Insight from the outside: The solar cycle from a heliospheric perspective

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Overview

- A quick summary of the solar cycle
- Probing the heliosphere with electrons
- Interplanetary coronal mass ejections
- Evolution of the coronal/heliospheric field
- Summary

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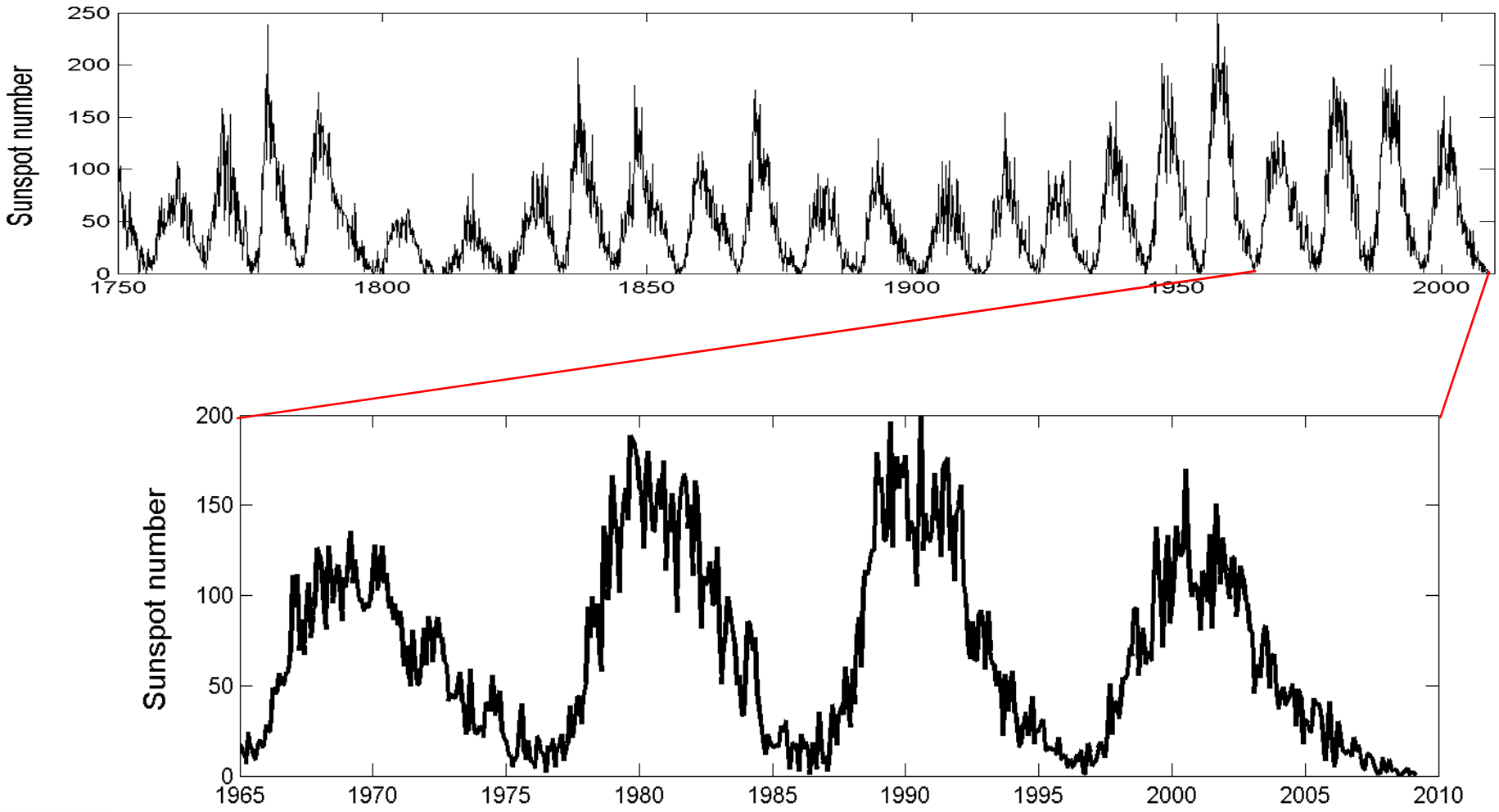
Sunspots



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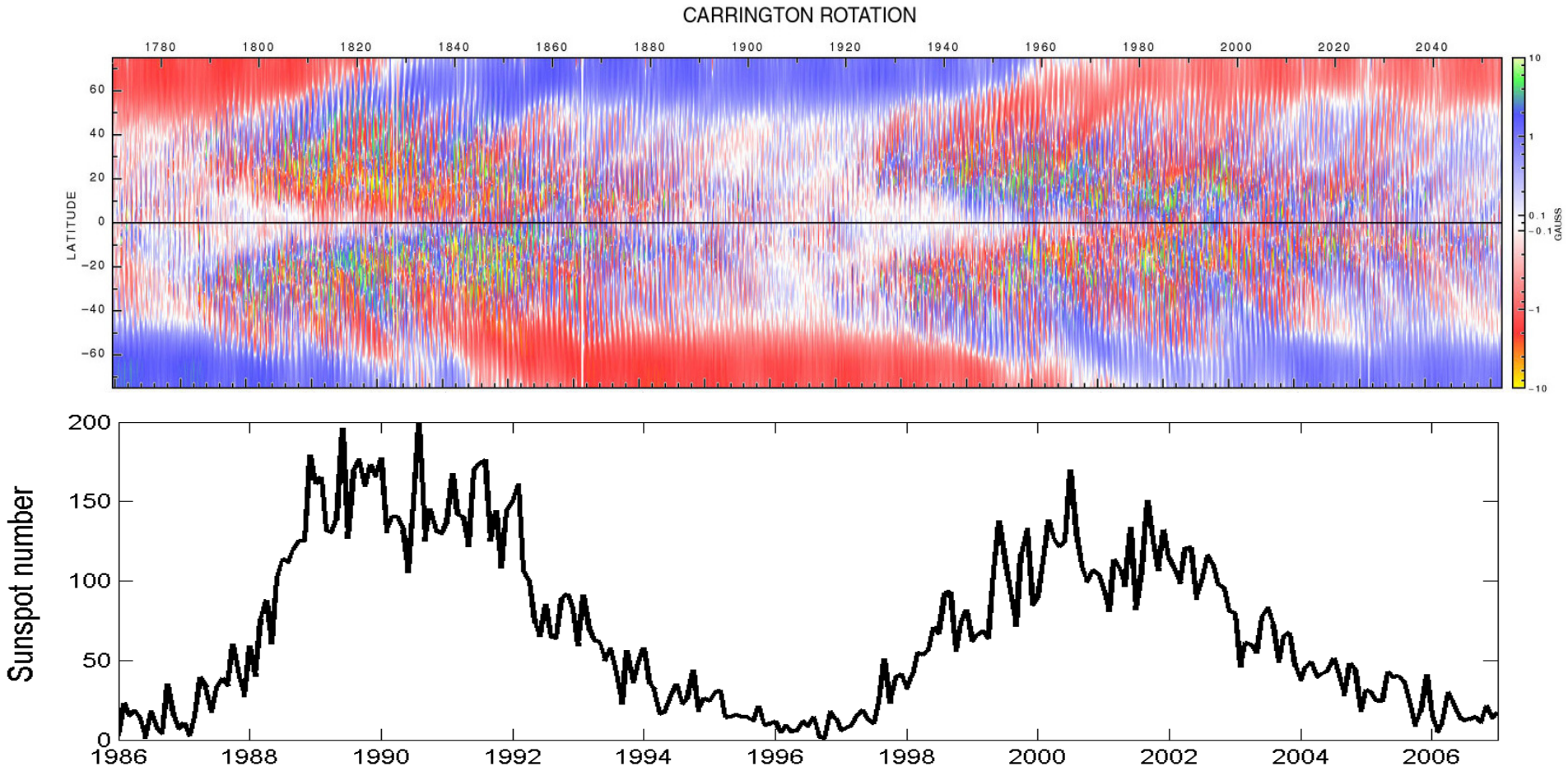
[Greenwich sunspot data]

Photospheric flux



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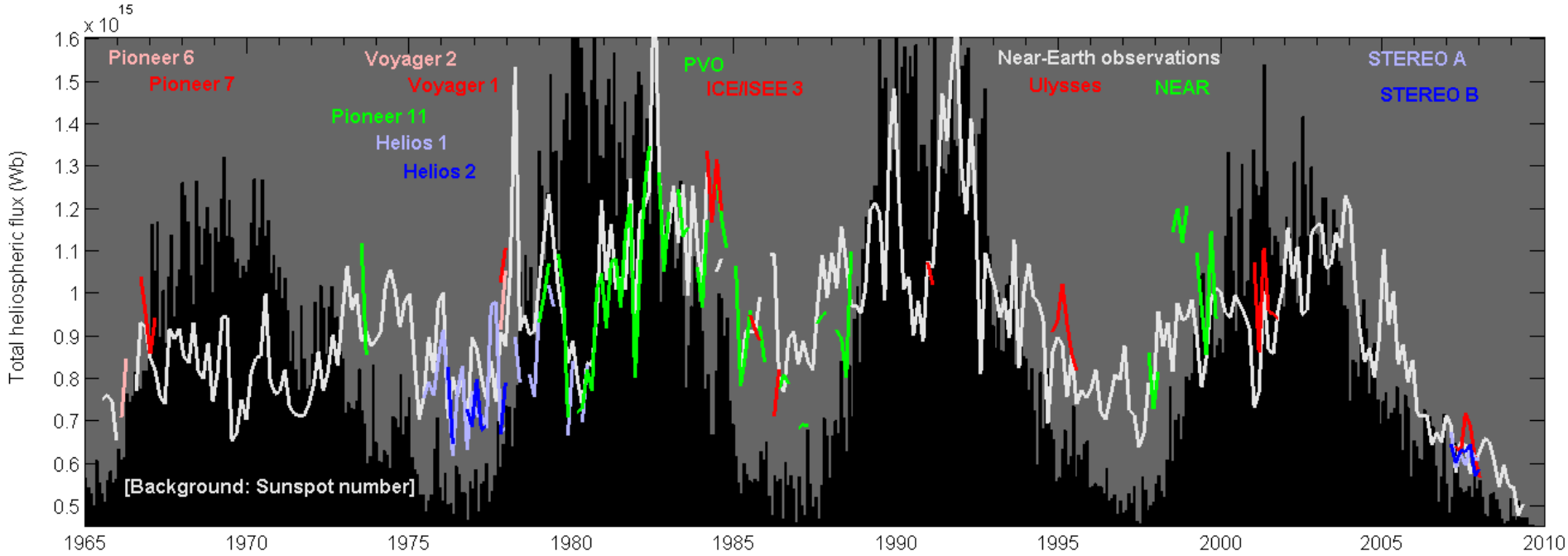
[Top: David Hathaway, Goddard]

Heliospheric flux



[Updated regularly at:
http://www.sp.ph.ic.ac.uk/~mowens/helioflux.htm]

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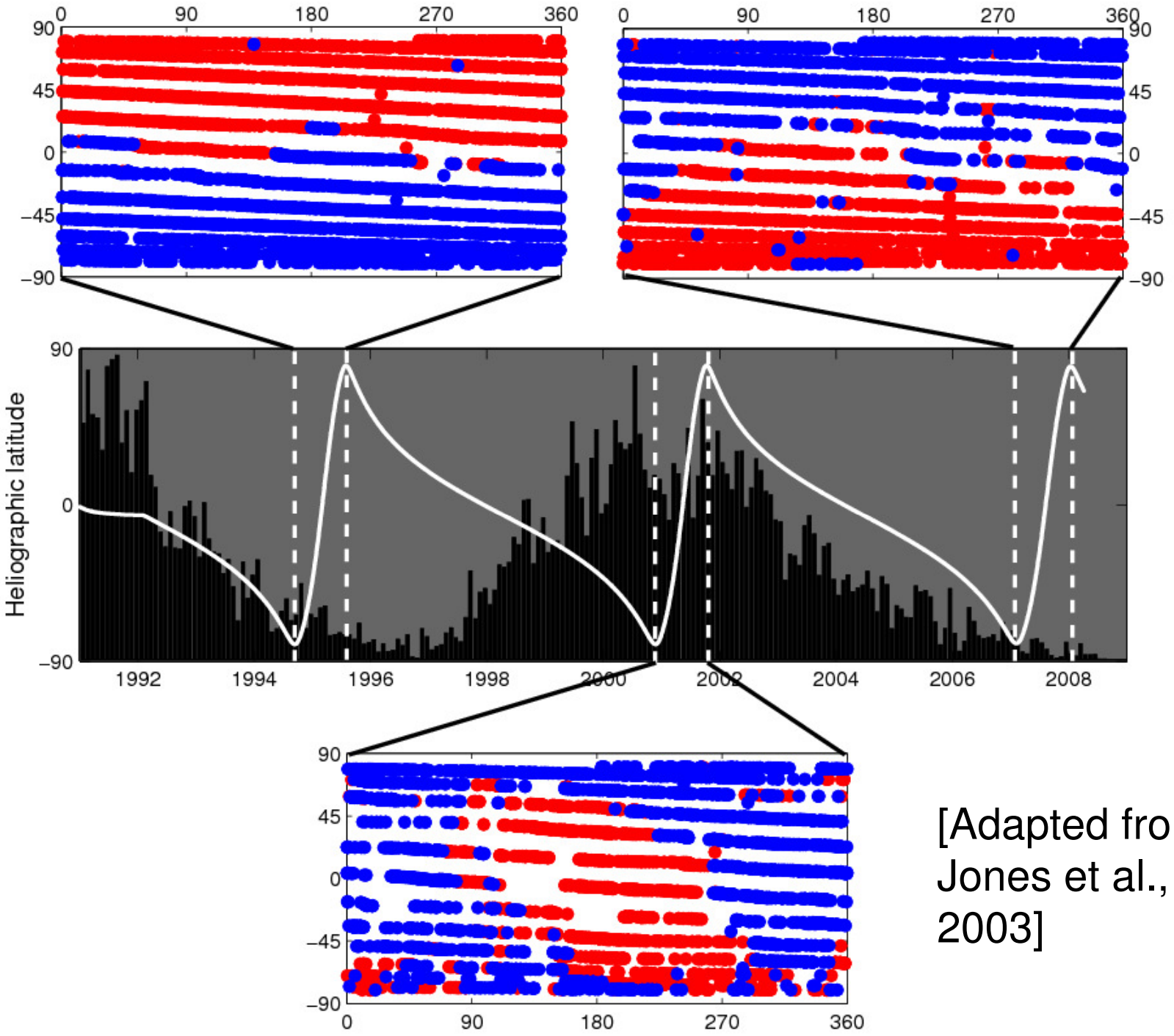


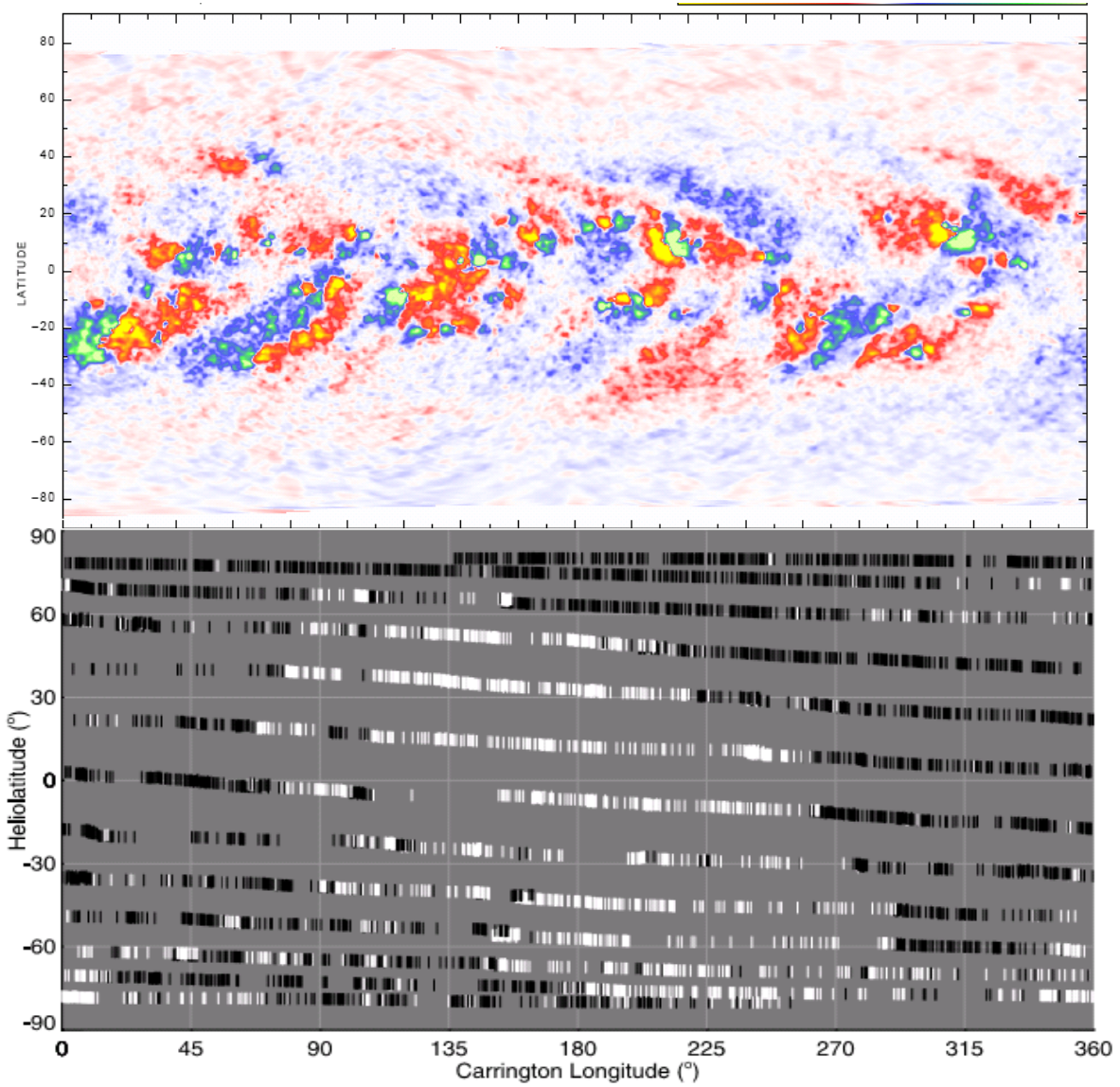
[Adapted from Jones et al., 2003]

A snapshot of solar maximum

[Top: Mt. Wilson magnetogram

Bottom: Jones et al., 2003

Both at solar maximum]



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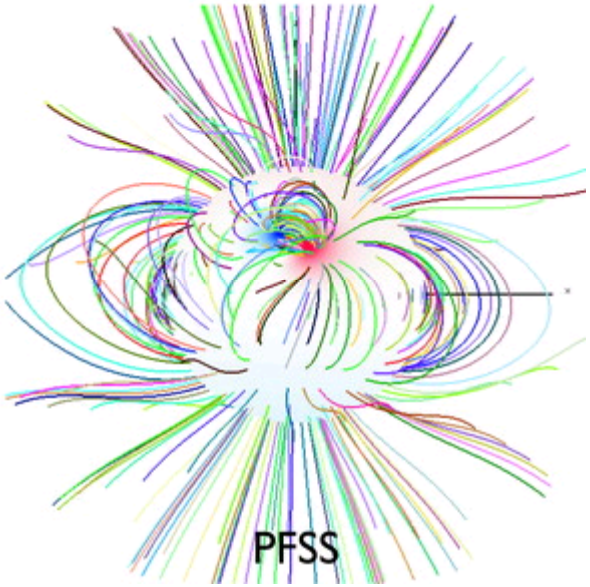
Solar cycle: corona



Riley et al., 2006

Yang Liu, SHINE 2006

How does the coronal field evolve?

