



# Active region emergence and its effect on the solar corona



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Thanks

- George Fisher (UCB)
- Alex Pevtsov (NSO)

- Isaac Klapper
  - B. Ravindra\*
  - Brian Welsch§
- } MSU

Dec. 2, 2008  
Bangalore, India

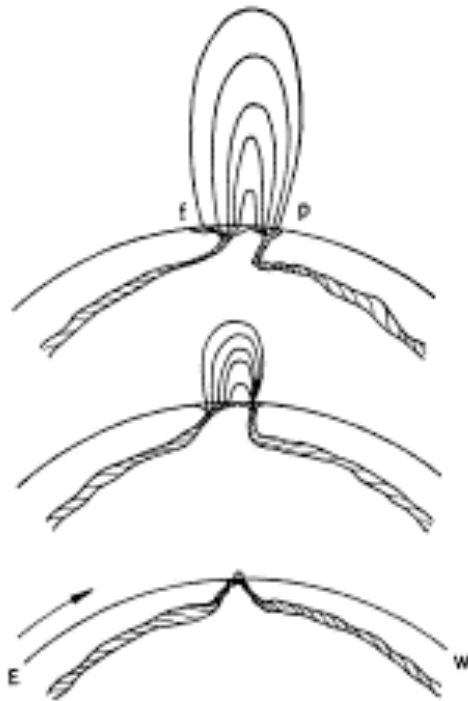
\* Presently IIA

§ Presently UCB

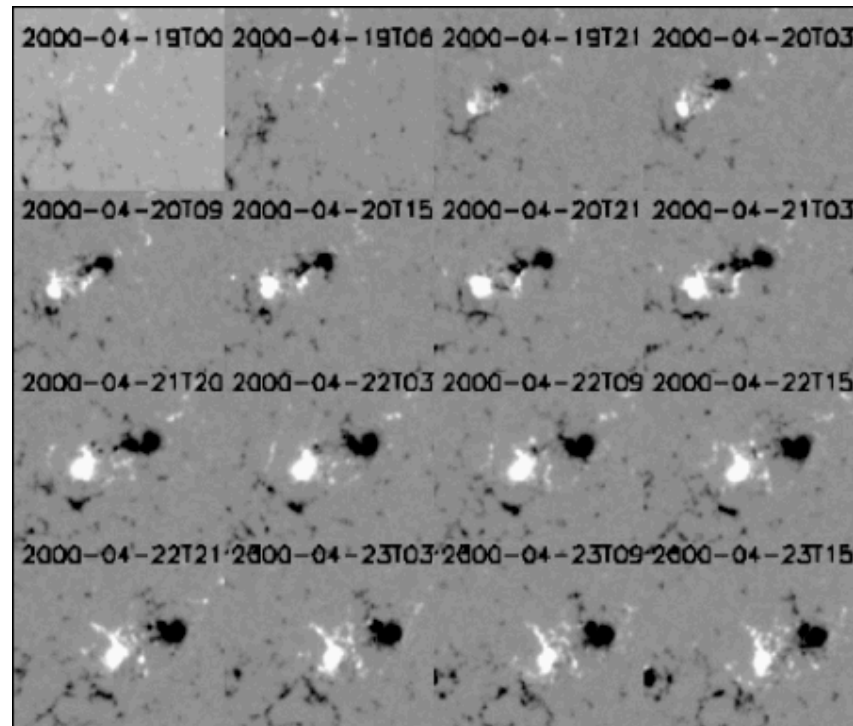
# Active regions: where they come from

Typical AR:  
8968

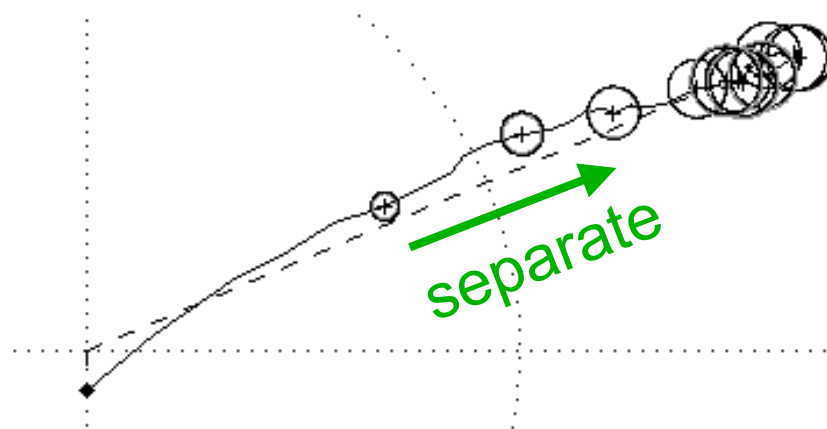
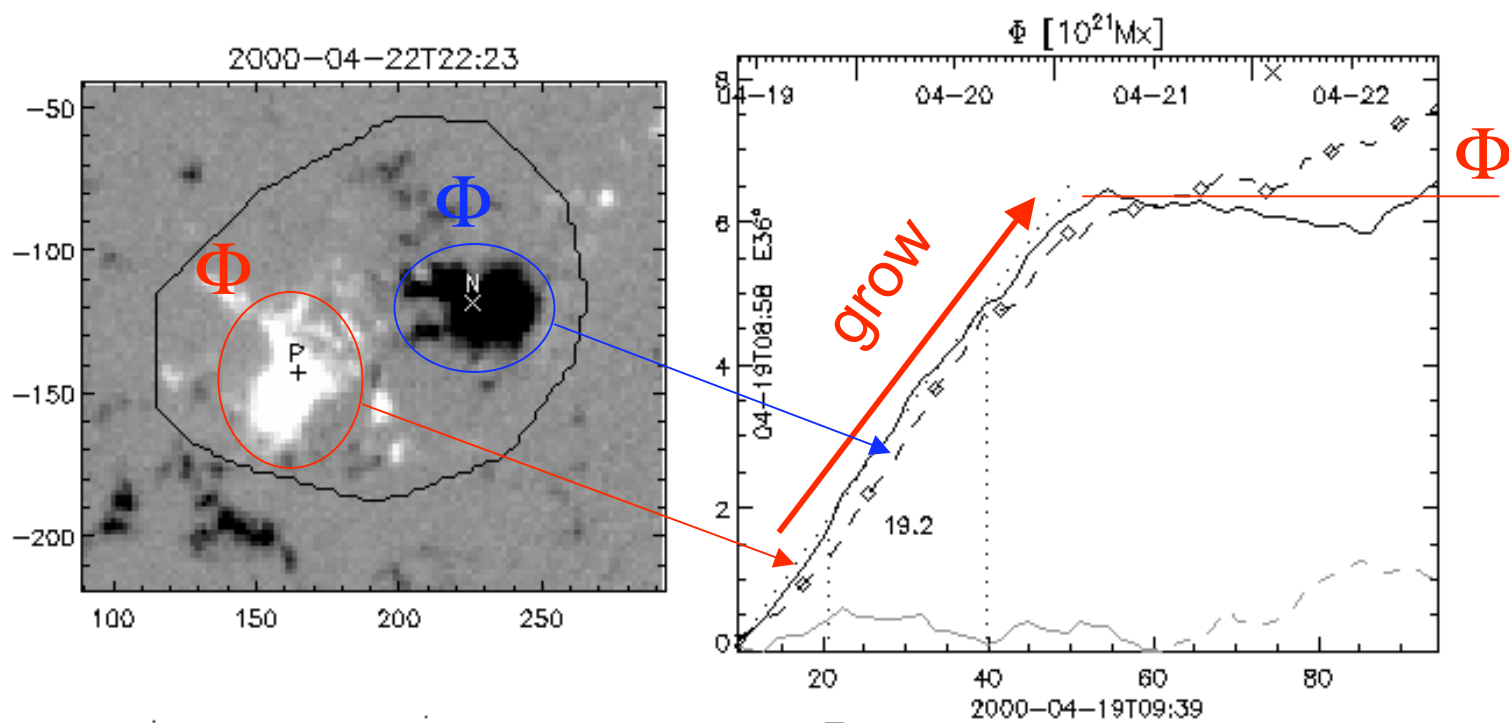
[movie](#)



Babcock 1961



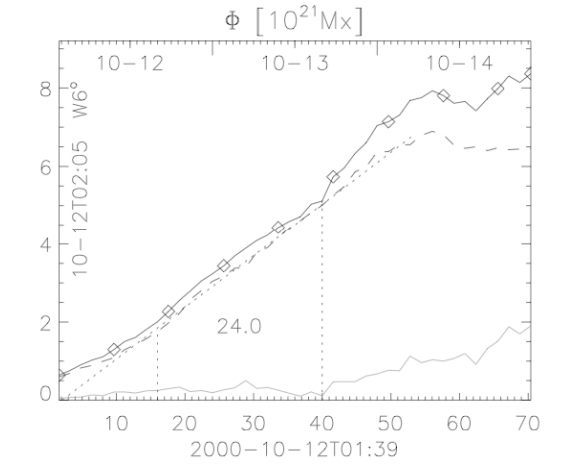
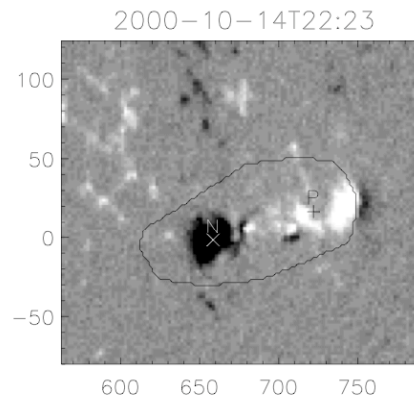
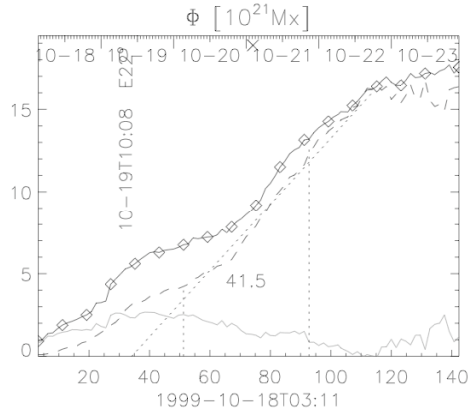
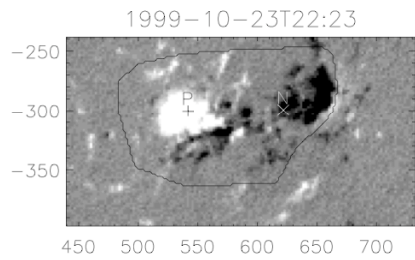
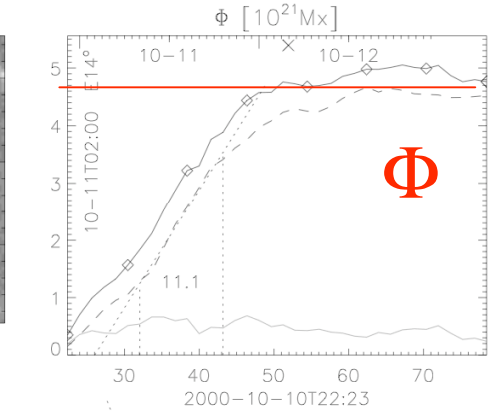
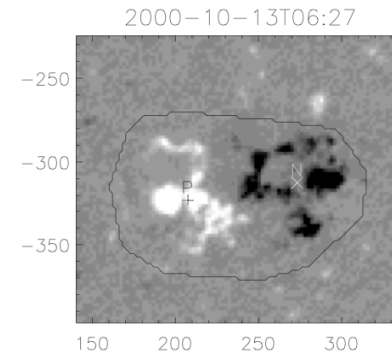
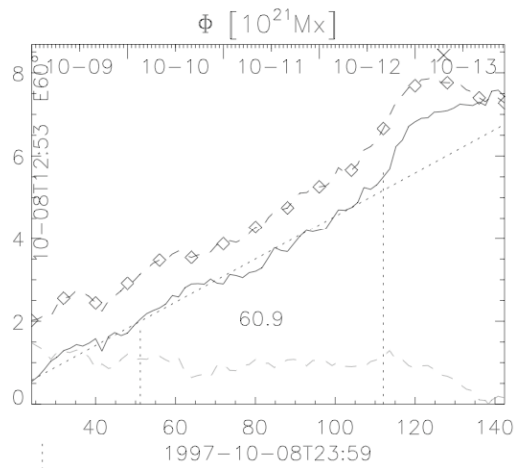
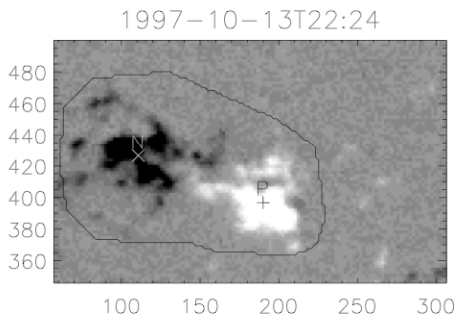
MDI



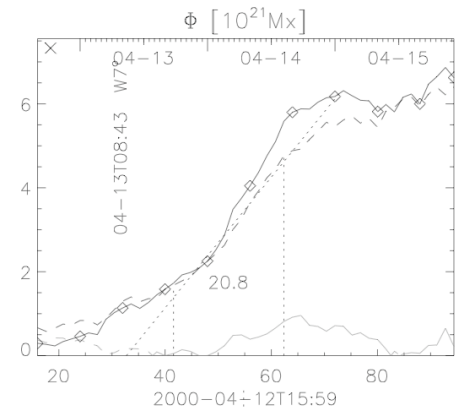
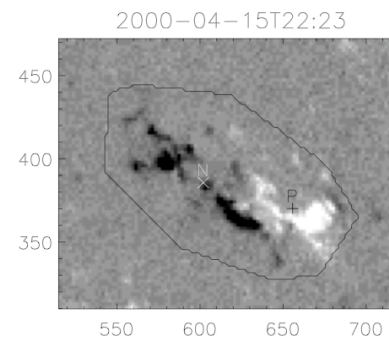
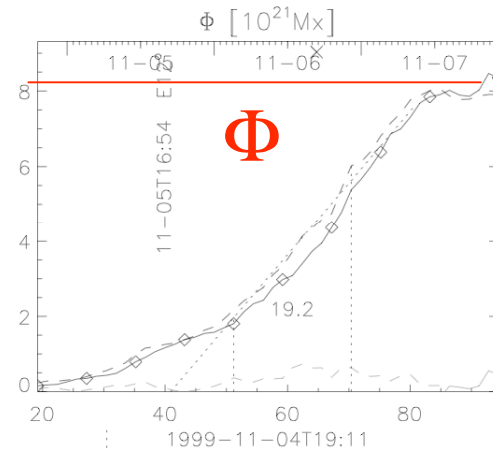
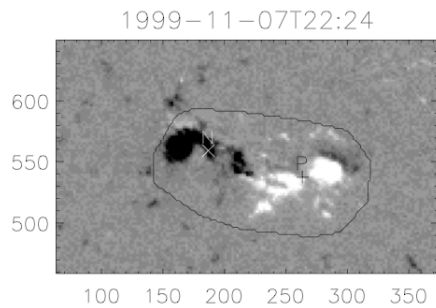
AR 8968

