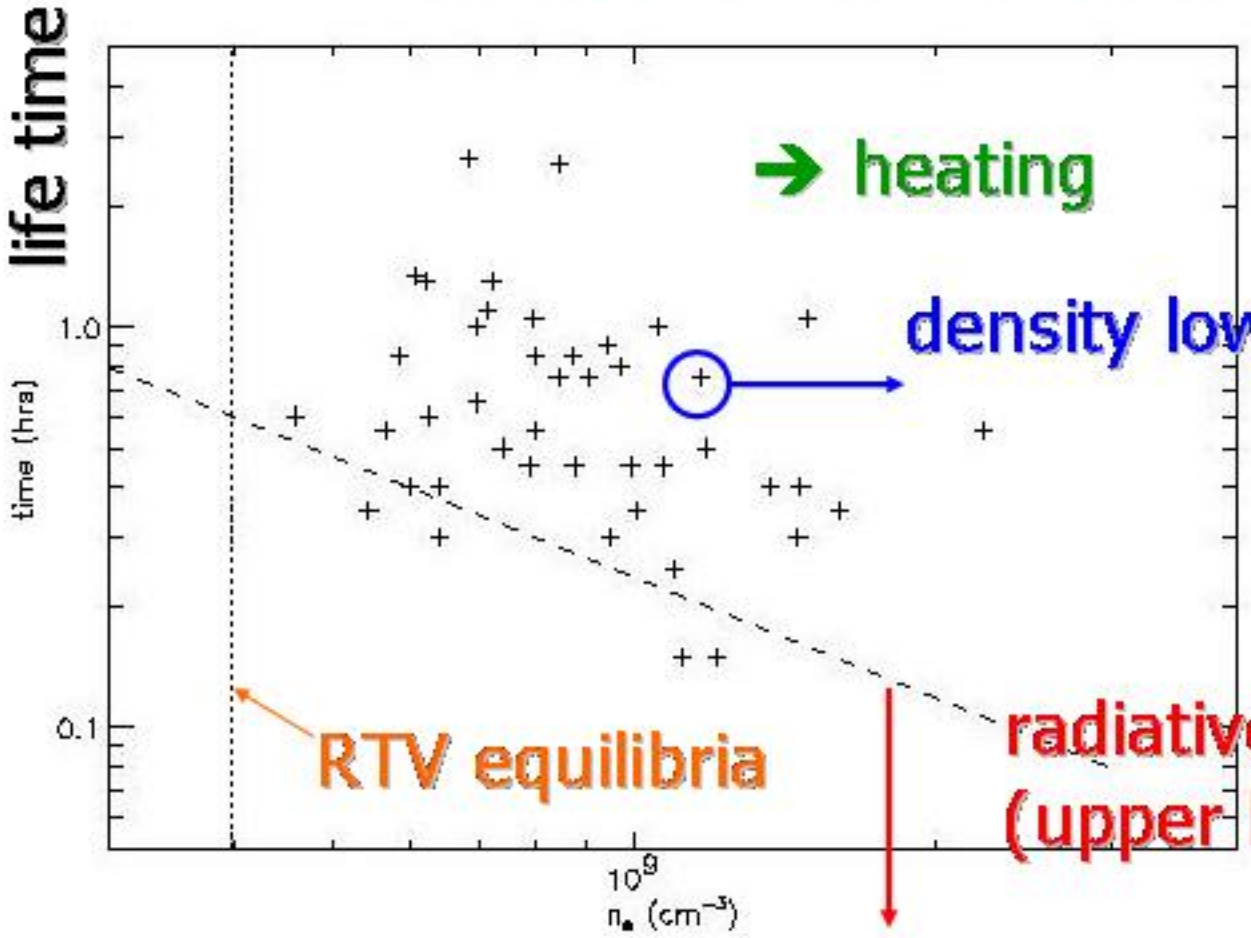


loop flurry ~9:00

There were no flares



The story of the loops



→ heating

density lower bounds

RTV equilibria

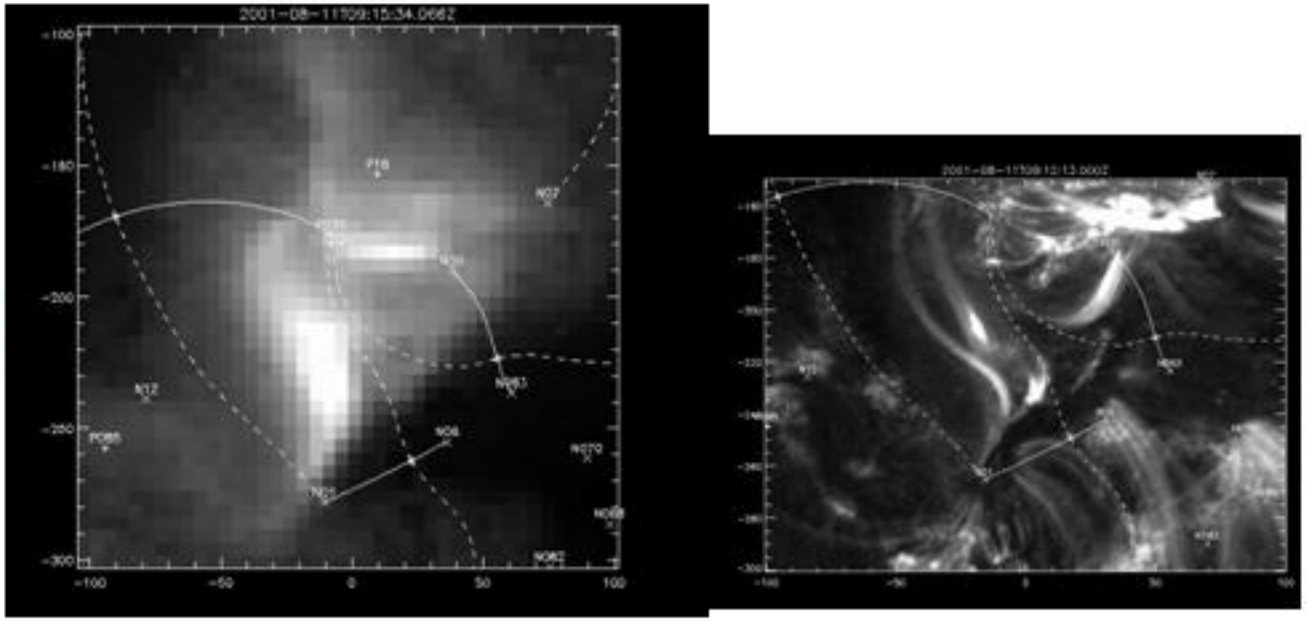
radiative cooling time
(upper bound on life)