- Wang & Sheeley: Emerging active region loops bring about field reversal by destruction of existing open flux
  - Series of PFSS solutions
- Fisk & Schwadron: Open flux is conserved, but reconfigured by reconnection
- B.C. Low: Magnetic helicity conservation means potential state cannot be reached by reconnection alone
  - CMEs required to shed the helicity
  - CMEs bodily remove flux to allow field reversal

Heliospheric magnetic fields

- Only have local measure of magnetic field
- Electrons can tell us about topology and connectivity
  - Suprathermal electrons
  - Jovian electrons

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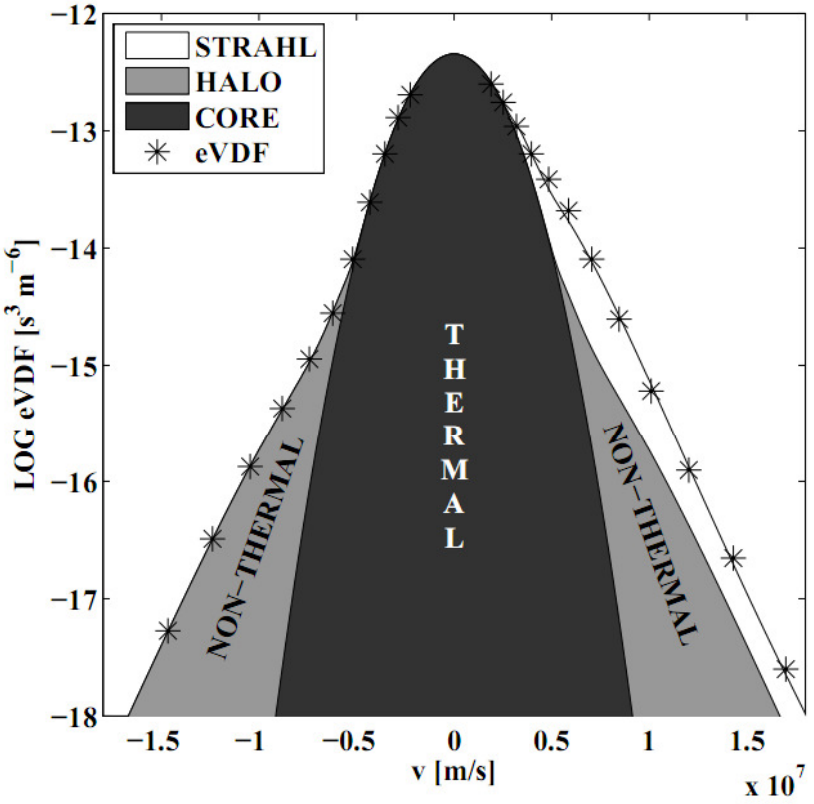
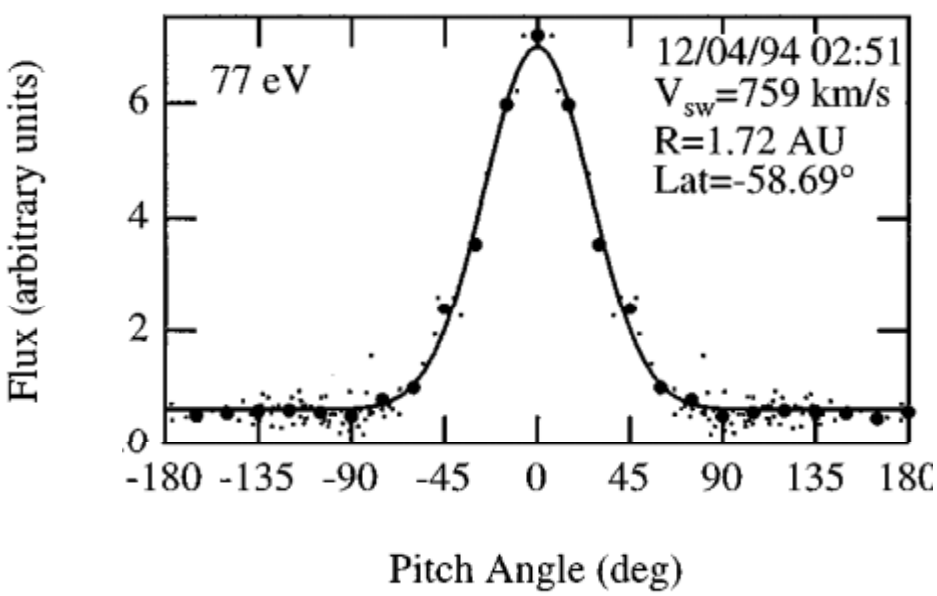
Suprathermal electrons



[Stverak et al., 2009]



[Hammond et al., 1996]

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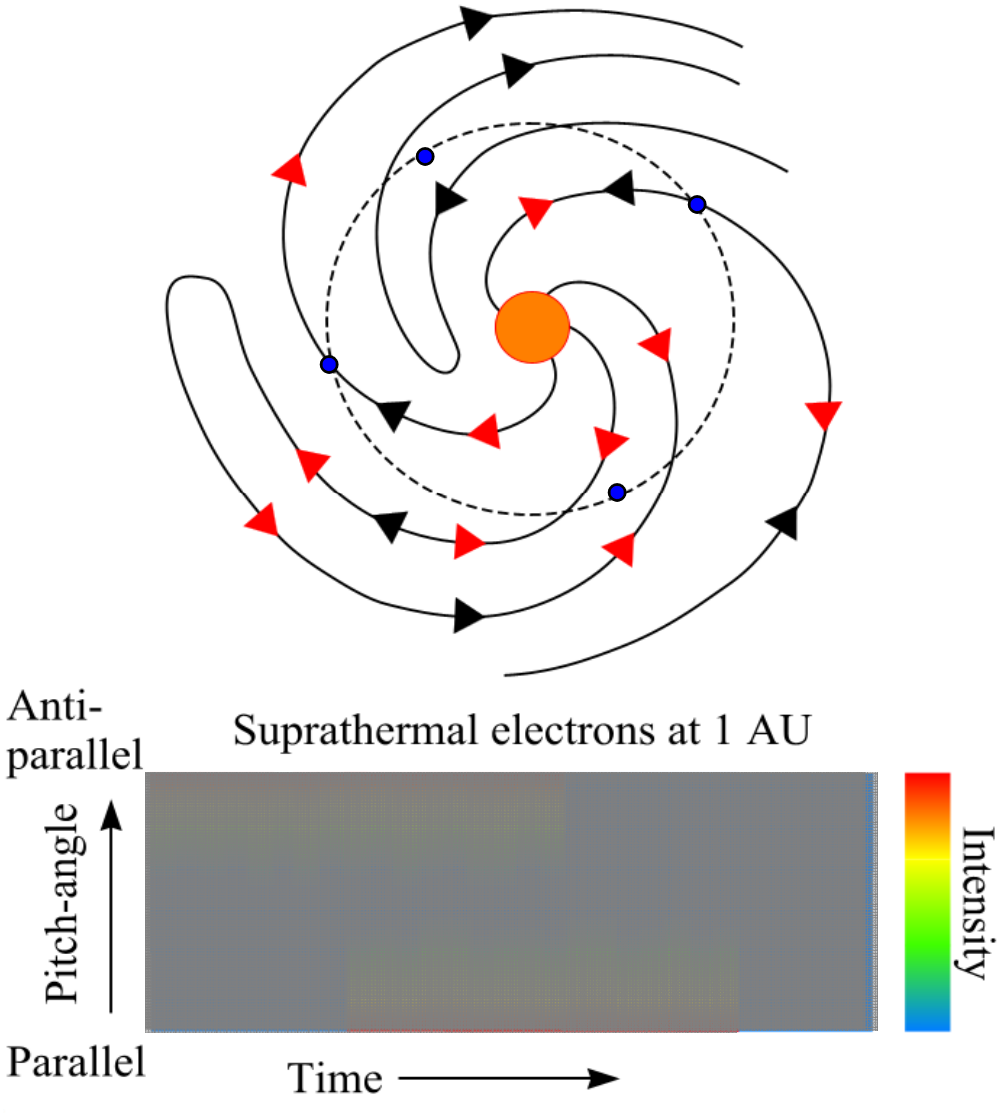
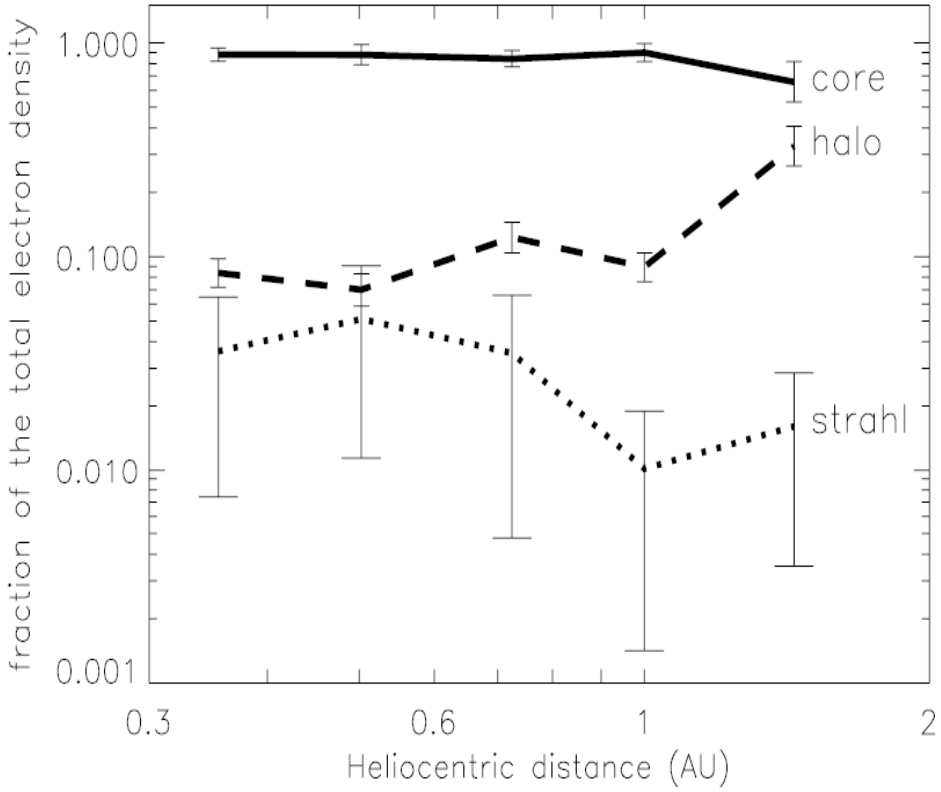
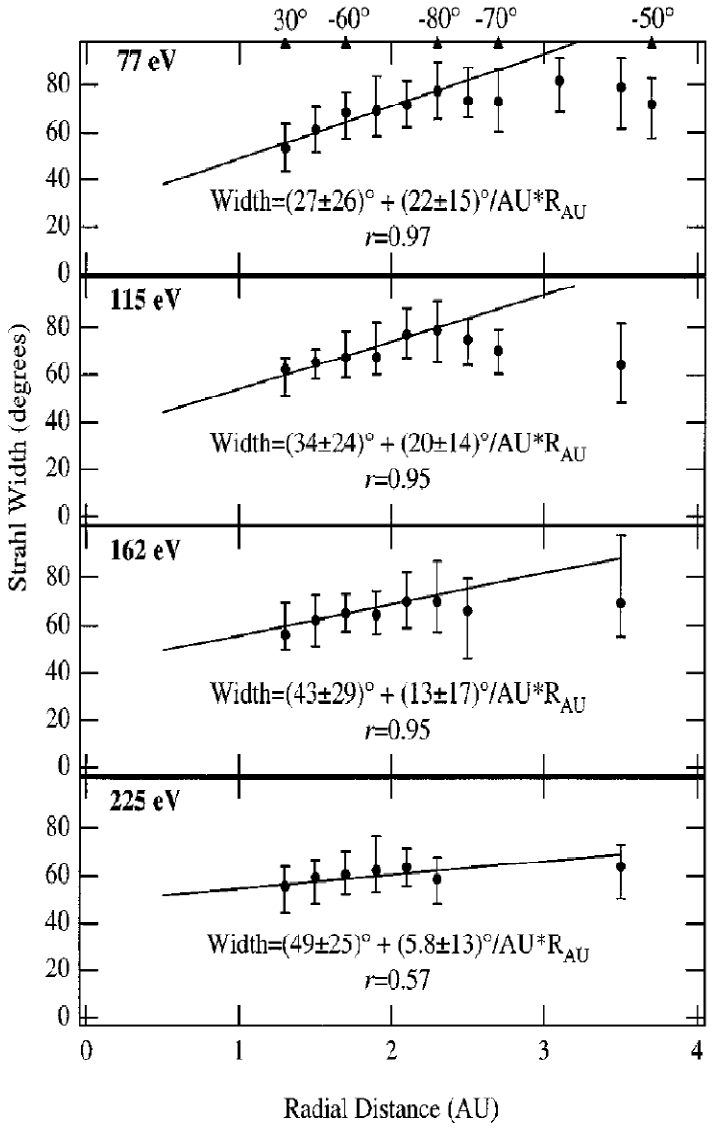
Suprathermal electrons



Suprathermal electron evolution



[Maksimovic et al.,2005]



[Hammond et al.,1996]

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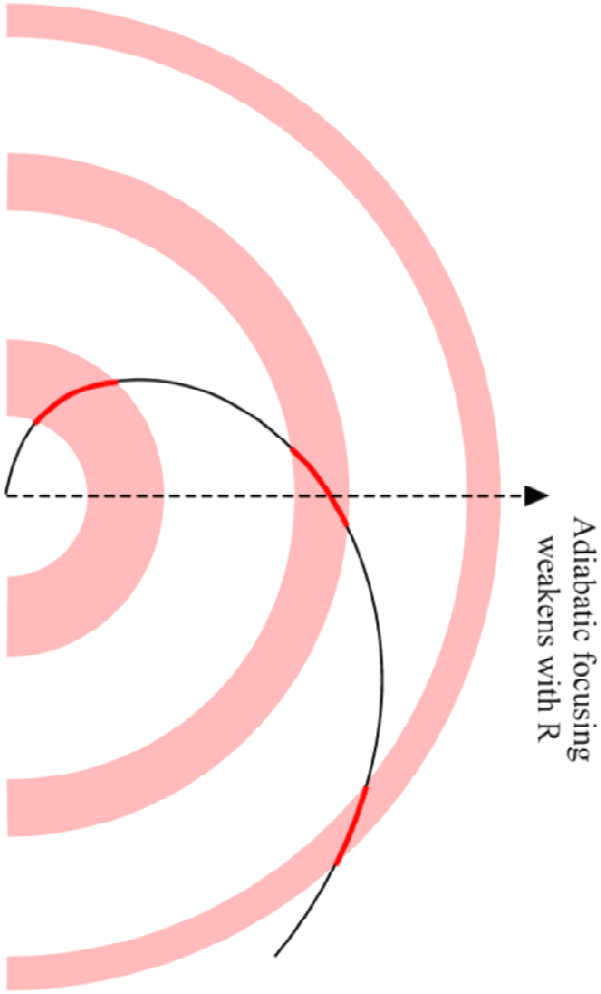
Explaining electron evolution

- Two competing effects:
  - Adiabatic focussing (conservation of magnetic moment) – R dependent
  - Pitch angle scattering – constant in time?
- Close to the Sun, focussing wins out
- Far from the Sun, scattering dominates



