Magnetic *Flux Loss* & *Flux Transport* in a Decaying Active Region

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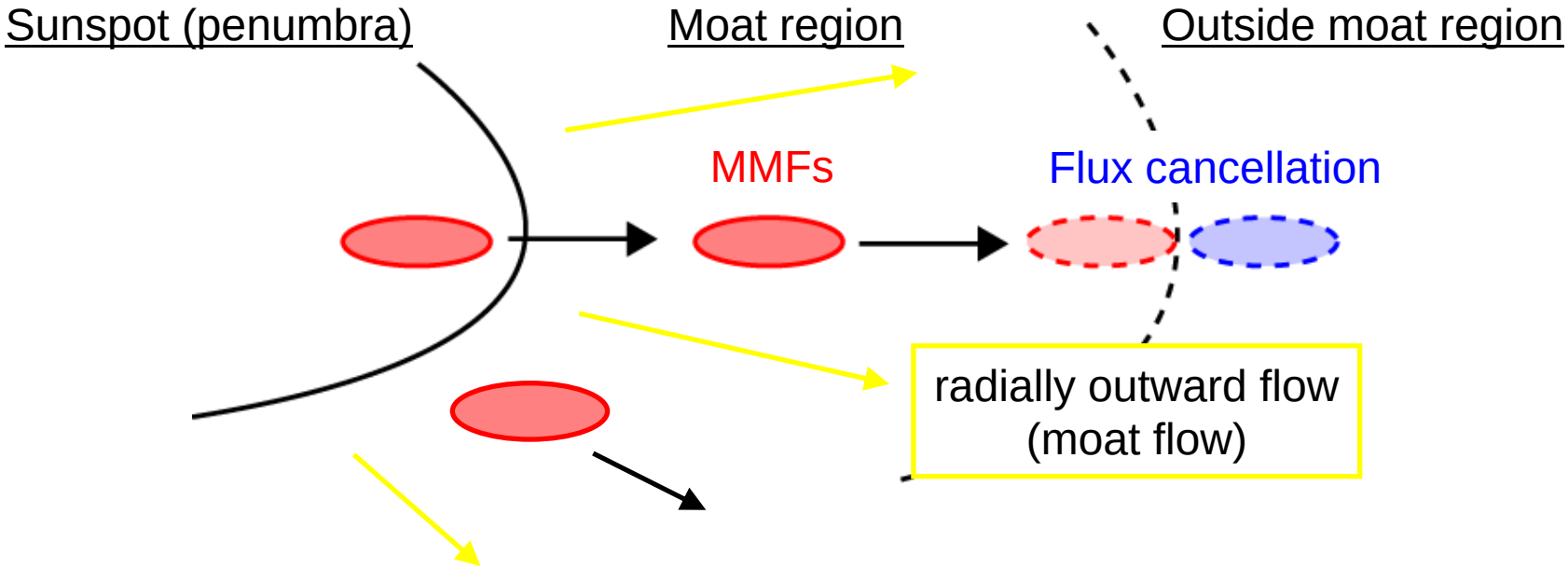
Flux loss of sunspots: How and Where

- Many small magnetic elements move away from sunspots.
  (Moving magnetic features: MMFs, Harvey & Harvey 1973)

  Ground-based observations (Martinez Pillet 2002; Kubo et al. 2007):
  The net magnetic flux carried by all the MMFs exceeds the flux-loss rate of the sunspot.

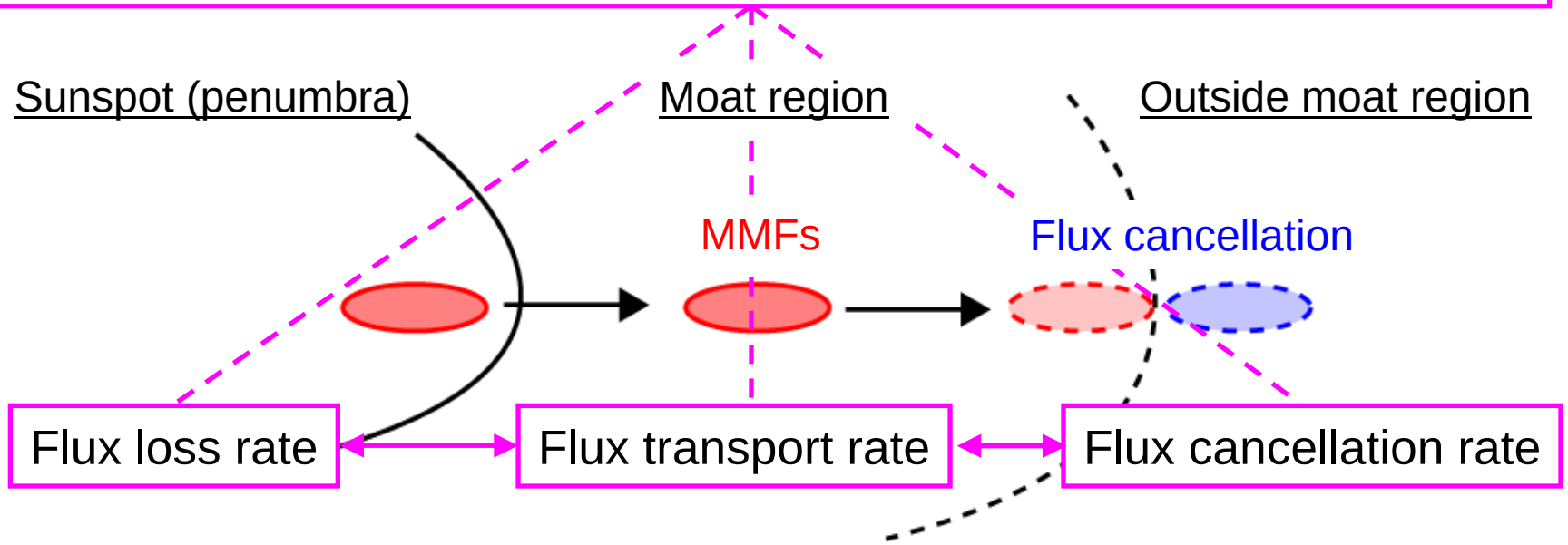
- "Magnetic flux cancellation" (Martin et al. 1985) often occurs around the outer boundary of the moat region.



Flux loss of sunspots: How and Where

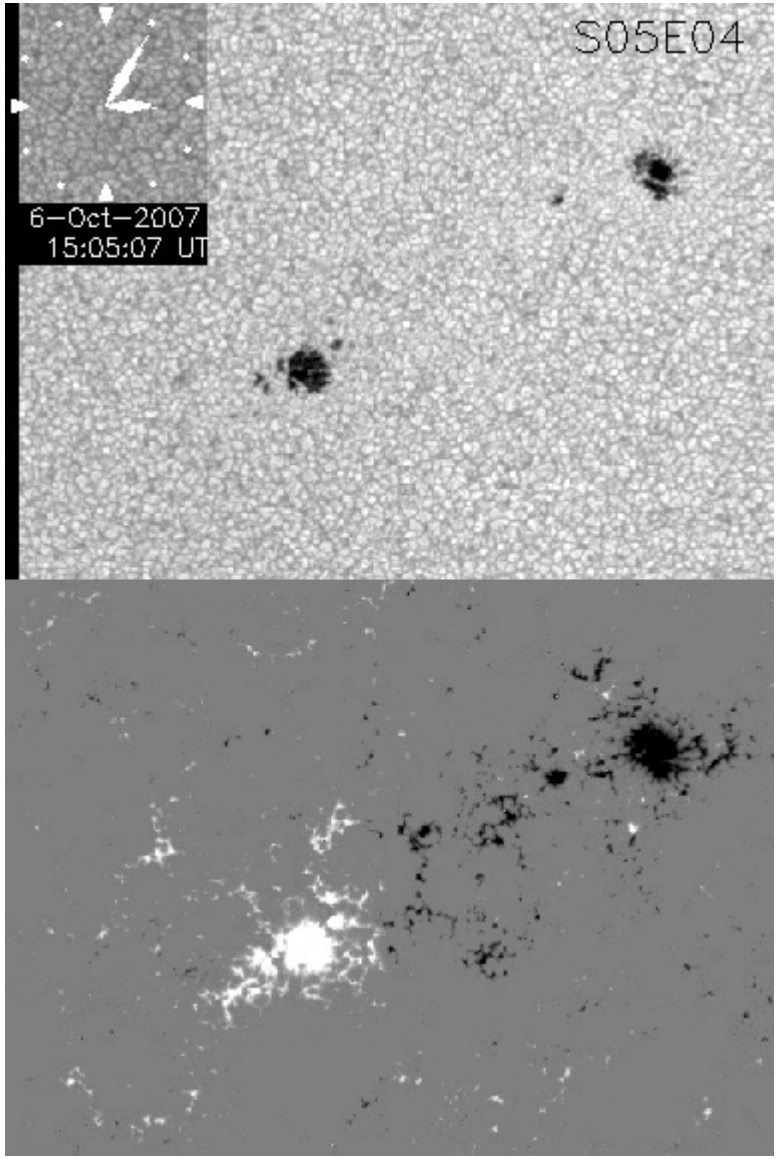
- How much magnetic flux is carried away from the sunspot to the outer boundary of the moat region?
- How much magnetic flux is removed from the photosphere?