Dec. 2, 2008  
Bangalore, India

# various sizes...



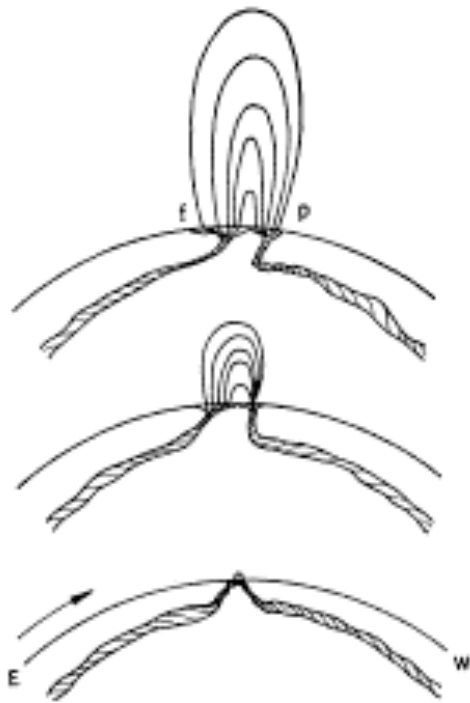
# ... same story



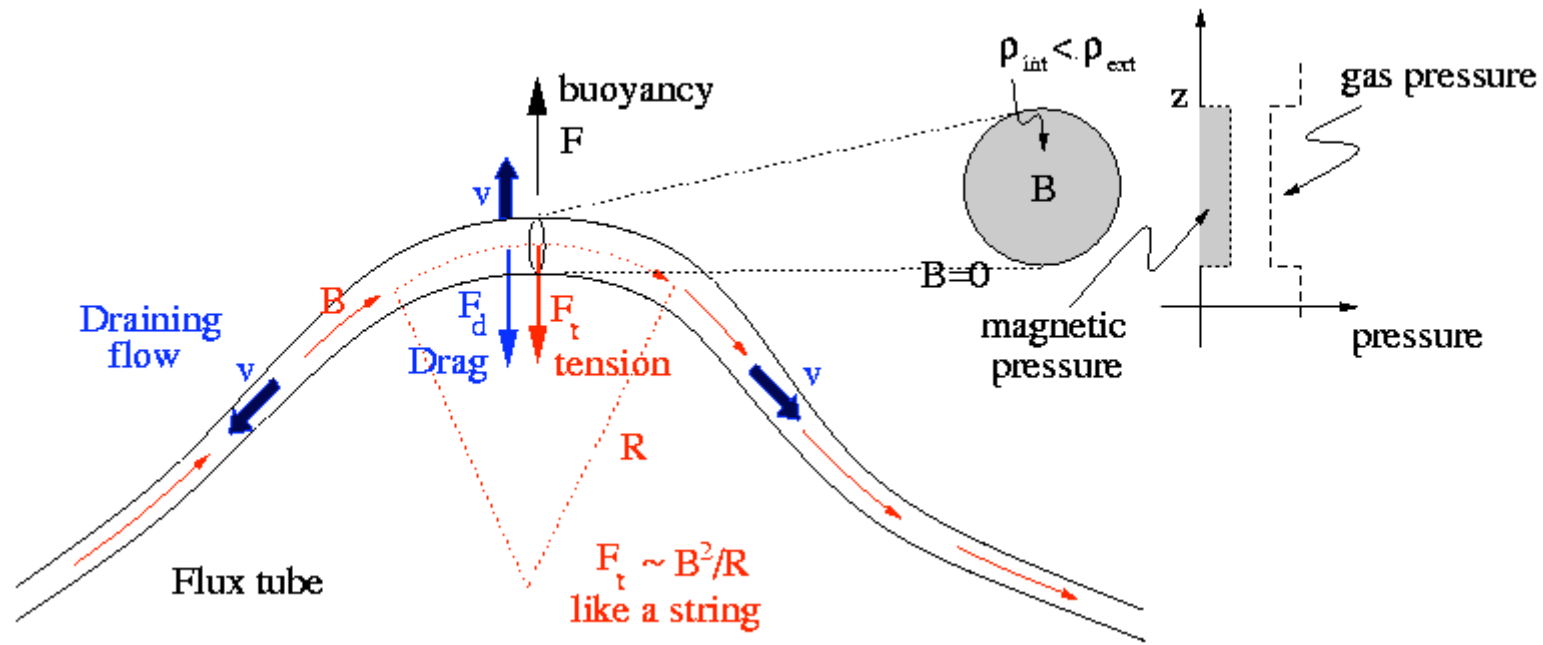
# How do these emerging flux tubes affect the corona?

## Outline

1. Dynamics of emergence
2. Twist (helicity) in emerging tubes
3. Transport of helicity into the corona by emerging tubes



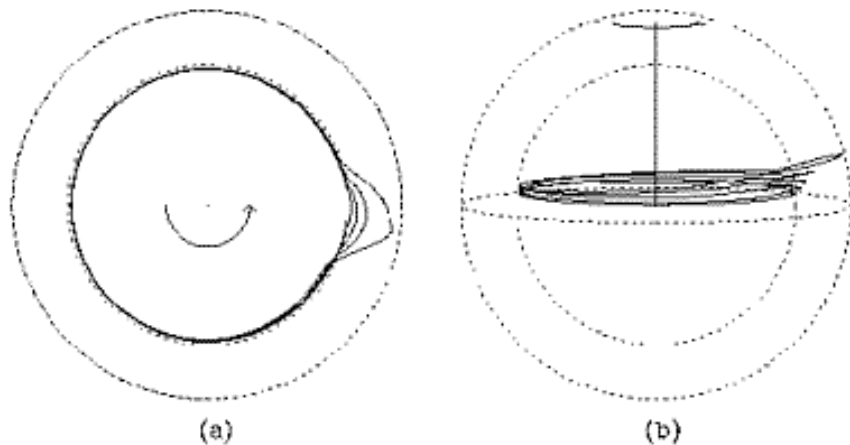
# Dynamics of rising flux tubes



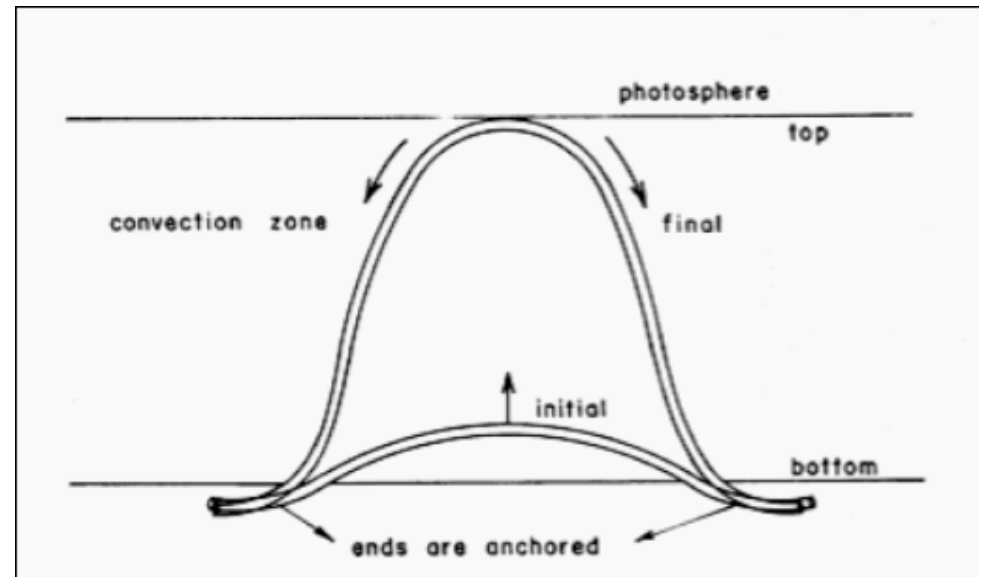
- Isolated tube, pressure-confined, “thin”  $\leftrightarrow a \ll H_p$
- Axis of tube: space curve  $\mathbf{x}(s,t)$
- Dynamical equations: Spruit 1981, Choudhuri & Gilman 1987

# Model evolution of AR tubes

- Initialize tube at base of CZ
- Follow evolution of emerging tube - thin FT eqns.
- Predict configuration of observed AR



Fan *et al.* 1994

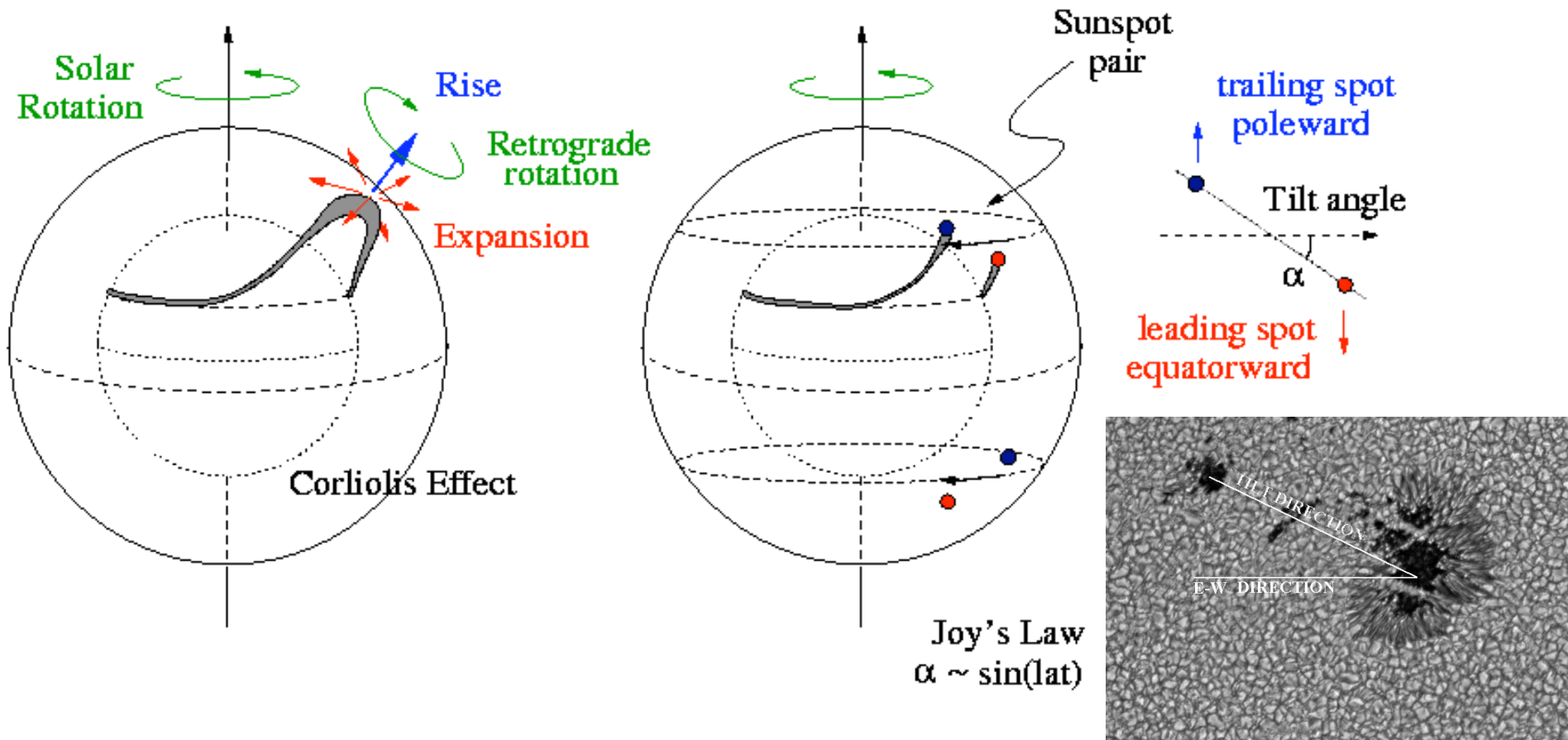


D'Silva & Choudhuri 1993



# A Rising Flux Tube

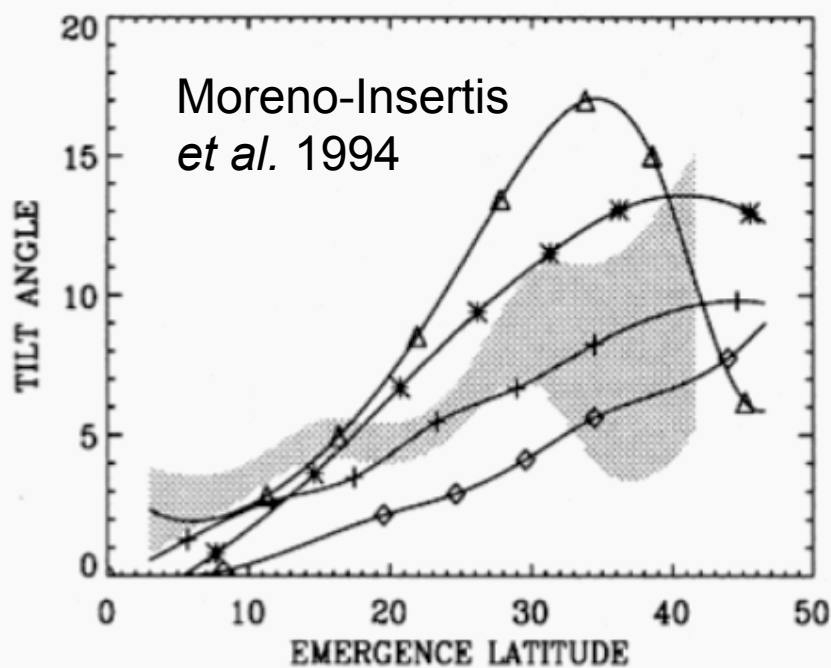
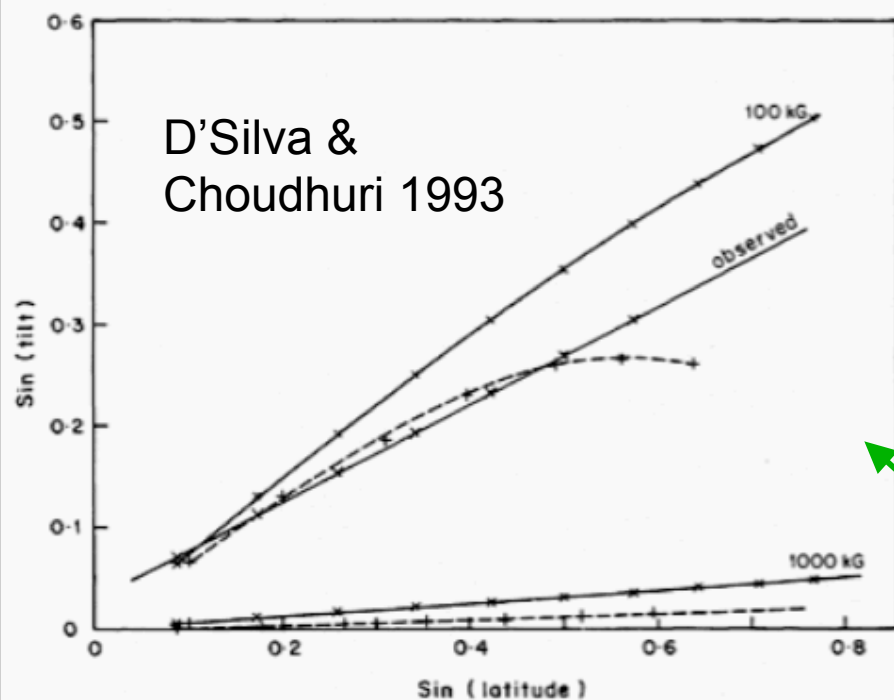
Deflection of rising tube by Coriolis effect → tilted pair of spots





