

*One mask to group them all,
One code to find them,
One file to store them all,
And in a structure bind them.*

William (Tolkien) Simpson



A Diachronic Topological Analysis of the 13th May 2005 Solar Flare

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Supervised by Angela Des Jardins

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Outline

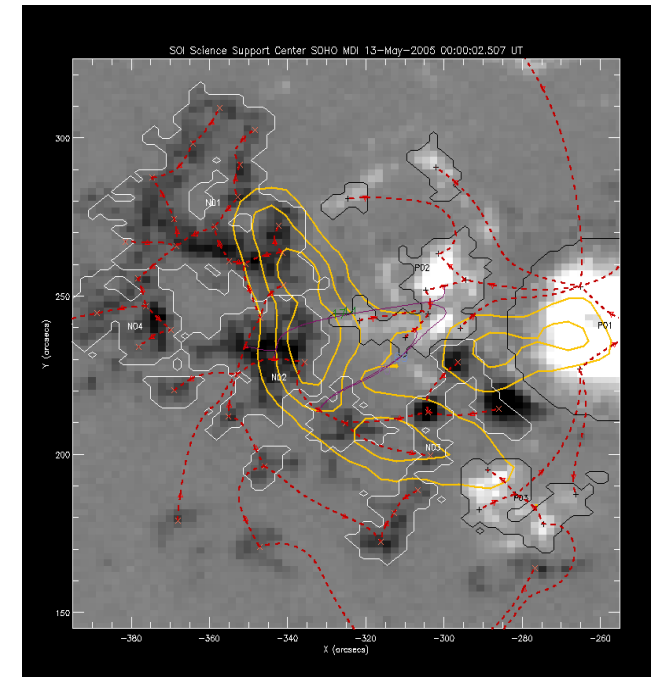
I. Background Theory and Objectives

1. The nature of solar flares
2. Energy release in solar flares
3. The stress hypothesis
4. The MCT topology

II. Analysis of the flare

1. The light curve
2. X-ray contours
3. Topologies through time
4. The mask maker
5. Calculating the flux and stress

III. Results and Conclusions



Theory: 1. The nature of solar flares

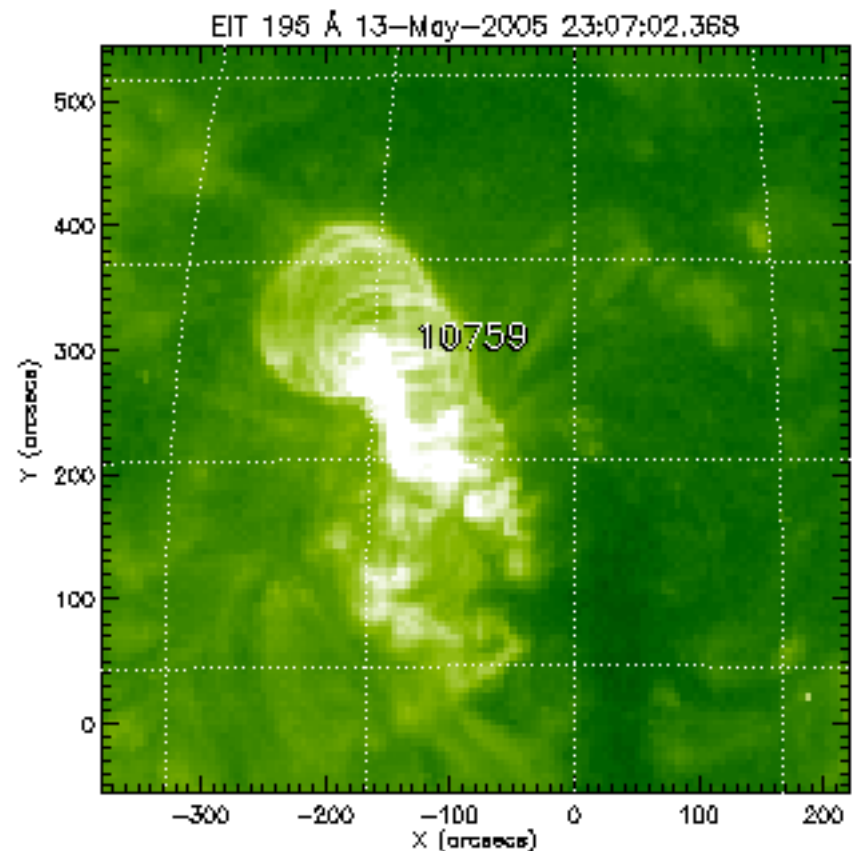
- Solar flare**
- explosion in intense magnetic regions of Sun
 - sudden, fast release of magnetic energy

X-ray brightness

- X-class (largest)
- M-class (1/10)
- C-class (1/100)

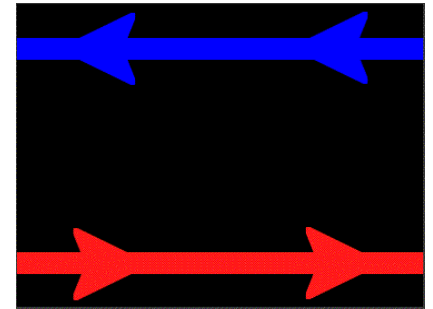
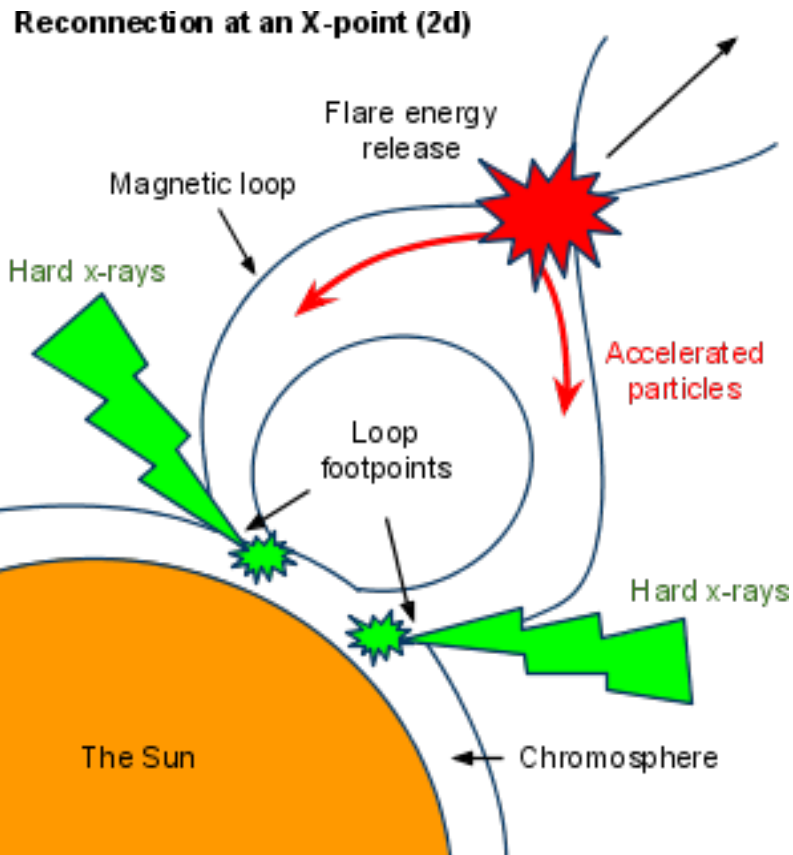
Some repercussions...