The story of the loops

Yohkoh SXT

TRACE 171 A

movie



~3,000,000 K

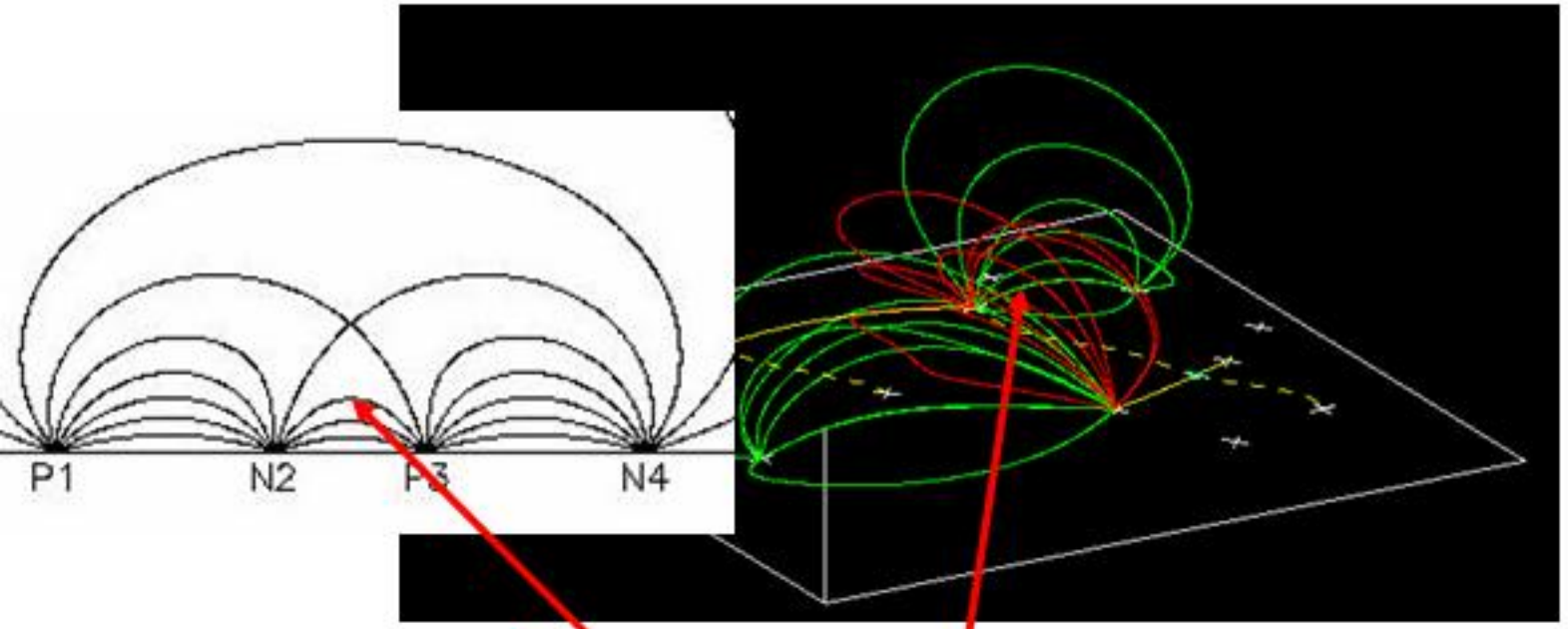
950,000 K

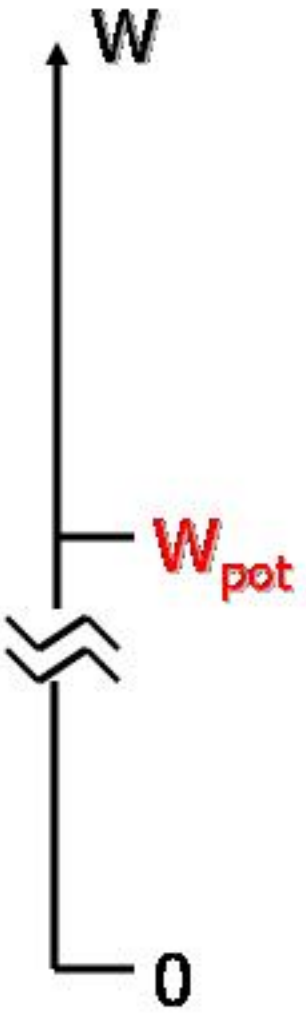
Loops are hot (~3MK) after reconnection…
Gradually cool into TRACE pass-band

(All of them?)