[Owens et al.,2008]

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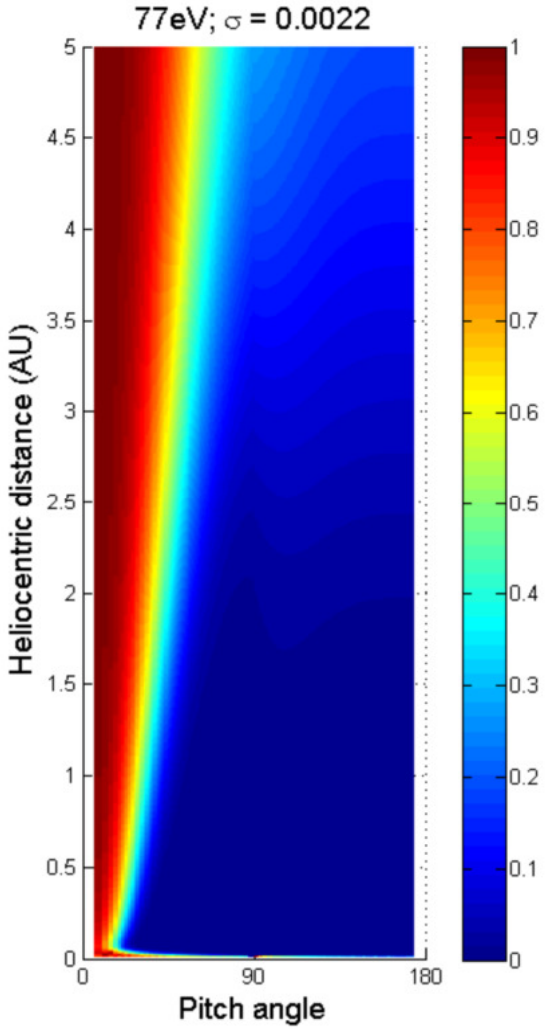
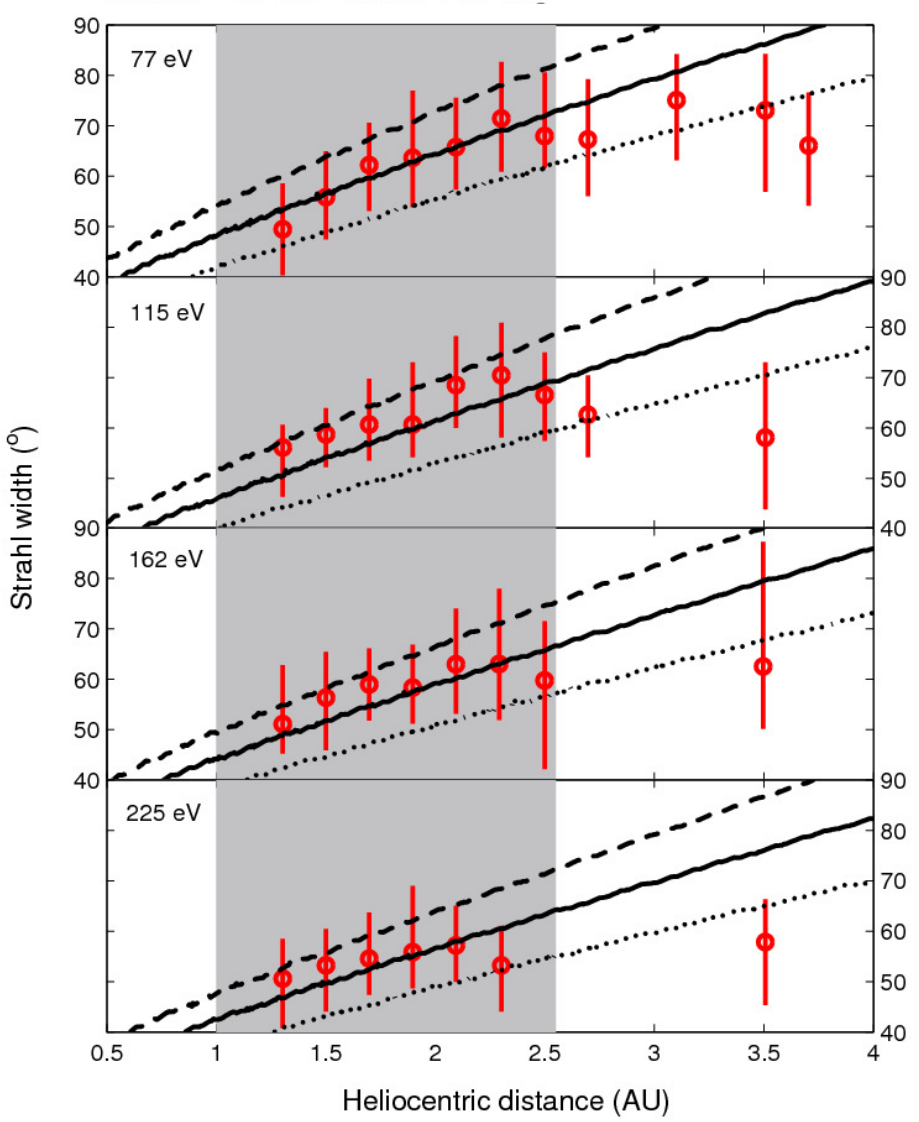
Modelling electron evolution





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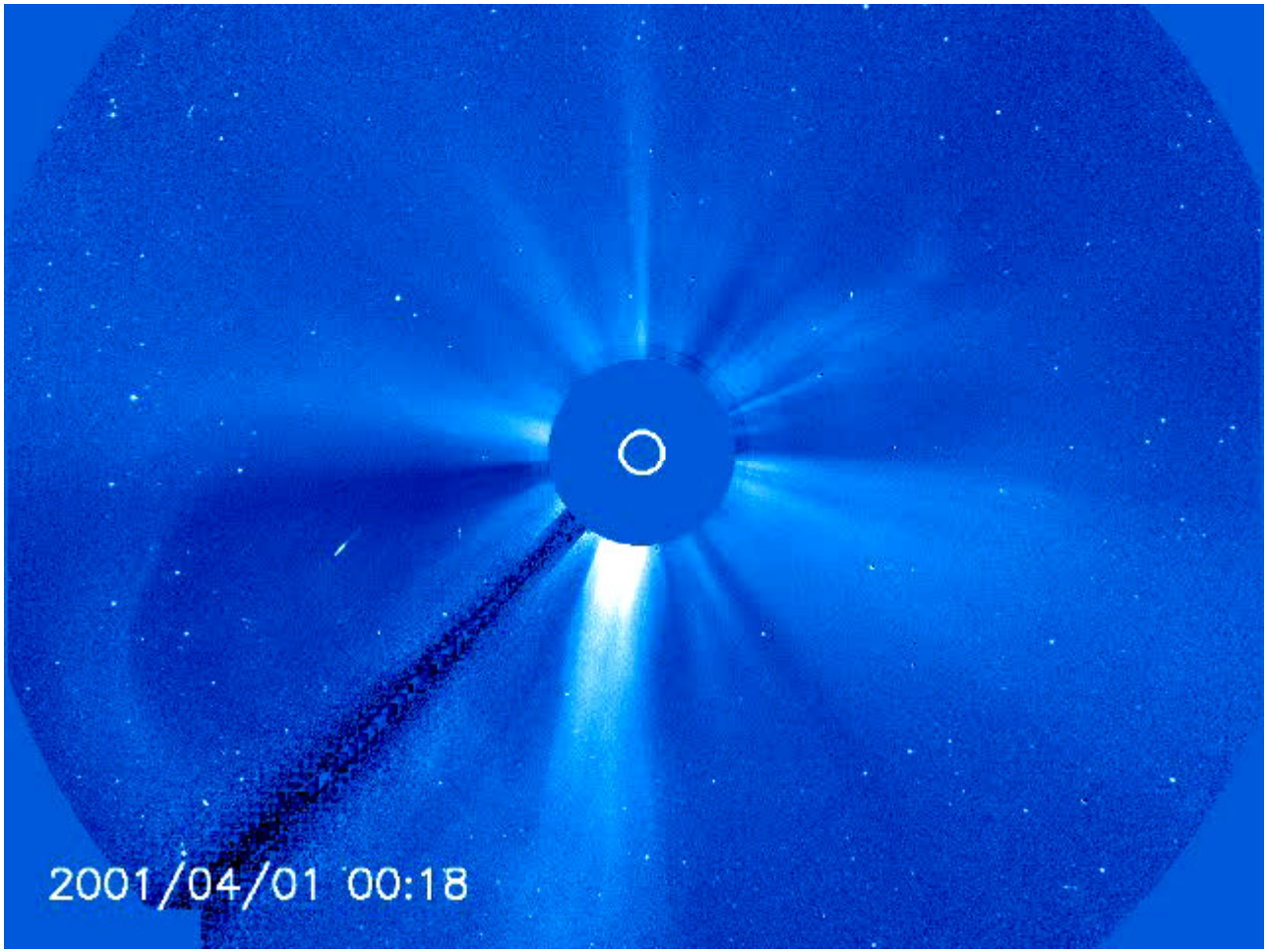
Coronal mass ejections



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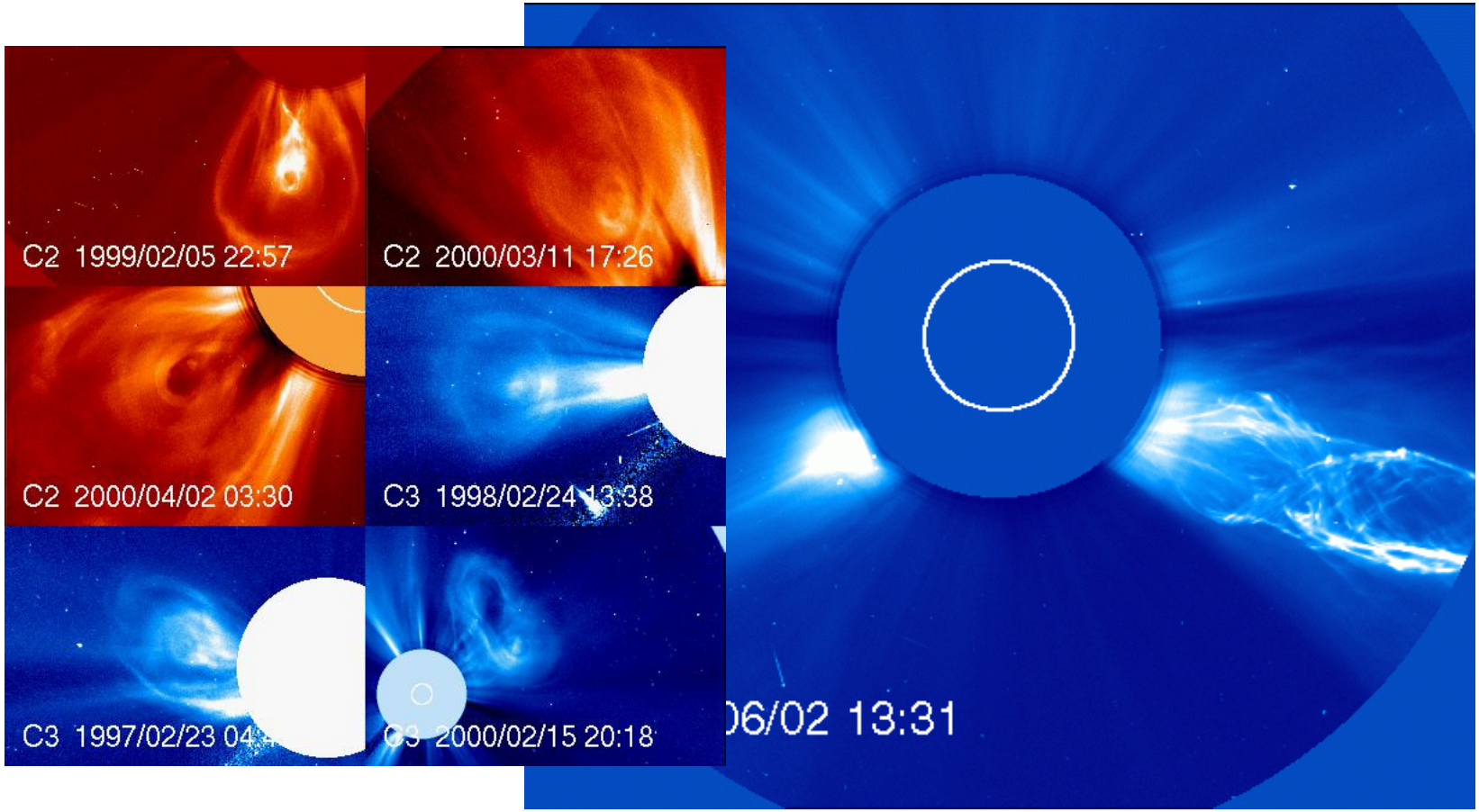
Flux ropes in CMEs?



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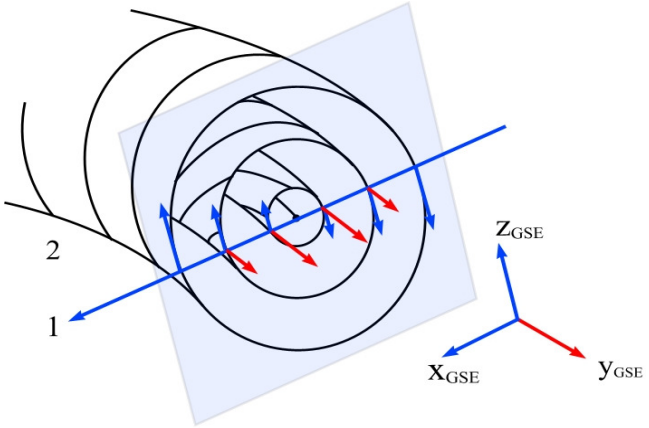
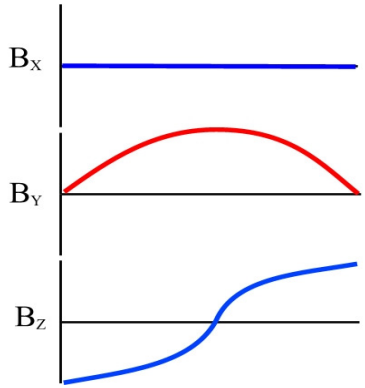
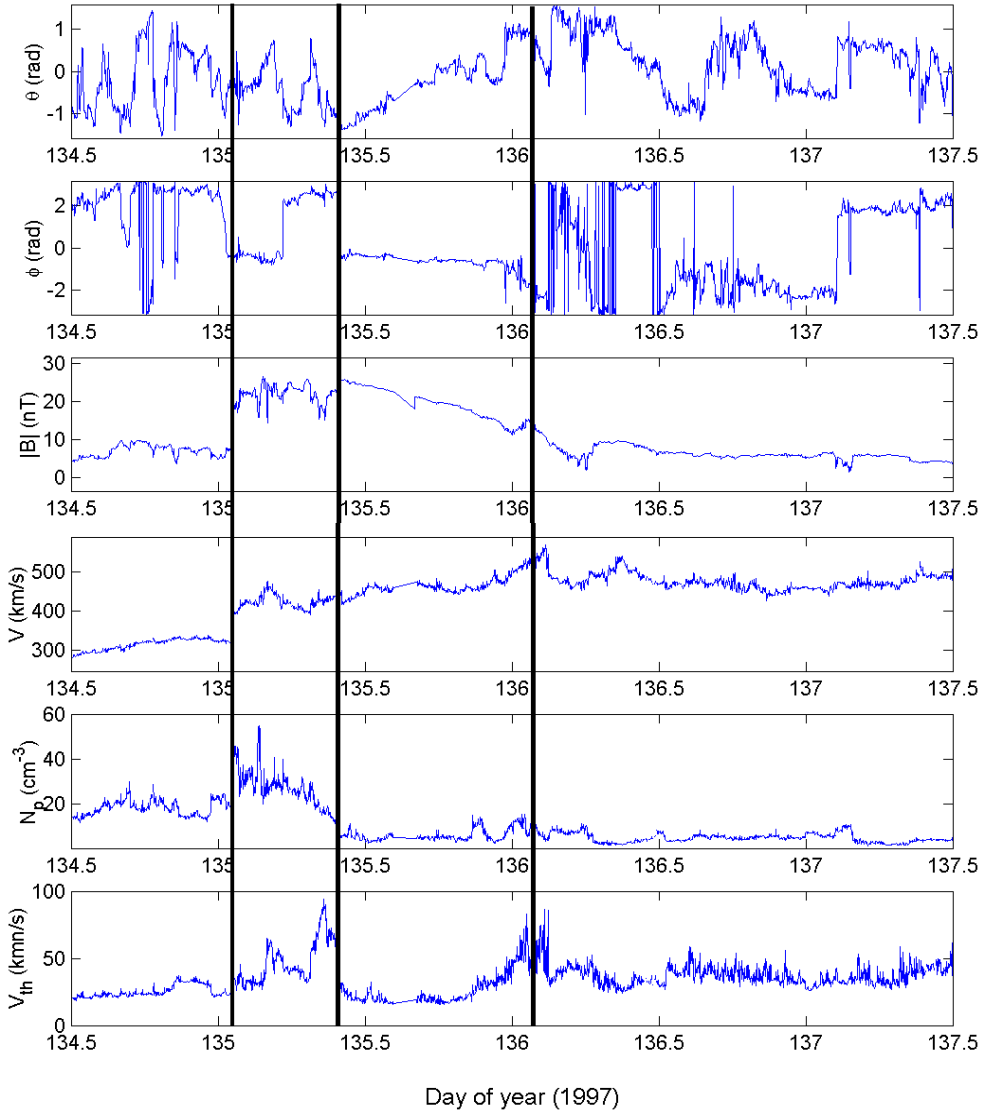
Flux ropes in ICMEs?