- high energy electrons and protons
- spacecraft interference
- coronal plasma ejections
- damage to power lines



Theory: 2. Energy release in solar flares

- Energy for flare stored in the **magnetic field**
- Release mechanism: **reconnection**



Separator reconnection (3d)

- Non-thermal electrons accelerated
- Channelled down loop - strike chromosphere
- Hard x-rays emitted at footpoints

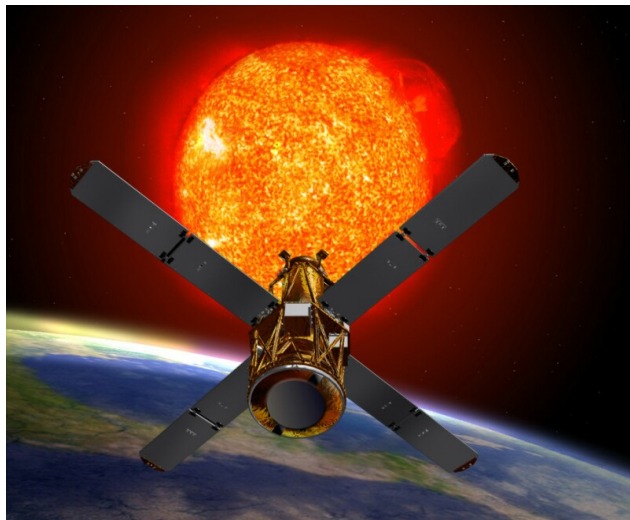
Detectable by RHESSI satellite - deduce possible reconnection sites



Theory: 3. The stress hypothesis

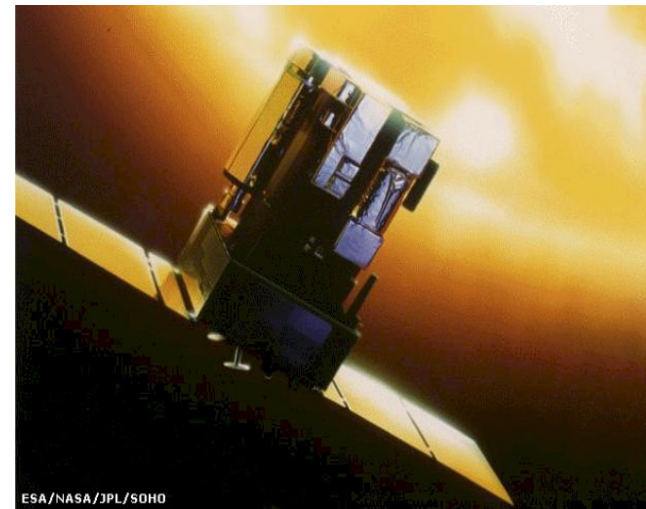
- Hypothesis: - magnetic field configuration becomes **stressed**;
- field becomes increasingly **non-potential** until some **critical point** is reached
- **Project aim:** - relate hard x-ray RHESSI observations to changes in magnetic field

Hard X-ray observations



RHESSI

Magnetic field observations



ESA/NASA/JPL/SOHO

SOHO (credit: NASA)



Theory: 4. The MCT Topology

- Need a way of **modelling the magnetic field**. Require:

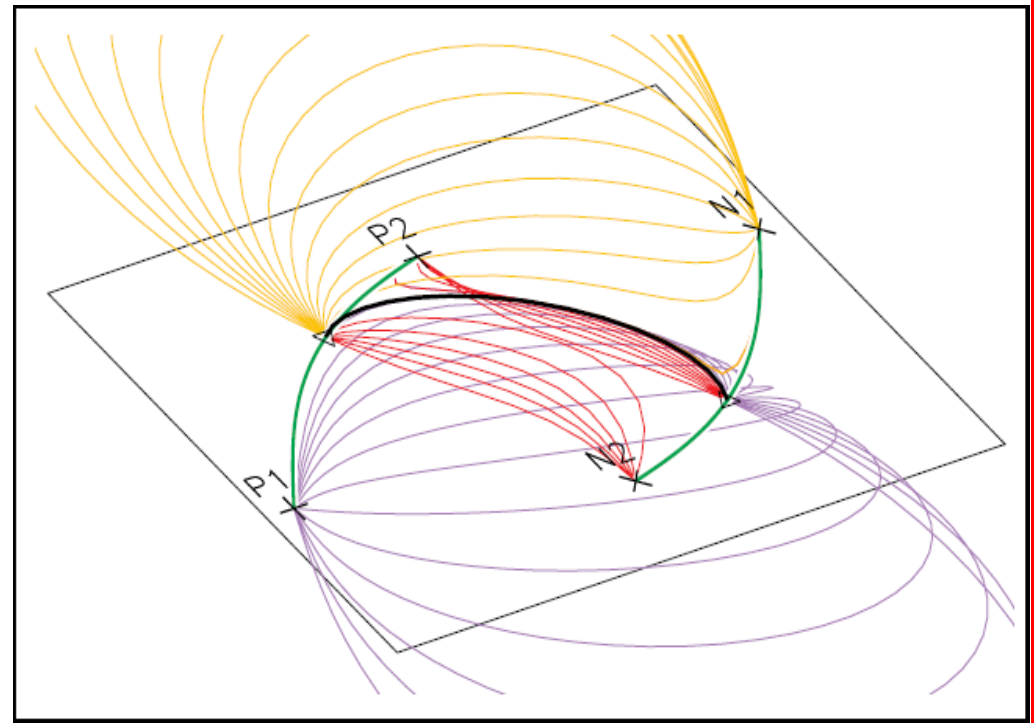
- 1. topological features *quantitatively* defined
- 2. computationally inexpensive
- 3. photospheric boundary quantitatively represents l.o.s. magnetogram

Use a *Magnetic Charge Topogy*.

Quadrupolar example.

Main topological features:

- P2 and P1 (+) **+ve poles**
- N1 and N2 (×) **-ve poles**
- triangles are **null points**
- green lines are **spine lines**
- black line is the **separator**

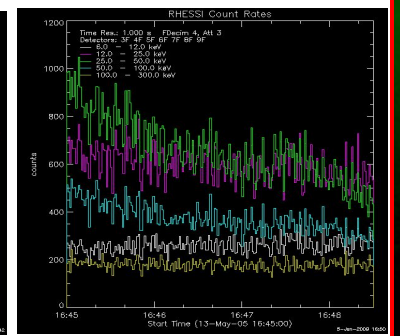
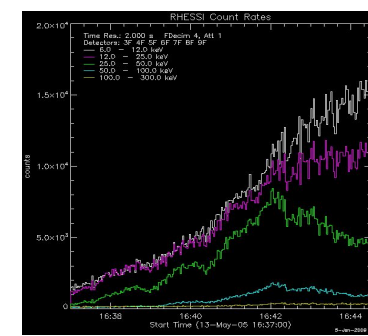
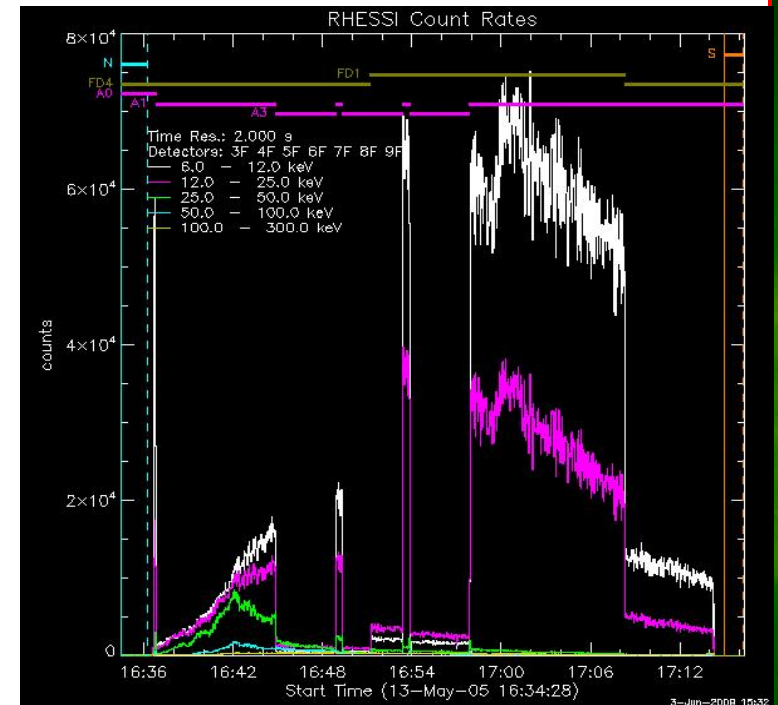
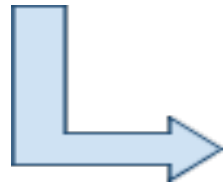