Model of energy storage

Unconstrained minimum: $\nabla \times \mathbf{B} = 0$

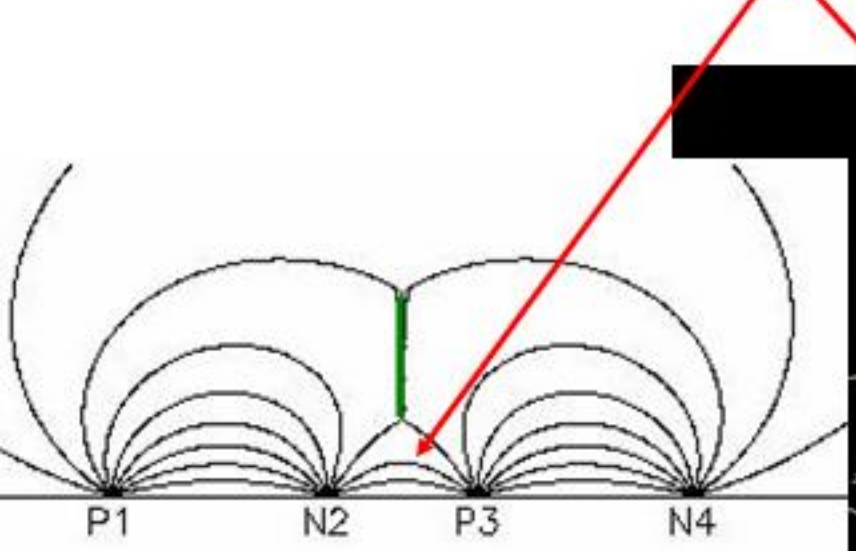


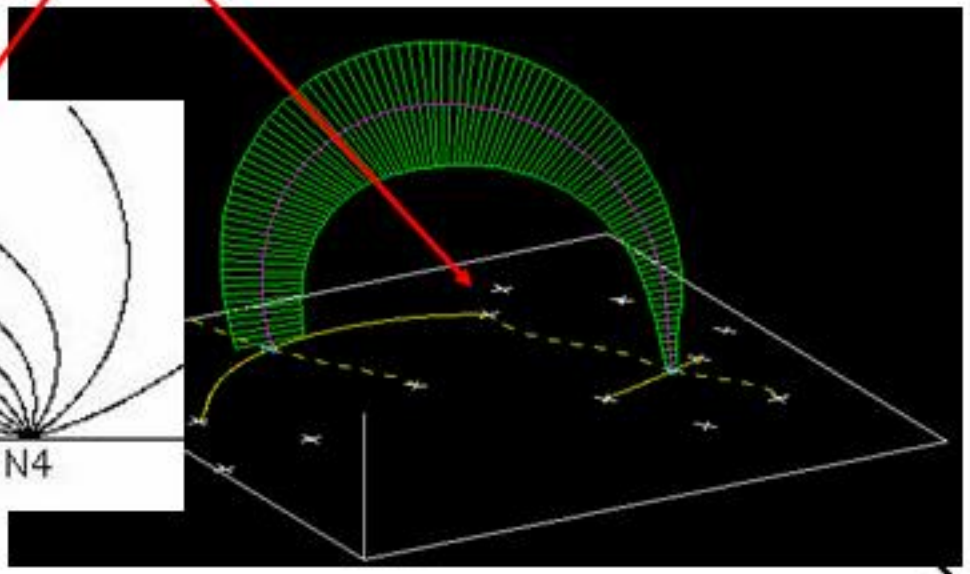


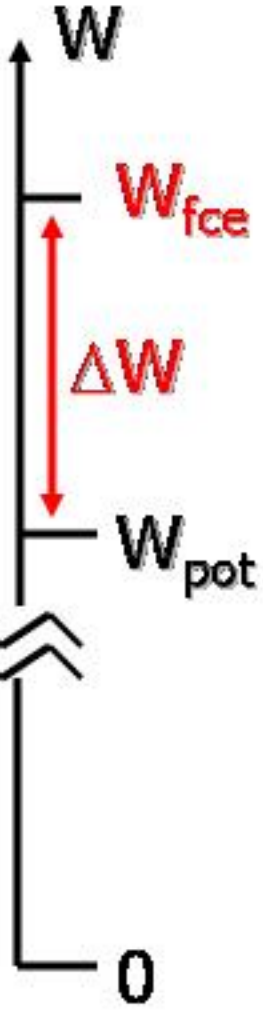
Flux $\Psi=\Psi(v)$ linking poles

Model of energy storage

Constrain Flux Ψ & minimize energy…







Flux Constrained Equilibrium

(Longcope 2002)

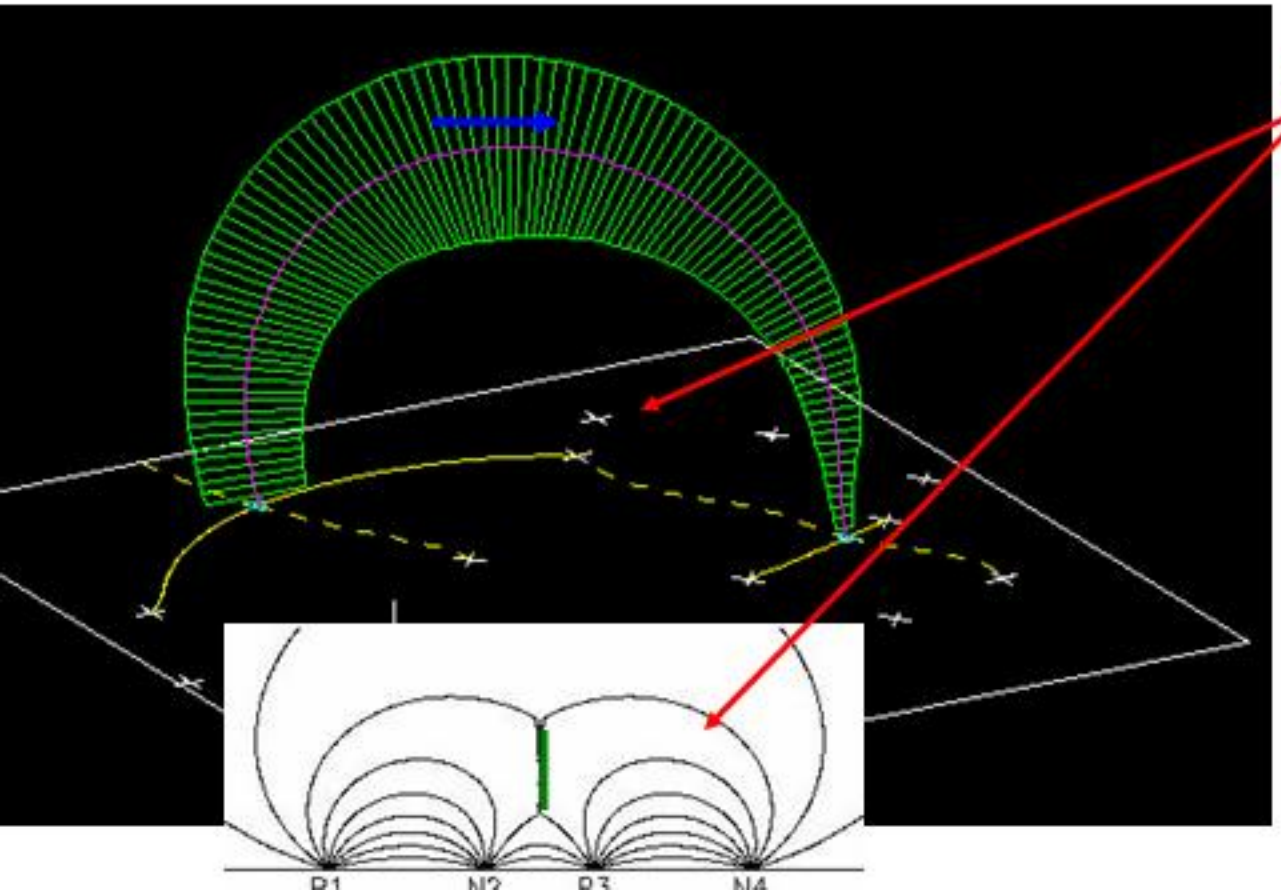
$$\Delta W \approx \frac{\left(\Psi - \Psi^{(v)}\right)^2}{2L}$$