## Thin flux tube successes:

- Hale's polarity law
- Joy's law for tilt angles  
(D'Silva & Choudhuri 1993)
- p-f asymmetry  
(Fan *et al.* 1993)
- post-emergence velocities  
(Moreno-Insertis *et al.* 1994)
- Statistical dispersion  
(Longcope & Fisher 1996)

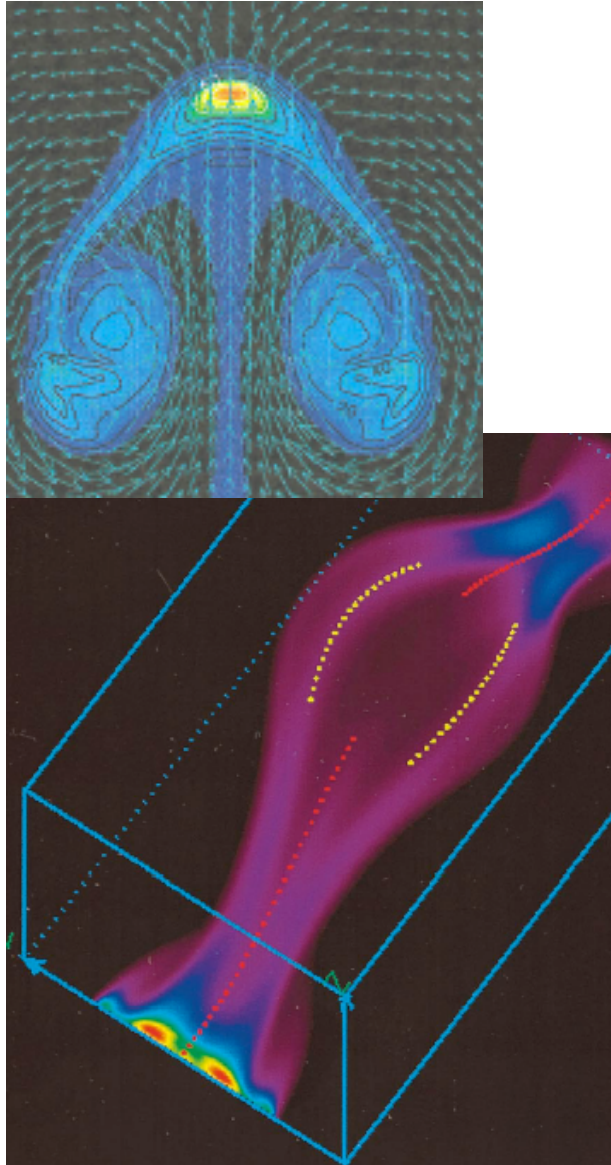


# Flux Tube Twist

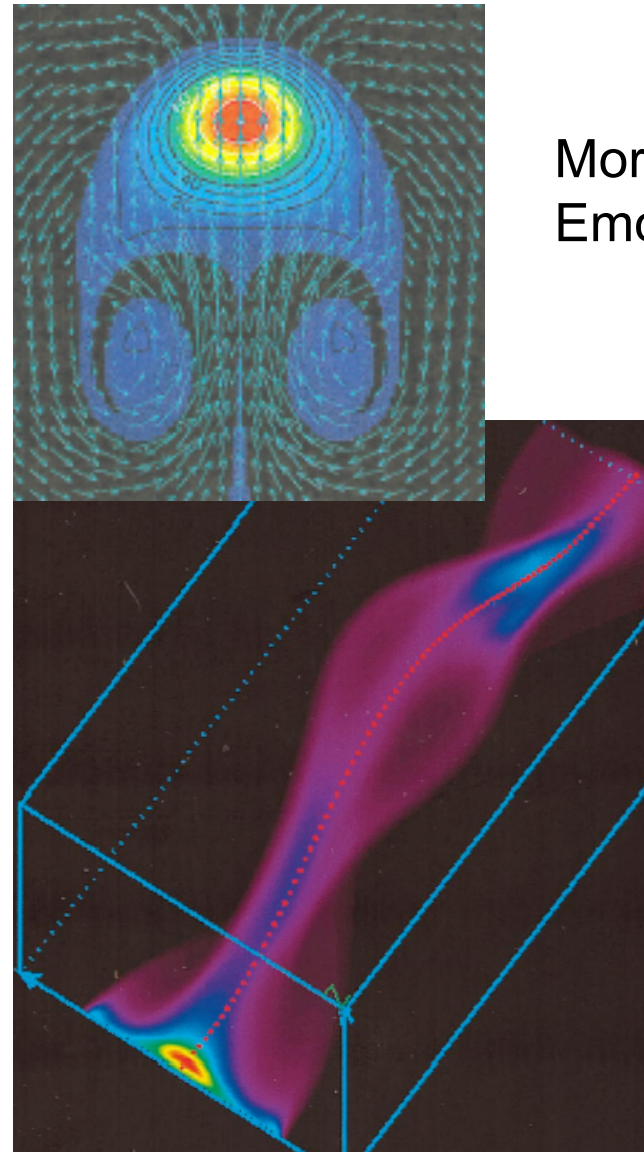


Flux tubes must be twisted in order to rise (Parker 1979)

untwisted



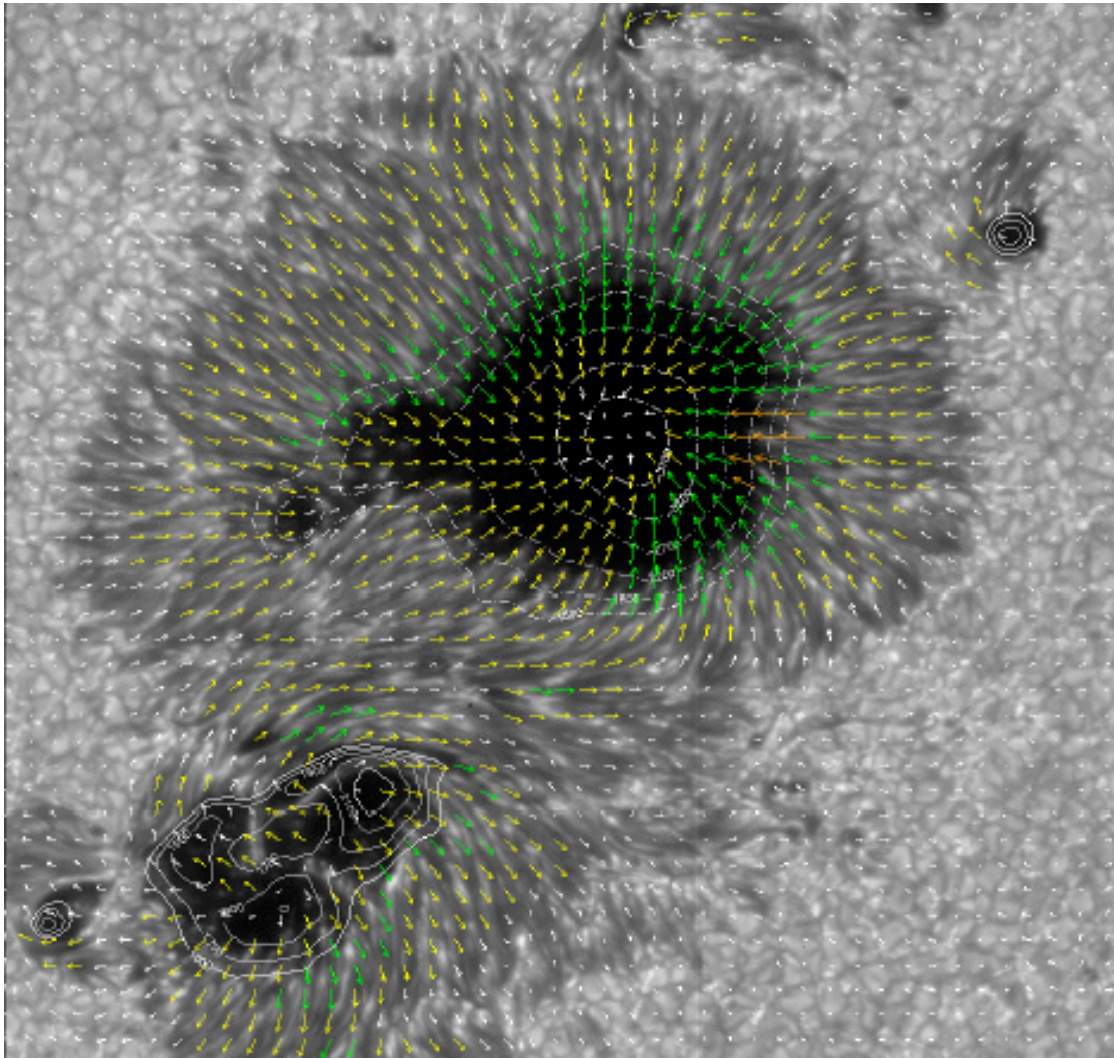
twisted



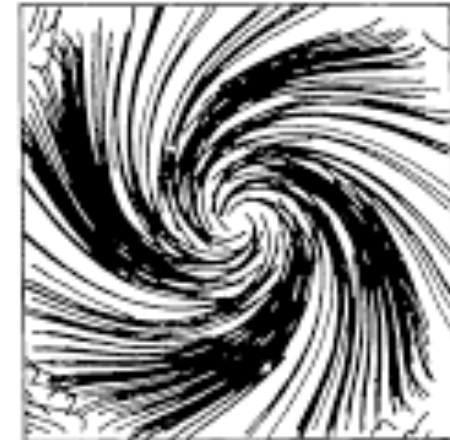
Moreno-Insertis &  
Emonet 1996

Abbett et al. 2000

# ... and AR fields are twisted



(courtesy T. Magara & Hinode)  
Bangalore, India

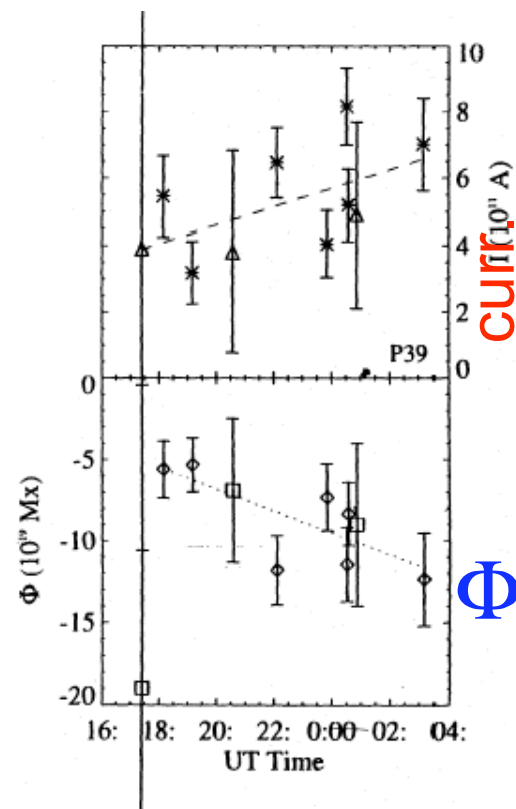
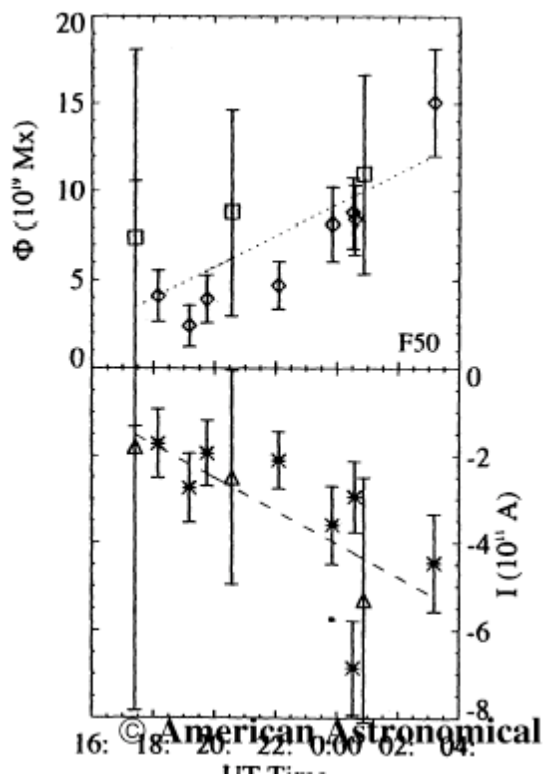
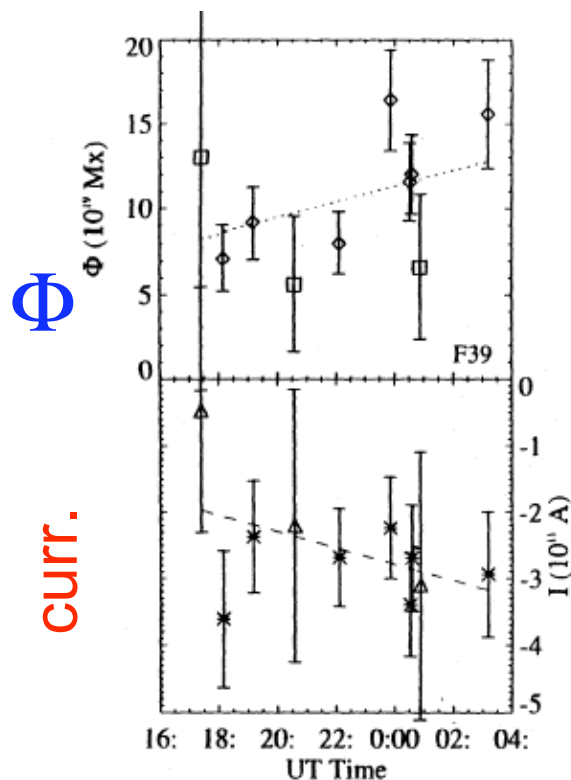


b1

(from Nakagawa  
et al. 1971)