Analysis: 1. The light curve

- lightcurve of total X-ray count rates over observation time interval
- depicts various energy bandwidths

Problem: attenuators alternating; total flux-counts changing

Solution: divide lightcurve over fixed-attenuator subintervals

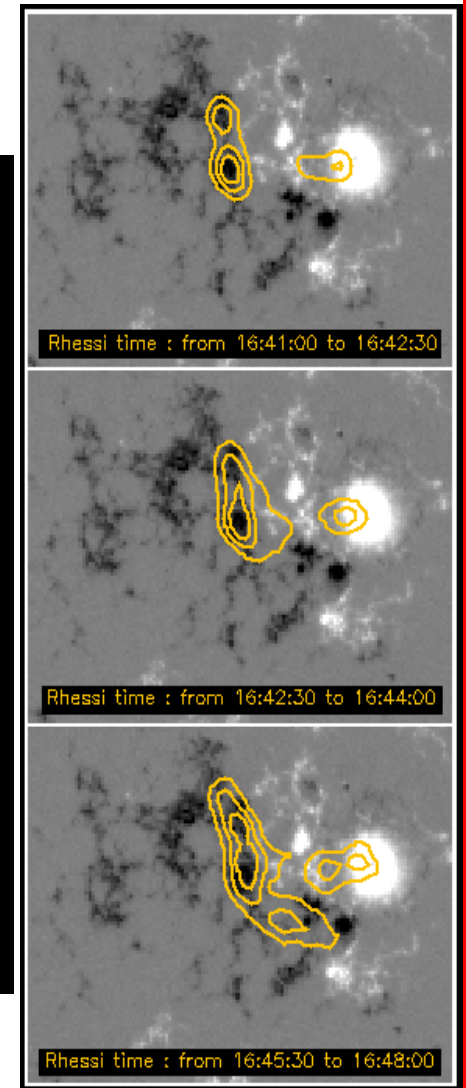
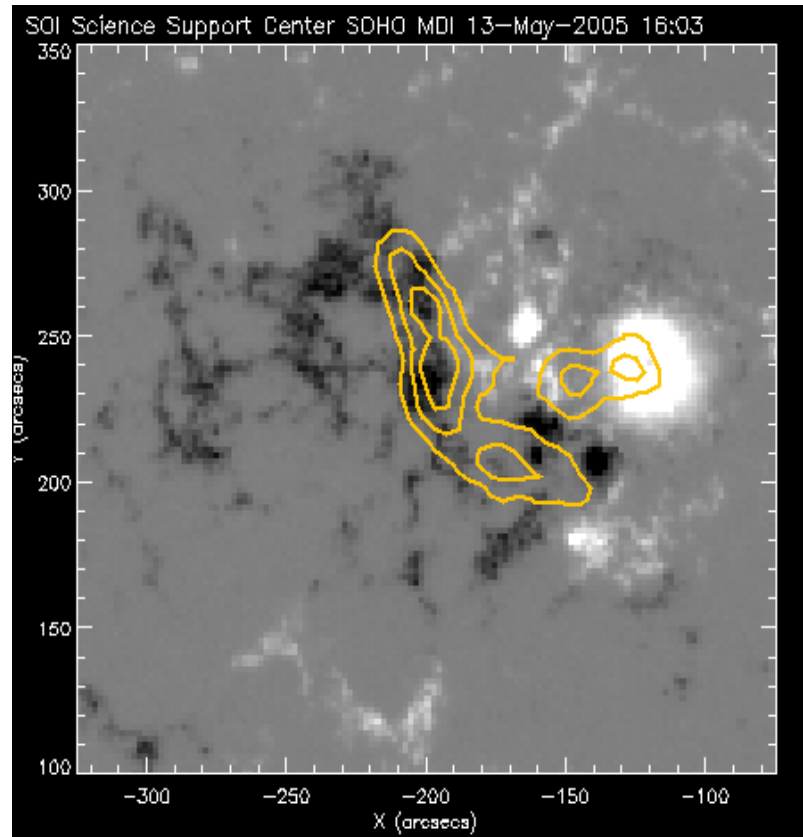


Analysis: 2. X-ray contours

Right: RHESSI x-ray contour plots overlaid on line-of-sight magnetograms

Observations

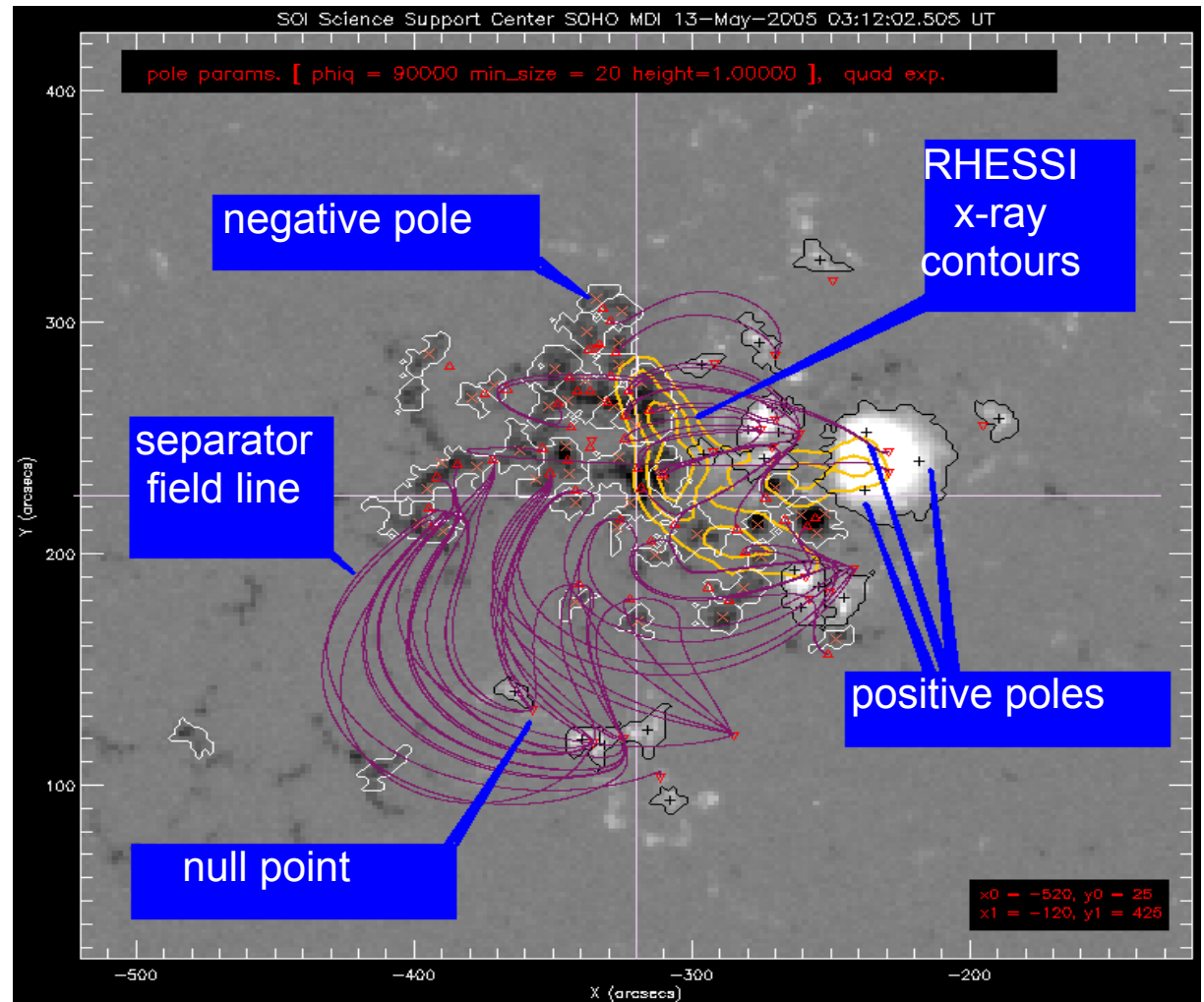
- positive side tightly bundled
- negative side more diffused
- x-ray footpoints not moving
- development of third source (16:42 - 16:45)