Hinode/SOT allows us, for the first time to measure flux change without any effects of atmospheric seeing through a lifetime of (small) sunspots.



Hinode/SOT observation of AR NOAA10972

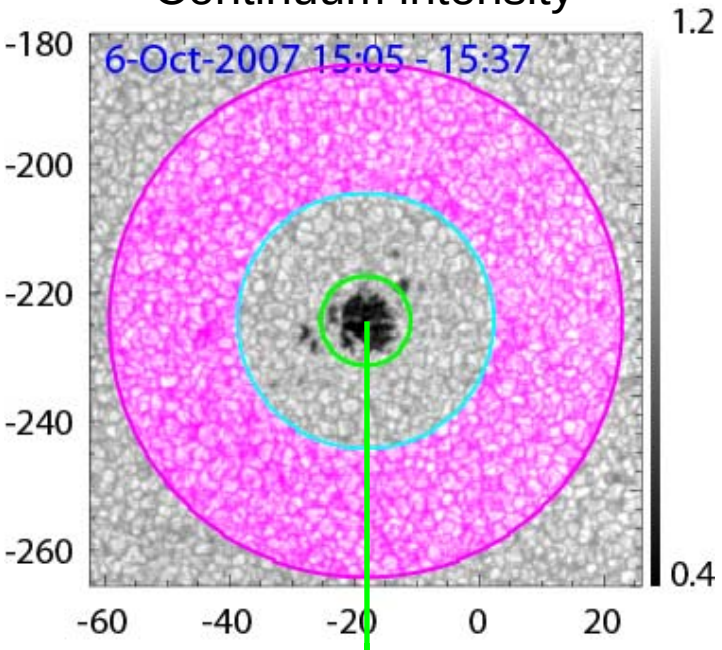
- Small bipolar sunspots almost disappear in two days (6-Oct-2007 ~ 8-Oct-2007).
- Many moving magnetic features are observed around the sunspots.
- Magnetic flux cancellations are observed around the center of the active region.



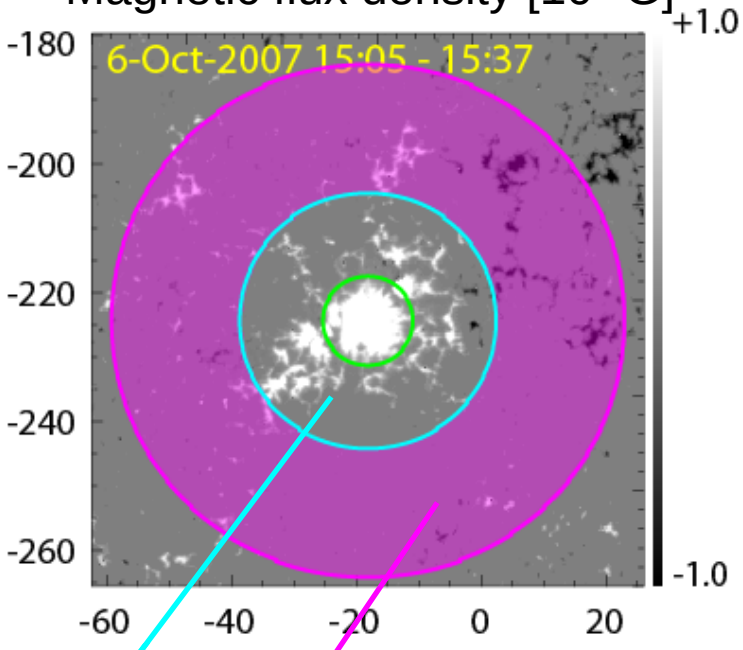
Upper: continuum intensity
Lower: flux density of vertical fields

Following sunspot & moat region→ 3 regions

Continuum intensity



Magnetic flux density [10^3 G]



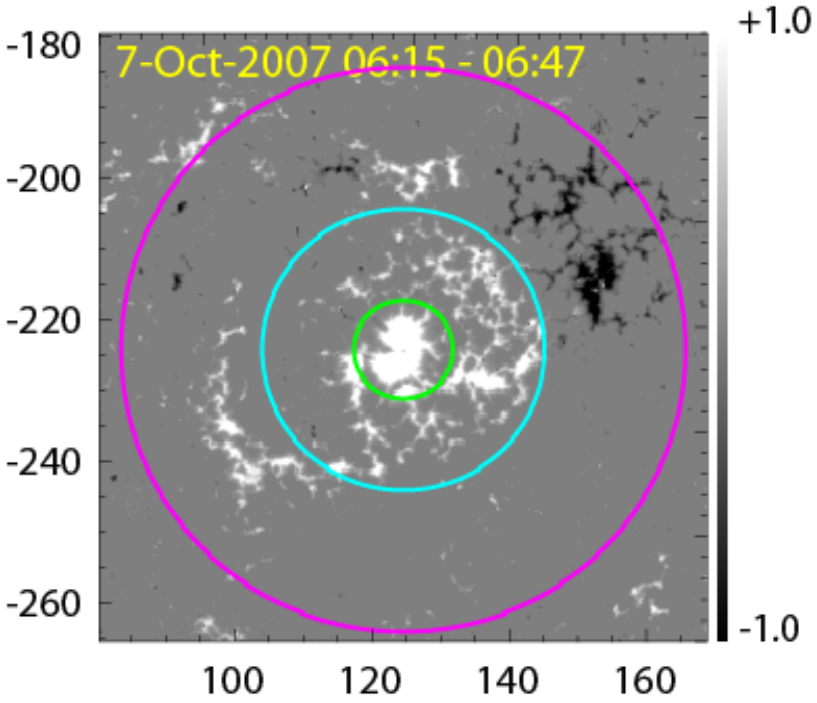
sunspot region: r < 7”