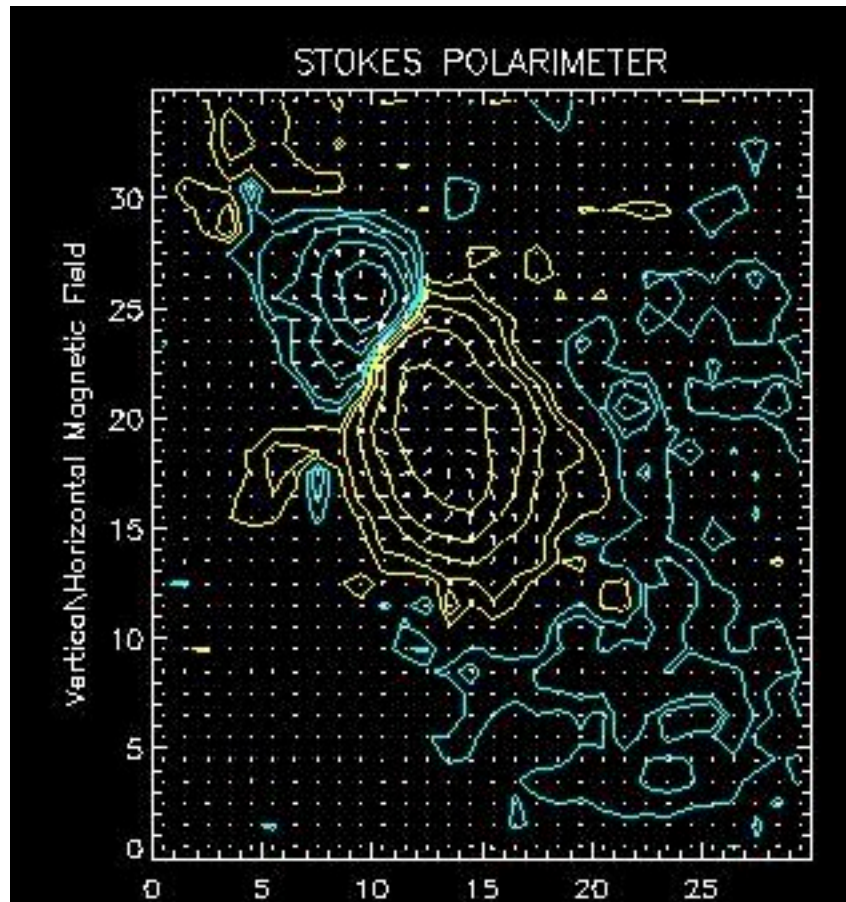


# Evidence that flux tubes emerge already twisted: Flux ( $\Phi$ ) and current increase together (Leka *et al.* 1996 )



DEC. 2, 2000  
Bangalore, India

# How twisted are the tubes?

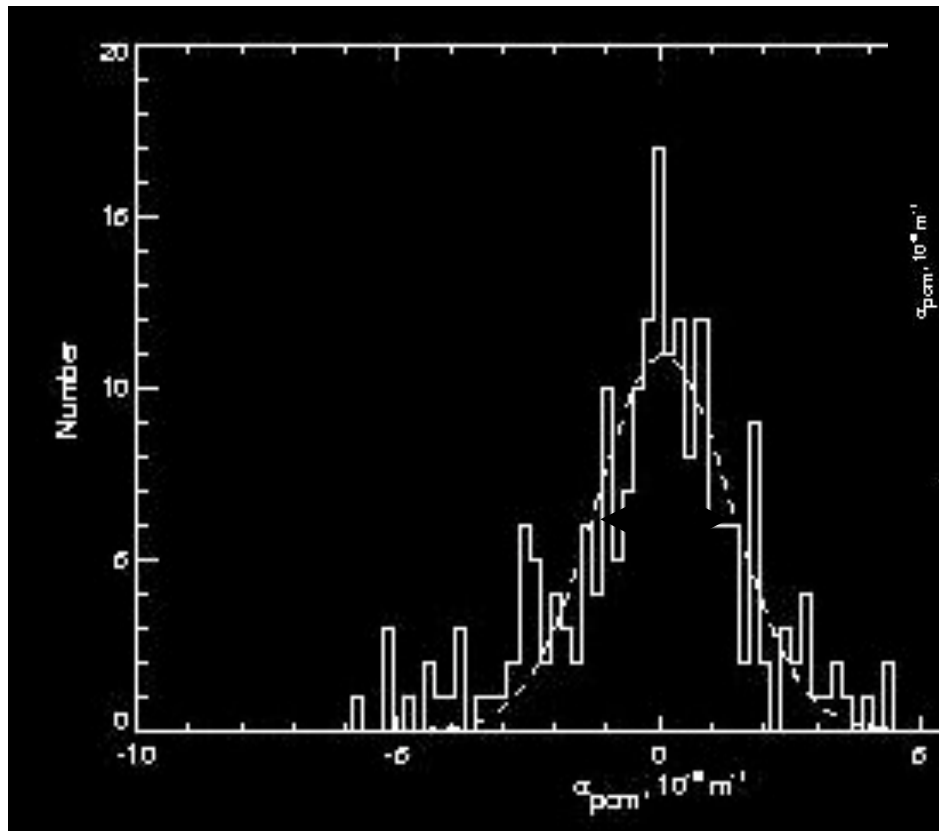


$\alpha_{\text{best}}$  introduced by  
Pevtsov, Canfield  
& Metcalf (1995)

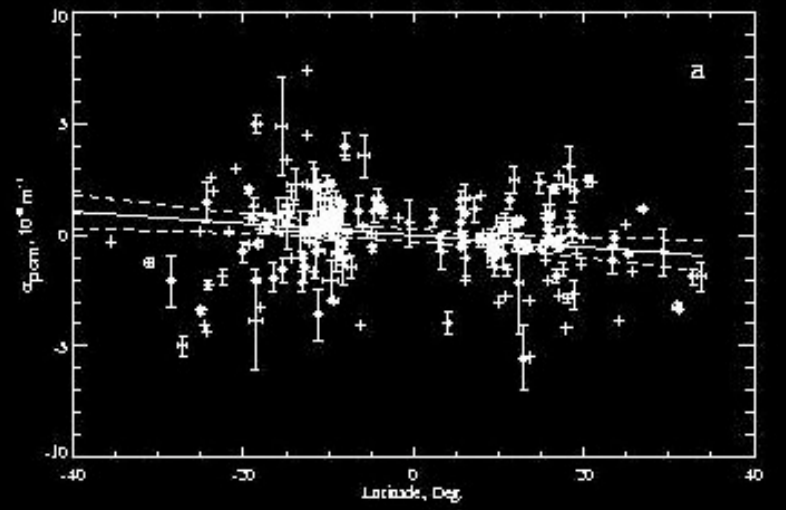
- calc  $\mathbf{B}_{\perp}^{(\alpha)}$  by extrapolating  $B_z$  w/ fixed value of  $\alpha$
- vary  $\alpha$  until  $\mathbf{B}_{\perp}^{(\alpha)}$  best matches observed  $\mathbf{B}_{\perp}$   
i.e. minimize

$$\sum_{i,j} |\mathbf{B}_{\perp}(i,j) - \mathbf{B}_{\perp}^{(\alpha)}(i,j)|^2$$

# How twisted are the tubes?



Linear trend removed  
(from Longcope, Fisher &  
Pevtsov 1998)

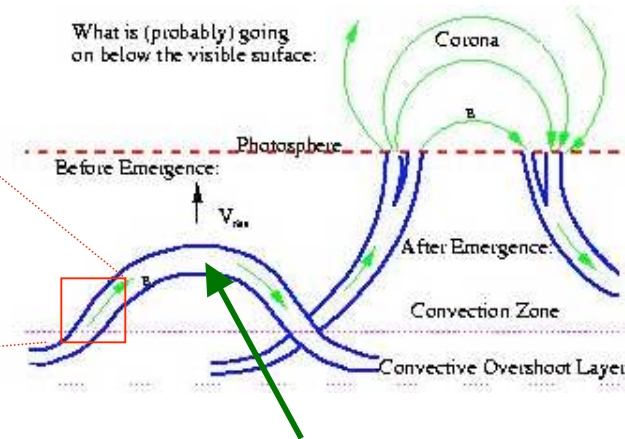
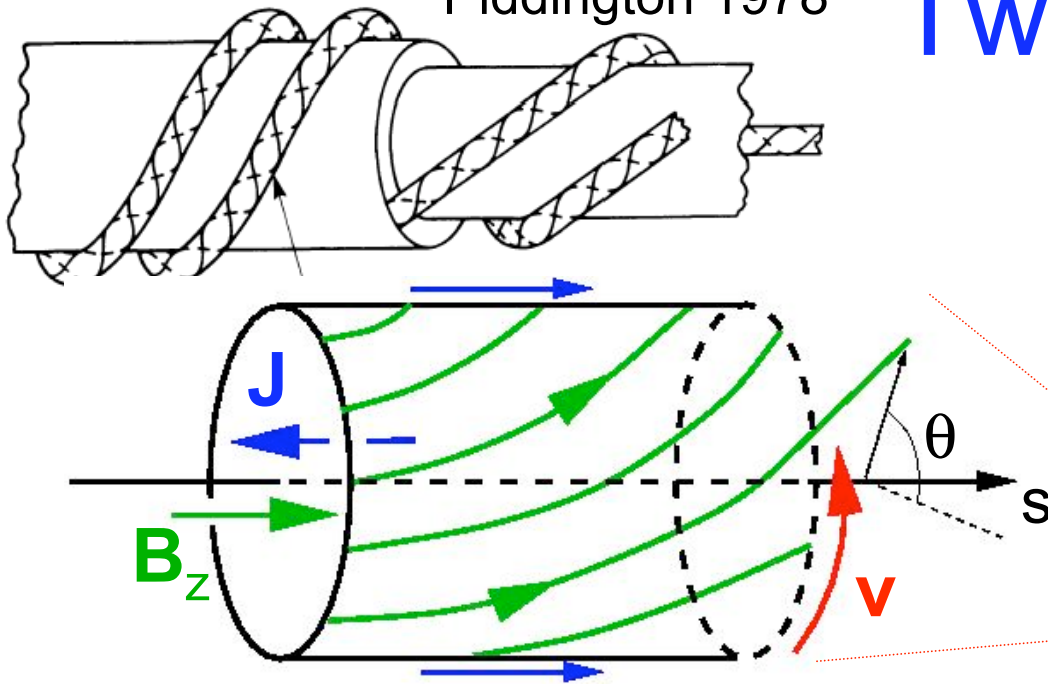


$\langle \alpha_{\text{best}} \rangle \sim 3 \times 10^{-9} \text{ m}^{-1}$   
varies /w latitude

$\Delta \alpha_{\text{best}} \sim 10^{-8} \text{ m}^{-1}$   
independent of latitude

Piddington 1978

# Twist in flux tubes



Field lines **twist** about axis at a rate

$$q(s,t) \text{ "="" } d\theta/ds$$

$$\alpha = 2q$$

Plasma **spins** about axis at rate

$$\omega(s,t) \text{ "="" } d\theta/dt$$

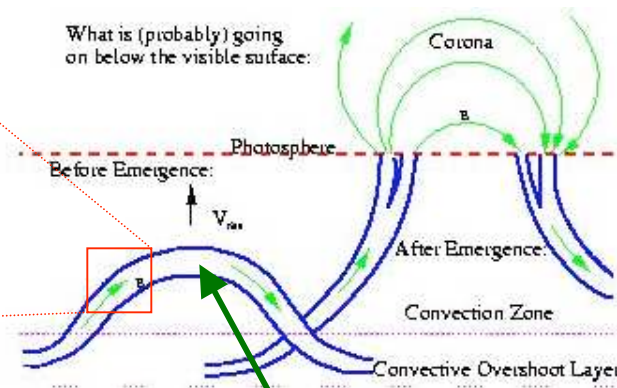
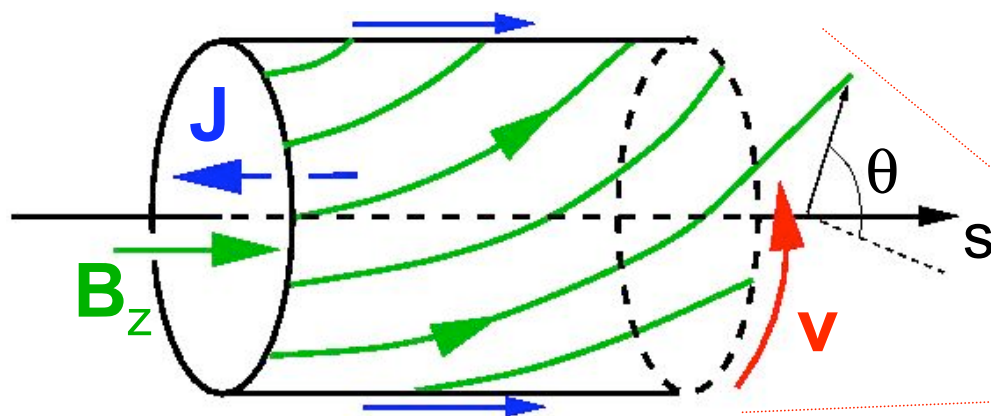
$$B_\theta = qr B_z$$