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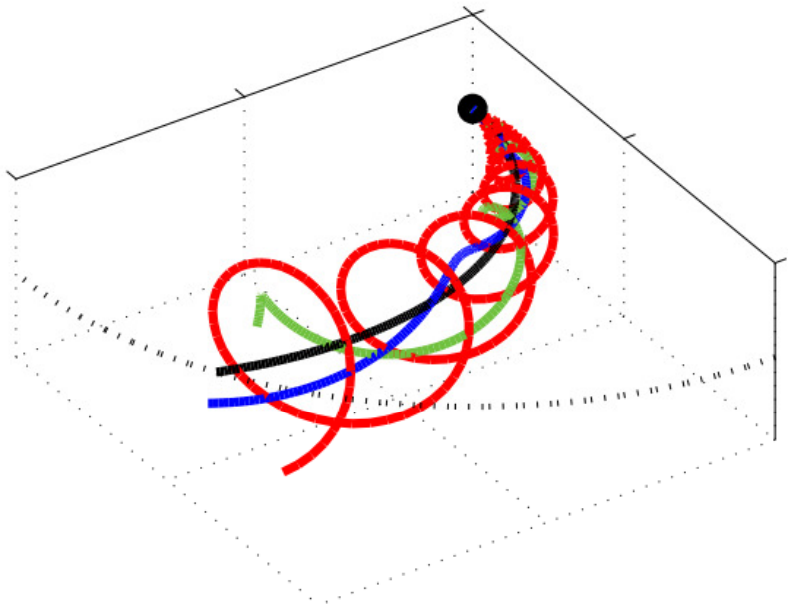
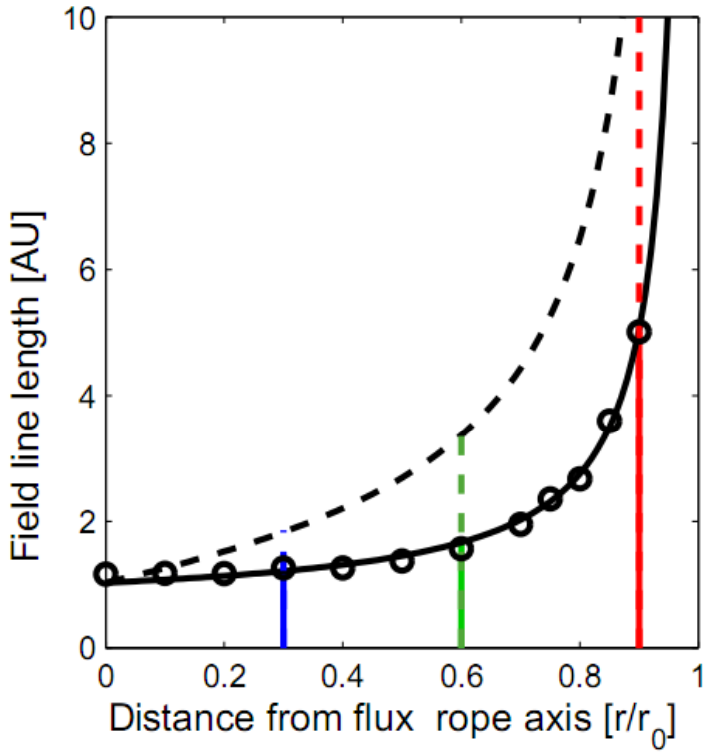
Field-line length





Some evidence from solar electron bursts [e.g., Larson et al., 1997], but sparse data

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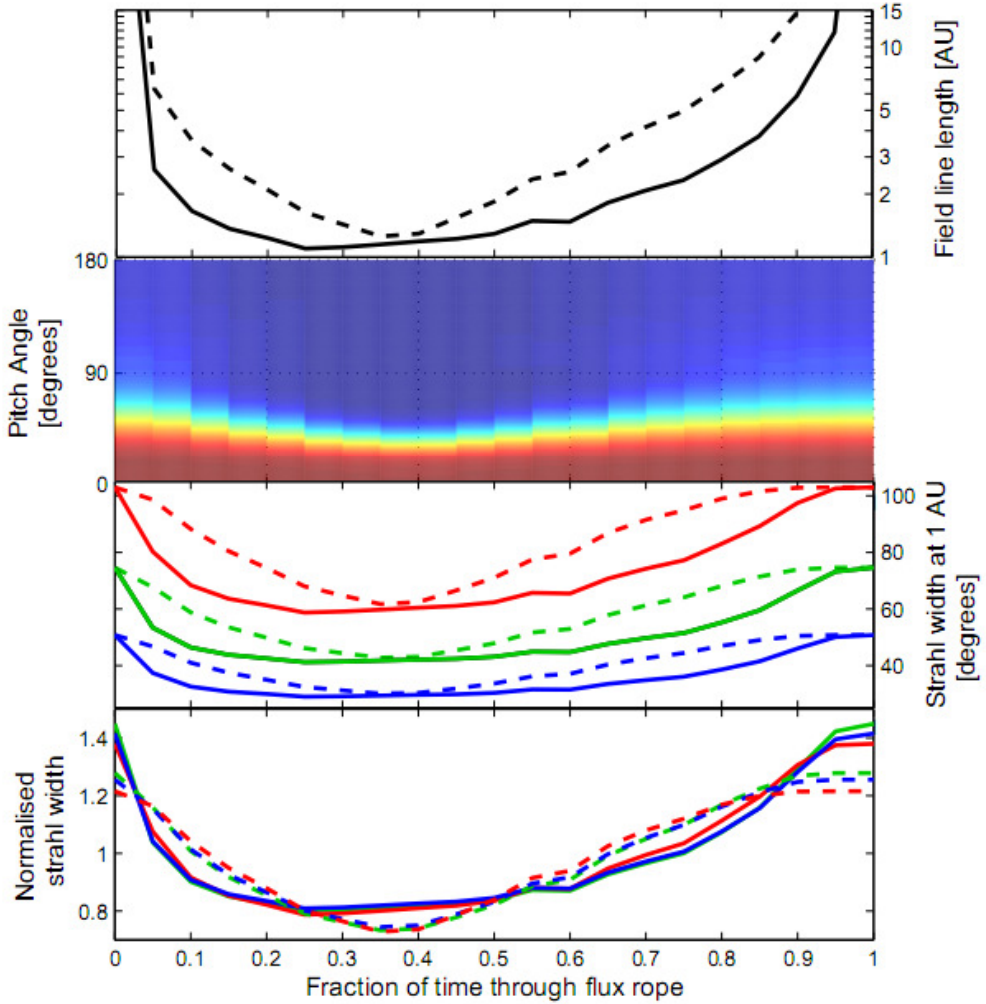
Expected electron profile



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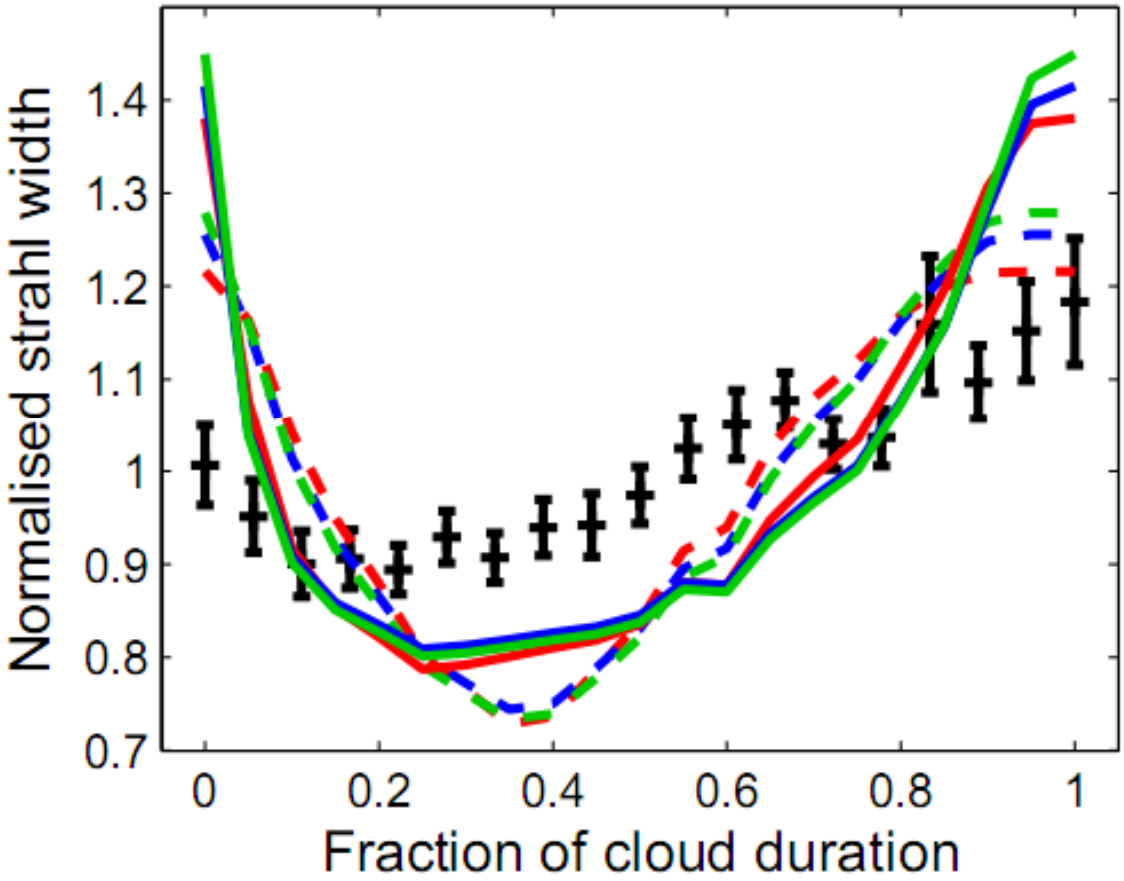
Analysis of ~100 magnetic clouds



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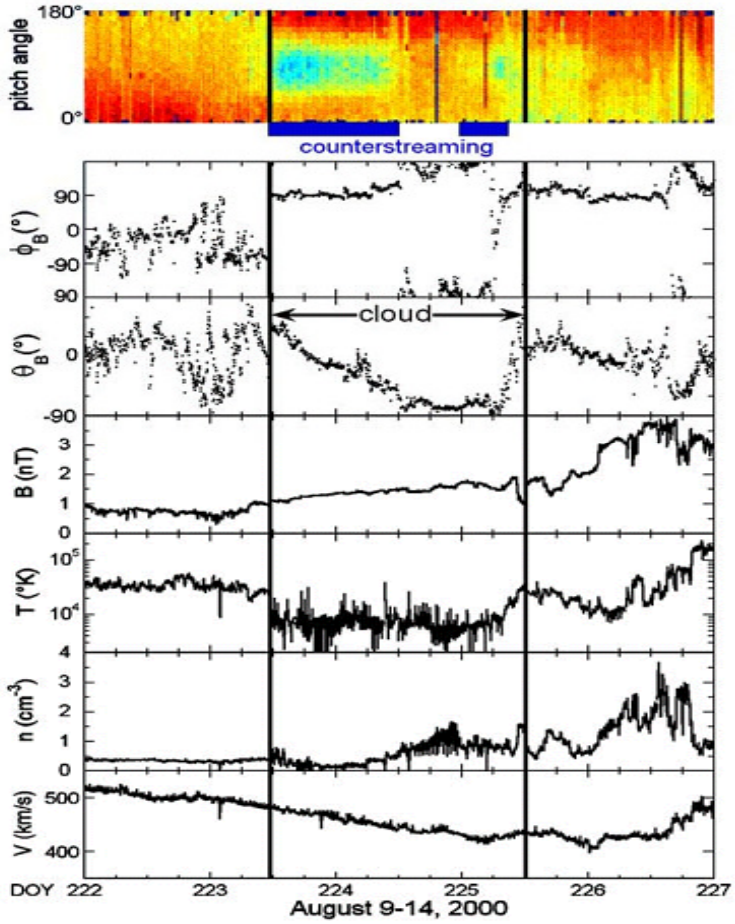
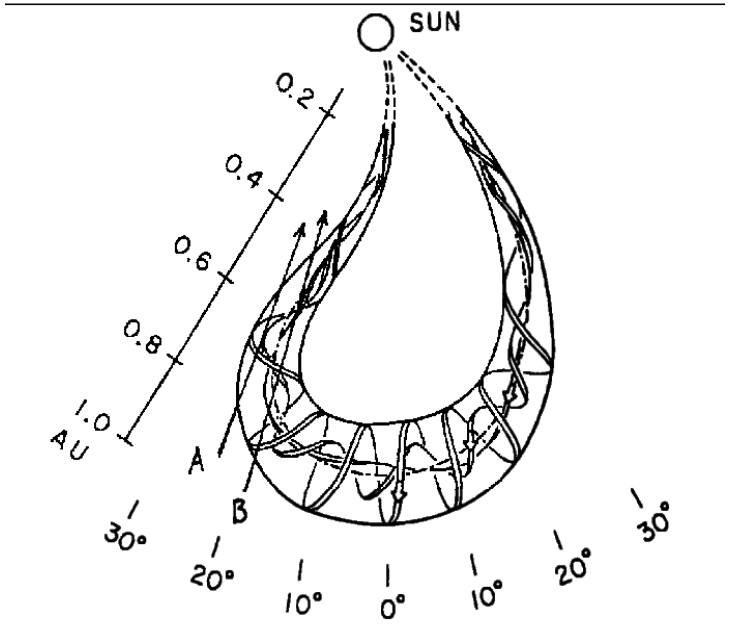
Solar connectivity



Crooker et al., 2004



Marubashi., 1997

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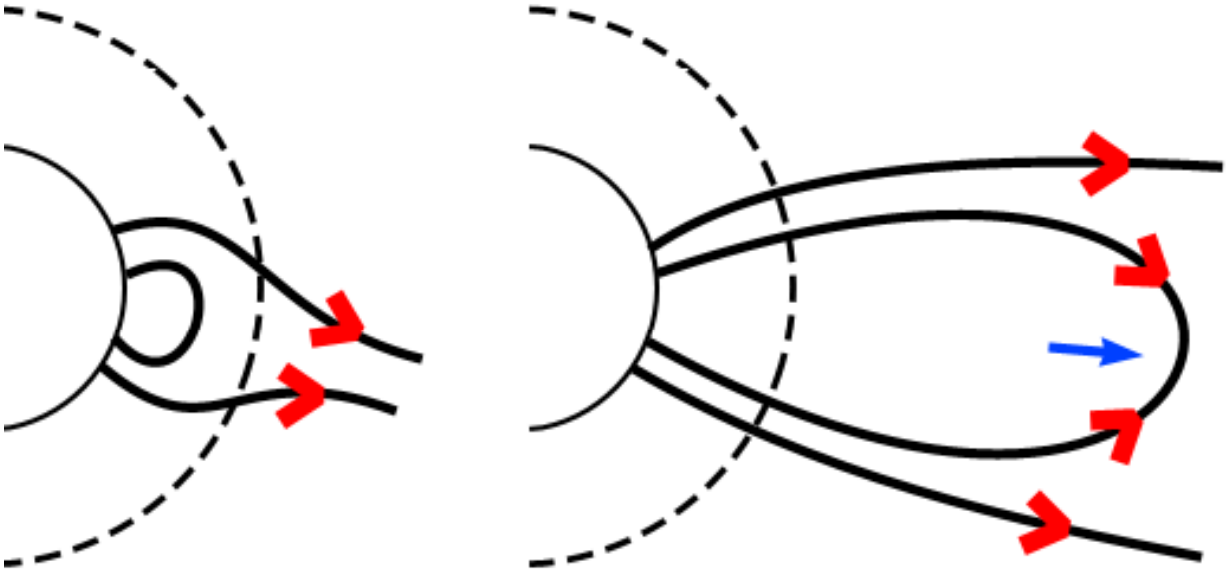
CMEs add flux to the heliosphere



Owens and Crooker, JGR, 2006

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Estimating the CME flux contribution

- Need values for:
  1. Flux contained in a typical CME
  2. CME rate over the solar cycle
  3. Background “open” flux (i.e., non-CME flux)
  4. Timescale for CME flux removal

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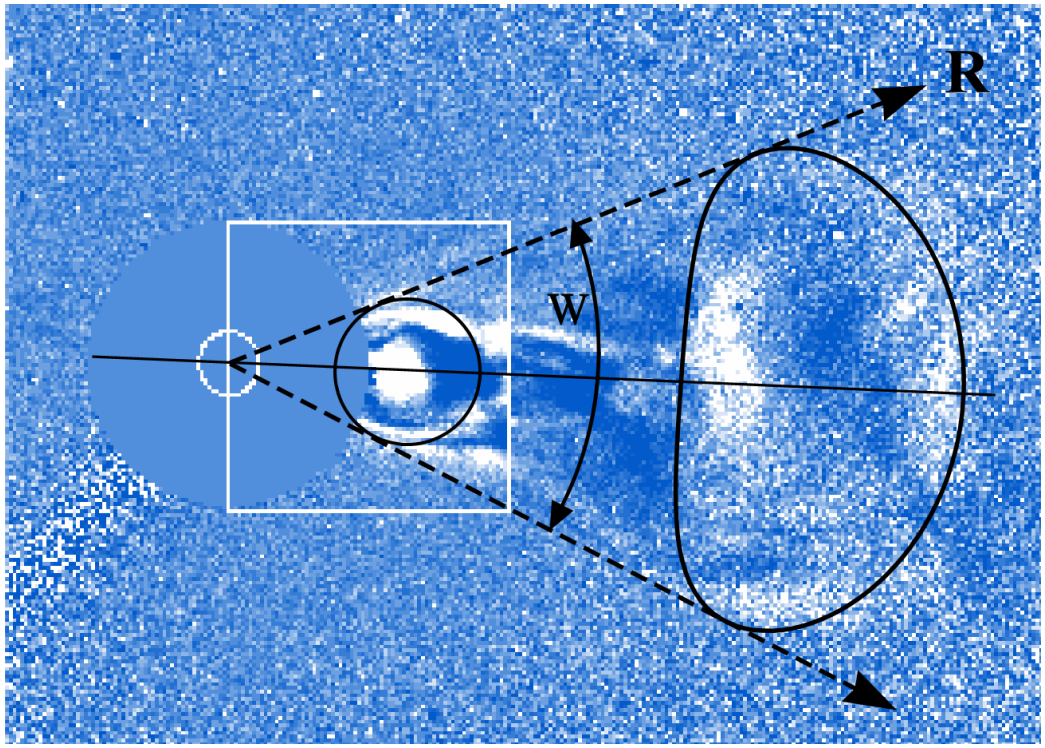
Cross-sectional elongation