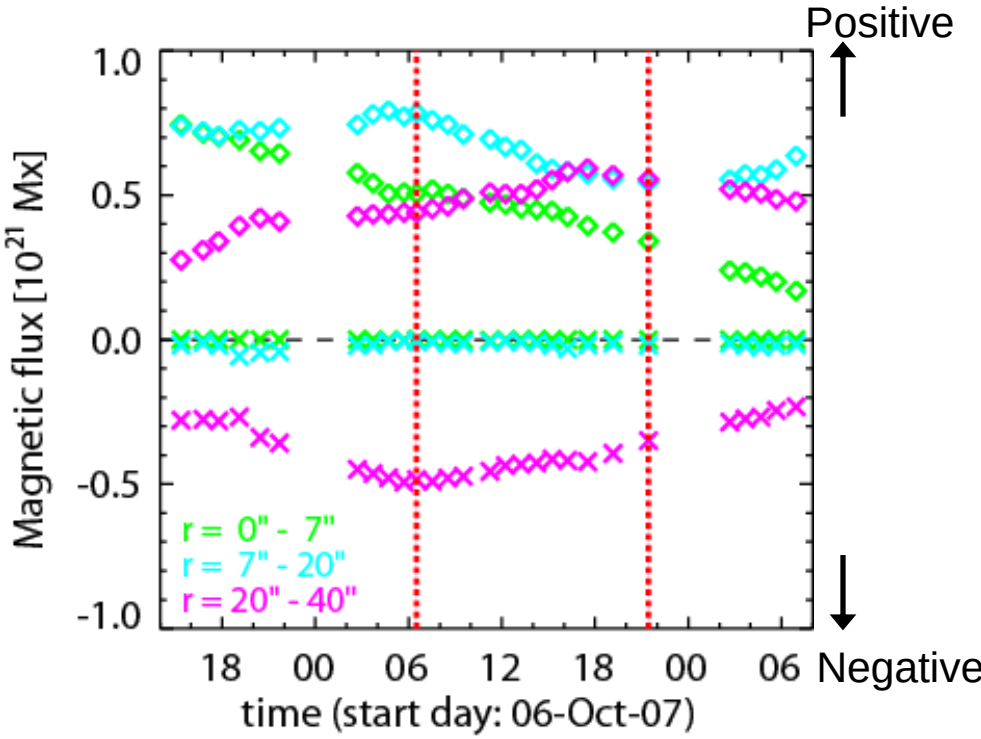
r: radius from the sunspot center

unipolar region: 7” < r < 20”
→ (inner and middle of) moat region

Mixed polarity region: 20” < r < 40”
→ outer boundary of the moat region

Evolution of total magnetic flux





- Magnetic flux normal to the solar surface

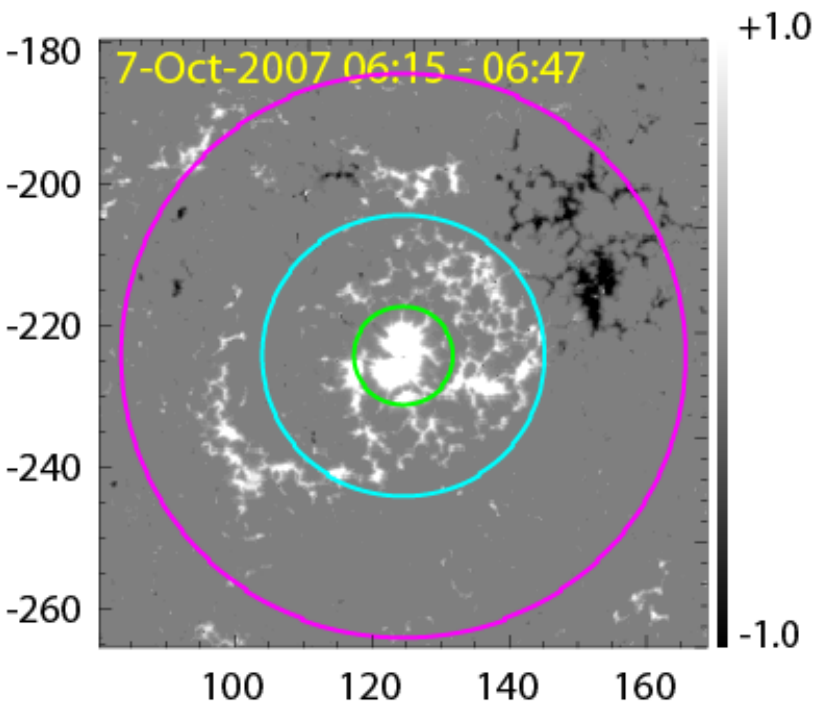
$$F = \sum_{r=r_1}^{r=r_2} \frac{1}{\cos\theta} f \,|B| \cos\gamma$$

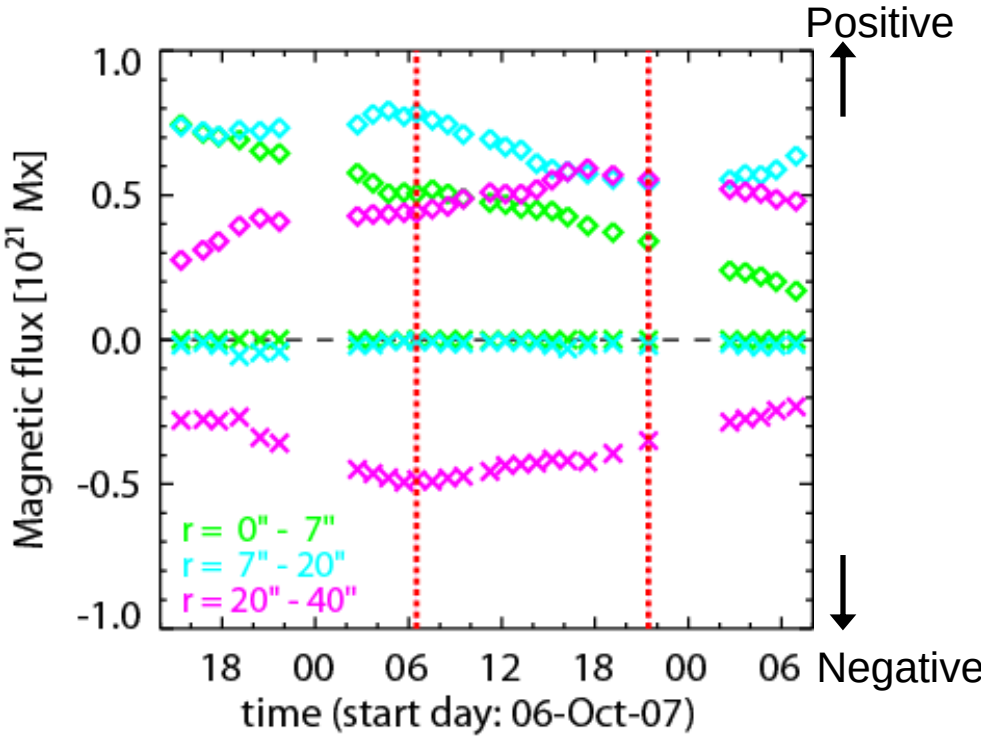
SP observations

θ : heliocentric angle
f : filling factor
B : magnetic field strength
γ : inclination with respect to the local vertical

*Projection effects are corrected.

Evolution of total magnetic flux





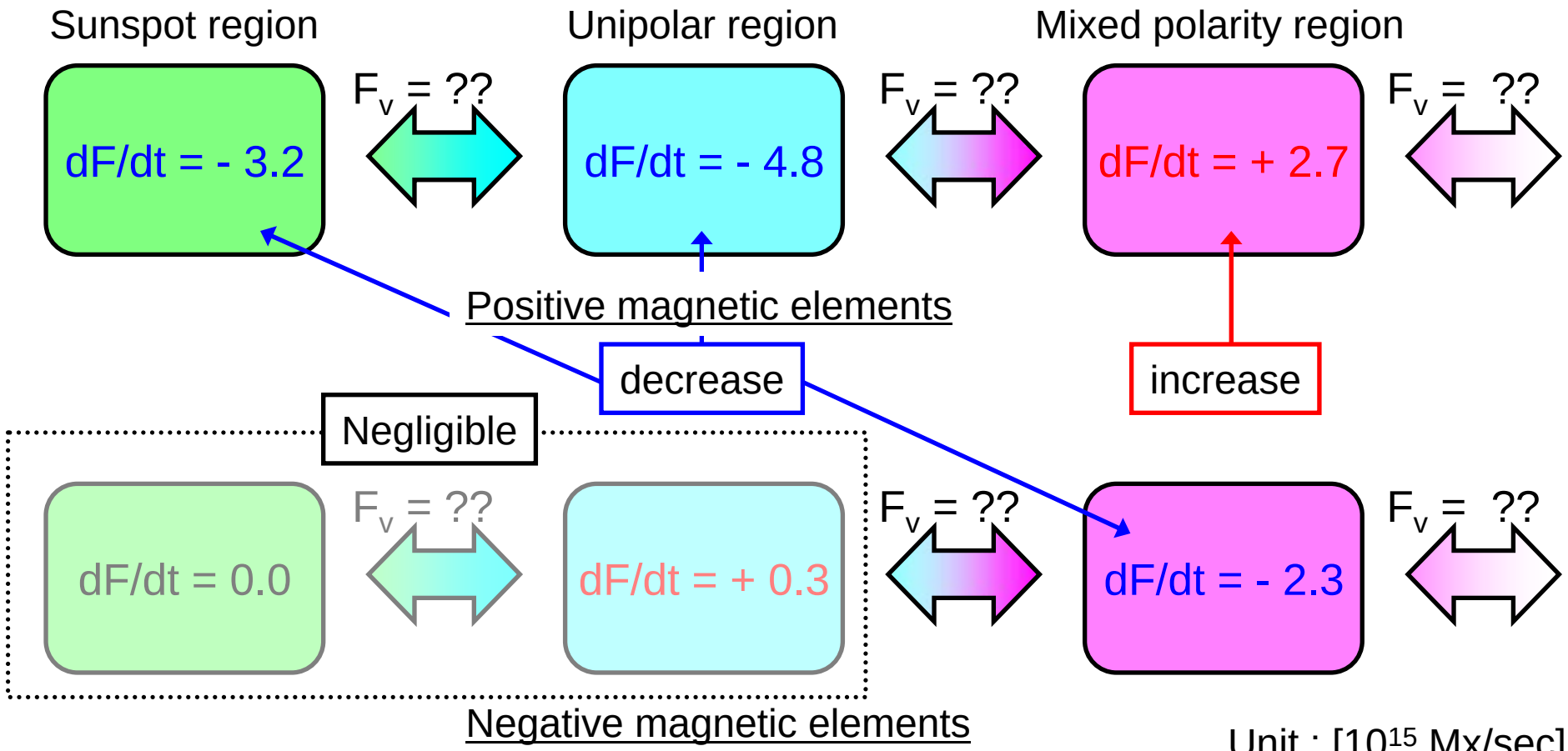
Flux change rates in the period between two red lines (06:15 – 21:26 on Oct 7)