Analysis: 3a. Topologies

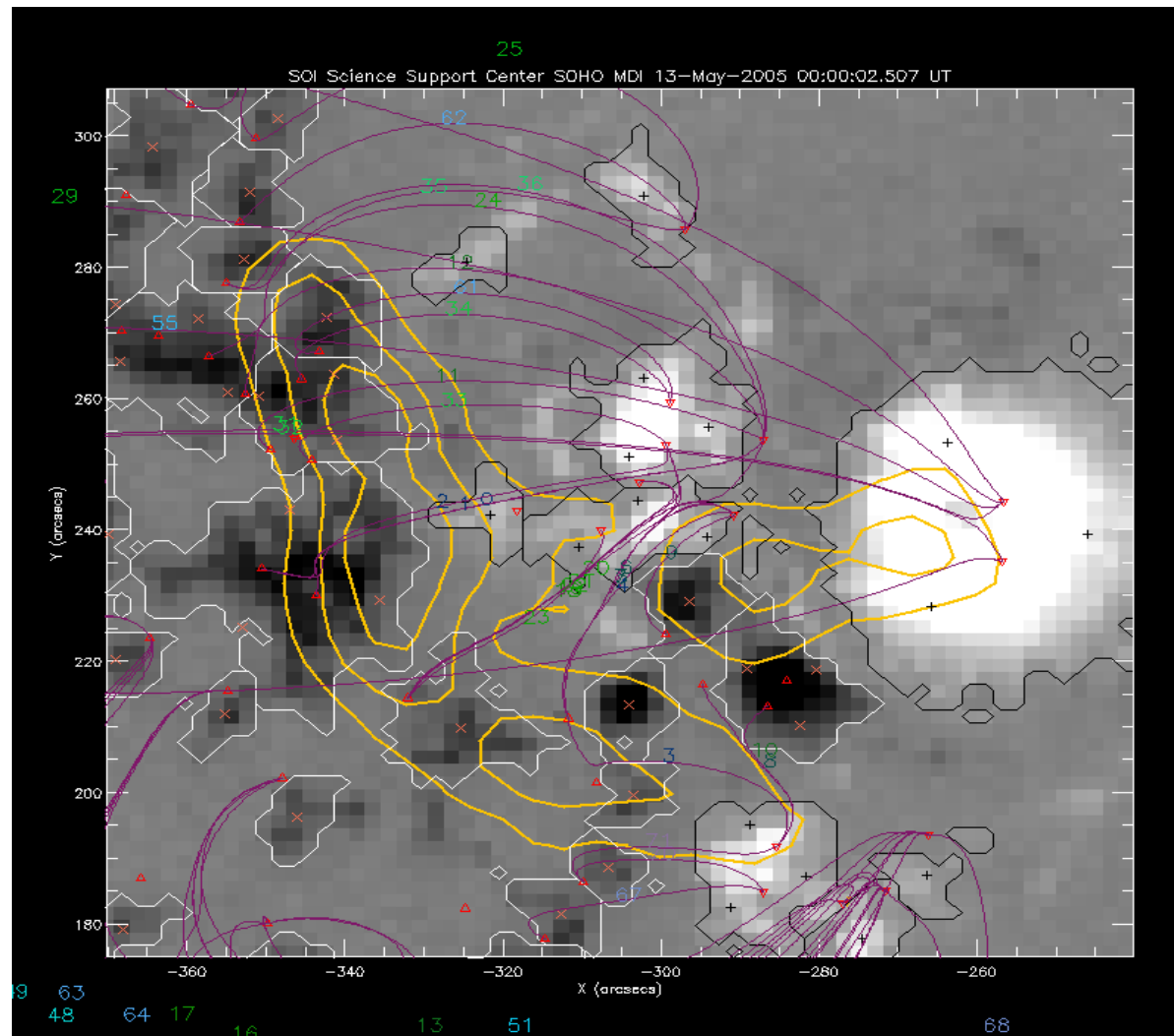
Right: Topology of active region at 03:12 UT.

- 15 topologies calculated
- 96 min. cadence
- in some cases, *quadrupole* field expansion used



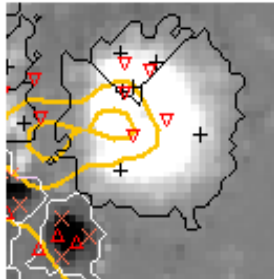
Analysis: 3b. A close up

Right: A close-up
at 00:00 UT.



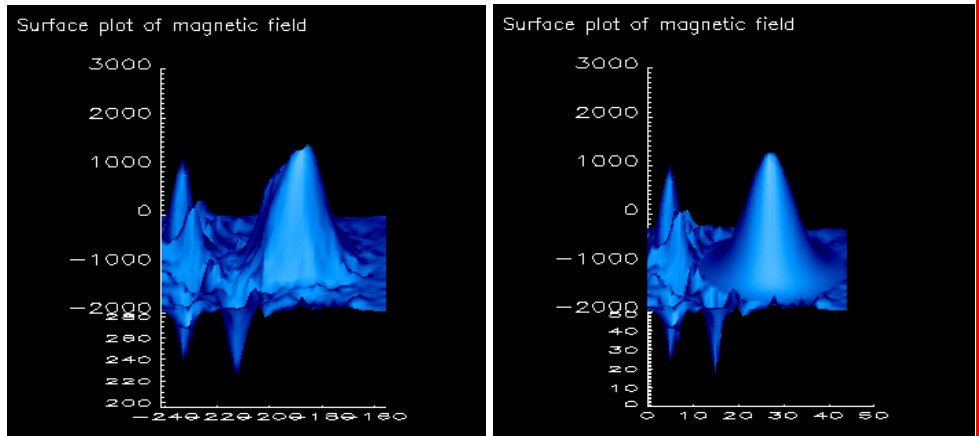
Analysis: 3. Topologies

Problem: Broken Mask

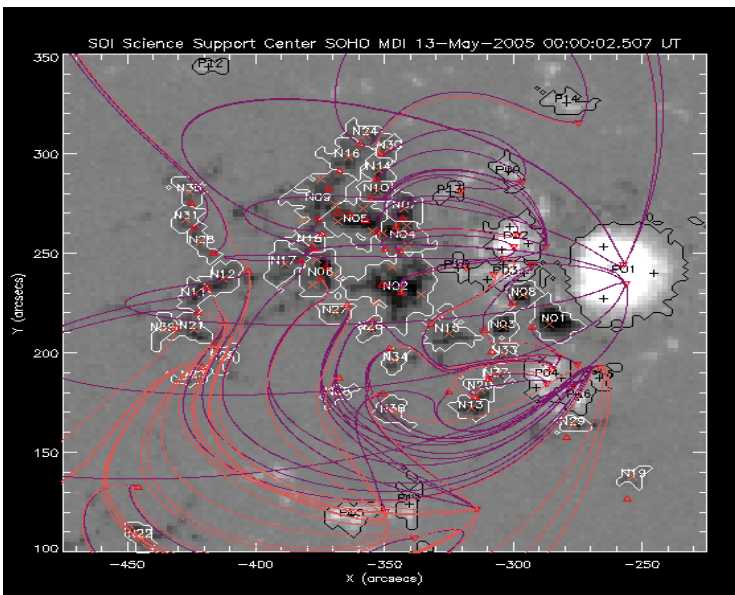


- Large +ve polarity topologically *mismodelled*
- Magnetogram faulty

Solution: Apply Gaussian fit, remodel



Above left: Surface plot of problem region
Above right: Remodelled with Gaussian



Problem: Tracking Separators

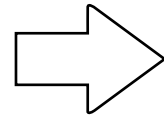
- topology changes significantly over the interval
- individual separators can't be tracked

Proposed Solution: track *groups*.