- Radial motion will distort flux rope [Riley and Crooker, 2004]



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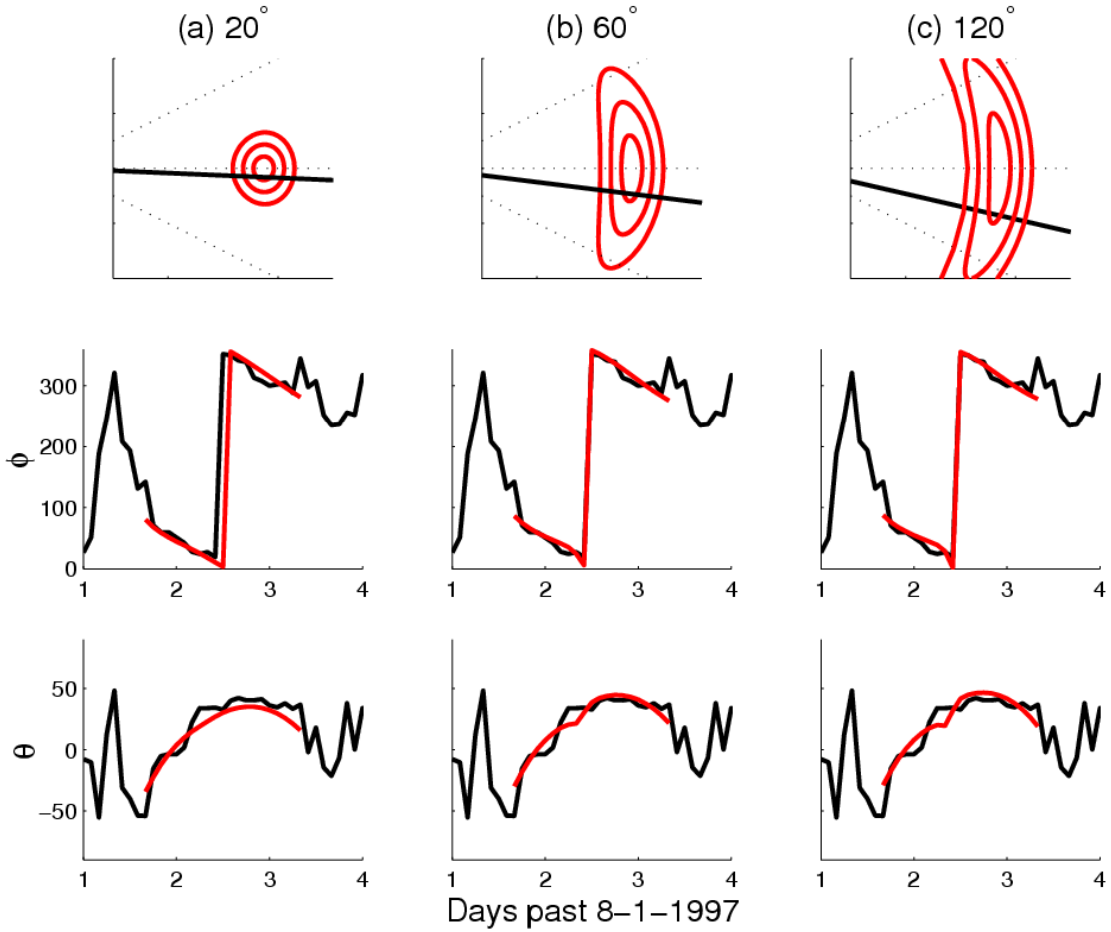
Cross-sectional elongation



[Owens, 2008]

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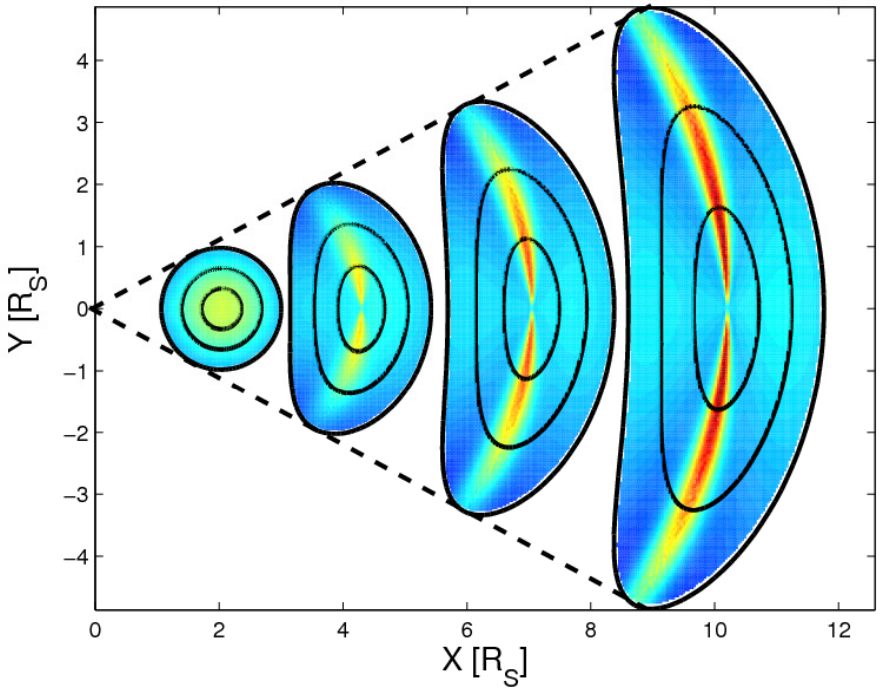

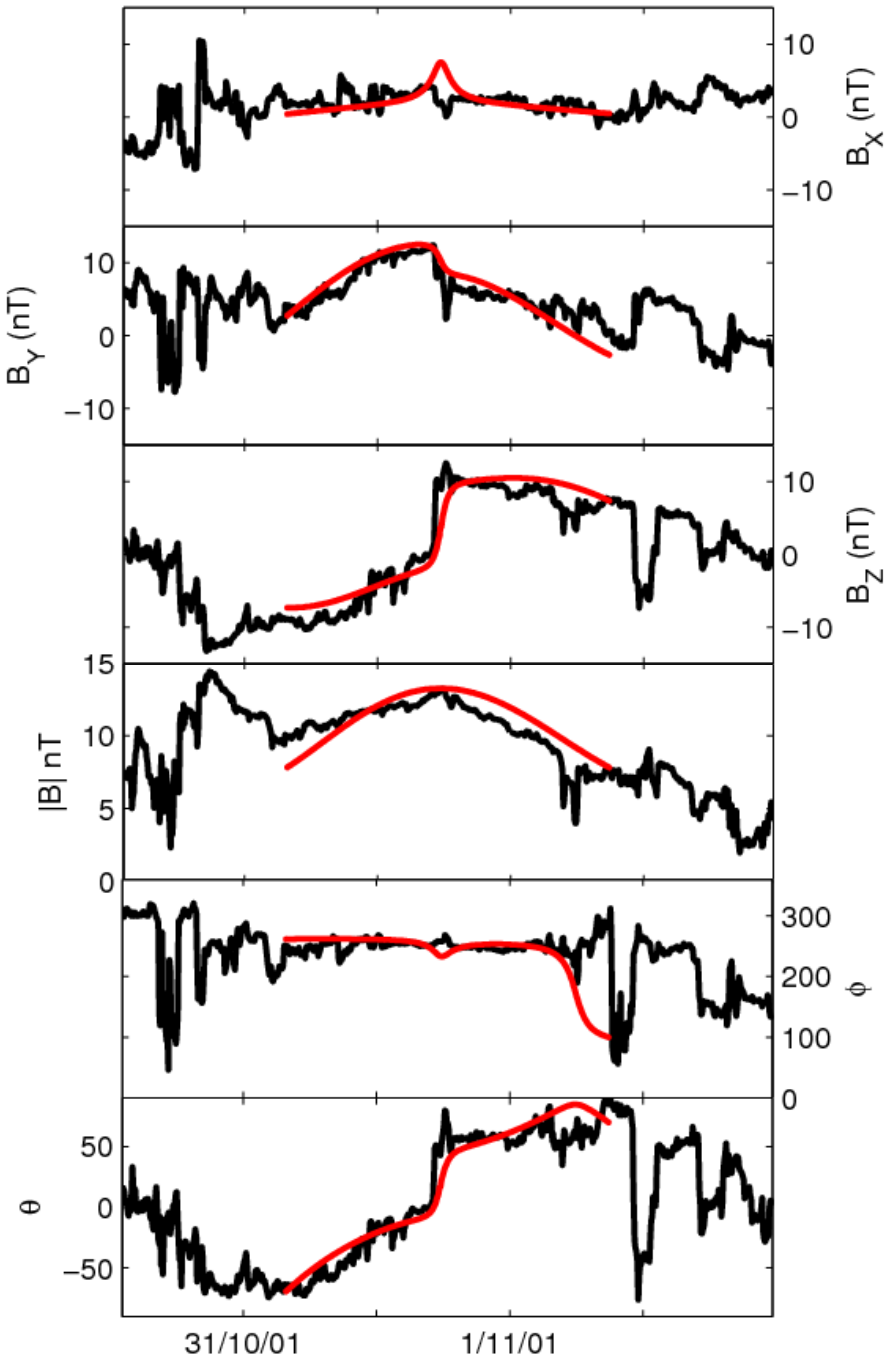

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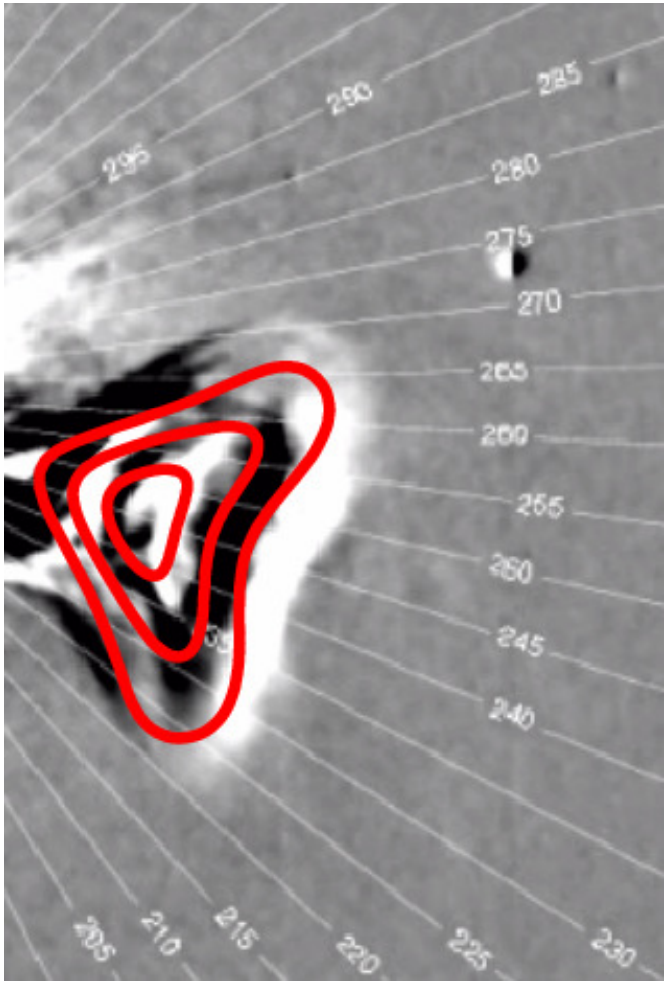
Combining remote and in situ observations

- LASCO/Ulysses
  - x5 more flux than force-free suggests
- ~10^{12}-10^{13} Wb of axial flux
- How important a source of magnetic flux are ICMEs?



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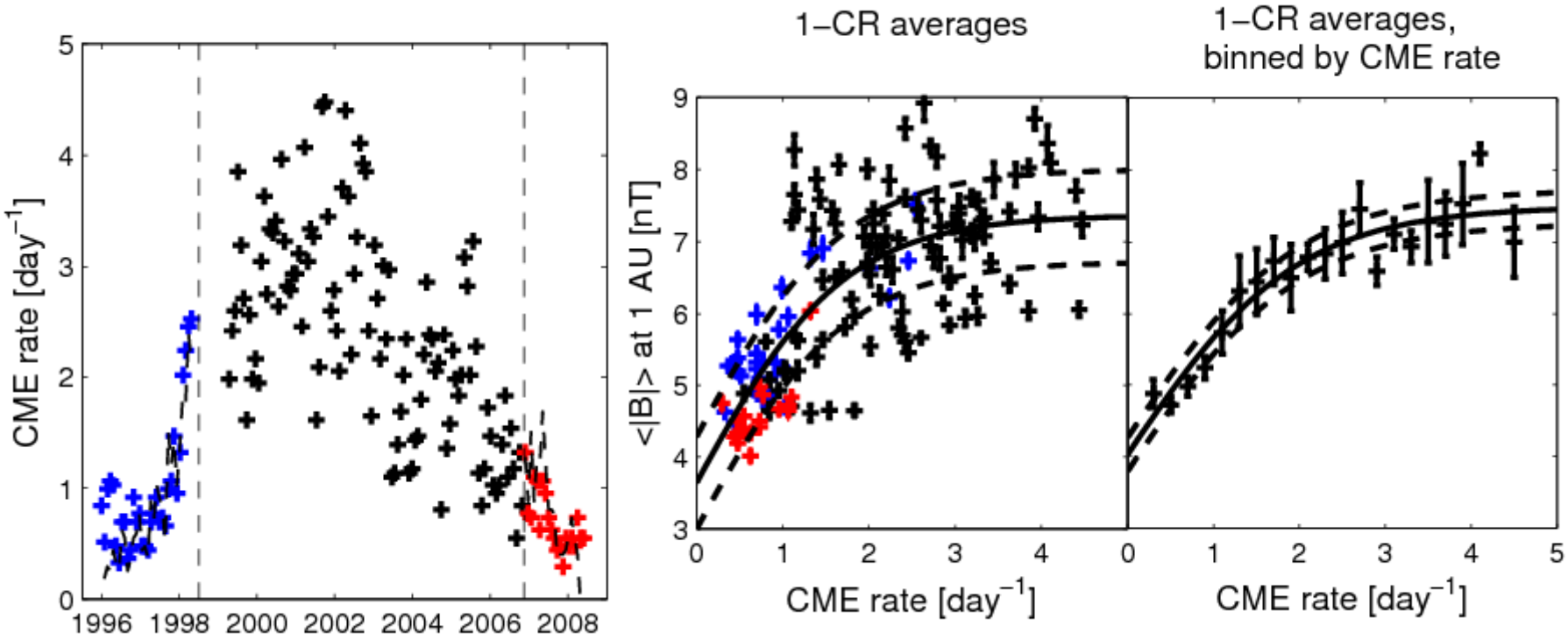
CME rates



Owens et al., GRL, 2008

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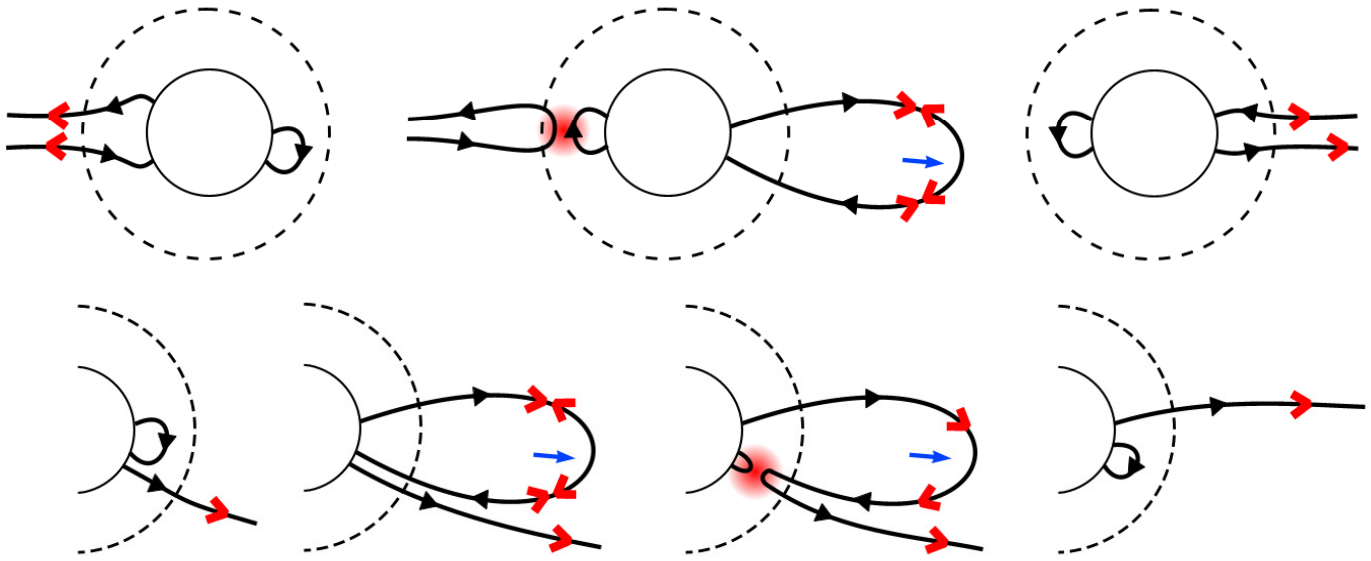
Removing CME flux