- The sunspot significantly decayed (but still survived).

- No significant flux emergence (form visual inspection)

Flux increase and decrease rates

"dF/dt" is estimated by a linear fit to the flux change from 06:15 to 21:26 on October 7, 2008.



* Negative dF/dt indicates a decrease of magnetic flux for both polarities.

Definition of radial flux transport rate (F_v)

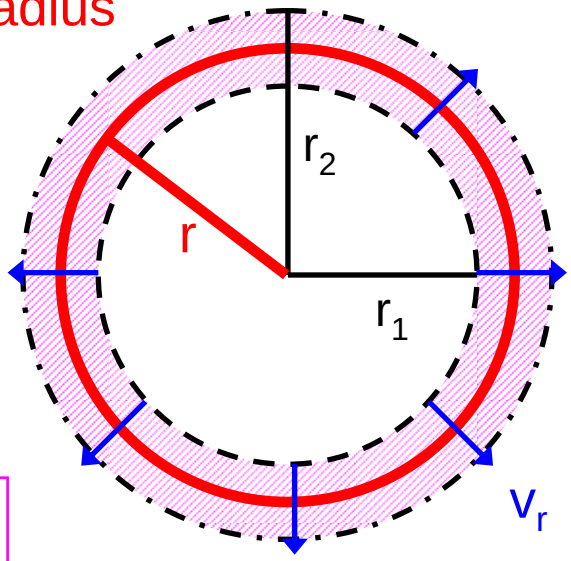
- Magnetic flux passing through the circle with a radius of "r" from the sunspot center per unit time

$$F_v(r) = \sum_{r=r_1}^{r=r_2} 2\pi \left(\frac{r_1 + r_2}{2} \right) v_r(r) \frac{|F(r)|}{\pi(r_2^2 - r_1^2)}$$

[Mx/sec]

Cross-section

Magnetic flux averaged over the region between r_1 and r_2



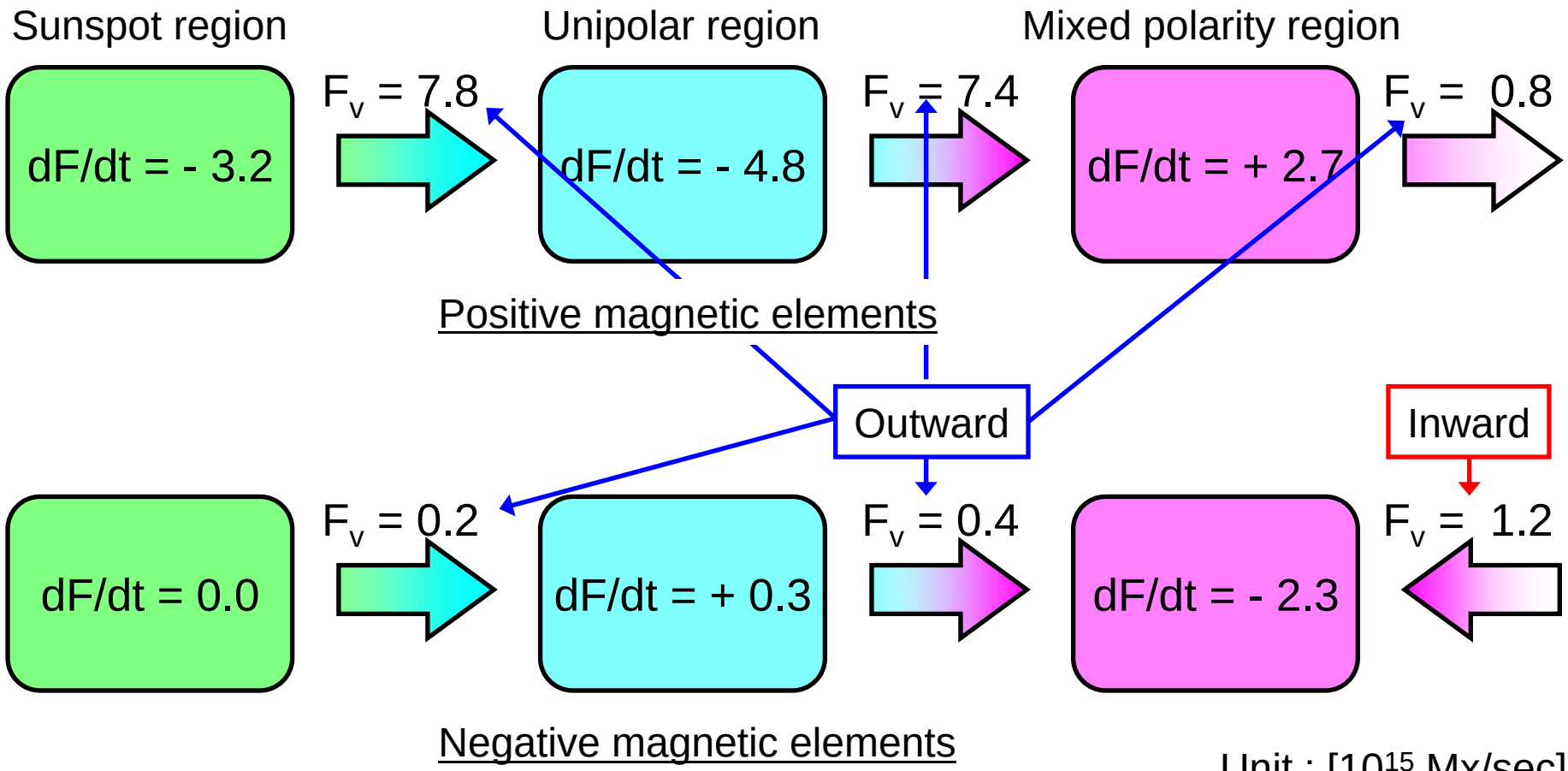
r_1, r_2 : r $\pm$ 1 arcsec

F(r) : Magnetic flux density normal to the solar surface (SP data)

v_r (r): Radial component of horizontal velocity
(The local correlation tracking technique is applied for line-of-sight magnetograms with NFI)

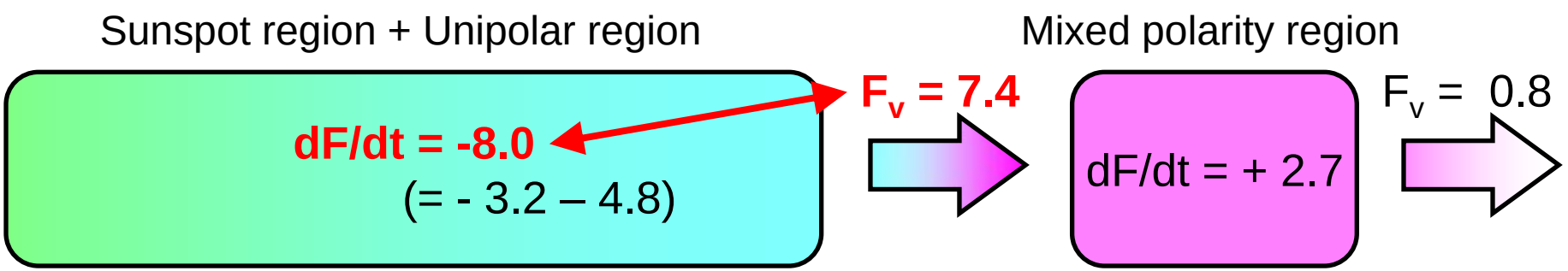
Summary of magnetic flux budget

"F_v" is averaged over the flux transport rates obtained in the same period as "dF/dt".