$$v_\theta = \omega r$$

**Axis of tube:**



# Twist in flux tubes

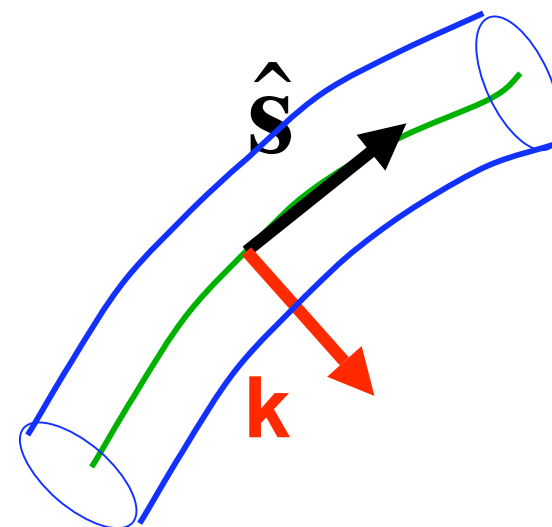


## Evolution of twist & spin

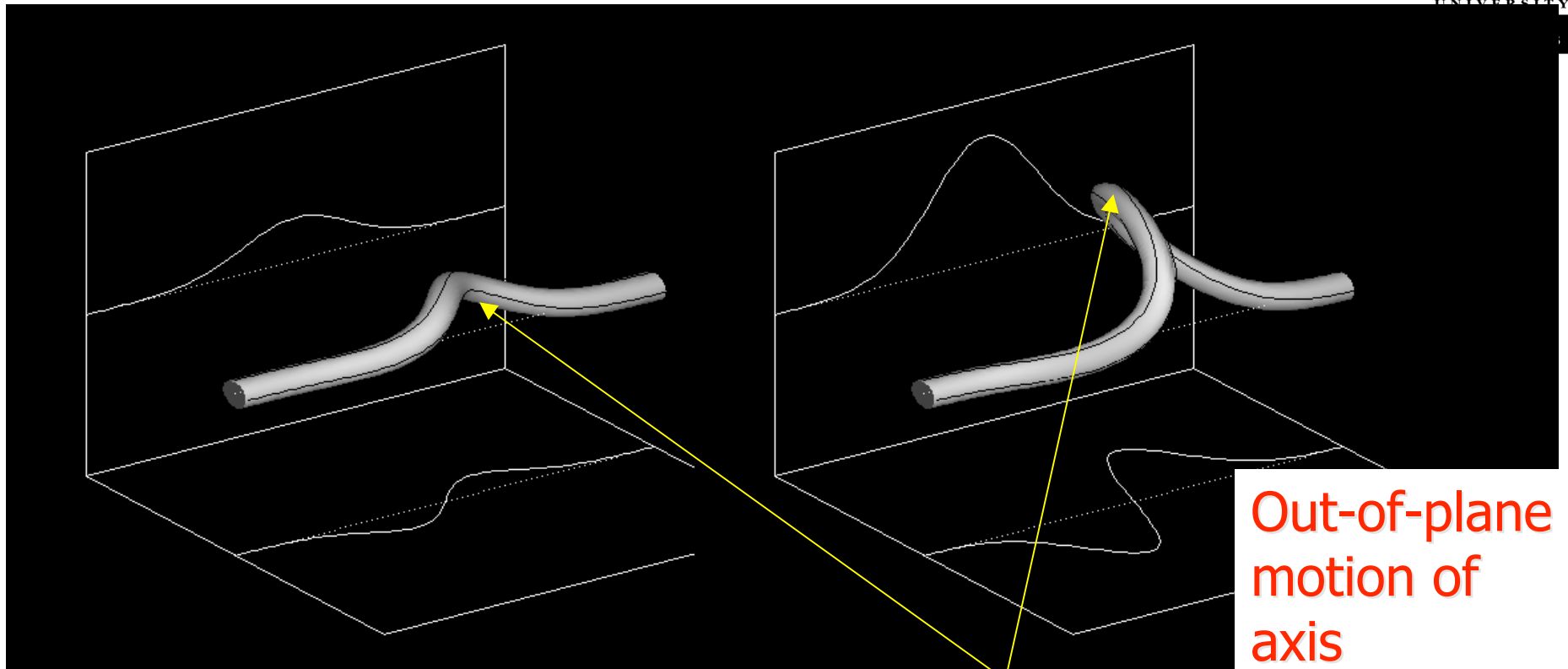
$$\frac{d\omega}{dt} = v_A^2 \frac{\partial q}{\partial s} - \frac{2}{a} \frac{da}{dt}$$

$$\frac{dq}{dt} = \frac{\partial \omega}{\partial s} - \left( \hat{s} \cdot \frac{\partial \mathbf{v}}{\partial s} \right) q + (\hat{s} \times \mathbf{k}) \cdot \frac{\partial \mathbf{v}}{\partial s}$$

Axis of tube:



# Dynamics of twist

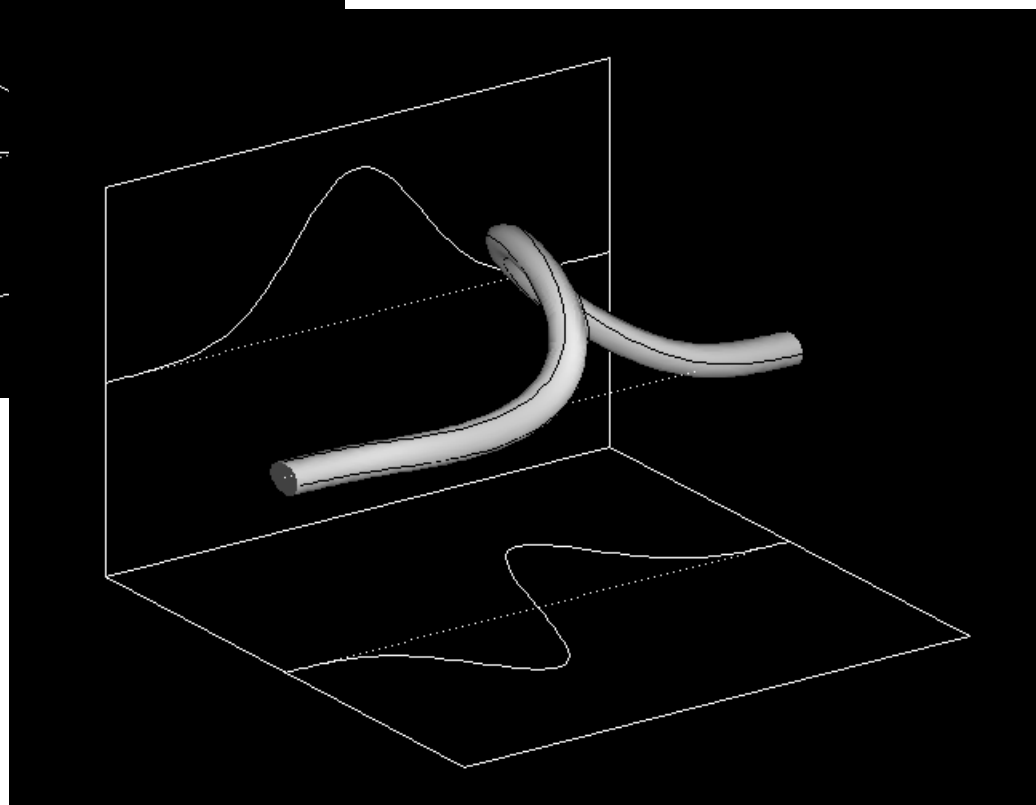
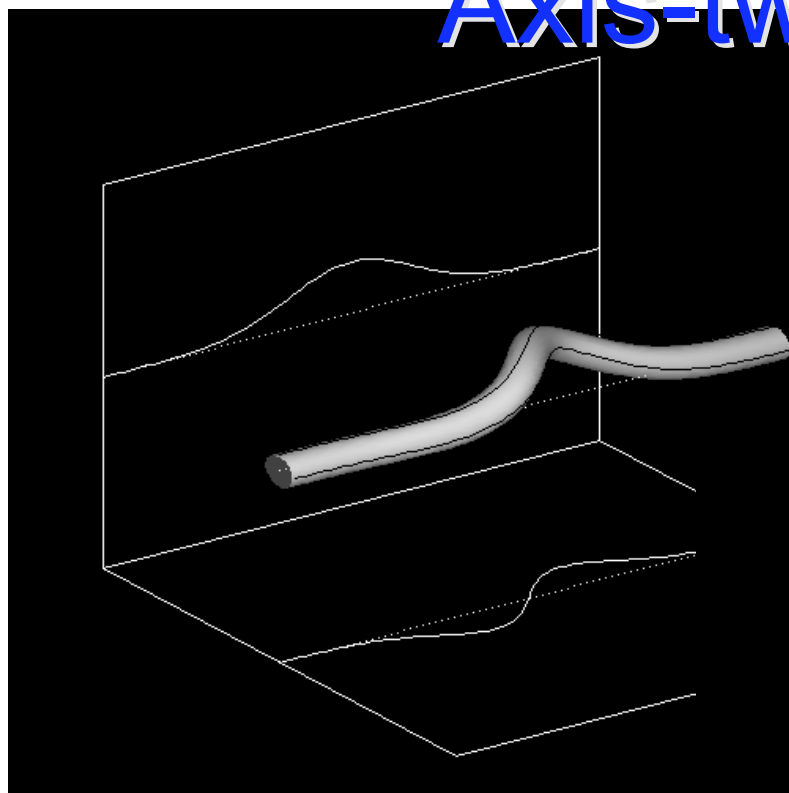


$$\frac{dq}{dt} = \frac{\partial \omega}{\partial s} - \left( \hat{\mathbf{s}} \cdot \frac{\partial \mathbf{v}}{\partial s} \right) q + \left( \hat{\mathbf{s}} \times \mathbf{k} \right) \cdot \frac{\partial \mathbf{v}}{\partial s} \leftarrow \Sigma(s)$$

indep. of  $q$  or  $\omega$

# Axis-twist coupling

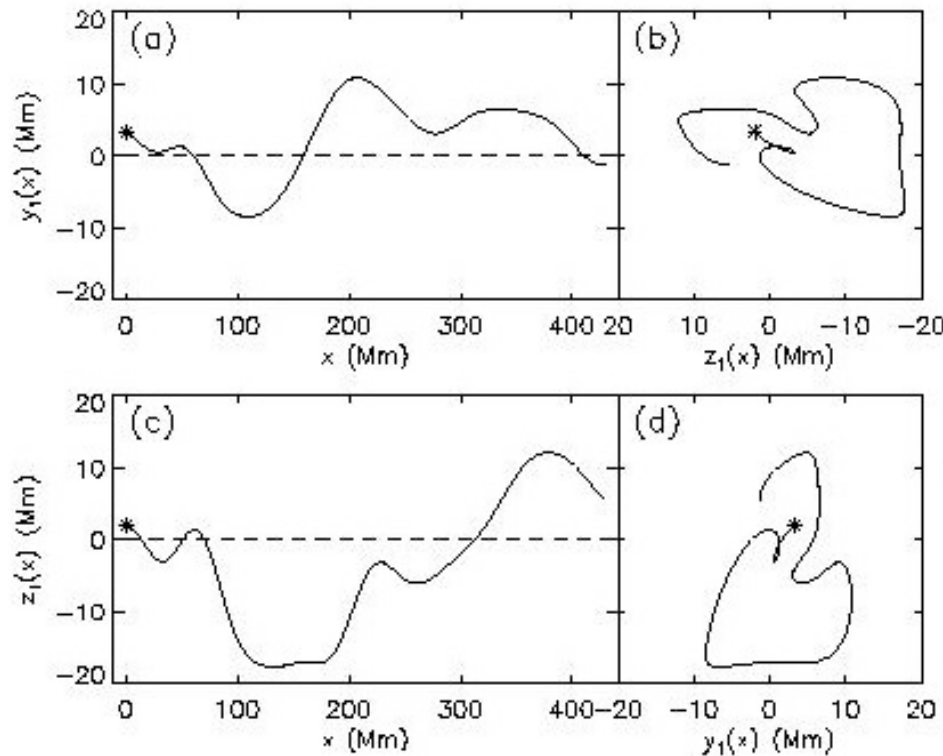
$$\frac{dq}{dt} = \Sigma = (\hat{\mathbf{s}} \times \mathbf{k}) \cdot \frac{\partial \mathbf{v}}{\partial s} > 0$$



Increasing LH  
**writhe** ( $dWr/dt < 0$ )  
→ Increasing RH  
**twist** ( $dTw/dt > 0$ )

Bangalore, India

# Writhe from Turbulence: The $\Sigma$ -effect (Longcope, Fisher & Pevtsov 1998)



*Spectrum of kinetic helicity*

$$\langle \mathbf{v}^e \cdot \nabla \times \mathbf{v}^e \rangle = -\frac{1}{3} \tau_c \int F(k) dk$$

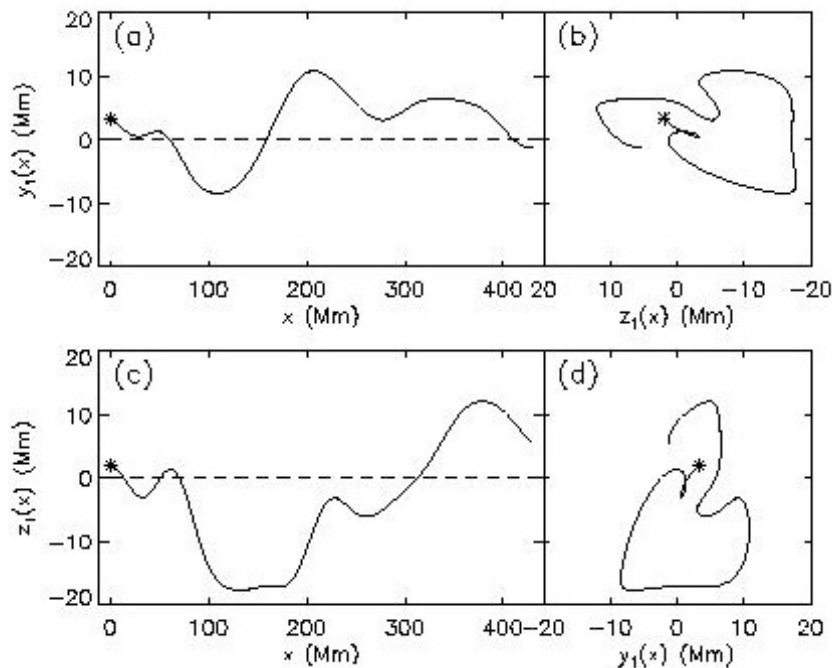
$$\Sigma \approx (\hat{\mathbf{s}} \times \mathbf{k}) \cdot \frac{\partial \mathbf{v}^e}{\partial s} \quad \text{Twist source}$$

**Averaging over turbulence:**

$$\langle \Sigma \rangle \approx -\frac{1}{5} \tau_c \int k^2 F(k) dk$$

**Variance of twist source:**  $\langle \Sigma^2 \rangle \approx |\mathbf{k}|^2 \int k^2 E(k) dk \gg \langle \Sigma \rangle^2$

# $\Sigma$ -effect vs. $\alpha$ -effect



$$\langle \Sigma \rangle \approx -\frac{1}{5} \tau_c \int k^2 F(k) dk$$

*Spectrum of kinetic helicity*

Compare to  $\alpha$ -effect:

$$\alpha \approx -\langle \mathbf{v}^e \cdot \nabla \times \mathbf{v}^e \rangle = \frac{1}{3} \tau_c \int F(k) dk$$

# Cause of the observed twist

## Observed properties

- ✓ Twist in CZ flux tube
- ✓ LH twist in North
- ✓  $\langle \alpha \rangle \sim 3 \times 10^{-9} \text{ m}^{-1}$
- ✓ 25% violation of trend
- ✓  $\Delta \alpha \sim 10^{-8} \text{ m}^{-1}$
- ✓  $\Delta \alpha$  indep. of latitude