Simple picture:

- Disconnection: EDs, no decay in CSE
- Interchange: no EDs, decay in CSE



Owens and Crooker, JGR, 2007

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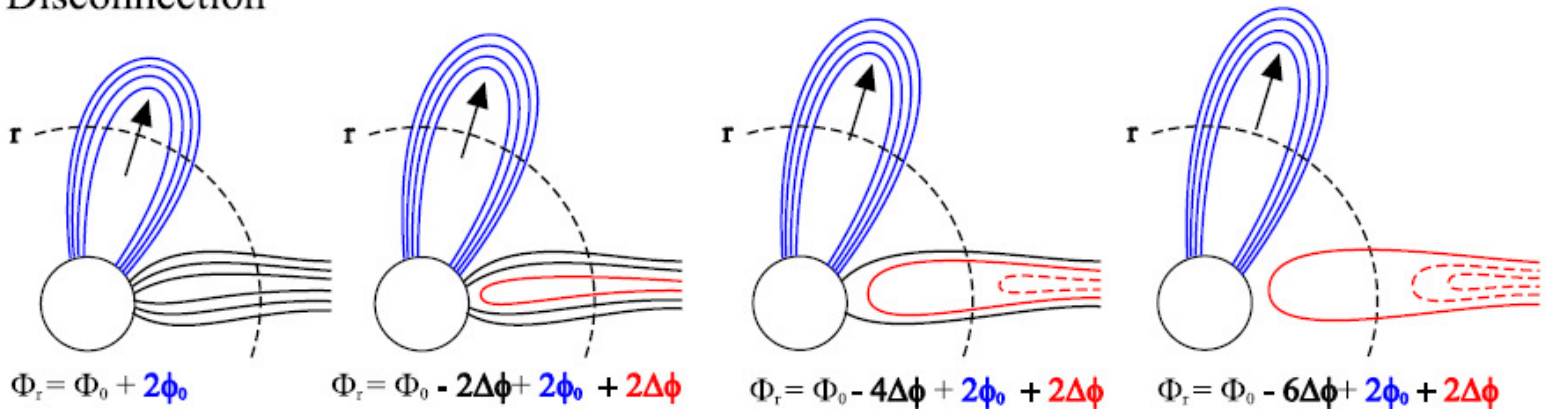
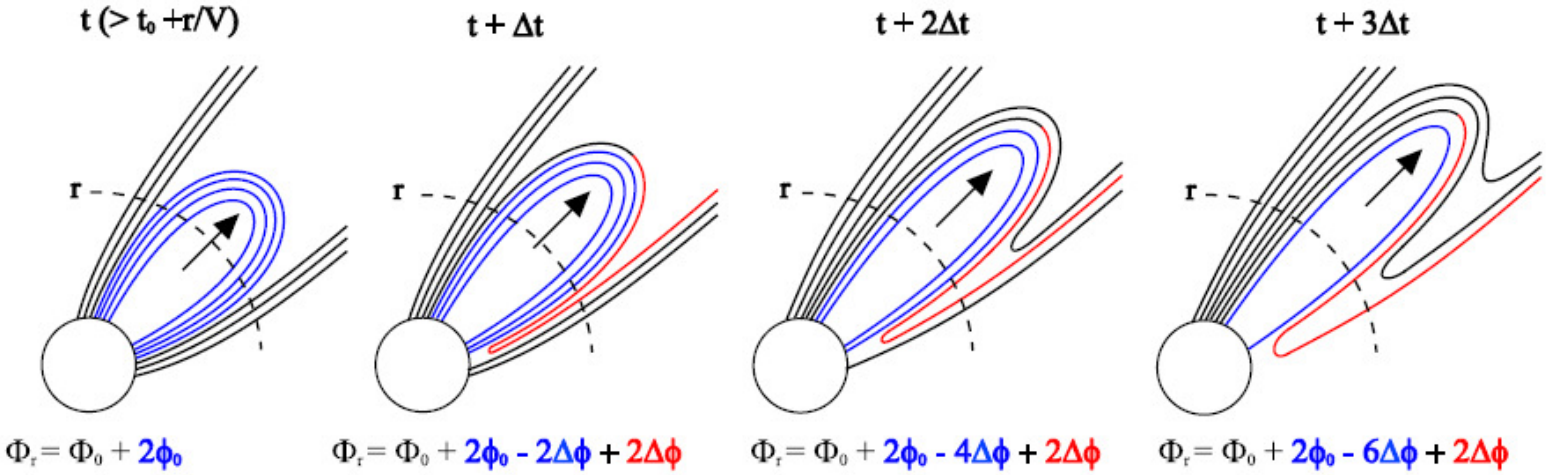
Both reduce flux at same rate

Disconnection



Interchange reconnection



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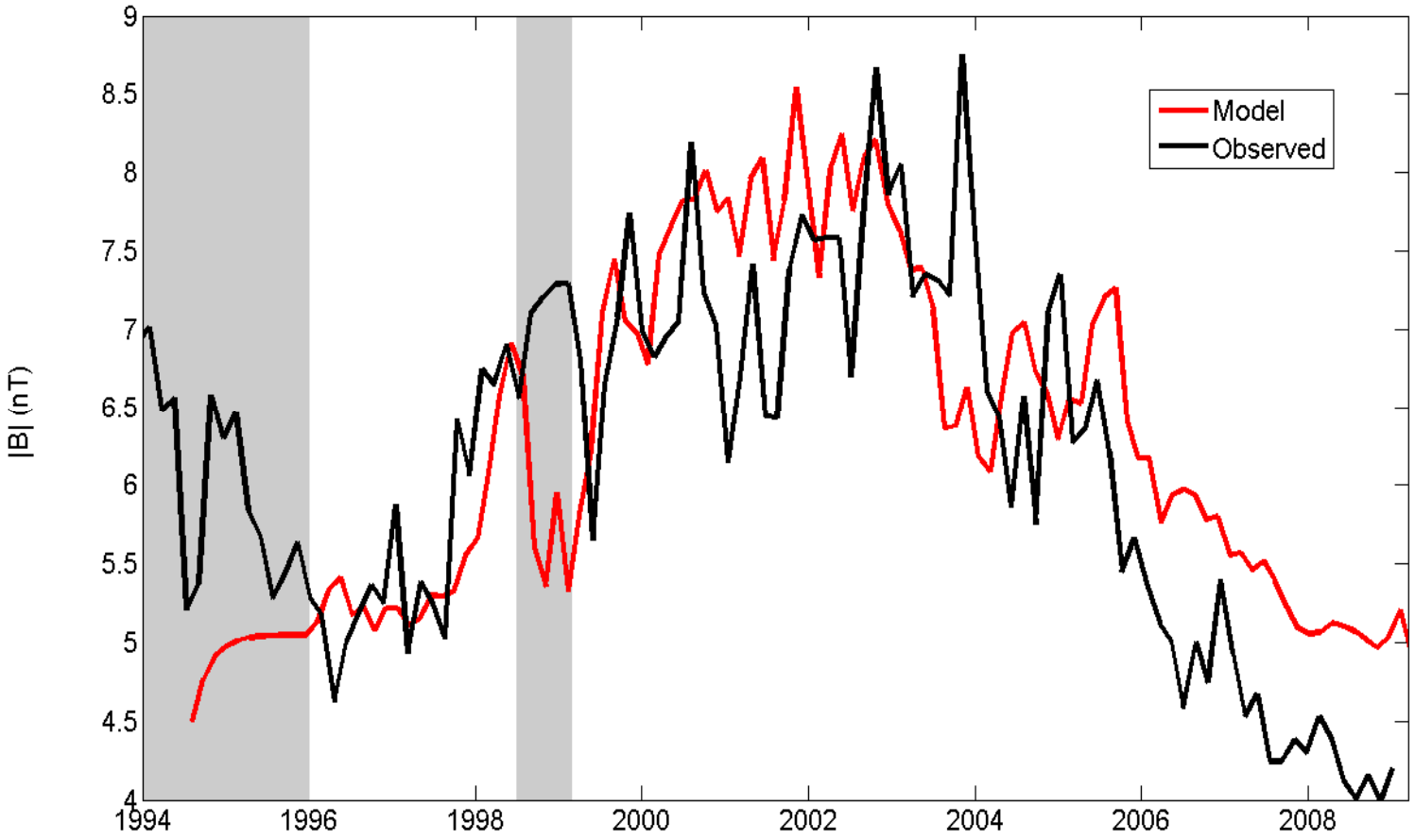
Model estimates: 40-day timescale?



Model of Owens and Crooker [2006] using updated data

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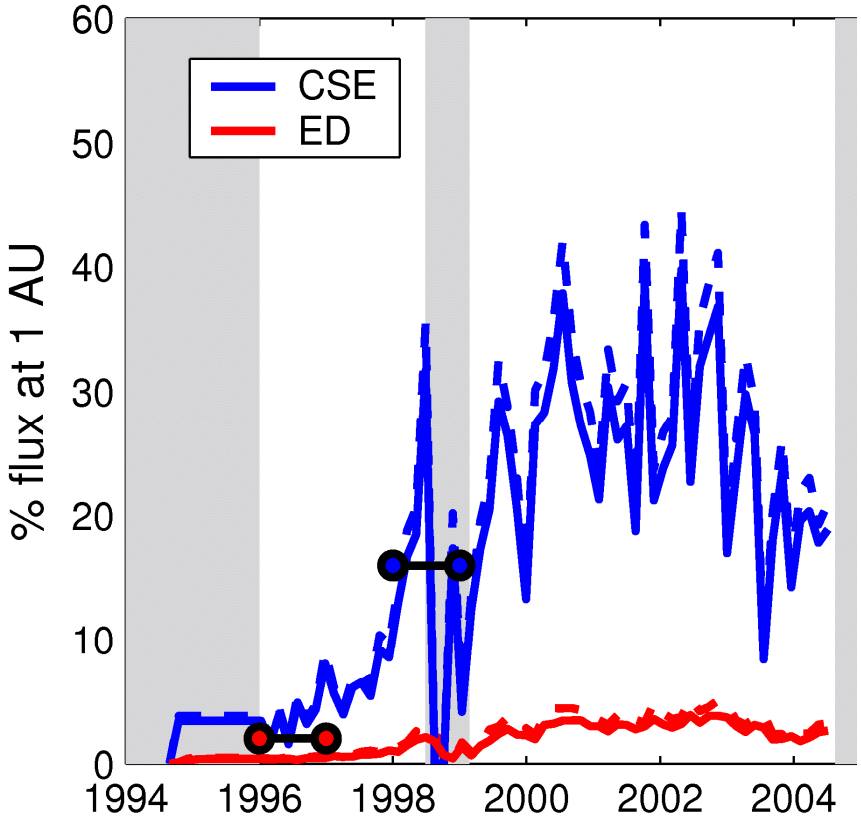
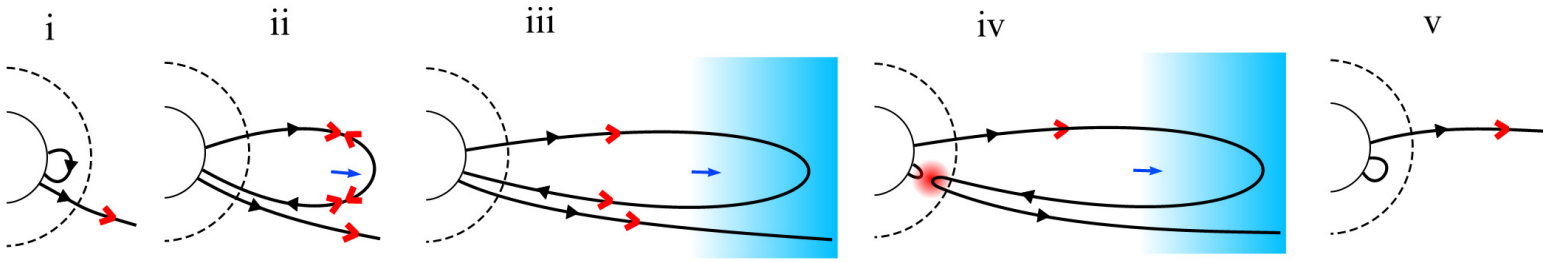
Long CME opening times?

- How quickly is the CSE signature removed due to scattering?
  - 8 AU?





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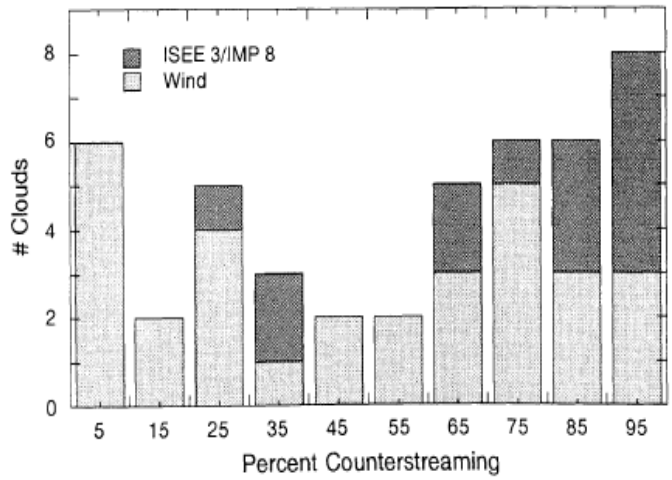
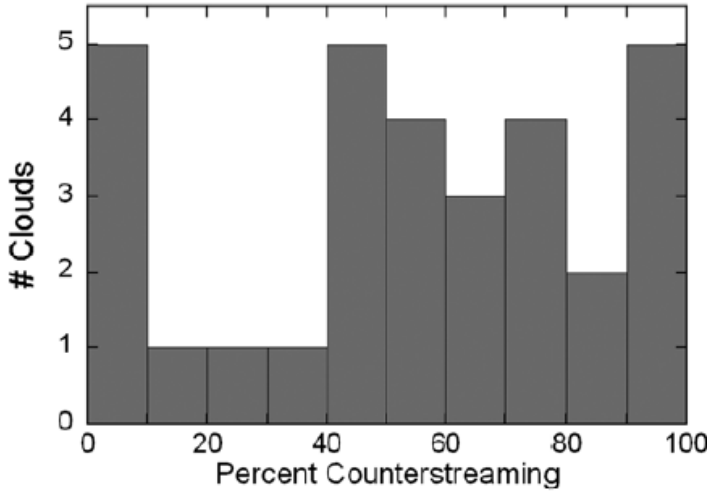
[Owens and Crooker, 2007]