Model of energy storage

Lowest Energy w/ fixed Ψ:

Flux Constrained Equilibrium

(Longcope 2002)



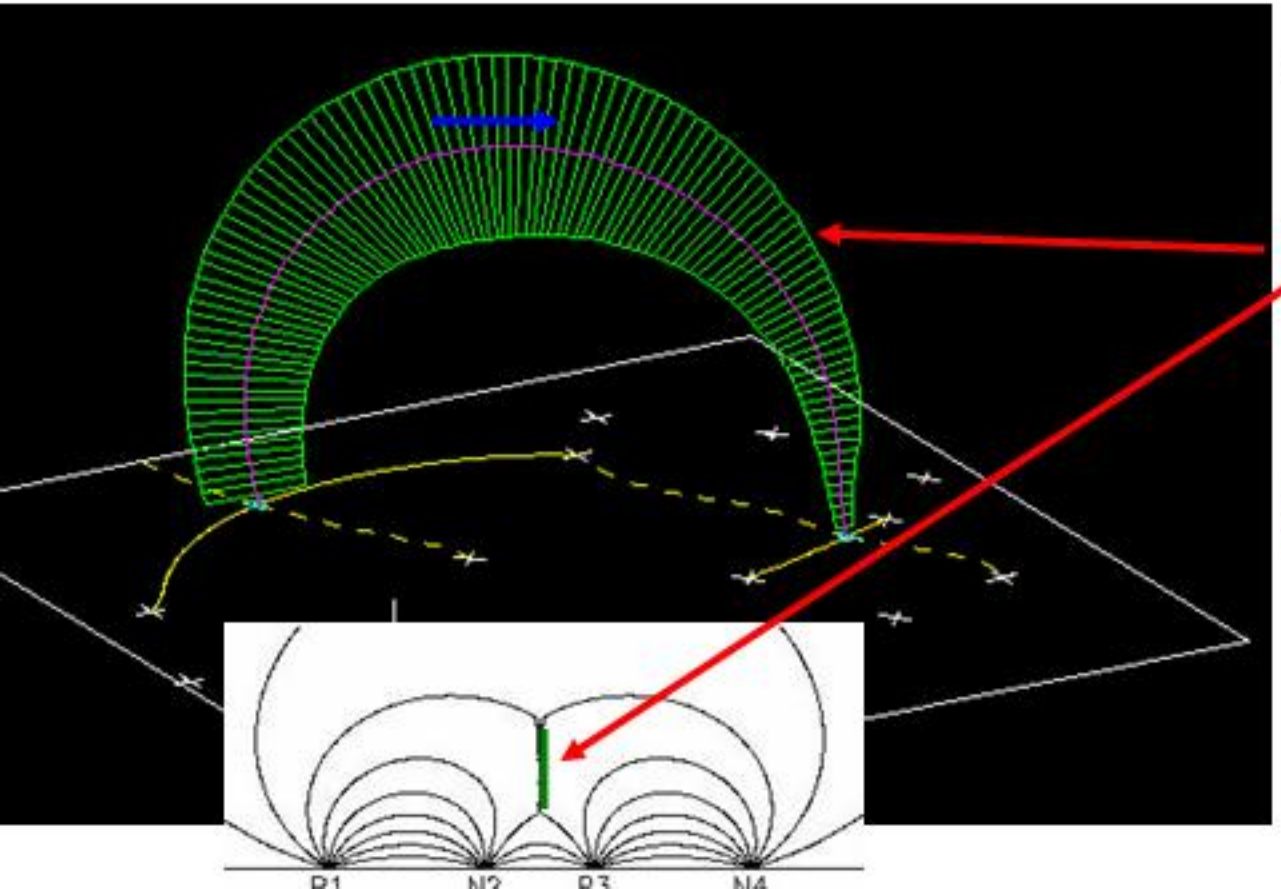
- Current-free except …

Model of energy storage

Lowest Energy w/ fixed Ψ:

Flux Constrained Equilibrium

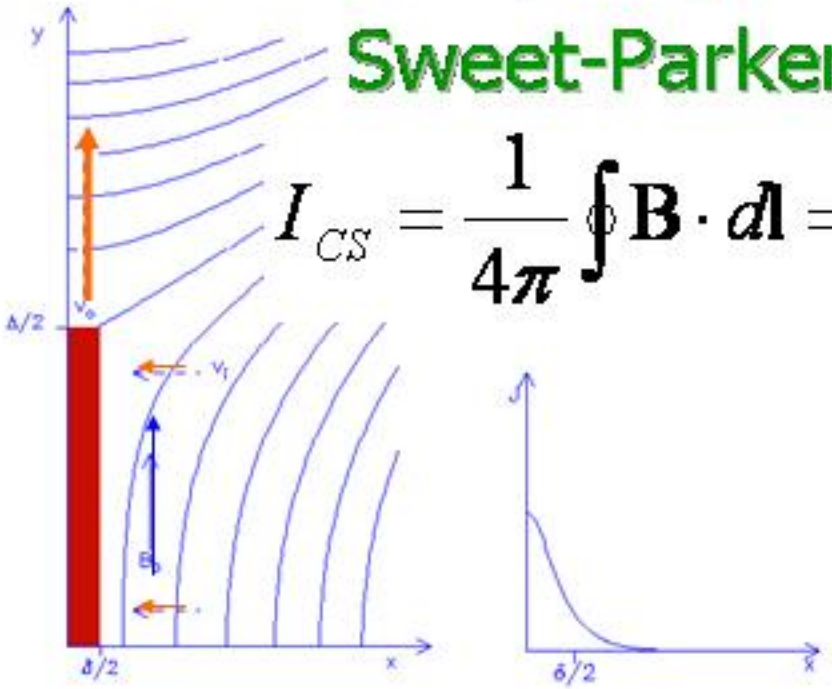
(Longcope 2002)



- Current-free except …
- **Current Sheet @ separator**
  $I(\Delta\Psi)$
- Mag. Energy in excess of potential
  $\Delta W(\Delta\Psi)$

Steady Reconnection?