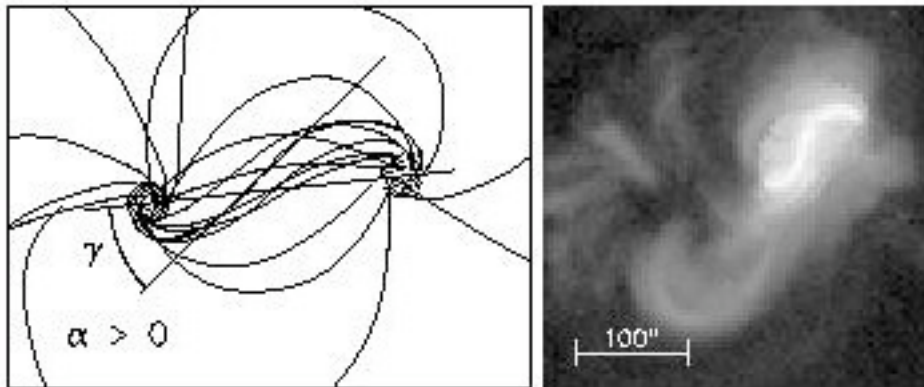


## Kinetic helicity:

- RH writhe in North
- $\langle \alpha \rangle \sim 3 \times 10^{-9} \text{ m}^{-1}$
- Fluctuates (turbulence)
- Level indep. of latitude
- $\Delta \alpha \sim 10^{-8} \text{ m}^{-1}$

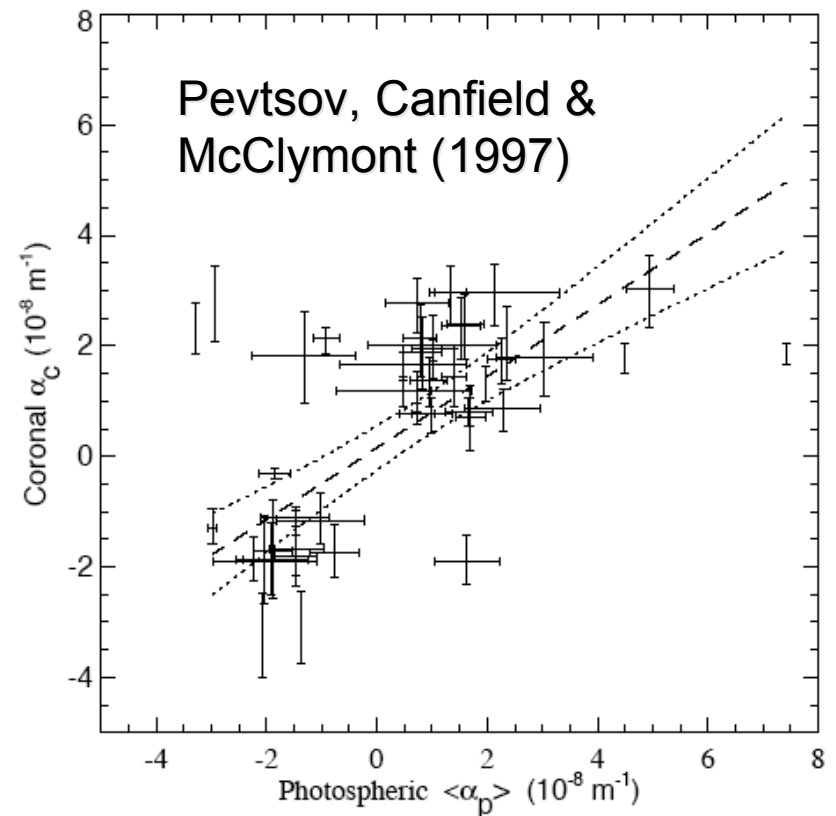
# Twist: Photosphere vs. Corona

Force-free-field  
w/ constant- $\alpha$



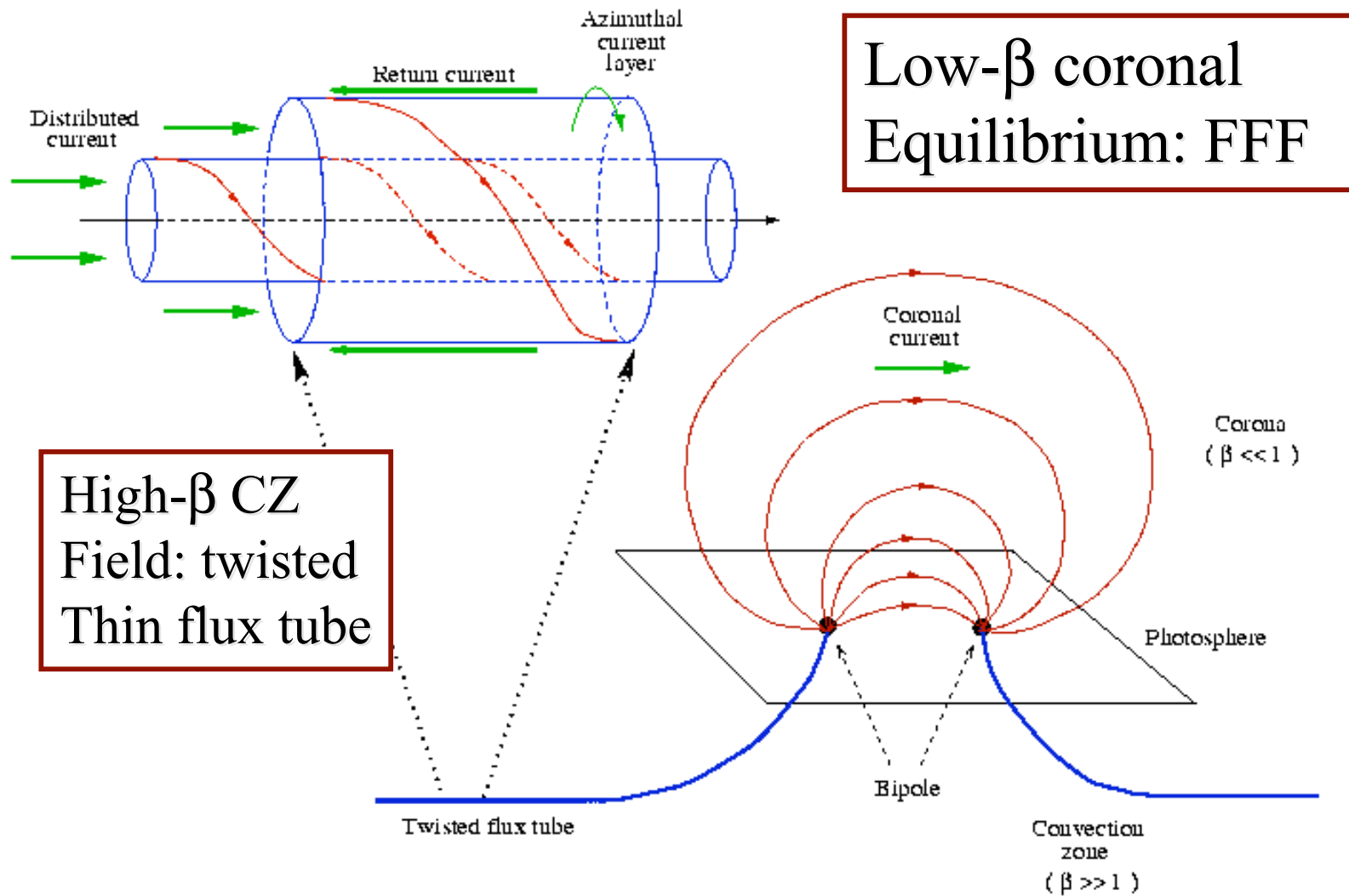
$\alpha_{\text{best}} \sim \alpha$  in coronal field

- $\alpha_{\text{best}}$  and  $\alpha$  for 140 ARs
- Found  $\alpha_{\text{best}}$  correlated with  $\alpha$



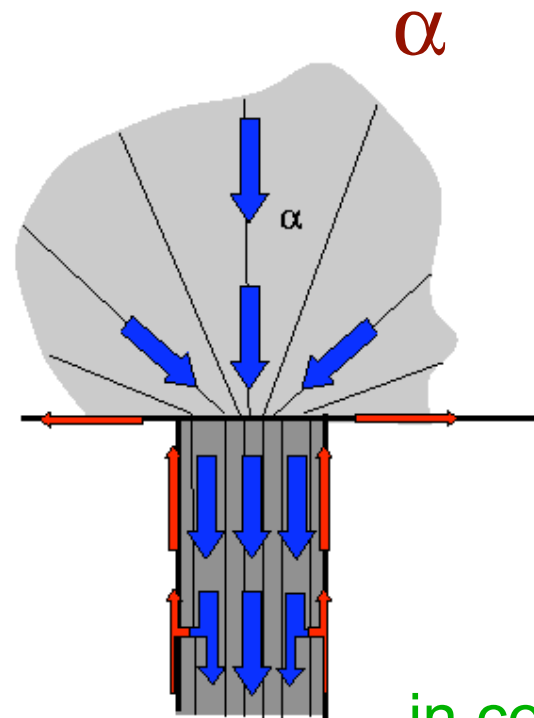
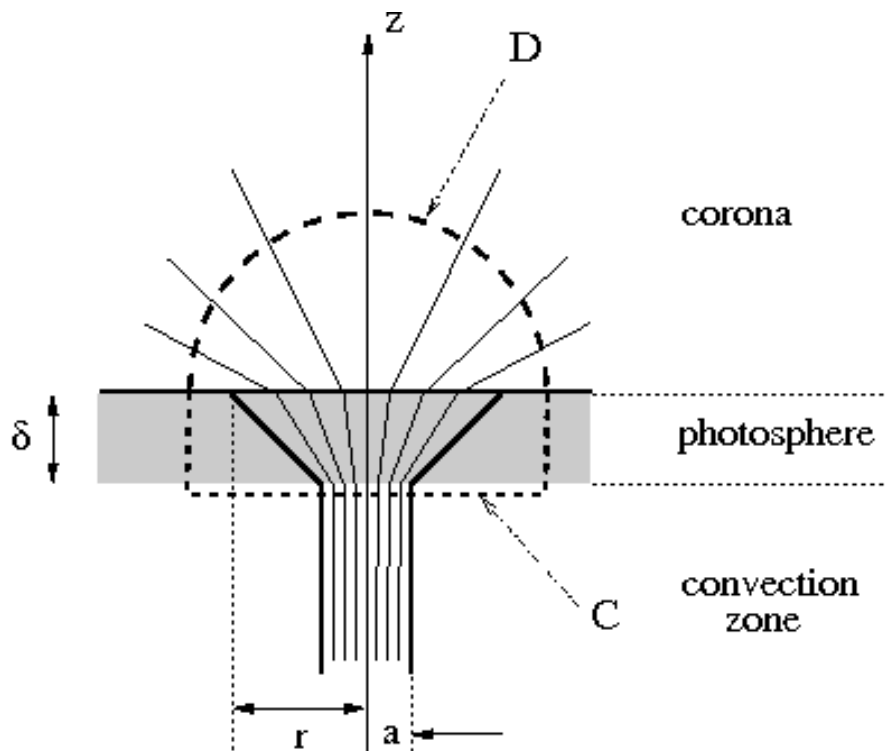


# Coupling flux tube to corona



# Coupling flux tube to corona

Balance of net torque



Current matches across interface

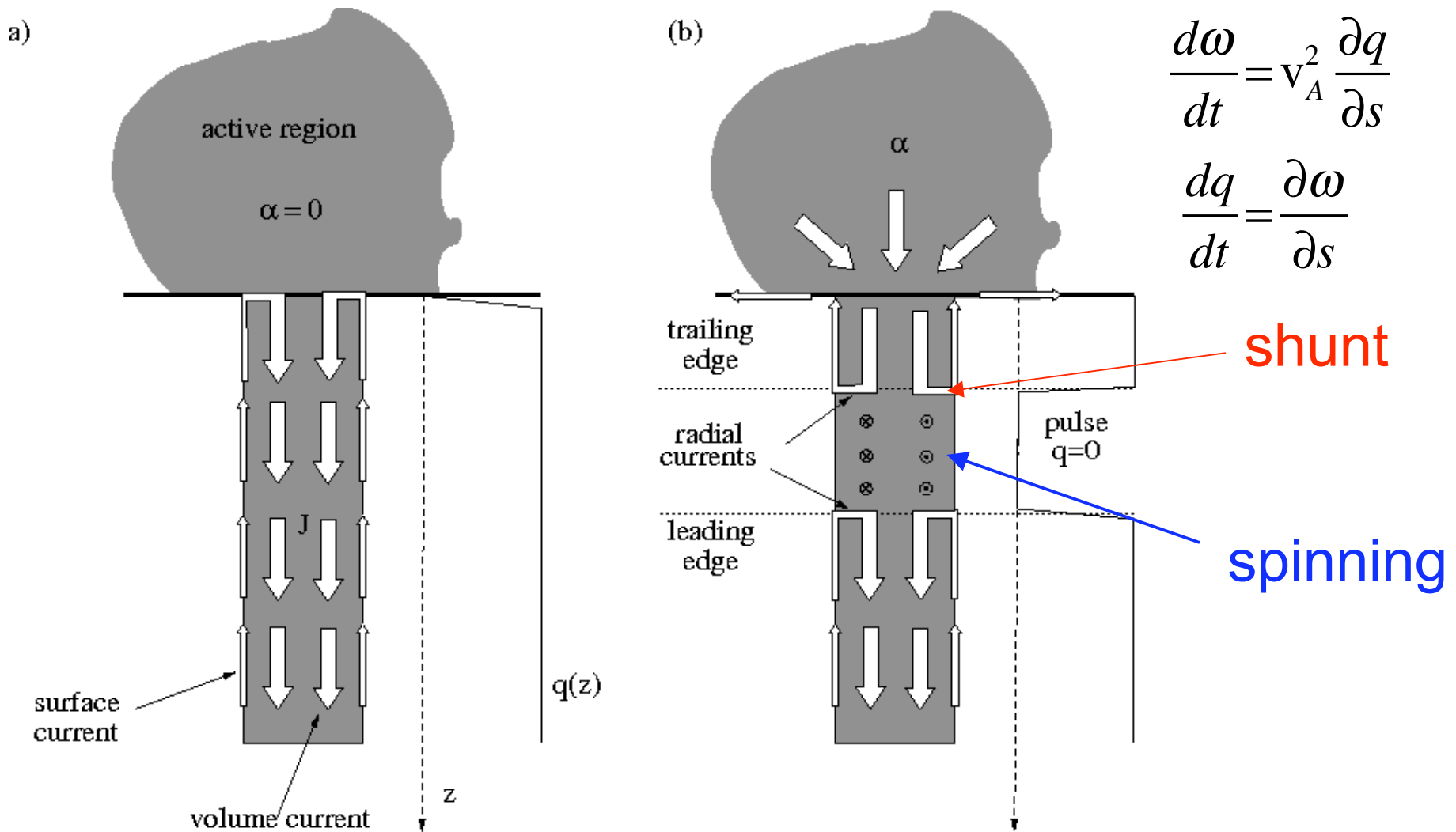
$$\rightarrow \alpha = 2q$$

in corona      in tube

(Longcope & Weslch 1998)