Unit : [10^{15} Mx/sec]

Flux transport for sunspot's polarity



Positive magnetic elements

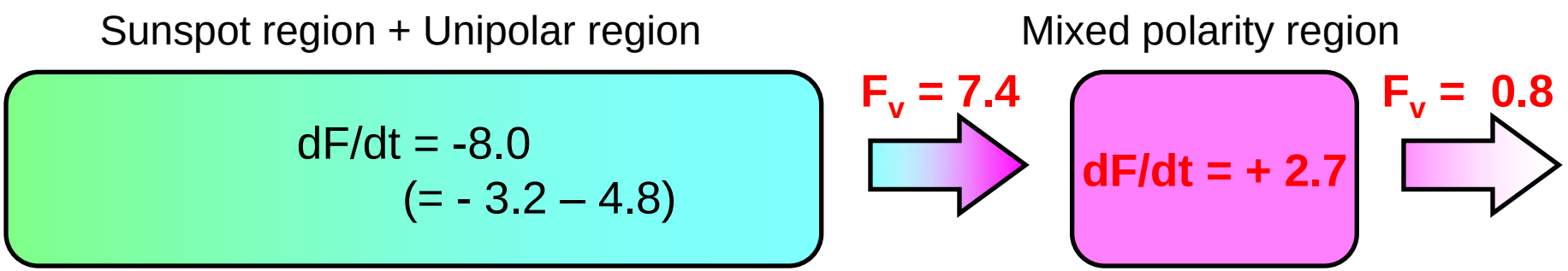
Unit : [10^{15} Mx/sec]

- The total of flux decrease rates in the sunspot and unipolar regions are similar to the flux transport rate at the outer boundary of the unipolar region.

→ **Most of magnetic flux disappeared in the sunspot and the unipolar regions are transported to the mixed polarity region.**

- The transported magnetic flux is larger than the increase of the positive flux in the mixed polarity region and the flux transport rate at its boundary.

Flux transport for sunspot's polarity



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Magnetic flux cancellation at moat boundary

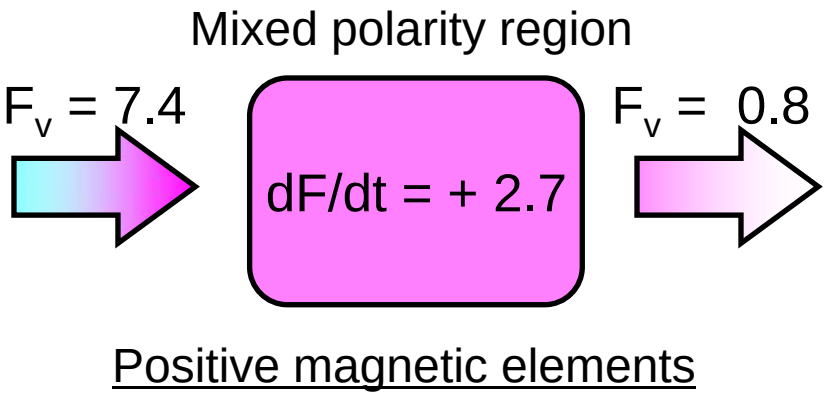
- Magnetic flux loss rate:

$$\left(\frac{dF}{dt}\right)_{Loss} = \left(\frac{dF}{dt}\right)_{Emerge} - \left(\frac{dF}{dt}\right)_{Obs} \pm (F_v)_{Obs}$$

Observations

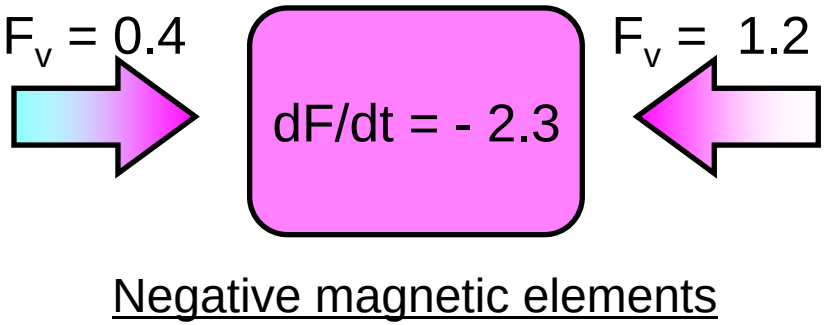
- Positive: **3.9** [= -2.7 + 7.4 - 0.8] x 10^{15}

- Negative: **3.9** [= -(-2.3) + 0.4 + 1.2] x 10^{15}



The flux loss rates of positive and negative elements balance each other in the mixed polarity region

→ **Magnetic flux cancellation!**

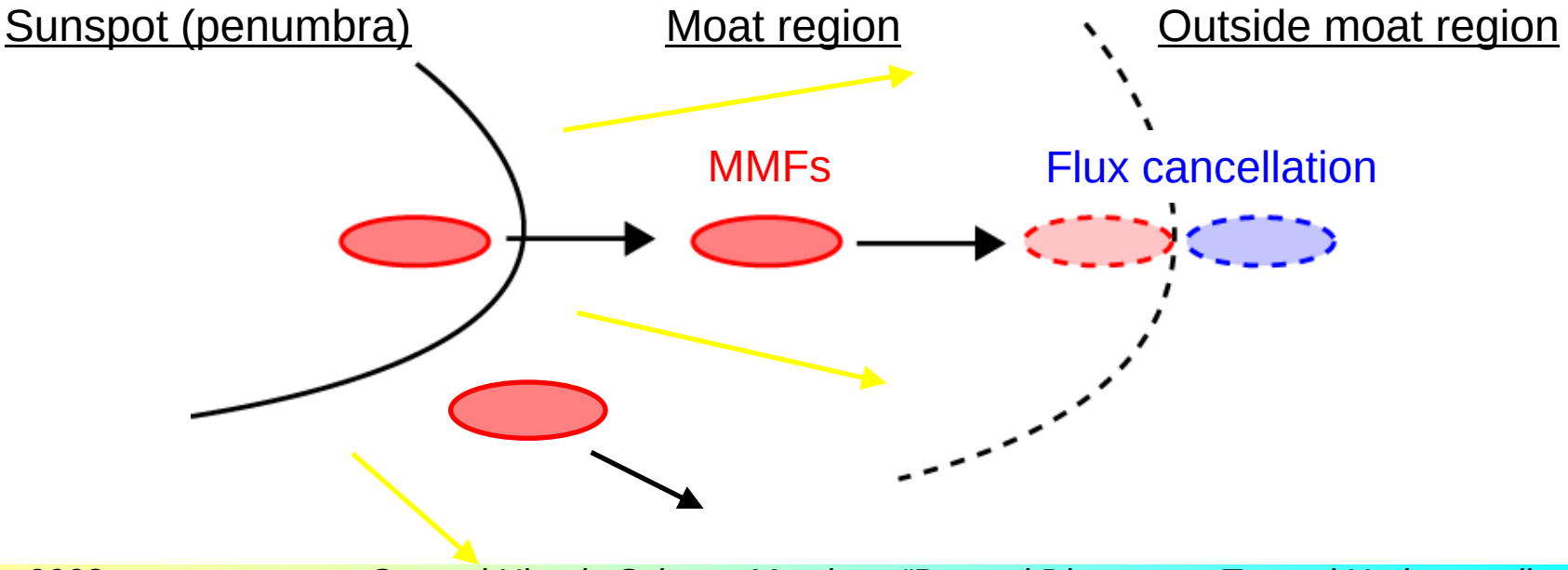


Unit : [10^{15} Mx/sec]

Conclusions

- Most of the magnetic flux removed from the sunspot (and inner moat region) is transported to the outer boundary of the moat region as moving magnetic features.