Sweet-Parker:



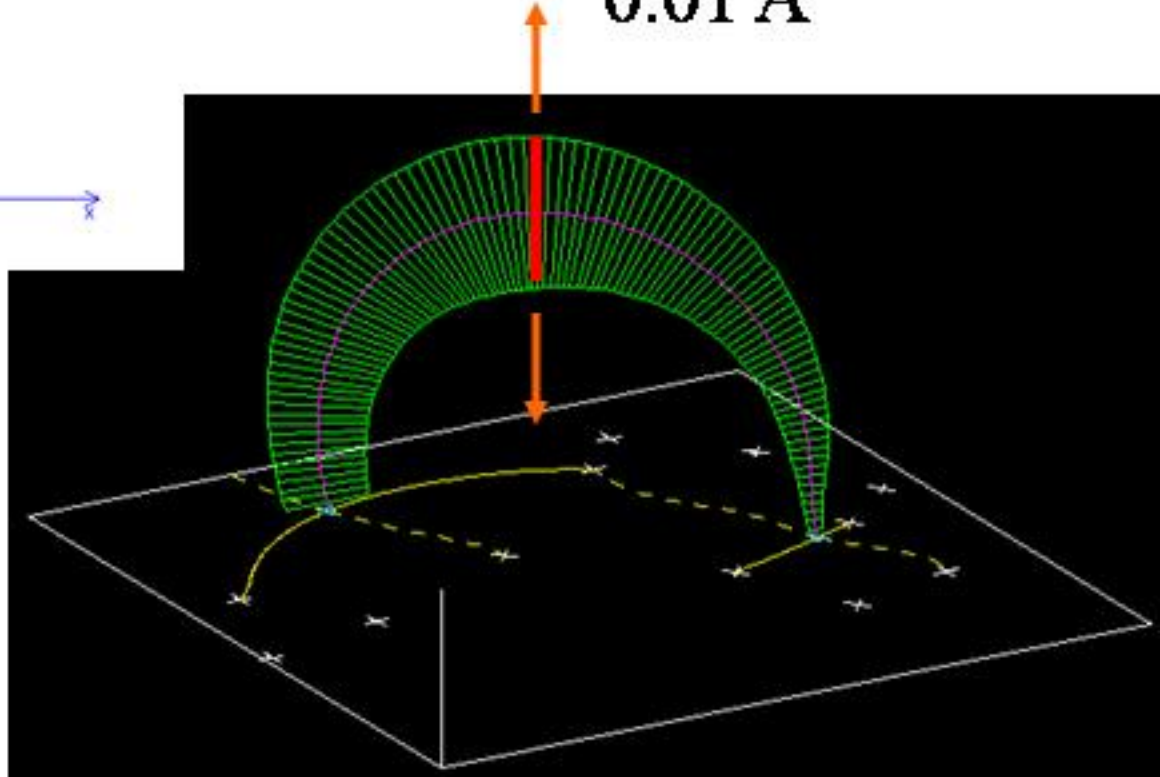
$$I_{CS} = \frac{1}{4\pi}\oint \mathbf{B}\cdot d\mathbf{l} = \frac{B_0\Delta}{2\pi}$$

$$S_{CS} = \left(\frac{\Delta}{\delta}\right)^2 = \frac{B_0\Delta}{\eta\sqrt{4\pi\rho}}$$

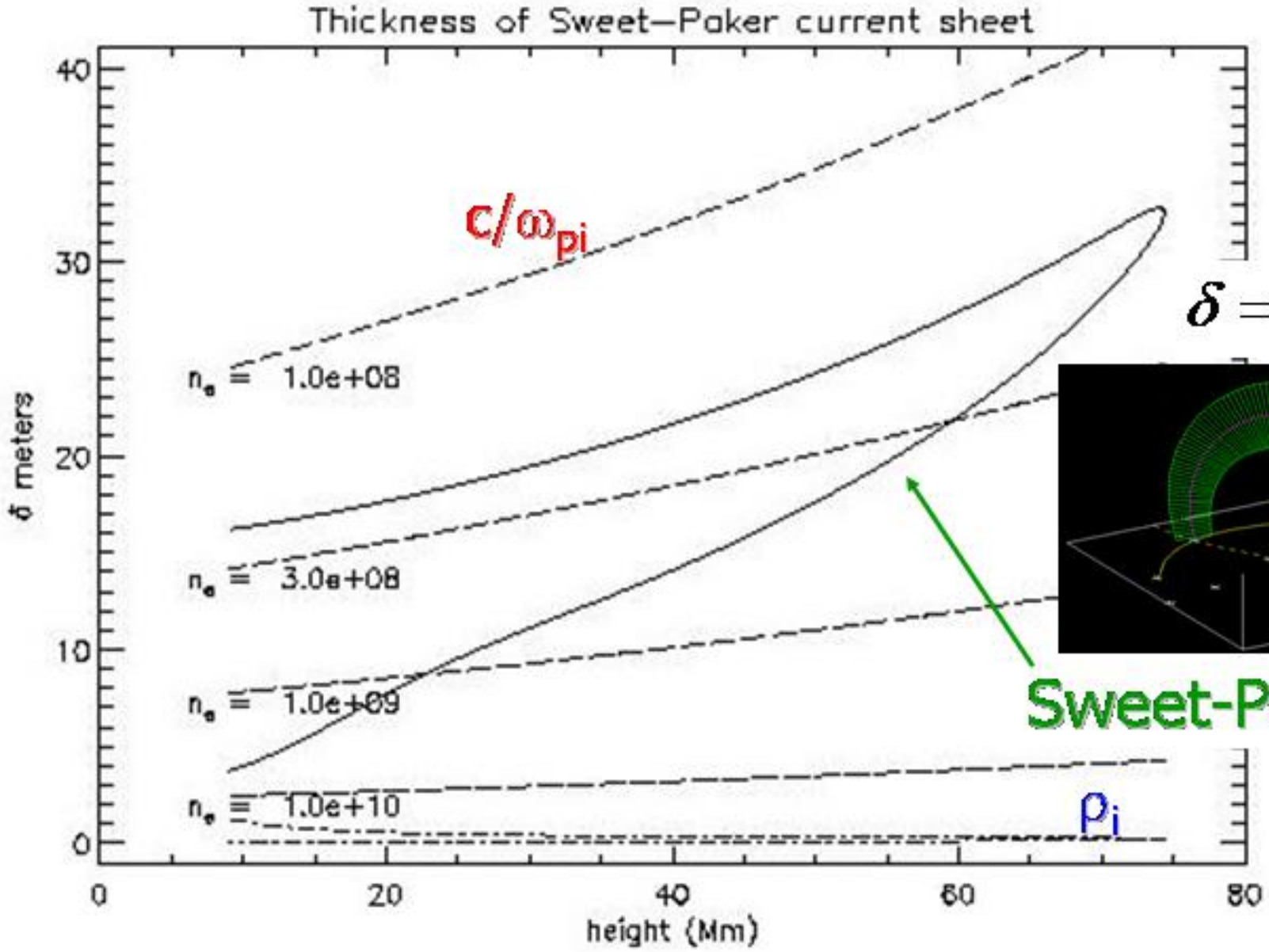
$$S_{CS} = \frac{I(\Delta\Psi)}{0.01\ \mathrm{A}}$$