Left: The changing topology through time

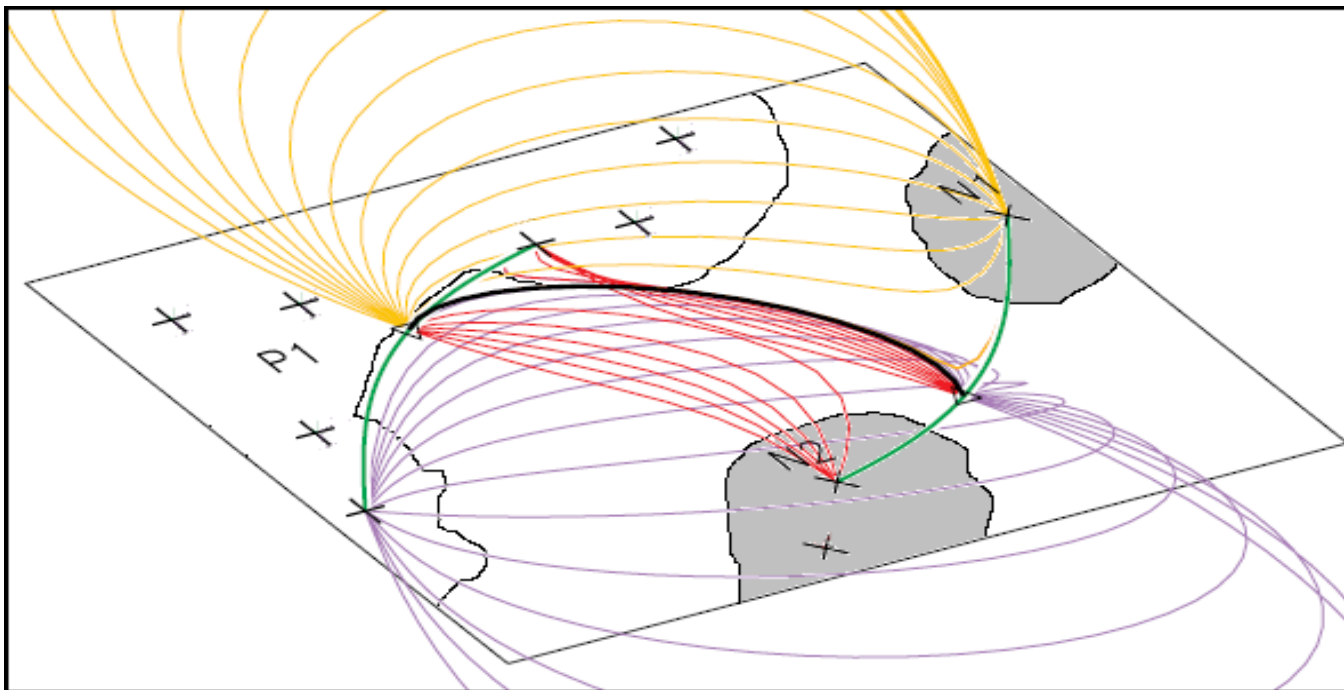
Analysis: 4a. Forming Connectivity Groups

1. **Separators** connect to **nulls** (1 to 2)
2. **Nulls** connect to **poles** (1 to 1)
3. **Poles** belong to **masked regions**
4. **Masked regions** can be **grouped**



Form separator
connectivity groups

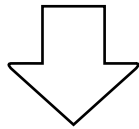
eg. { P1; N1, 2 }



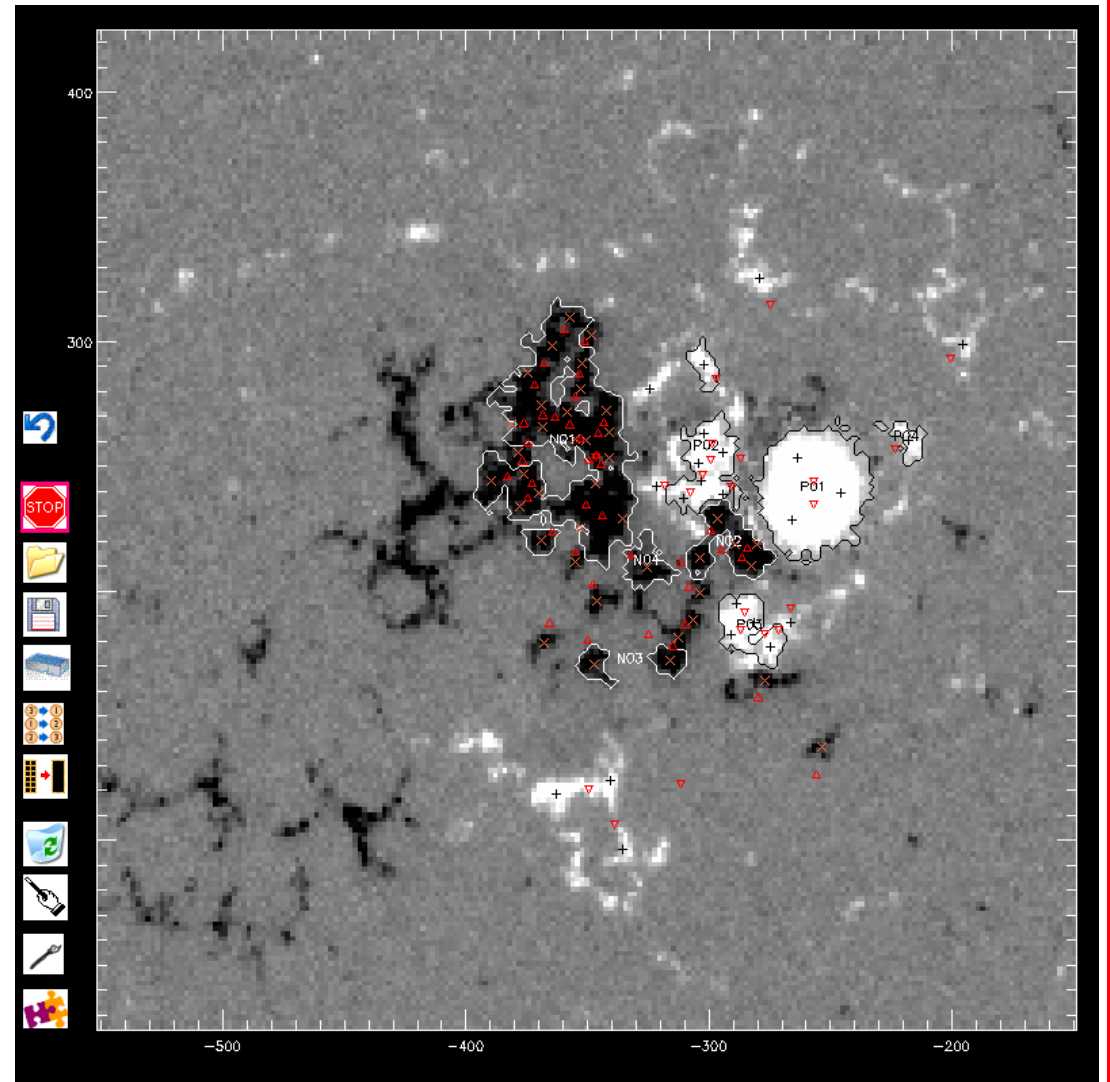
Analysis: 4b. The Mask Maker

Mask Maker

- program developed to form 'mask groups'
- automatically 'bleeds' contiguous polar regions
- user controls for fine-tuning