- The transported magnetic flux is removed from the photosphere by the flux cancellation at the outer boundary of the moat region.



Thank you!

Horizontal velocity

- A local correlation tracking (LCT) method for line-of-sight magnetograms

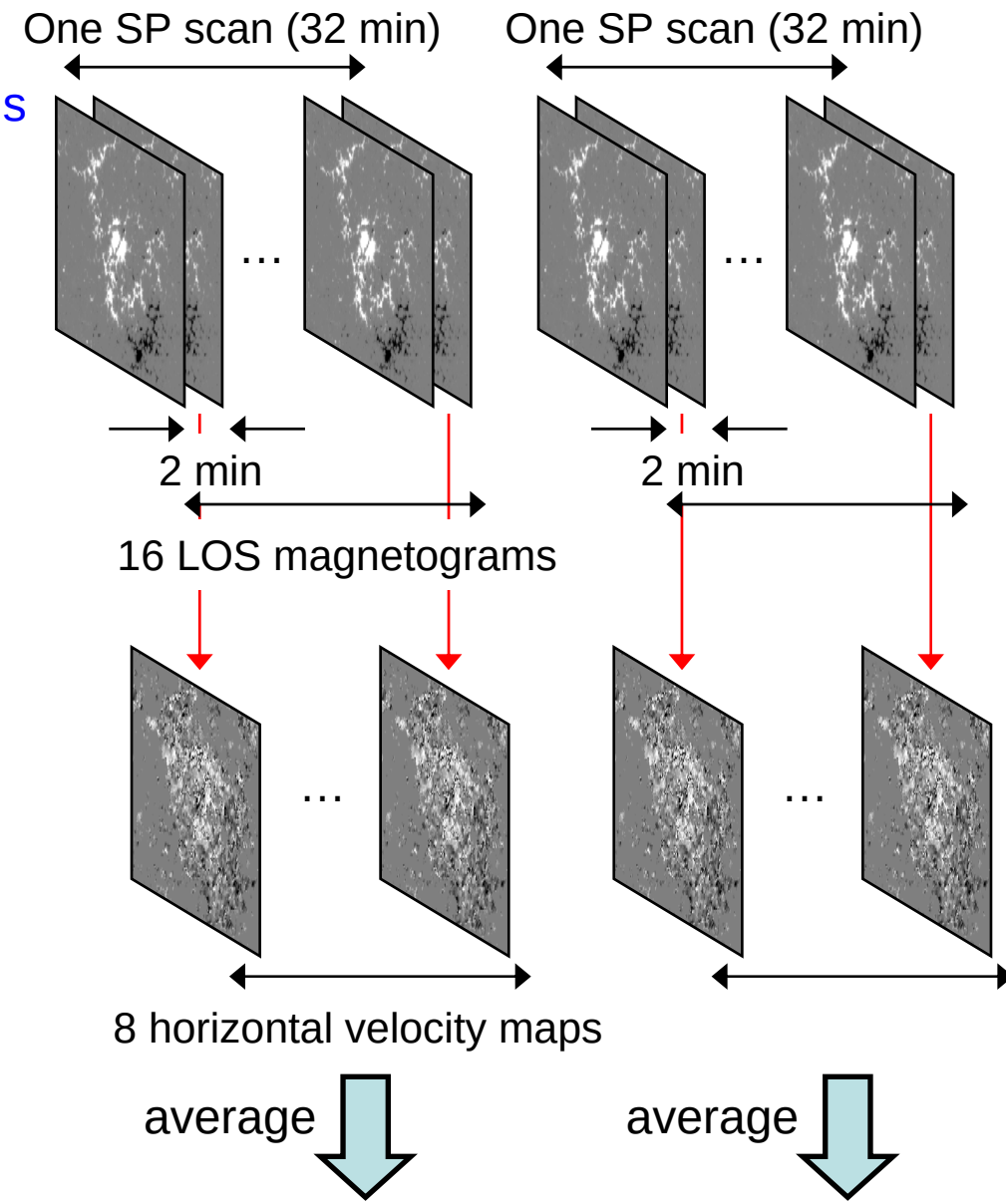
  - Na IV observations with NFI (2min cadence)

  - Apodization window:
    Gaussian with 1” FWHM

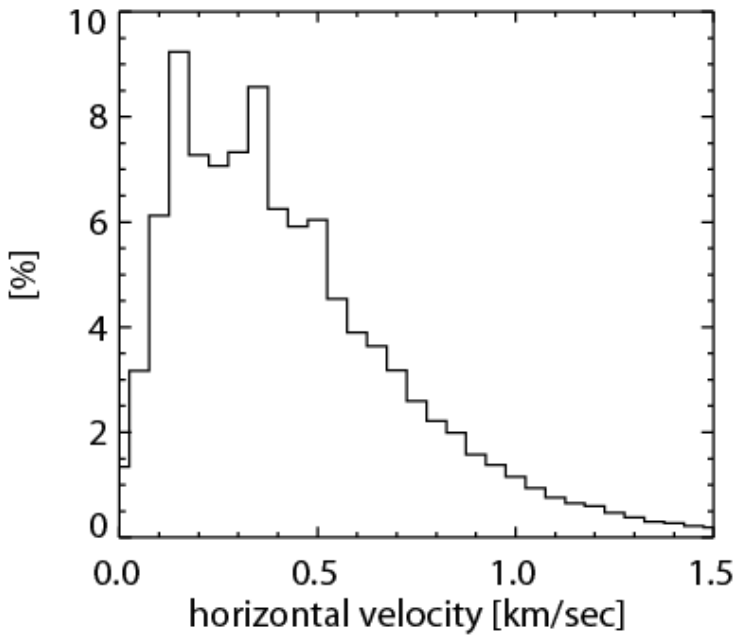
    Stokes V/I signal >0.0015

    Cross-correlation coefficient > 0.9

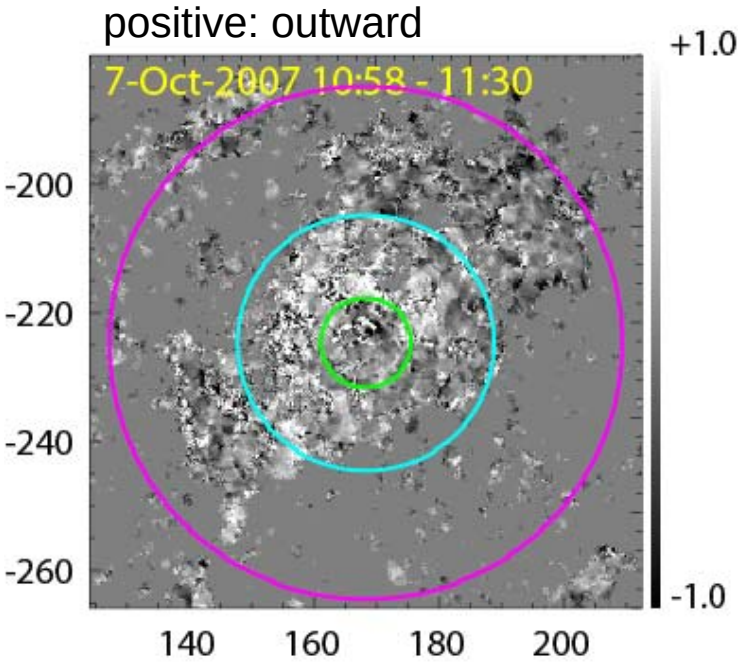
  - Averaged over horizontal velocity maps obtained during each SP scan (8 velocity maps).



Horizontal velocity (cont.)