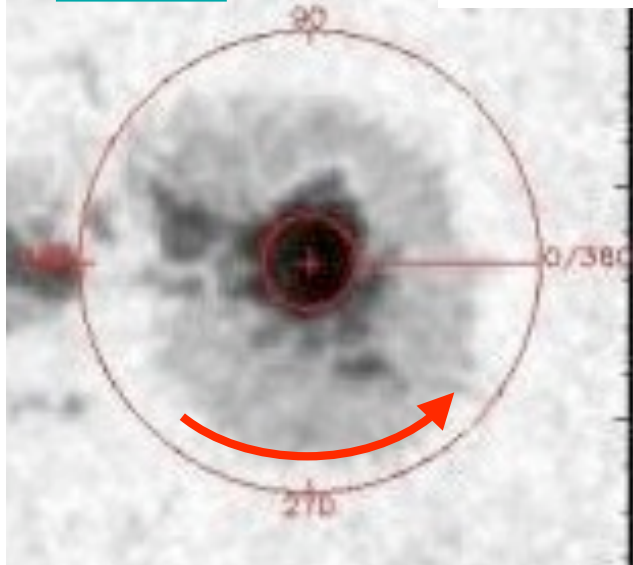
# Coupling flux tube to corona

Imbalanced torque (shunted current) → spin



movie

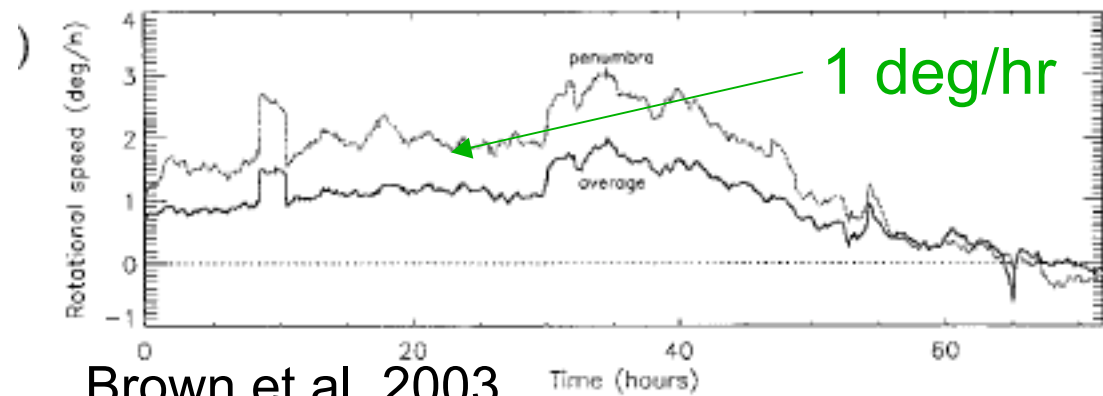
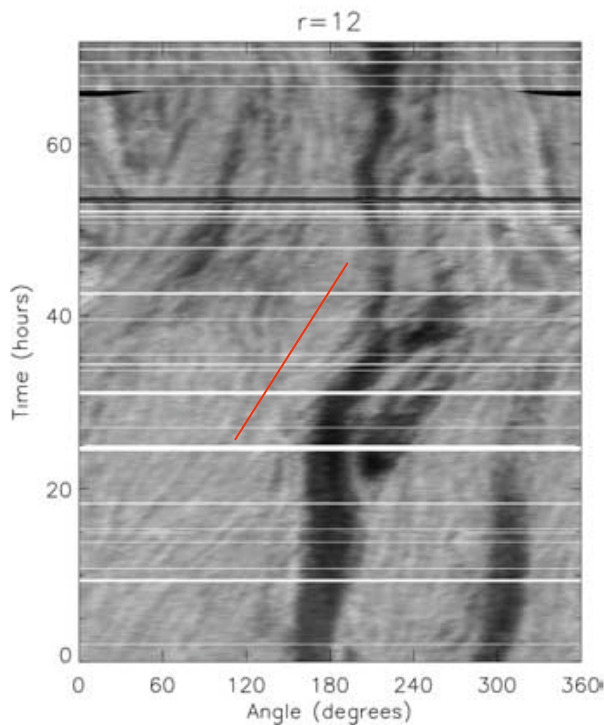
# Flux tube twist → sunspot rotation



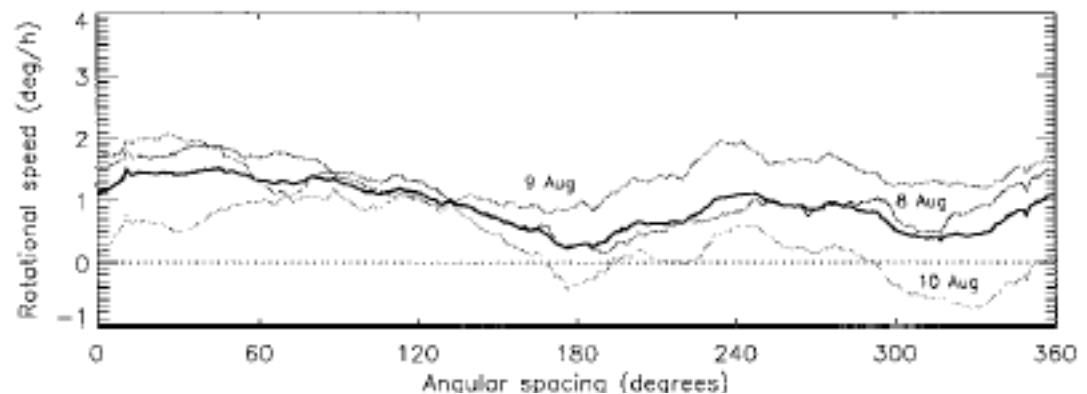
Summarising these results, we have a mean rotational movement of 0.35 km. per sec., and a radial motion of about 2 km. per sec. Combining them, we get a spiral or catharine-wheel movement opposite in the two hemispheres. This is represented graphically in the appended diagram (fig. 2), which shows the directions of the stream-lines in a northern and in a southern spot.



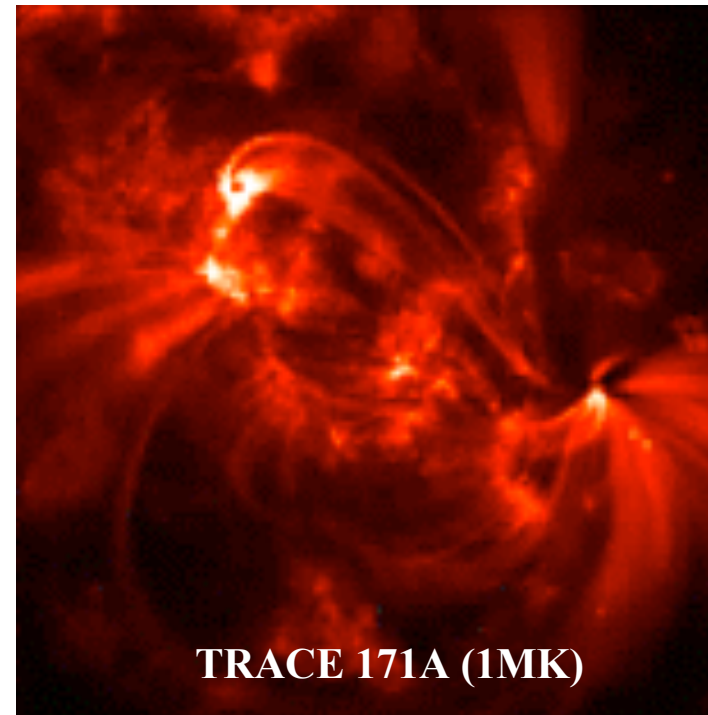
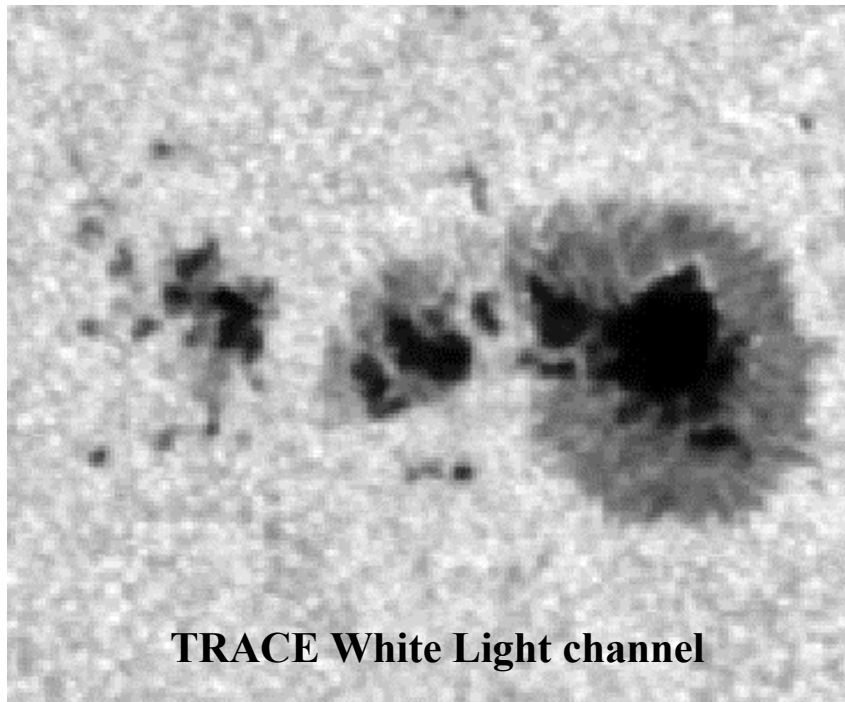
Evershed 1910



Brown et al. 2003



# Twist Creates Spin

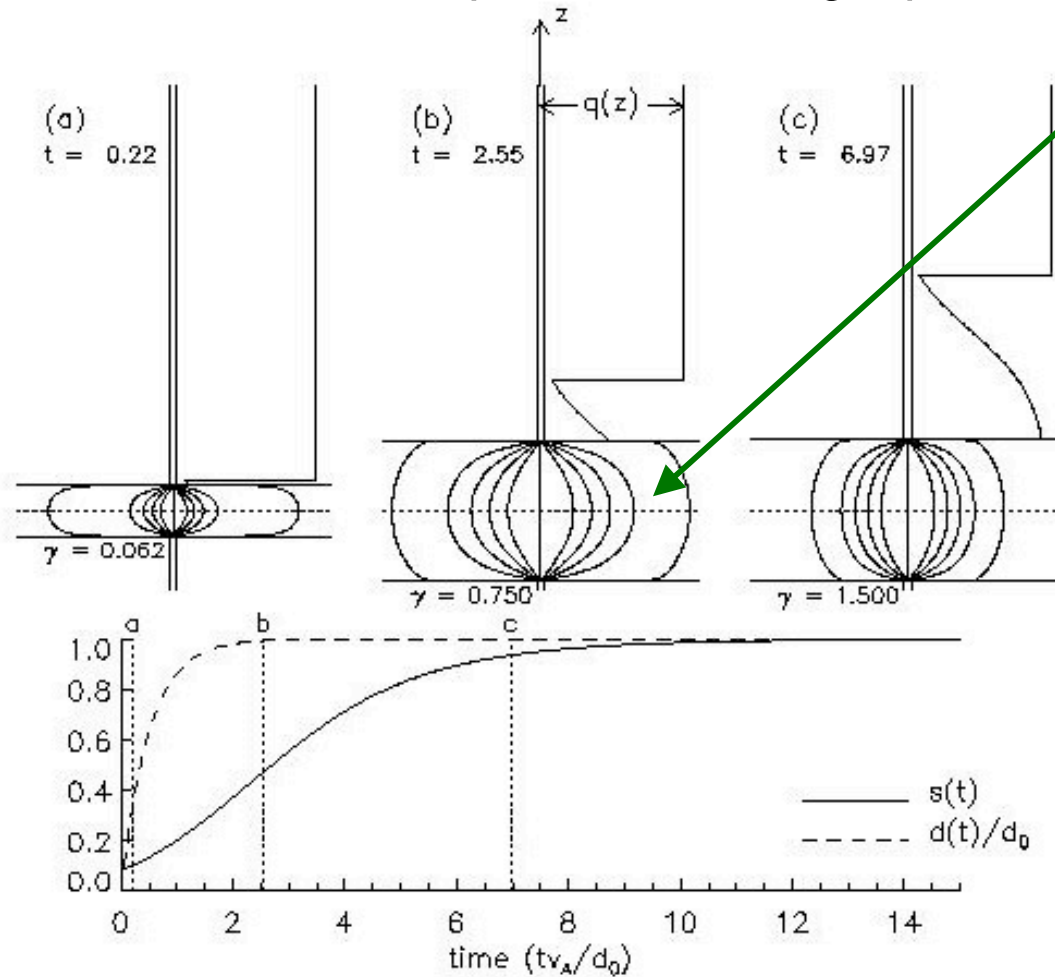


movie

(Courtesy D. Alexander)