diachronically stable
separator *groups*



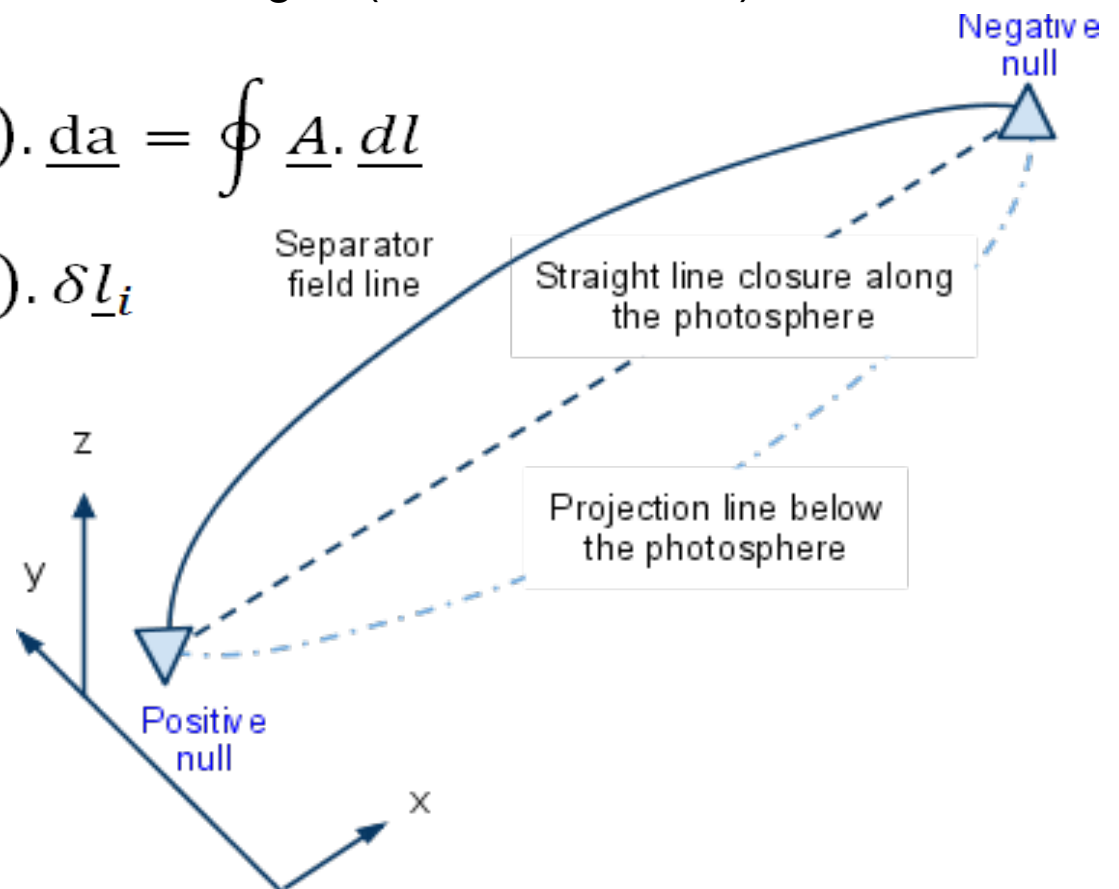
Analysis: 5a. Calculating the Flux and Stress

Calculating the flux

- Flux through separator reducible to line integral (Stokes' theorem)

$$F = \int \underline{B} \cdot \underline{da} = \int (\nabla \times \underline{A}) \cdot \underline{da} = \oint \underline{A} \cdot \underline{dl}$$
$$\Rightarrow F \approx \sum_i \underline{A}(\underline{x}_i) \cdot \delta \underline{l}_i$$

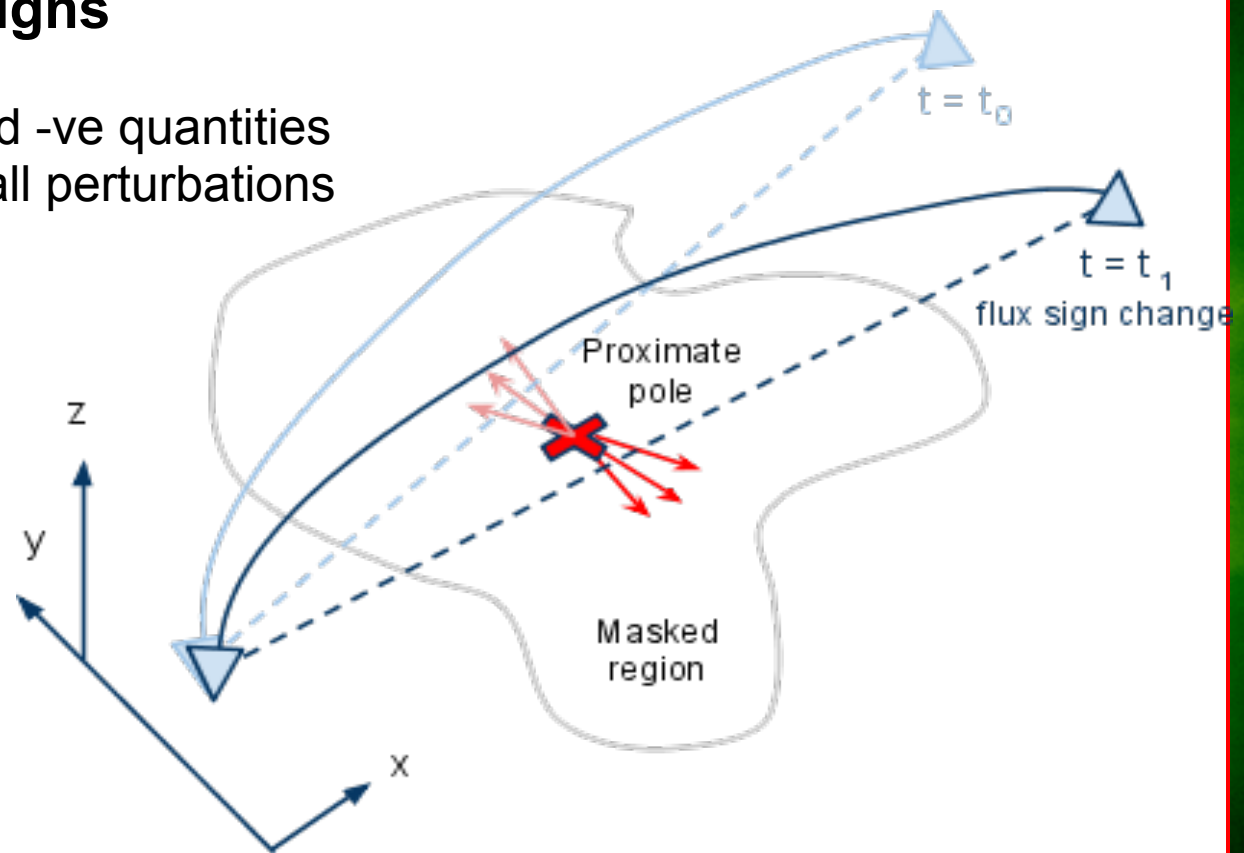
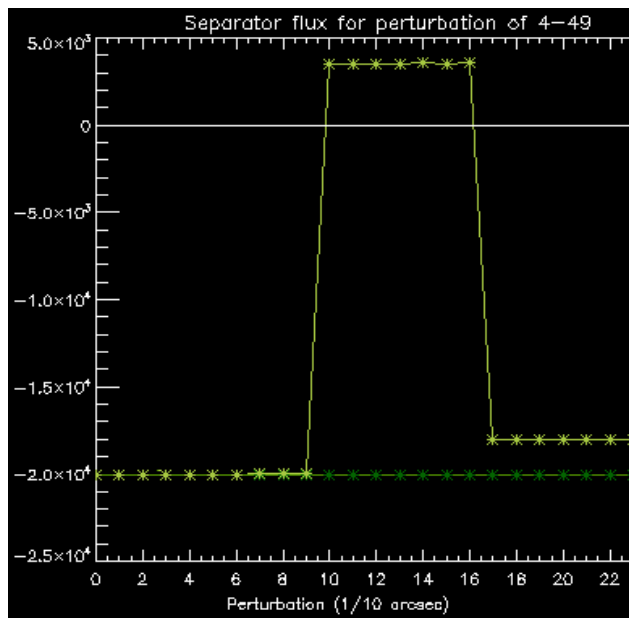
- But more than one way to close the loop...