Histogram of horizontal velocity in the unipolar region



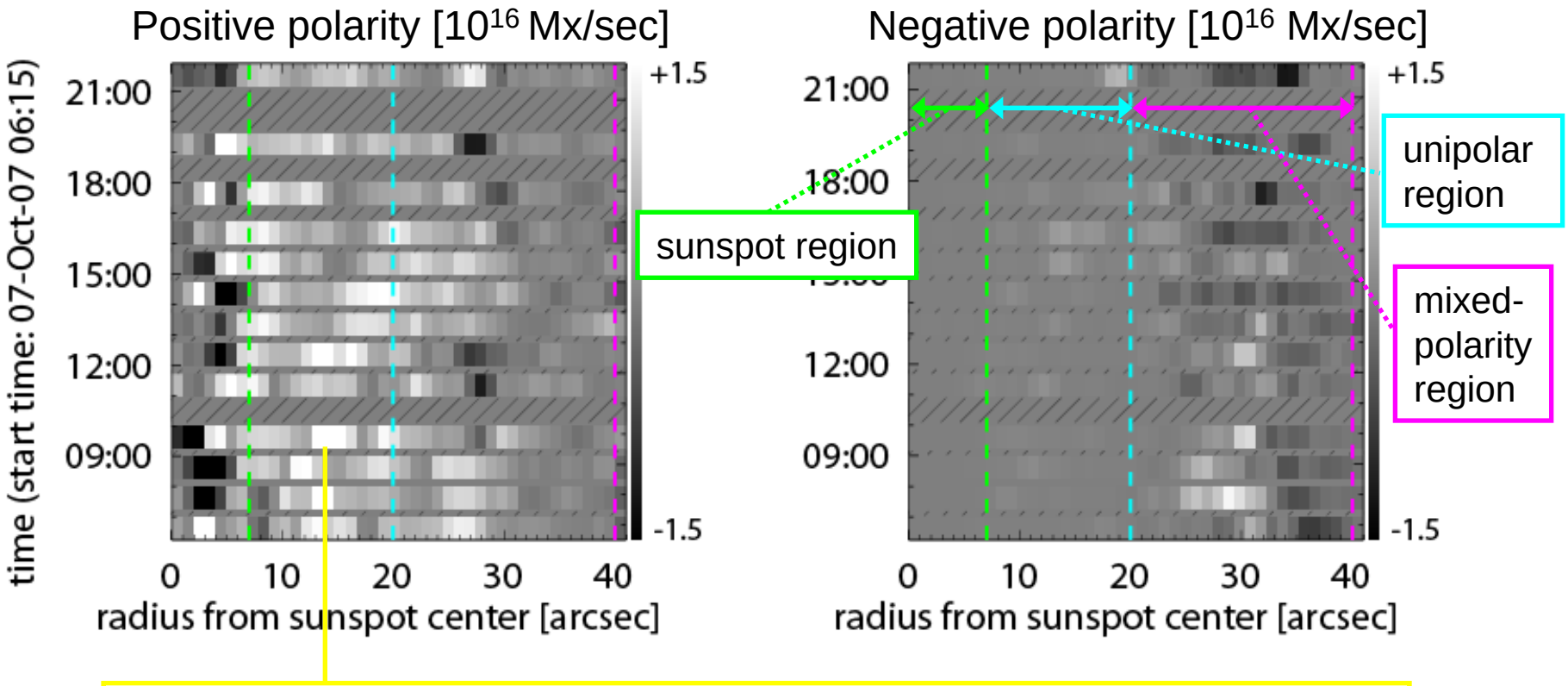
An example for radial component of horizontal velocity [km/sec]

The averaged horizontal velocity in the unipolar region is 0.5 km/sec.

→ This is similar to averaged speed of MMFs and moat flow in previous works.

Flux transport rate [$F_v(r)$] vs. Time

* The positive Fv (r) indicates magnetic flux moves radially outward for both polarities.



Outward motion of positive magnetic flux in the unipolar region

Outward motions of moving magnetic features

Flux transport rate [$F_v(r)$] vs. Time

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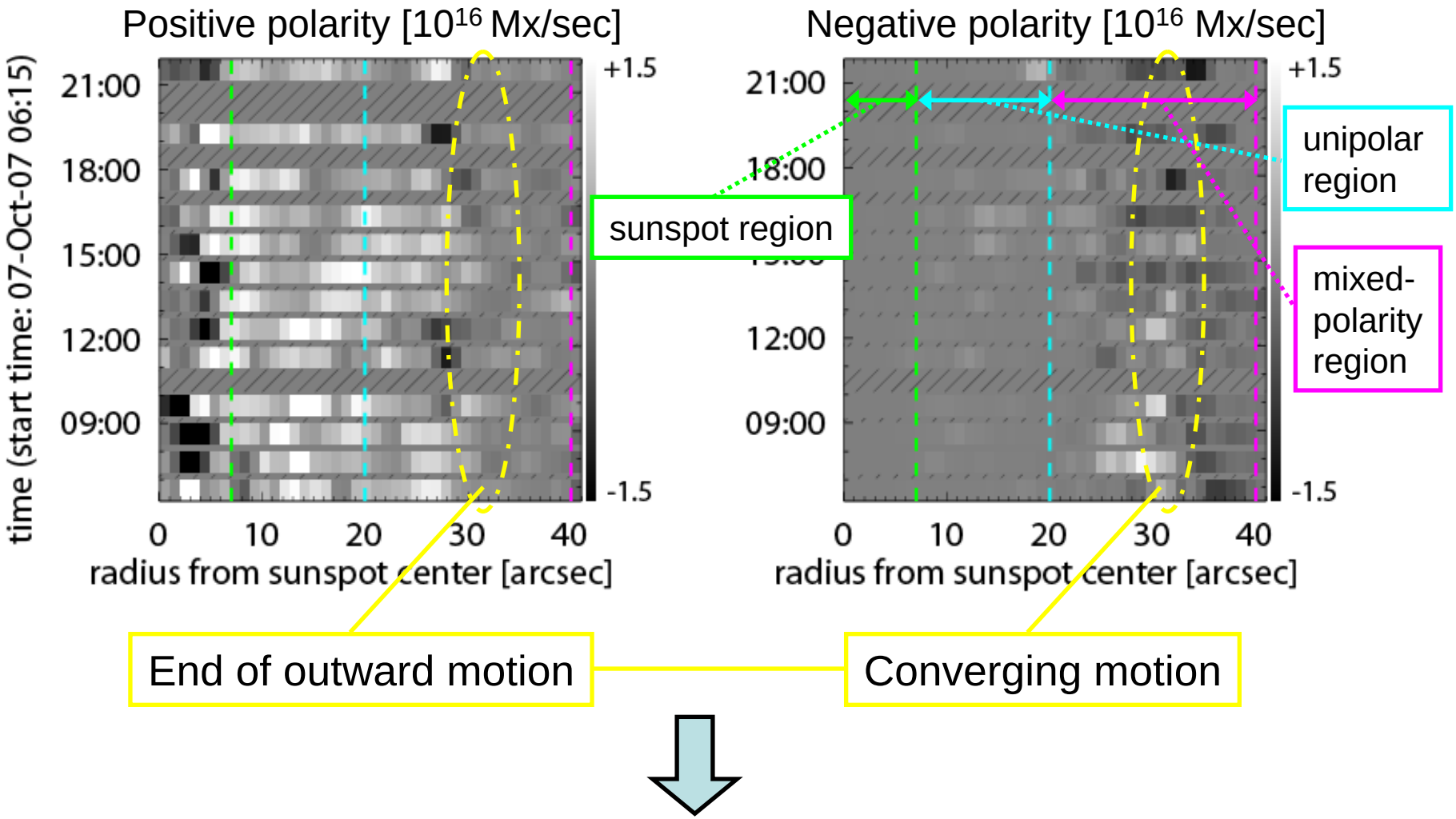
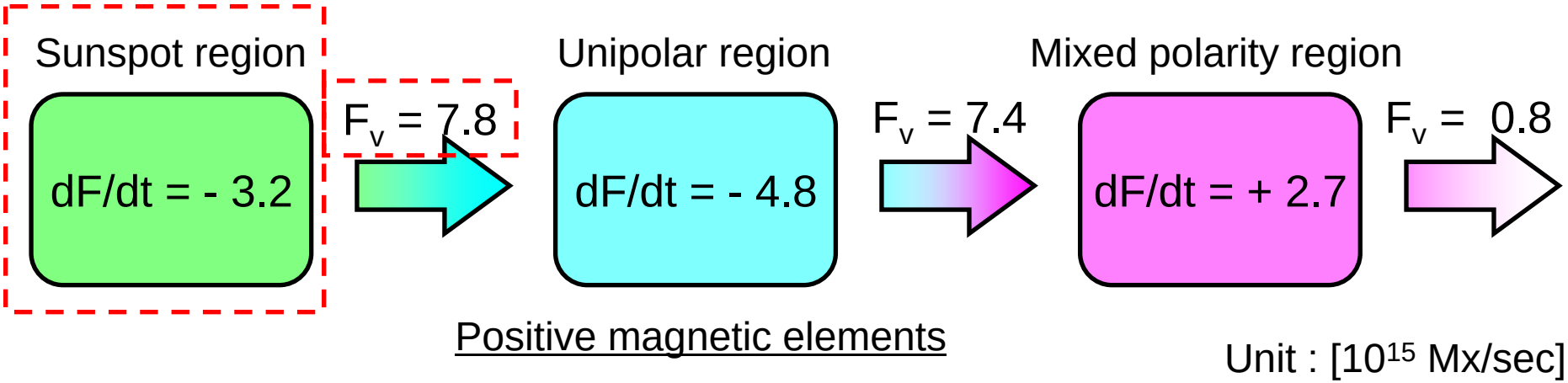