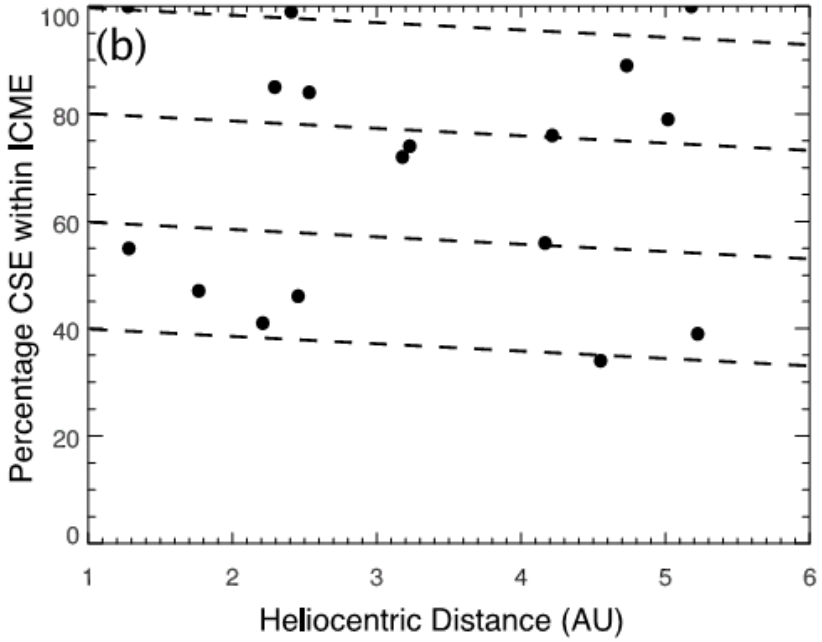
Evidence for CME loop opening



1 AU: Shodhan et al., 2002



5 AU: Crooker et al., 2002



Riley et al., 2004

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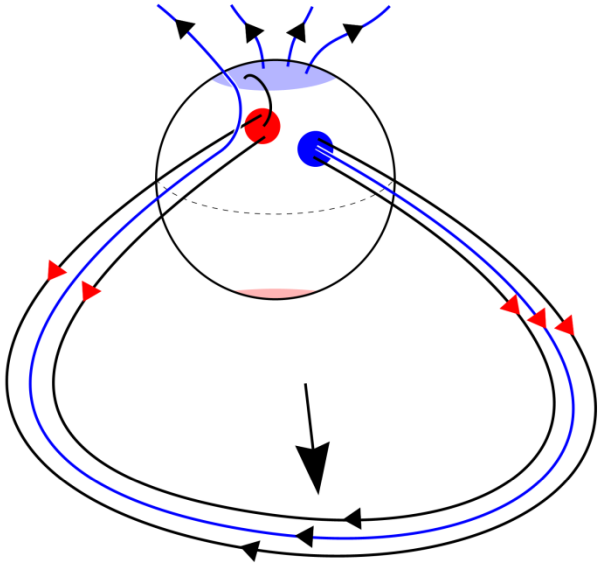
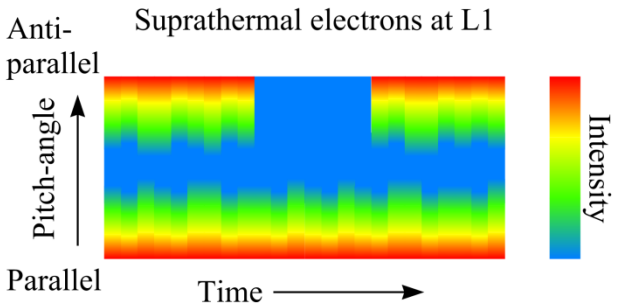
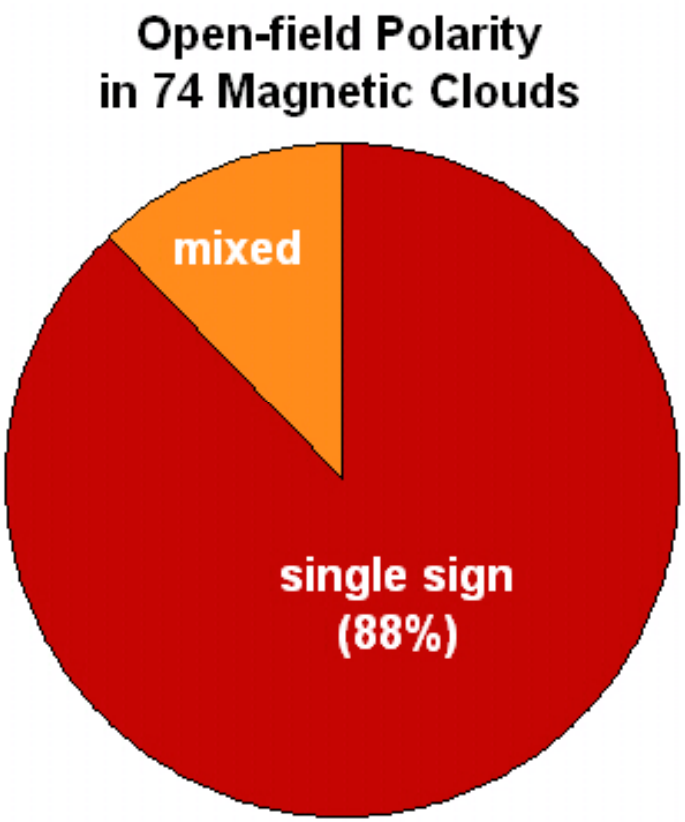
Evidence for CME loop opening





Owens et al., GRL, 2007



Crooker et al, JGR, 2008

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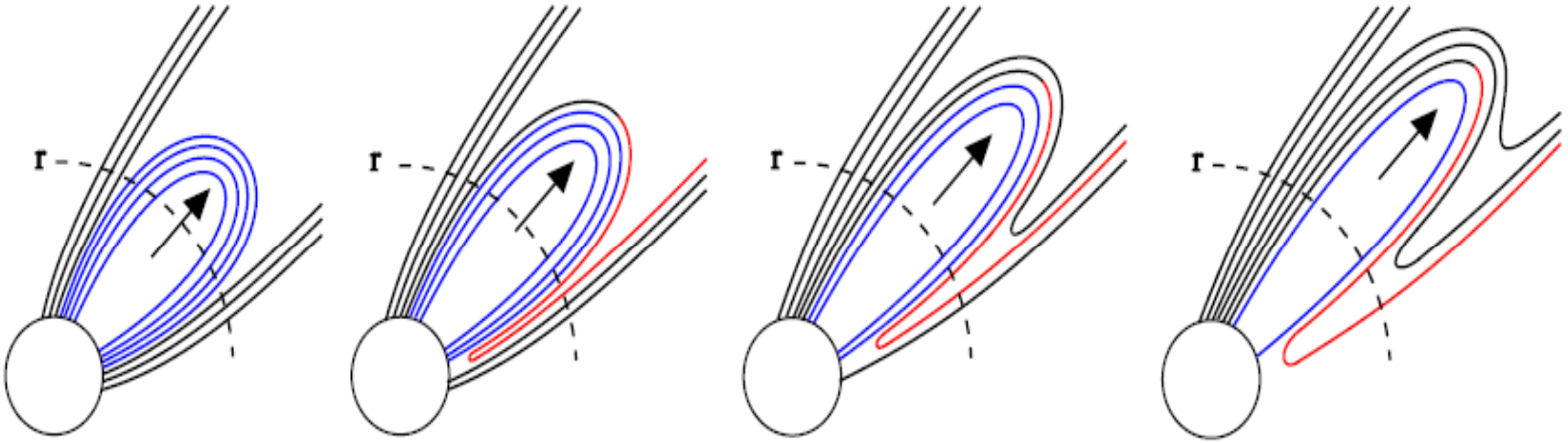
Transport of open flux



Owens and Crooker, JGR, 2007

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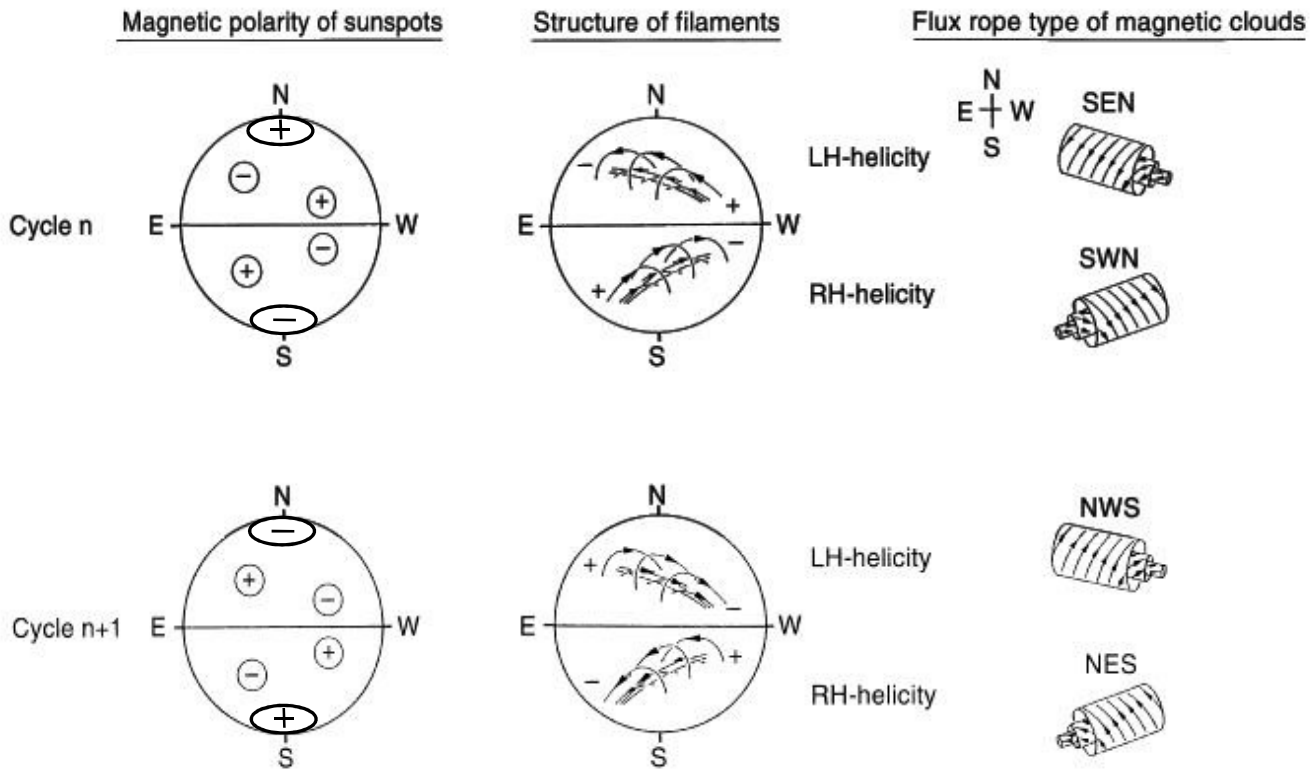
CME footpoint orientations



Bothmer and Schwenn, 1998

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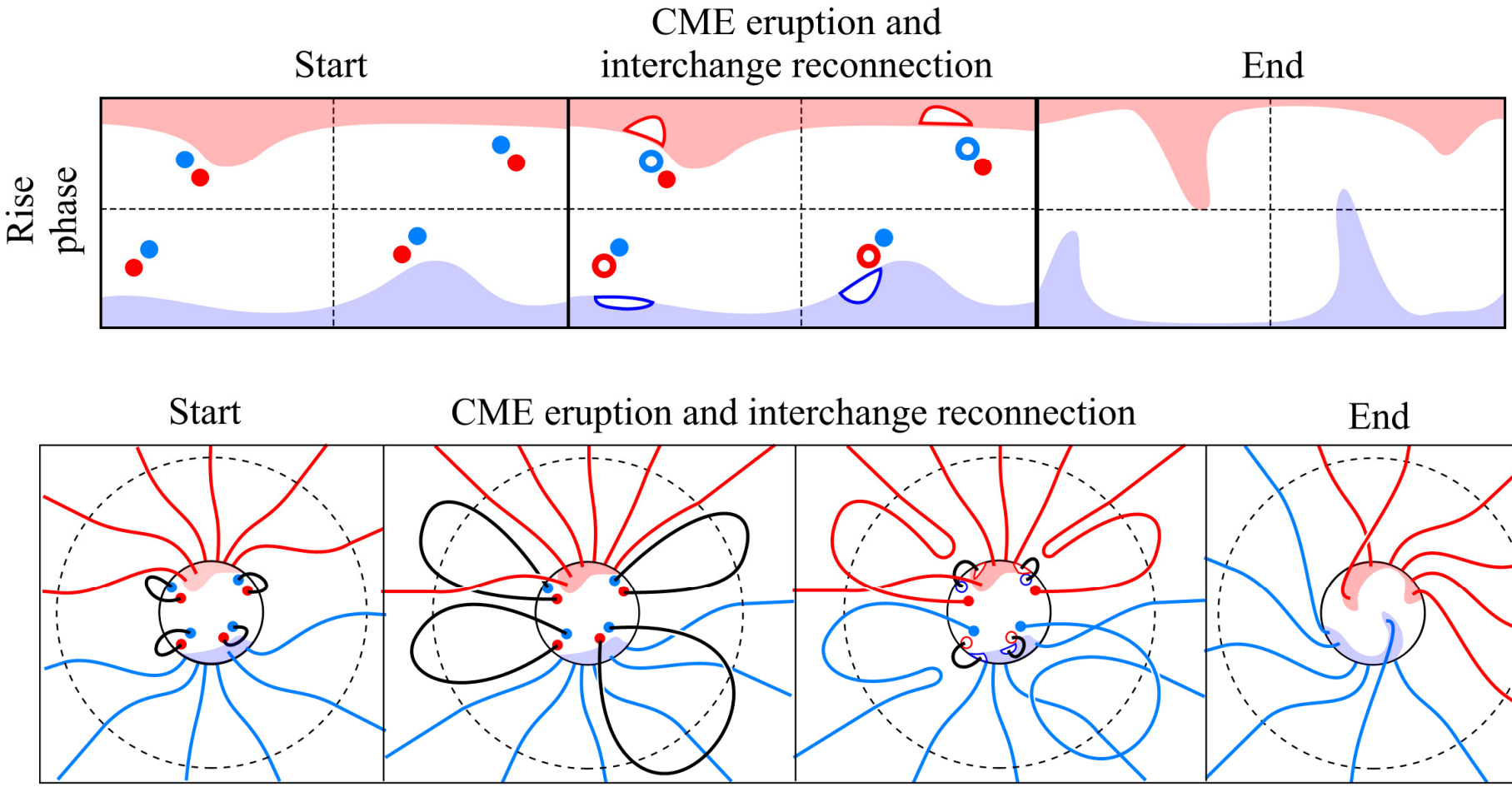
Polarity reversal



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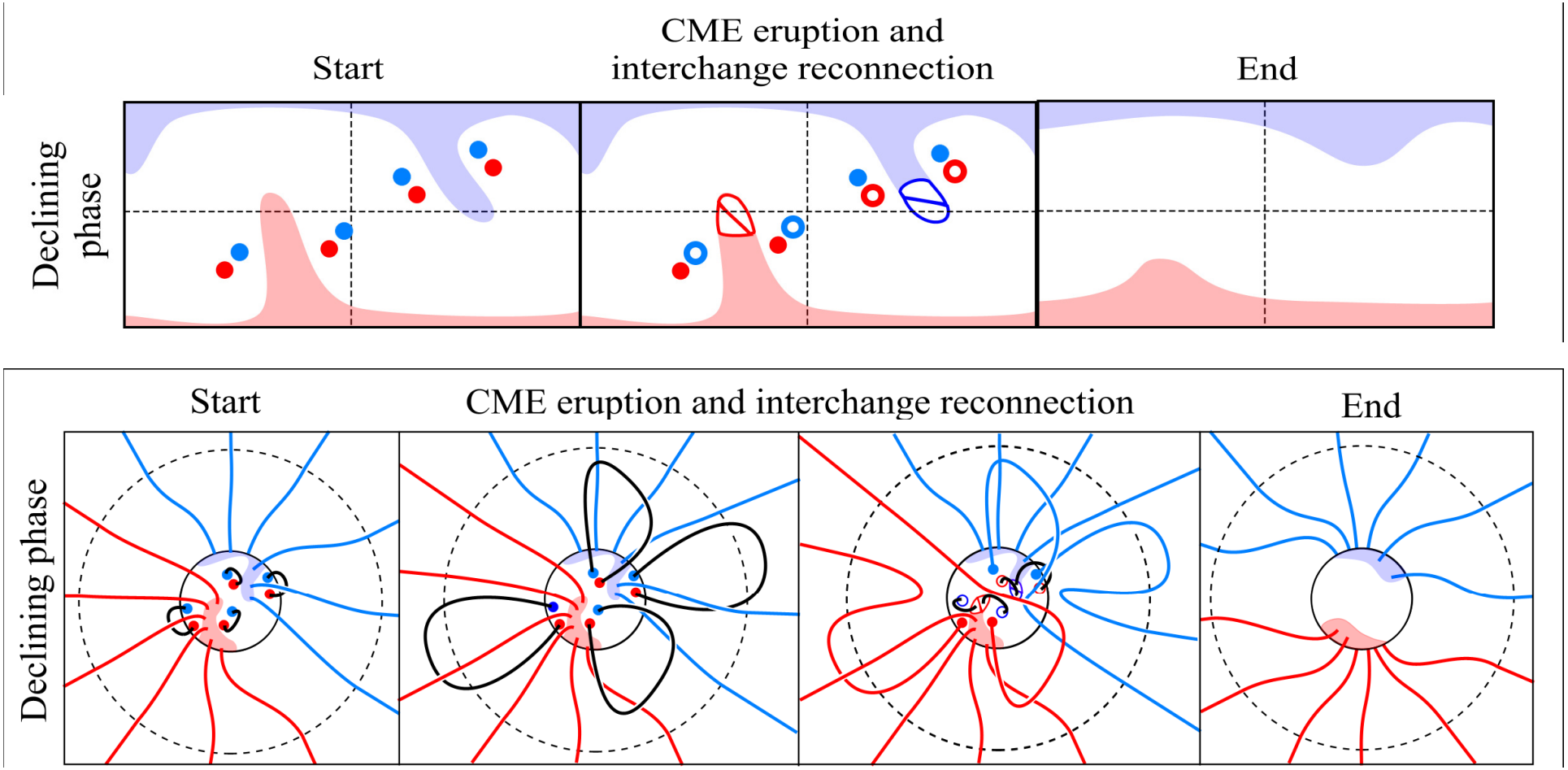
Owens et al, GRL, 2007

Declining phase



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Is there sufficient flux?