Analysis: 5b. Signed Flux Issues

Problem: Changing flux signs

- Group flux a mix of +ve and -ve quantities
- Investigations showed small perturbations could change flux sign



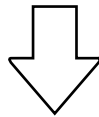
- Poles close to closure line mislead flux calc.
- size and sign in doubt

Analysis: 5c. Spreading the poles

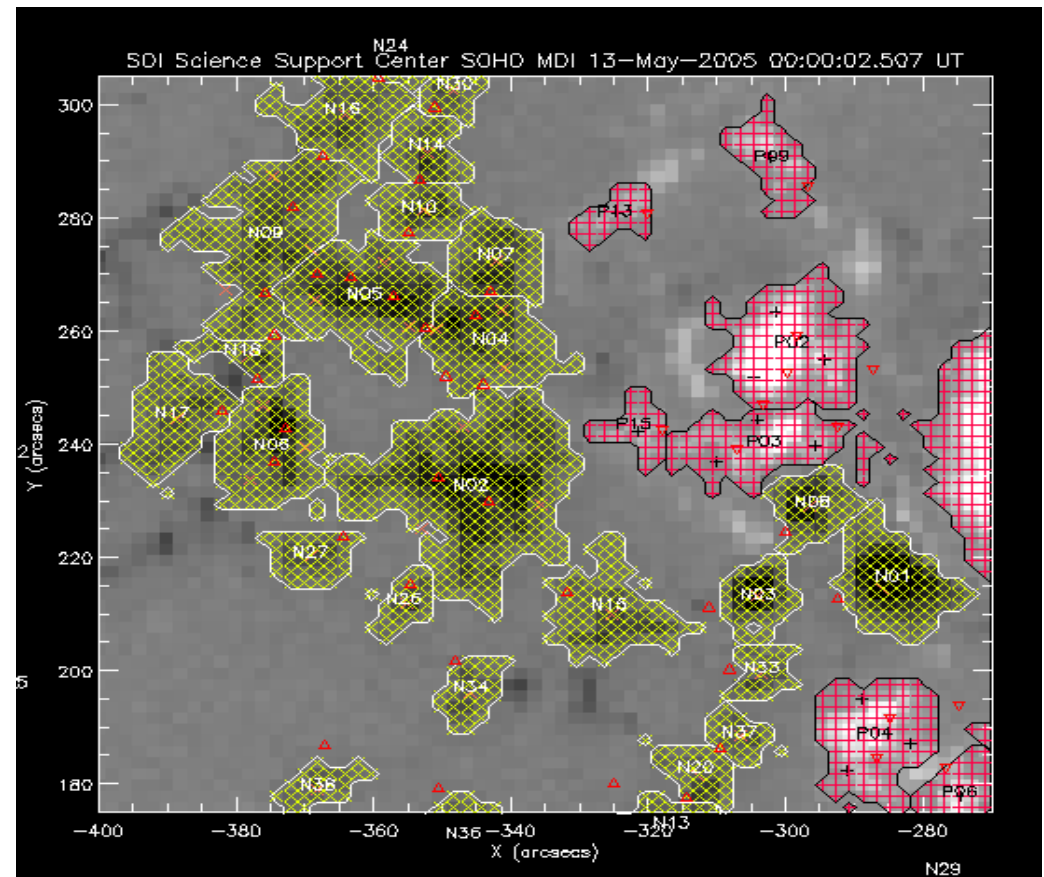
Proposed Solution : Spread the poles

Right: Hi-res. poles in red and yellow

Subdivide primary mask



- Obtain new set of [hi-res] poles
- Use hi-res. poles for flux calculation



Analysis: 5d. Calculating the stress

- Changing *photospheric* field \Rightarrow energy stored in coronal field

$$\phi_r = \phi_s - \phi_s^{(v)}, \quad \frac{d}{dt} \phi_r = -\frac{d}{dt} \phi_s^{(v)}$$

$$\Rightarrow \Delta\phi_r = -\Delta t_b \frac{d}{dt} \phi_s^{(v)} \approx \Delta t_b E_b l_s$$

$$\Rightarrow E_b \approx -\frac{1}{l_s} \frac{\Delta\phi_s^{(v)}}{\Delta t} \quad \text{'separator stress'}$$

- Stresses calculated for absolute flux, +ve contributions, -ve contributions

Analysis: 6. Summary of the approach

- Locate likely reconnection sites with **RHESSI x-ray contours**
- Model active region with **time-indexed, two-layer topology**
 - primary topology
poles, nulls, separators
 - secondary topology
hi-res. poles (from subdivision of primary mask)
- Form **connectivity groups**
- Calculate time-indexed group **quantities** using hi-res. poles
- Compare group **stresses** with RHESSI predictions

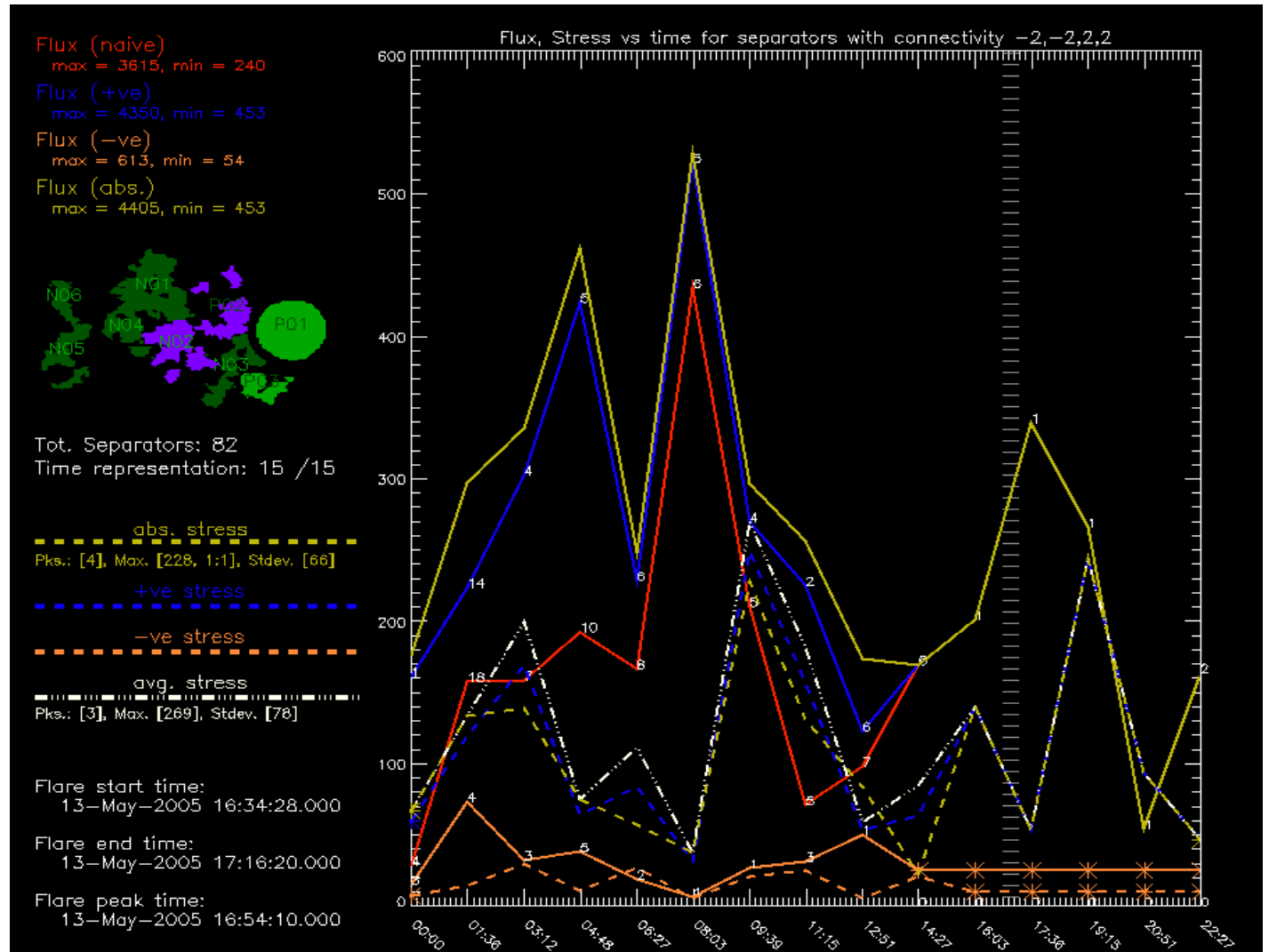
.

Do any patterns emerge...?

Results and Conclusions: 1. Interpreting the Plots

Right: Stress plot for Connectivity Group {N2; P2}.