$$\tau_{rx} = \frac{\Delta\Psi}{\dot{\Psi}} = \tau_A S_{CS}^{1/2}$$

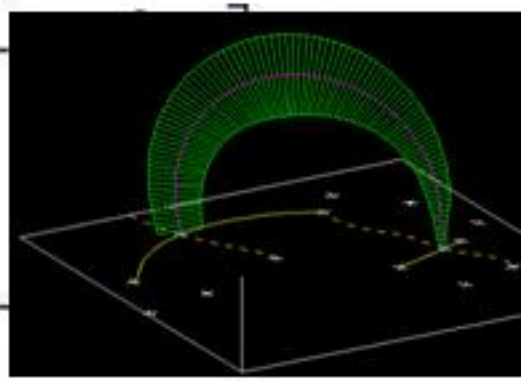
= 4 months



Comparison of scales

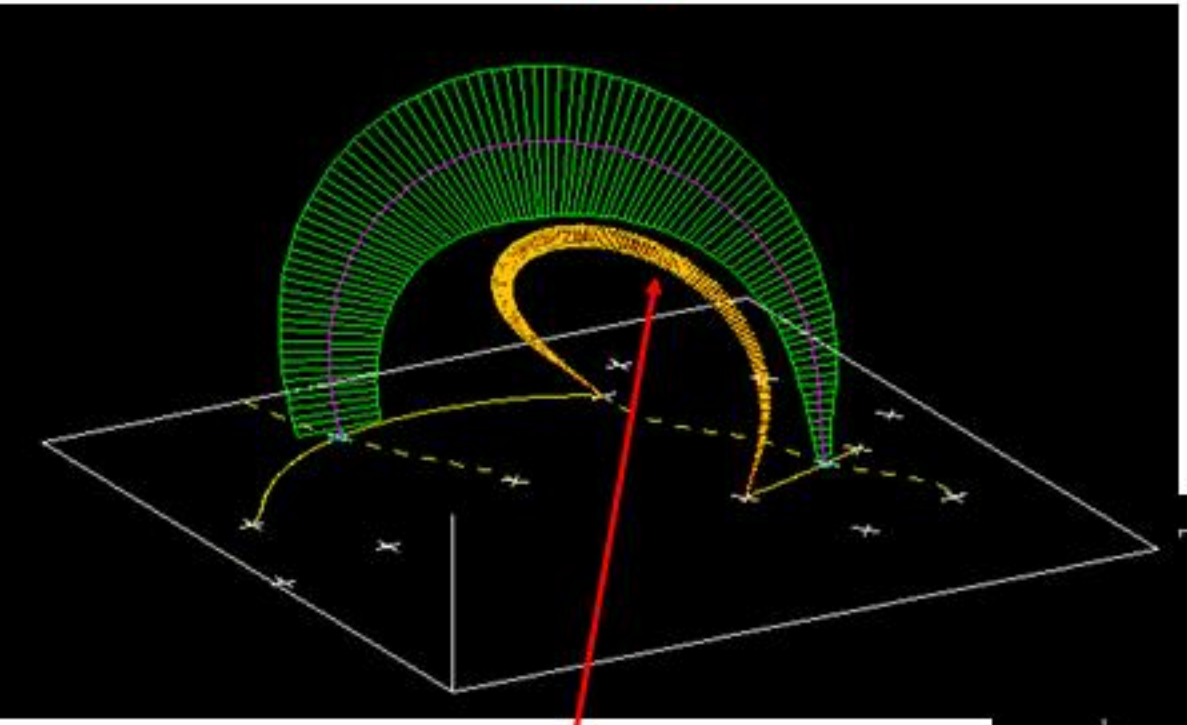


$$\delta = S_{CS}^{-1/2}\Delta$$



Sweet-Parker:

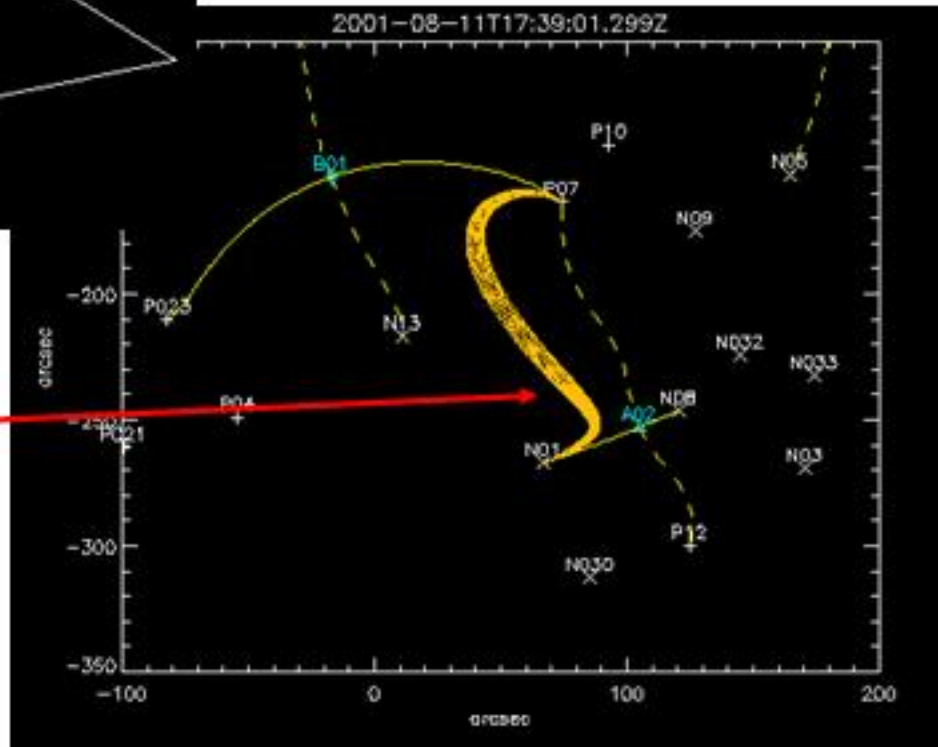
Role(s) of Current Sheet



Site of localized reconnection

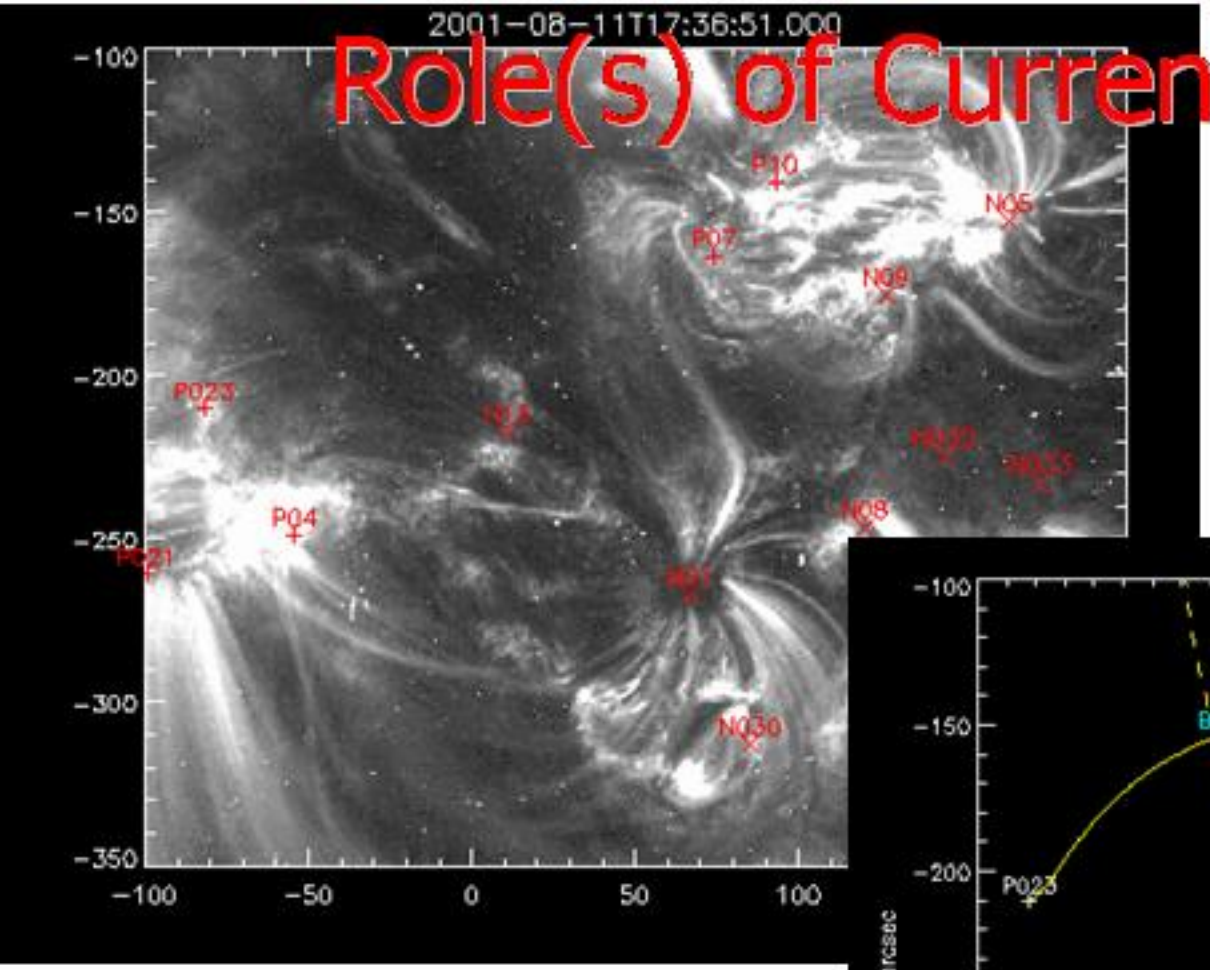
10^{18} Mx of newly **reconnected** flux

(1% of $\Delta\Psi$)