- Number of CMEs required to reverse polarity:

$$N = \frac{\Phi_0}{\phi}\frac{180^\circ}{d}$$

- Timescale for such a reversal

$$\tau = \frac{\Phi_0}{f\phi}\frac{180^\circ}{d}$$

$d > 5^o$

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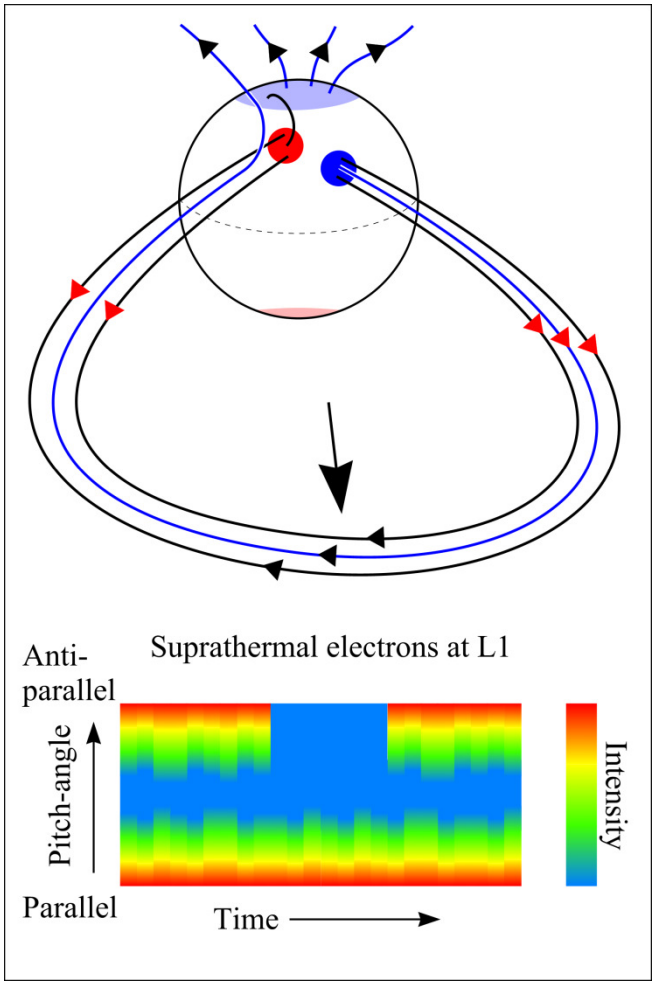
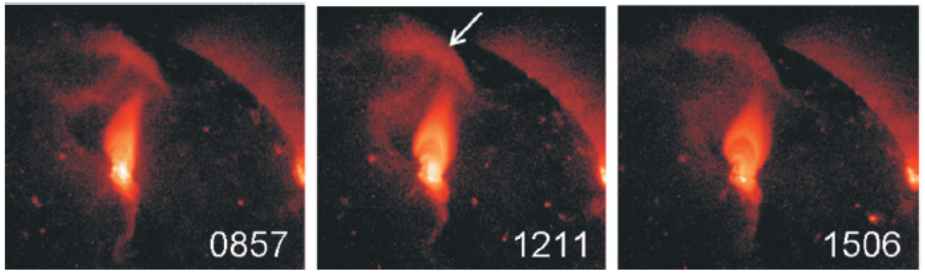
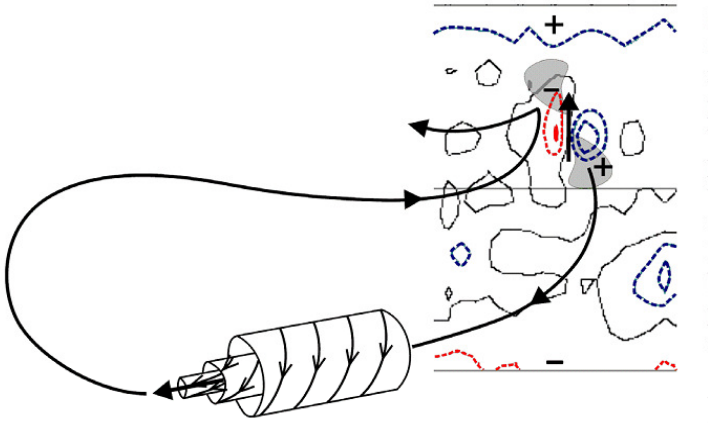
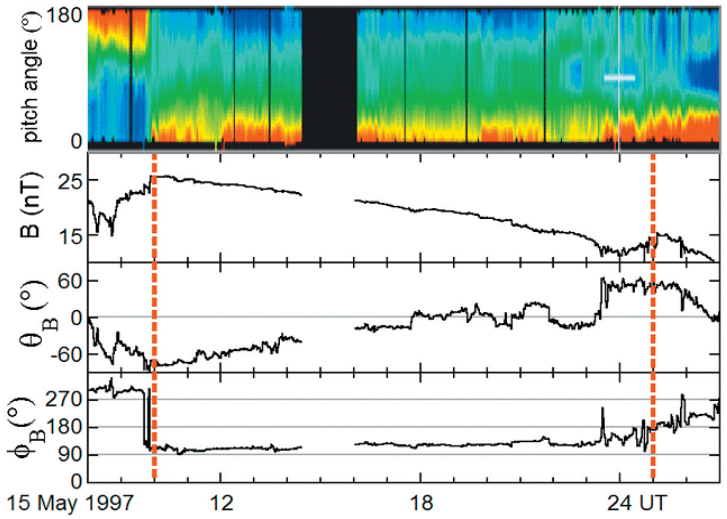
Observations



Owens et al, 2007







Crooker and Webb, 2006

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In summary...

- CMEs add flux to the heliosphere
  - May explain solar cycle variation in |B|
- CME flux removed by opening closed loops
  - Open flux is transported across foot points
- Coronal and heliospheric polarity reversal can be explained in this way

Still to be done

- Better estimates of CME flux content need to combine remote and in situ observations
- Open flux transport by CMEs
  - Identify sources of CMEs and location of reconnection
  - Compare with polarity of open flux in ICMEs
- Look for reconfiguration of closed flux in observations and PFSS solutions

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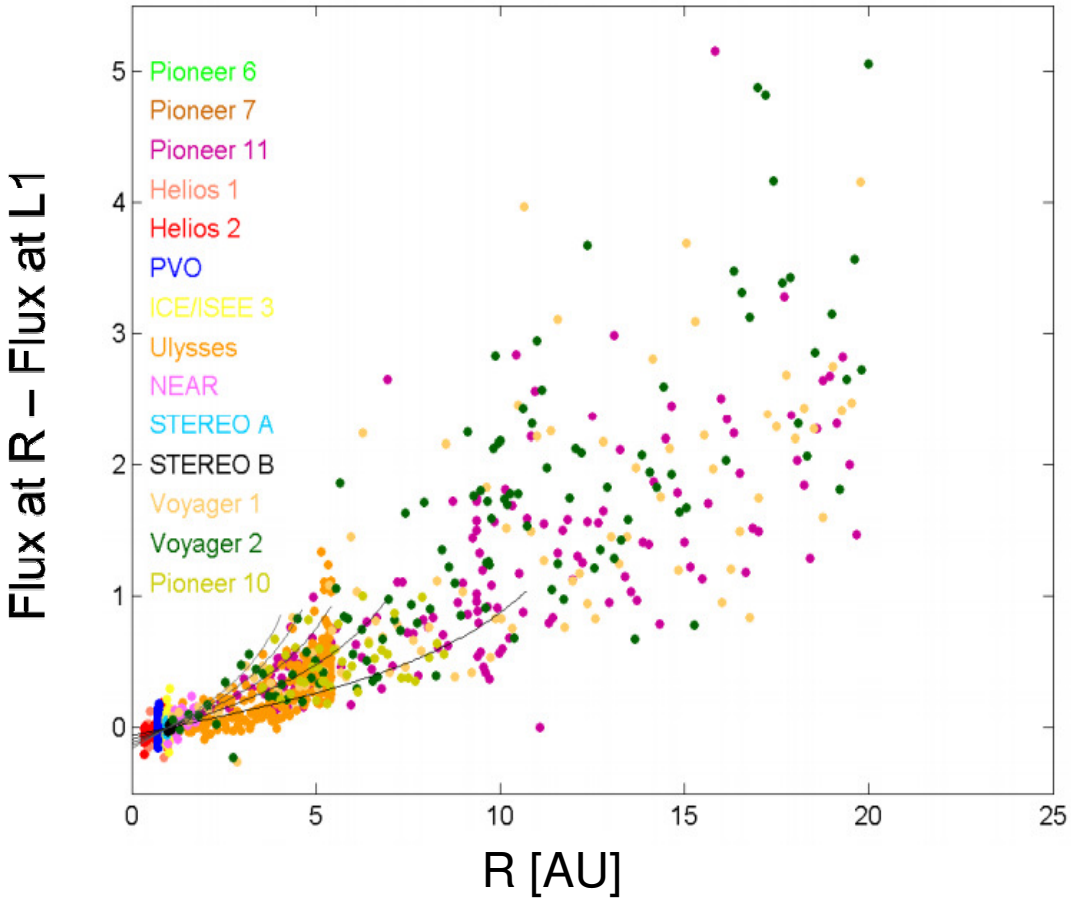
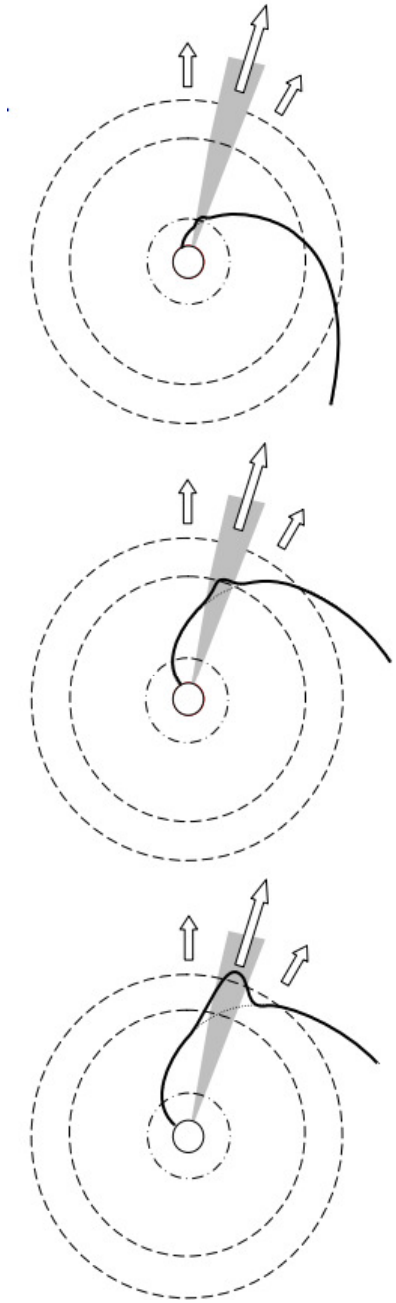
Flux excess





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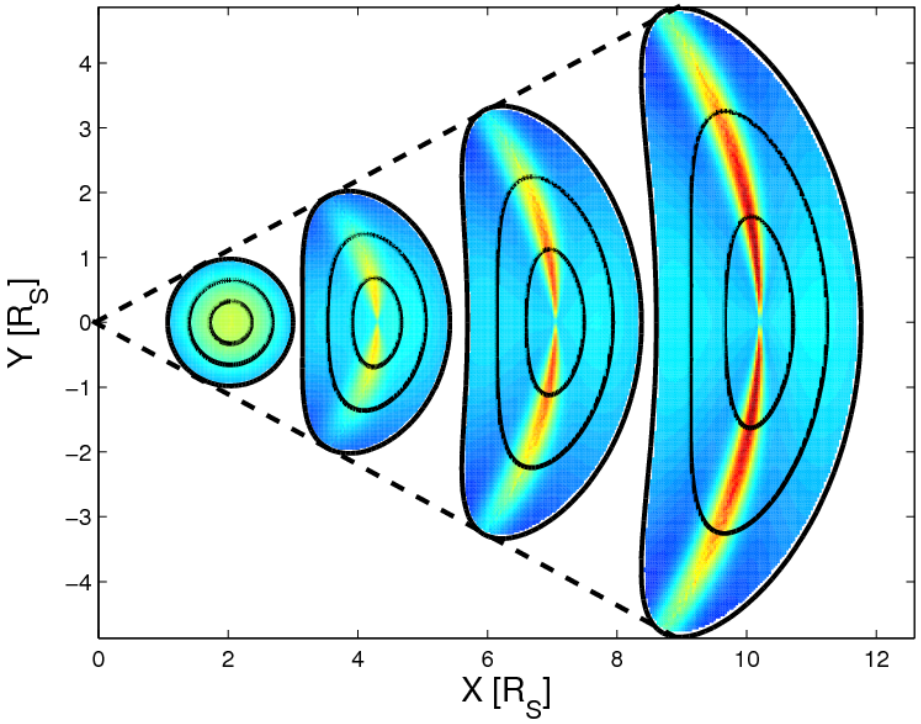
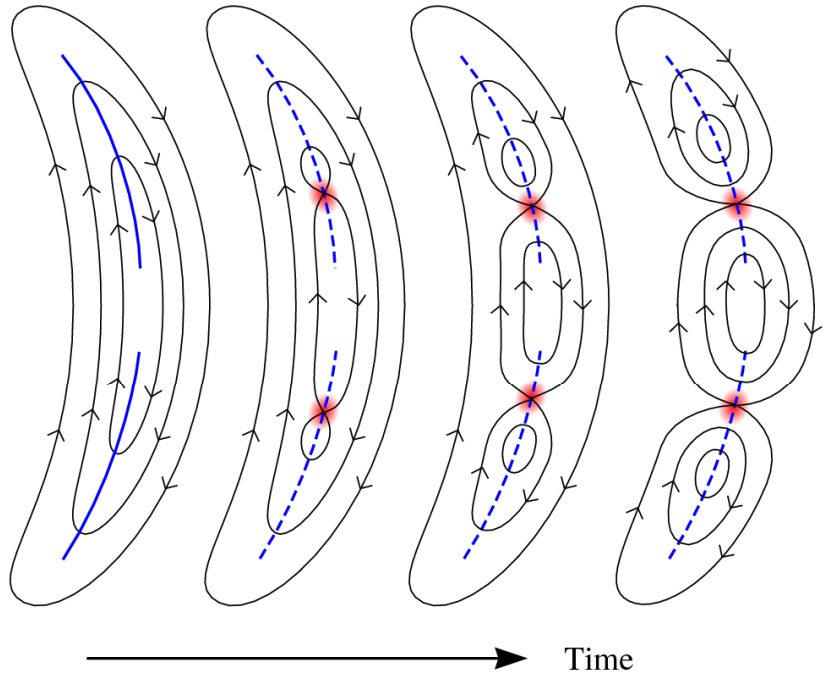
[Lockwood et al., 2009]

Reconnection?





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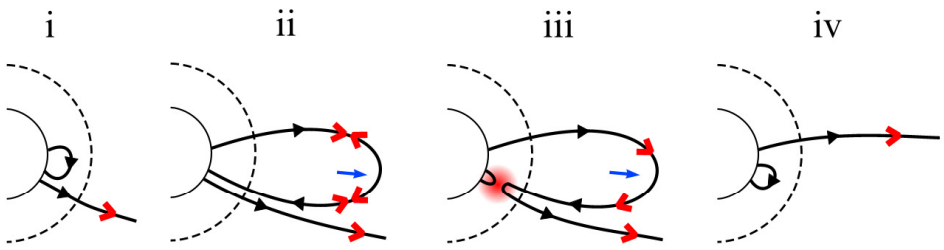
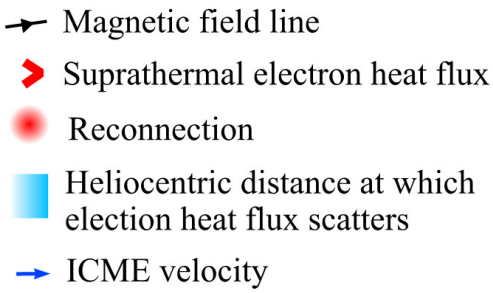
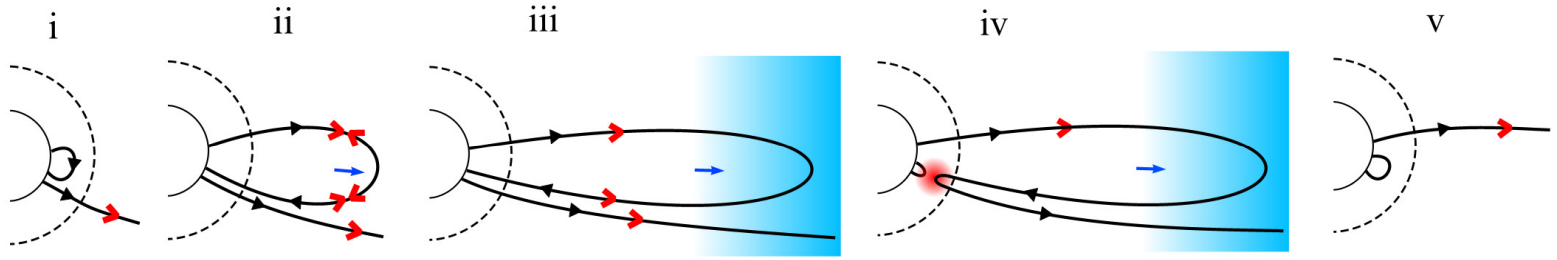
Interchange reconnection

a) Fast ICME flux opening

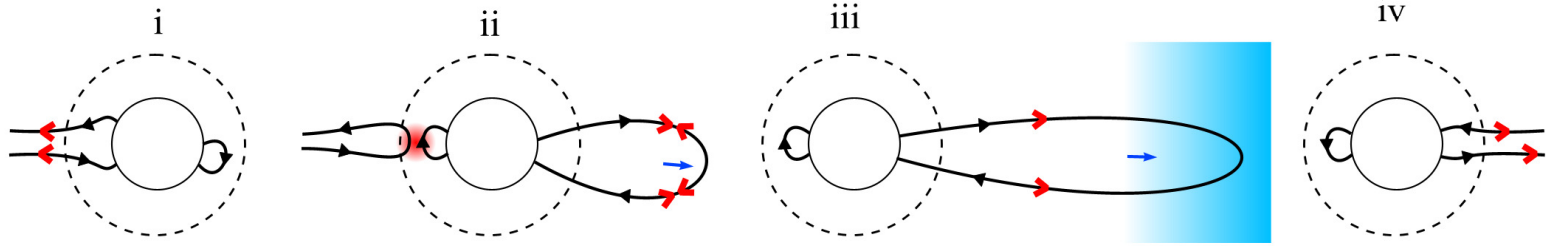




b) Slow ICME flux opening



Disconnection



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