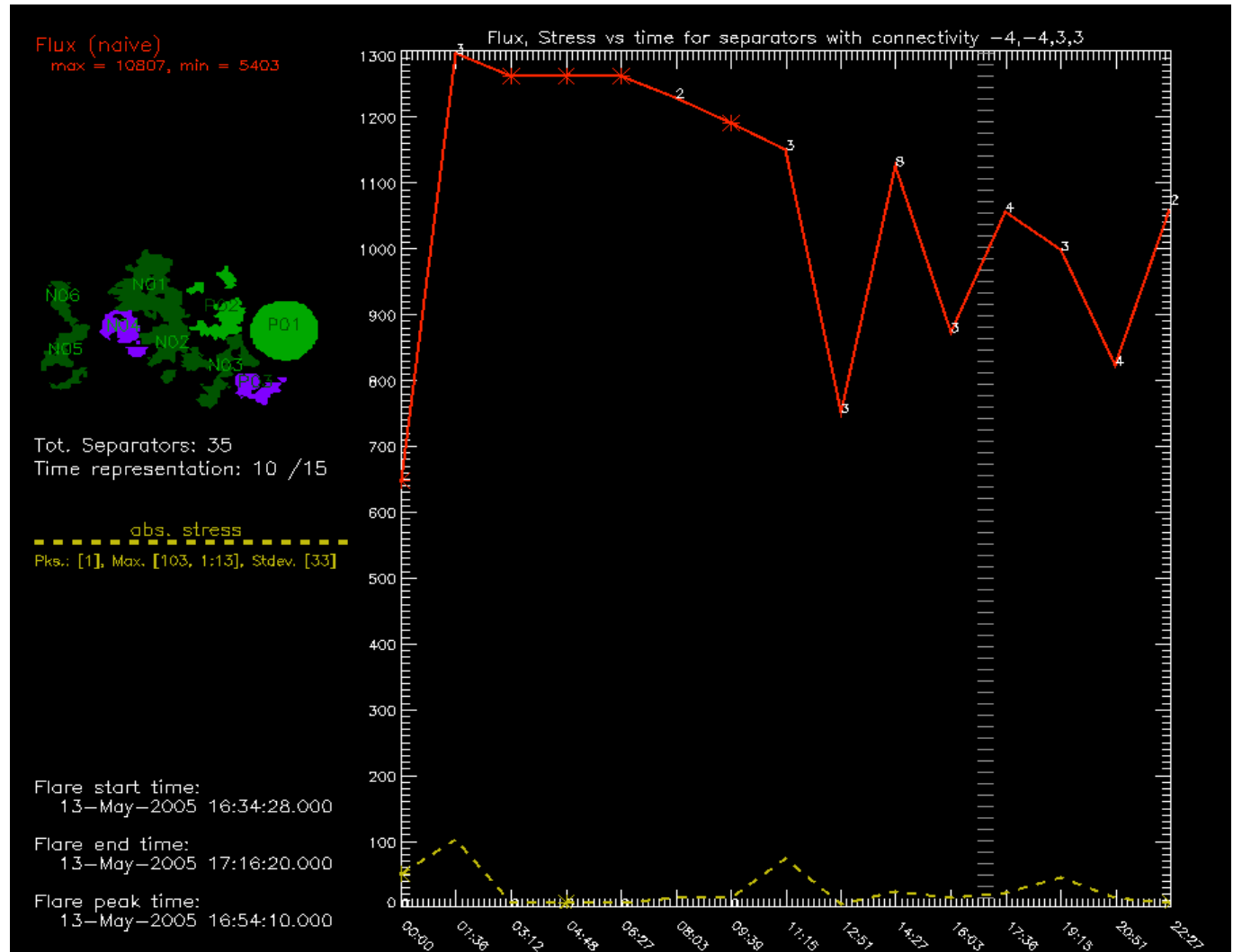
- RHESSI data indicates reconnection
- Topological analysis indicates stressing



Results and Conclusions: 1. Interpreting the Plots

Right: Stress plot for Connectivity Group {N4; P3}.

- RHESSI data does **not** indicate reconnection
- Topological analysis suggests no stressing



Results and Conclusions: 2. The picture so far...

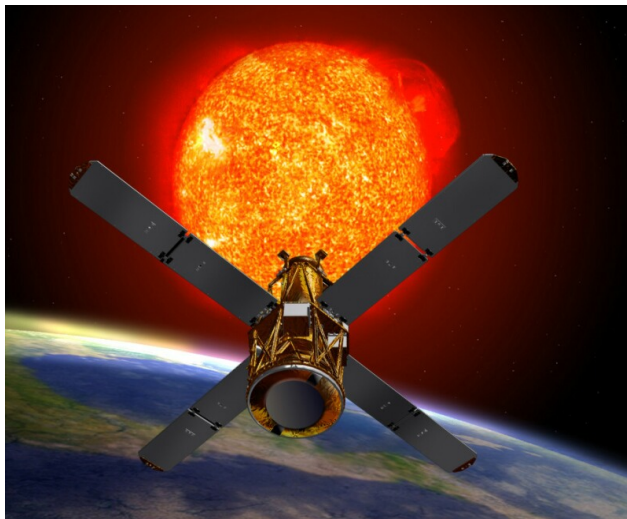
- 'Stress score' (0-5, 0 = no evidence, 5 = strong evidence) assigned on basis of
 - stress peak count
 - stand. dev.,
 - size of max. peak.,
 - max. stress peak to flux ratio

<u>Connectivity</u>	<u>Predicted?</u>	<u>Score</u>		<u>Connectivity</u>	<u>Predicted?</u>	<u>Score</u>
[-5,-5,1,1]	no	0		[-3,-3,1,3]	yes	4
[-5,-5,1,3]	no	0		[-3,-3,3,3]	yes	5
[-2,-2,2,2]	yes	5		[-1,-1,2,2]	yes	5
[-2,-2,1,2]	yes	5		[-3,-2,3,3]	yes	5
[-2,-1,1,2]	yes	5		[-3,-2,1,3]	yes	5
[-1,-1,1,2]	yes	5		[-3,-2,1,2]	yes	2
[-5,-4,1,1]	no	0		[-3,-3,1,2]	yes	3
[-5,-4,1,3]	no	0		[-6,-6,1,1]	no	0
[-2,-2,3,3]	yes	5		[-5,-4,3,3]	no	2
[-2,-2,1,3]	yes	5		[-5,-5,3,3]	no	0
[-4,-4,1,1]	no	3		[-4,-4,3,3]	no	0
[-4,-4,1,3]	no	5		[-1,-1,1,1]	yes	5
[-4,-1,1,1]	no	0				

Results and Conclusions: 3. Final words

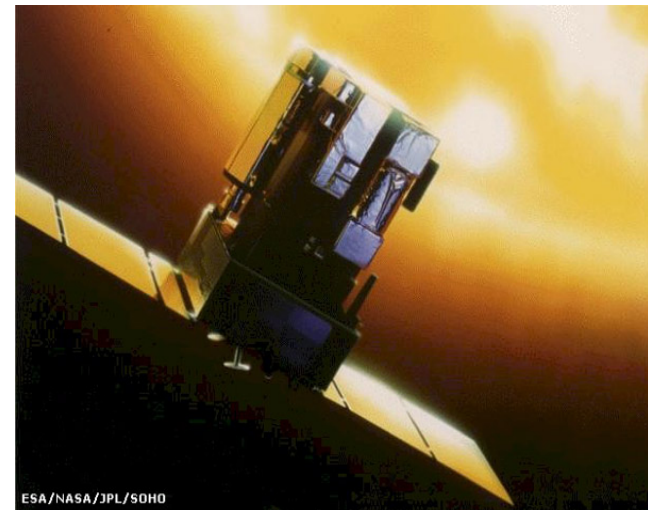
- Strong correlation between RHESSI-based predictions and topological stress analysis!

Hard X-ray observations
(*during* flare)



RHESSI

Magnetic field observations
(*before* flare)



SOHO (credit: NASA)



- A significant step in predicting solar flares (?)