The outer boundary of the moat region is ~ 30” from the sunspot center

Overestimation of flux transport at sunspot boundary

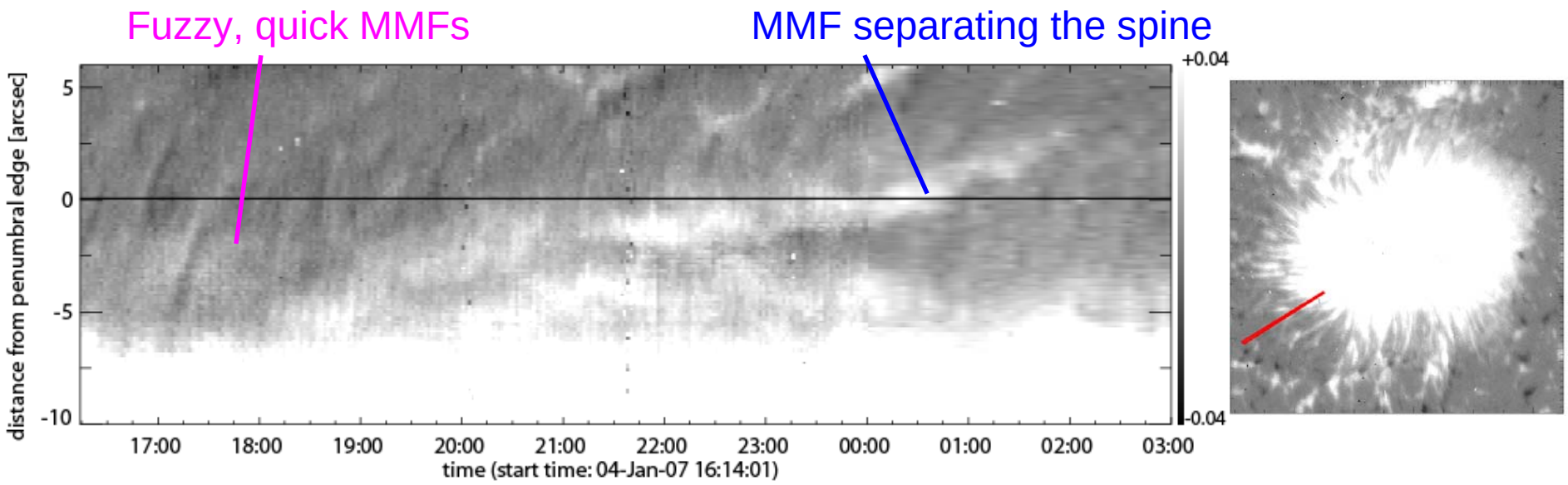


- The positive flux carried away from the sunspot region is bigger than decrease of the positive flux in the sunspot region.

  → The flux transport rate is overestimated at the outer boundary of the sunspot.

- This tendency was also reported in the previous work with lower (1”) spatial resolution (Kubo et al. 2007).

Fuzzy, quick moving magnetic elements



Space vs. time plot along the red line for line-of-sight magnetic field (V/I)

Flux transport rate at the outer boundary of the sunspot:

- Magnetic flux: MMFs with small horizontal velocity and large magnetic flux

- Horizontal velocity: Fuzzy magnetic elements with large outward motions

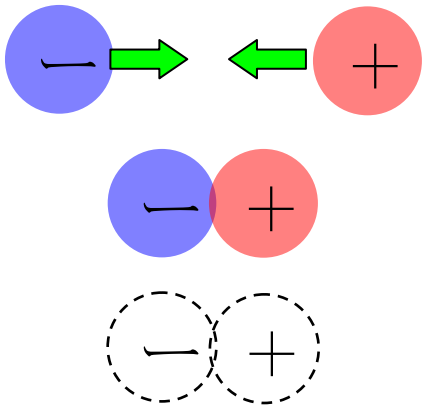
(Apodization window is gaussian with 1” FWHM in the LCT)

Magnetic flux "cancellation"

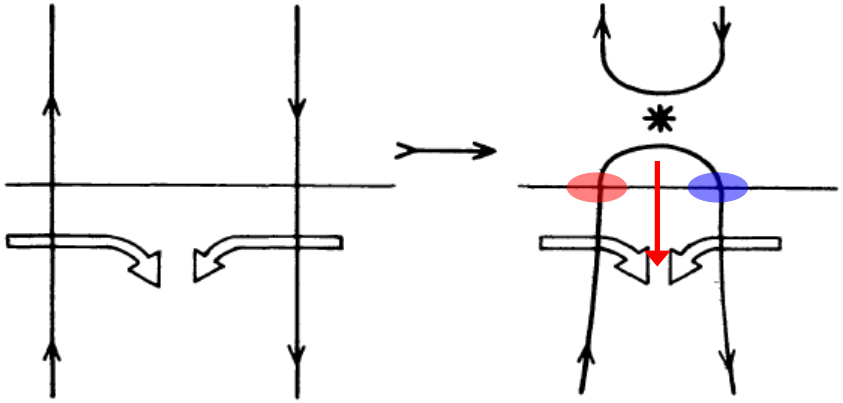
- One magnetic polarity element collides with another polarity element.

  → Disappearance of the magnetic elements

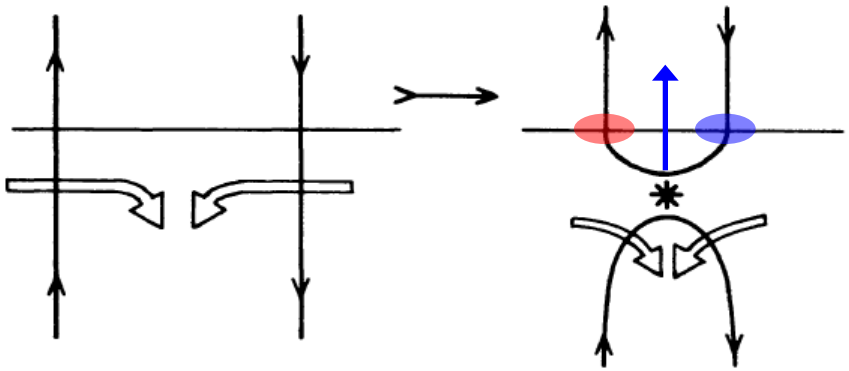
- The outer boundary of the moat region is one of major cancellation sites.
  (Martin, Livi, & Wang 1985; Yurchyshyn & Wang 2001; Chae et al. 2004; Bellot Rubio & Beck 2005)



Submerging Omega-loop



Emerging U-loop



Zwaan 1987