Aug 16, 2004

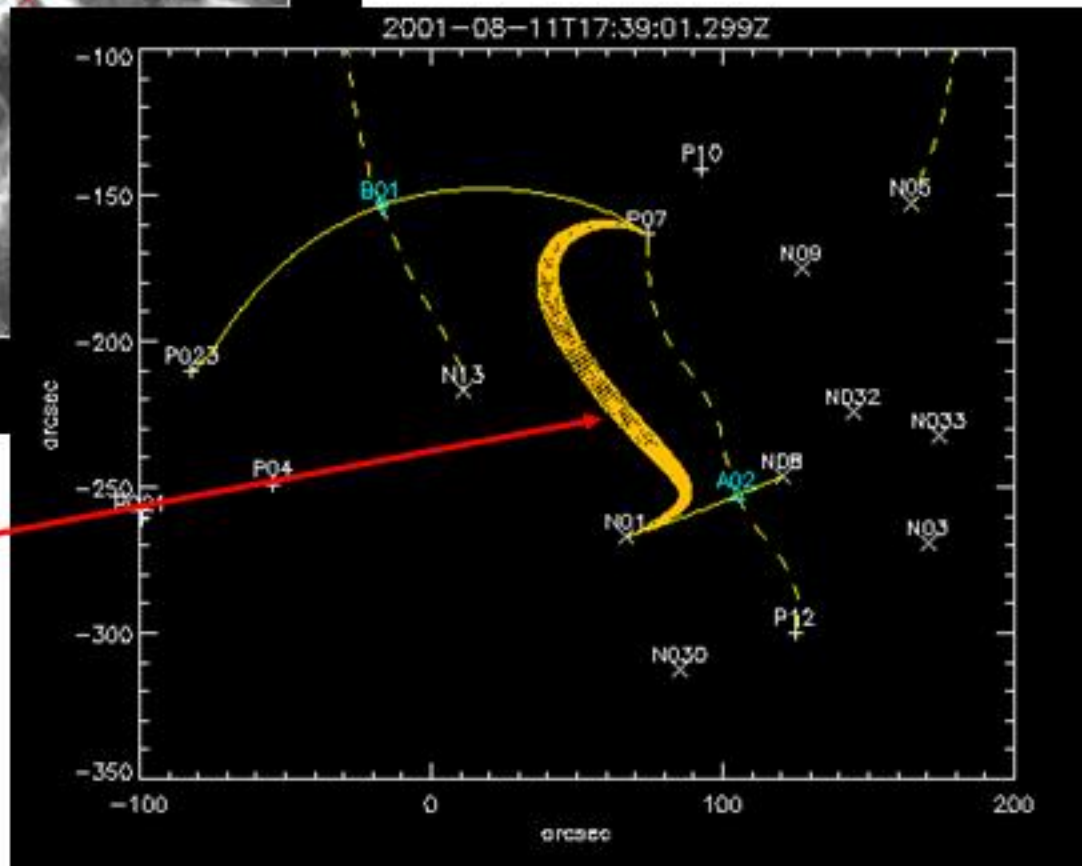
Role(s) of Current Sheet



Releases

$\Delta E \sim I \Delta\psi$

$\sim 10^{28}$ ergs



10^{18} Mx of newly reconnected flux

(1% of $\Delta\Psi$)

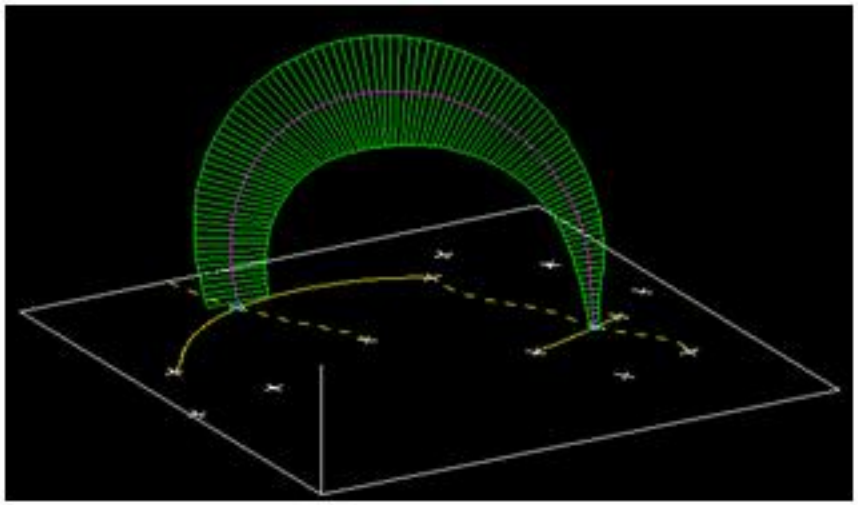
Aug 16, 2004

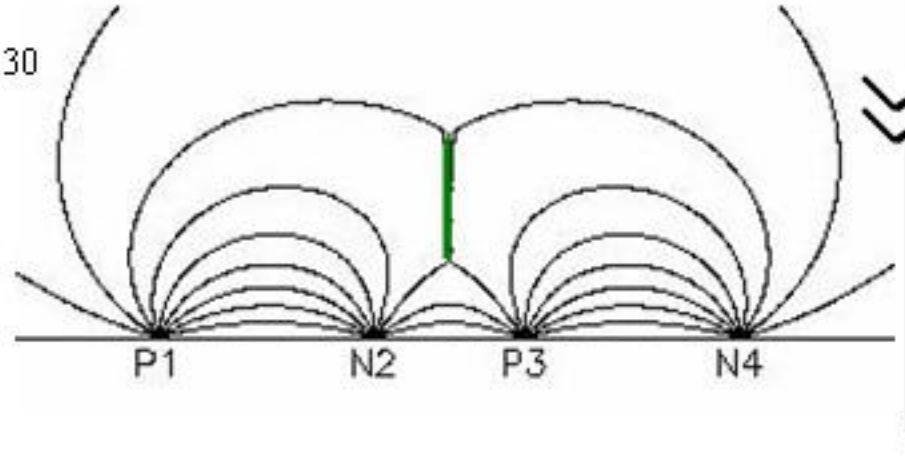
Role(s) of Current Sheets

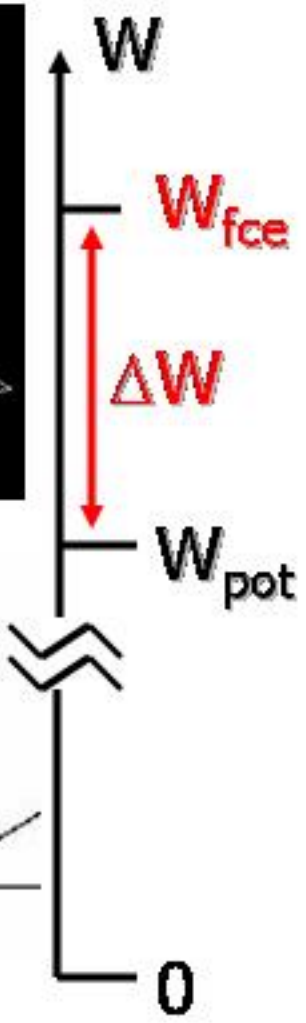
Energy storage:

W accumulates for 24 hrs. prior to reconn′ burst

$$\Delta W \approx \frac{(\Delta\Psi)^2}{2L} \approx 5\times 10^{30}$$







Rapidly released via local process

Summary

1. AR 9574: unambiguous reconnection
2. Reconnection in brief (6 hour) burst after delay of ~24 hours
3. Separator reconnection
4. Trigger? ... No evidence in p-sphere
5. Produces scores of ~10^{18} Mx loops
6. Observed flux accounts for 10% - 30% of maximum allowed (partial reconnection)