# Spin from Emergence

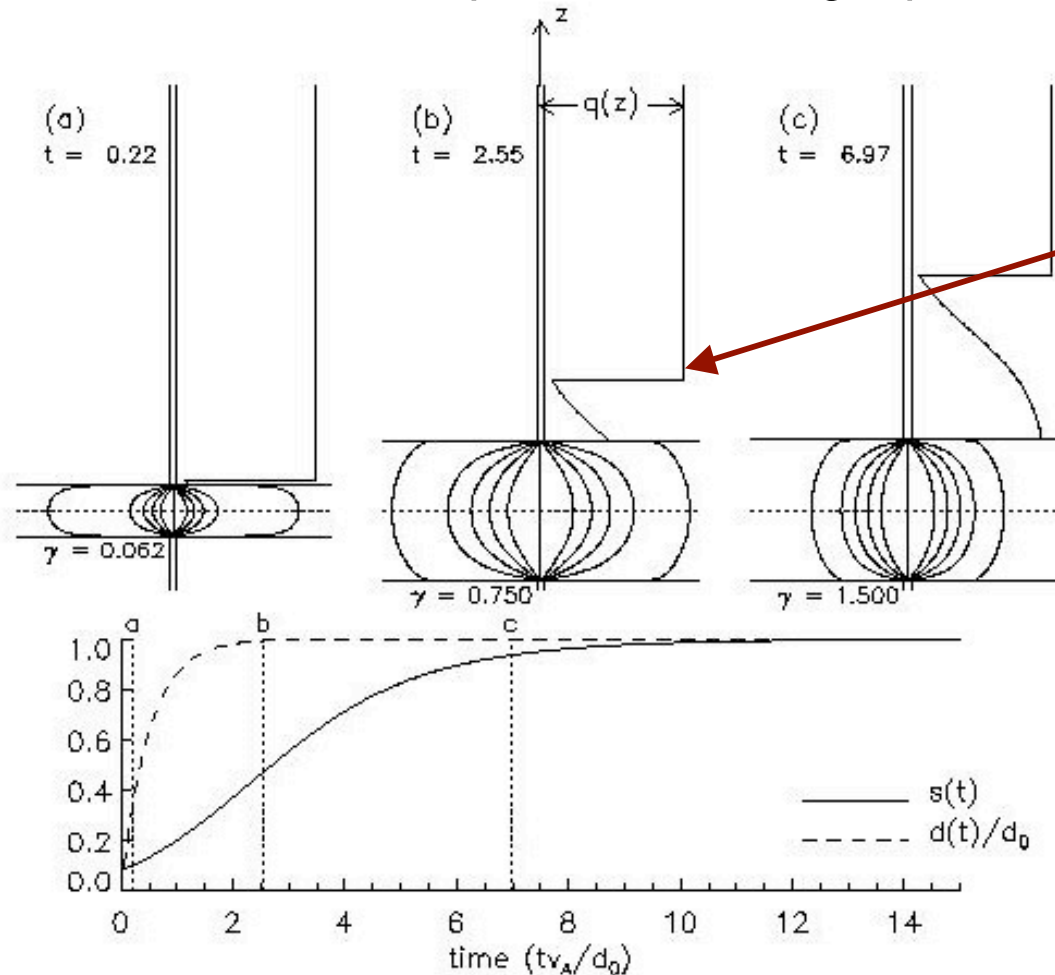
simple model: Longcope & Welsch 1998



- Twist propagates into corona

# Spin from Emergence

simple model: Longcope & Welsch 1998

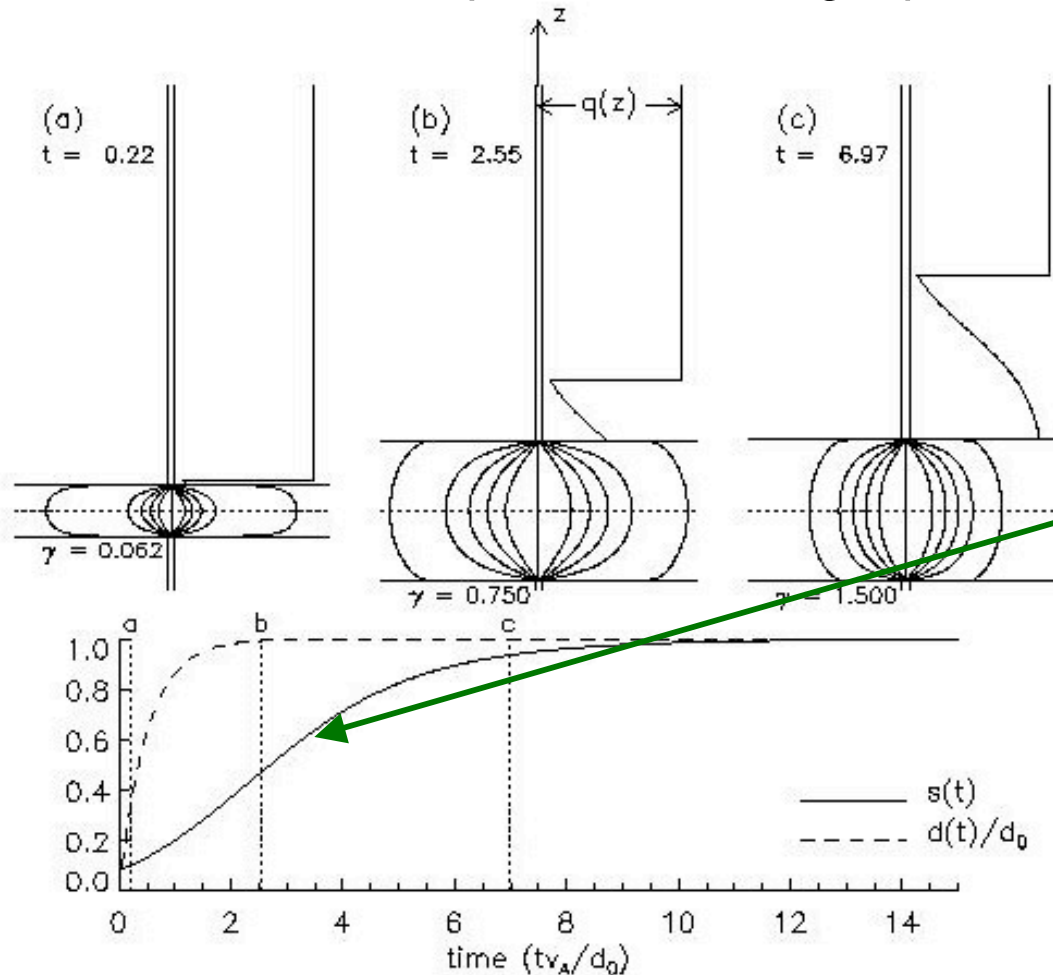


- Twist propagates into corona
- Twist-rarefaction waves propagates inward to CZ



# Spin from Emergence

simple model: Longcope & Welsch 1998



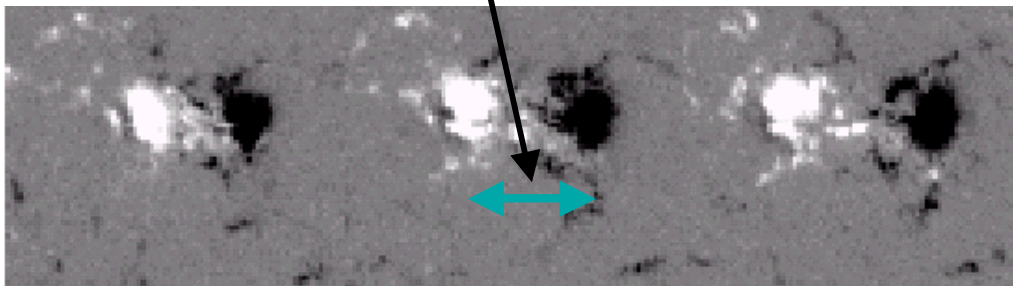
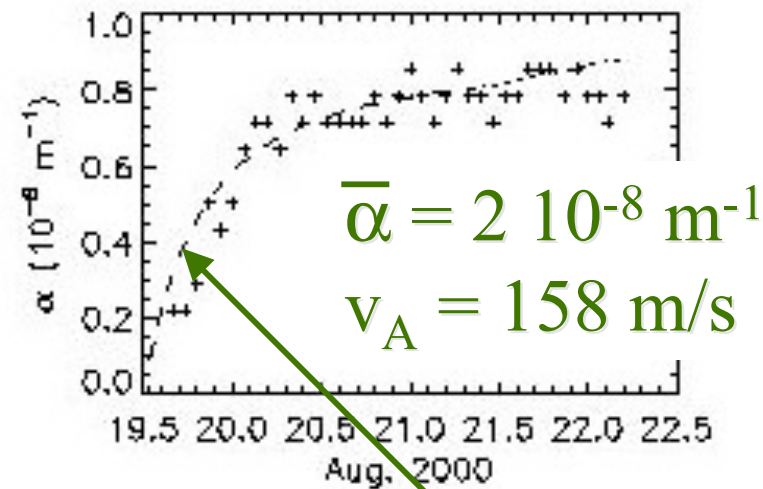
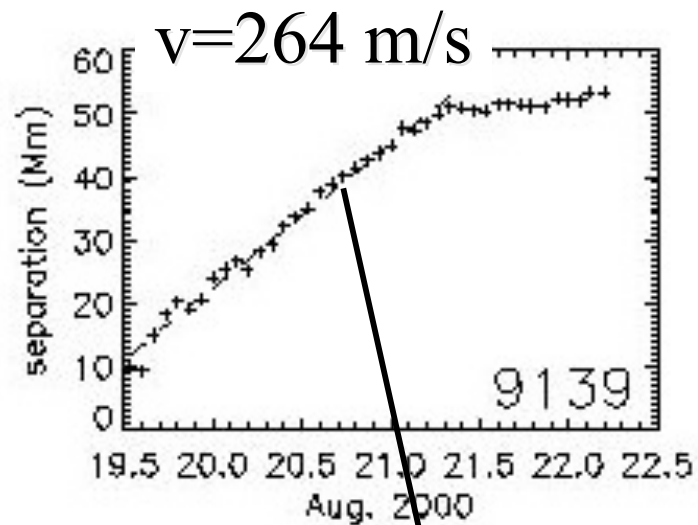
- Twist propagates into corona
- Twist-rarefaction waves propagates inward to CZ
- Characteristic time-scale for adjustment:

$$d/v_A \sim 1 \text{ day}$$

# Spin from Emergence

Observation: Pevtsov, Maleev & Longcope 2003

## Fit Model to Data

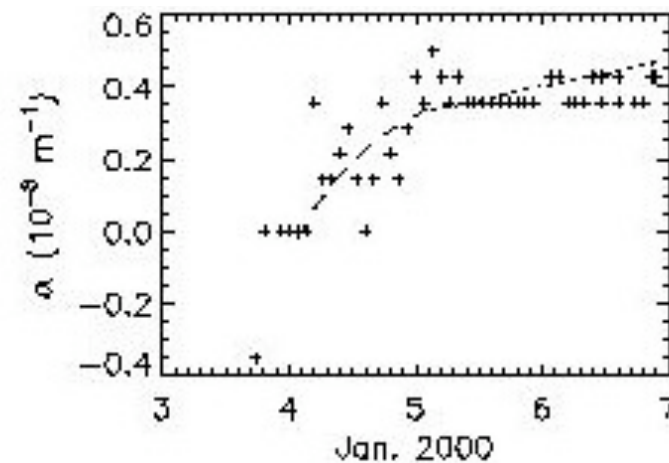
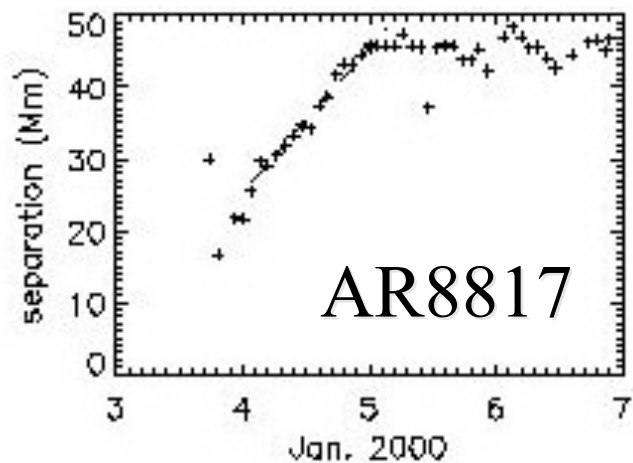
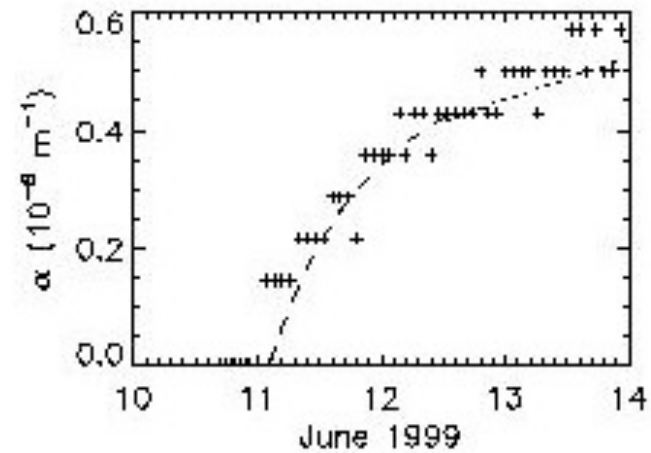
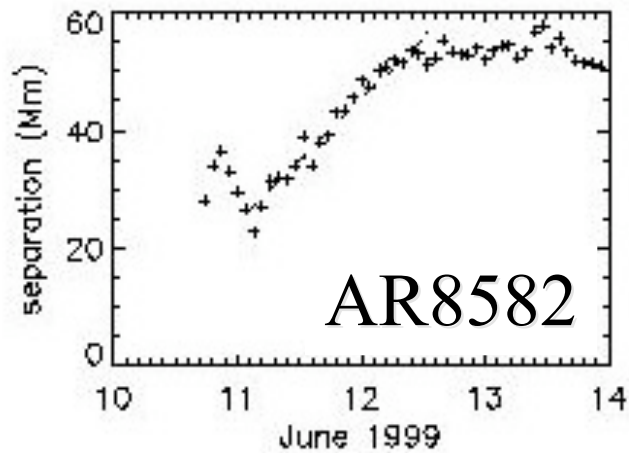


Bangalore, India

$$\alpha(t) = \bar{\alpha} \frac{v}{v+1} \left[ 1 - \left( \frac{d}{d_0} \right)^{-(v+1)} \right]$$

# Spin from Emergence

Observation: Pevtsov, Maleev & Longcope 2003



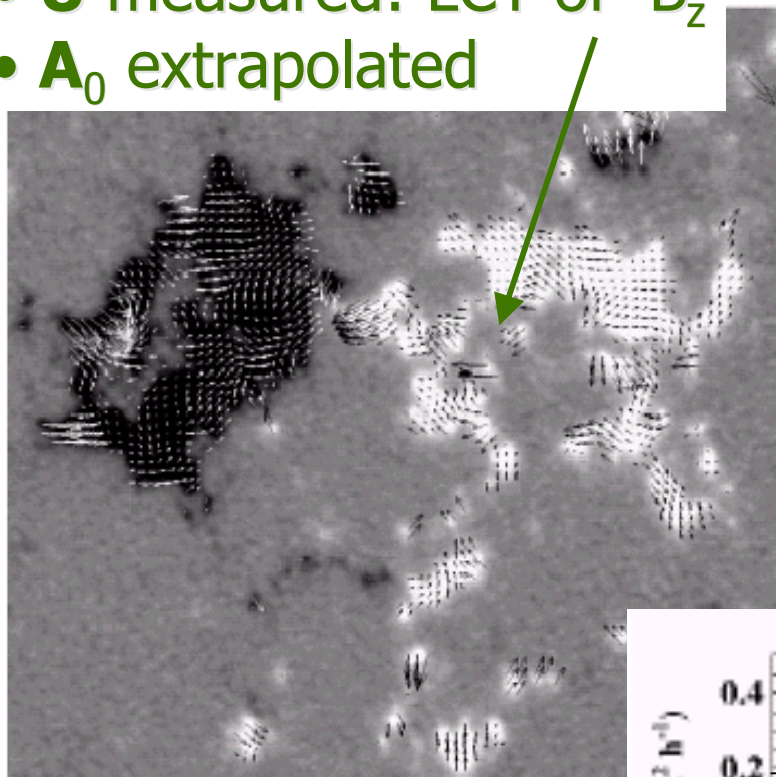
Dec. 2, 2008  
Bangalore, India

# Measured Velocity

$B_z$  measured: LOS mg

•  $\mathbf{U}$  measured: LCT of  $B_z$

•  $\mathbf{A}_0$  extrapolated

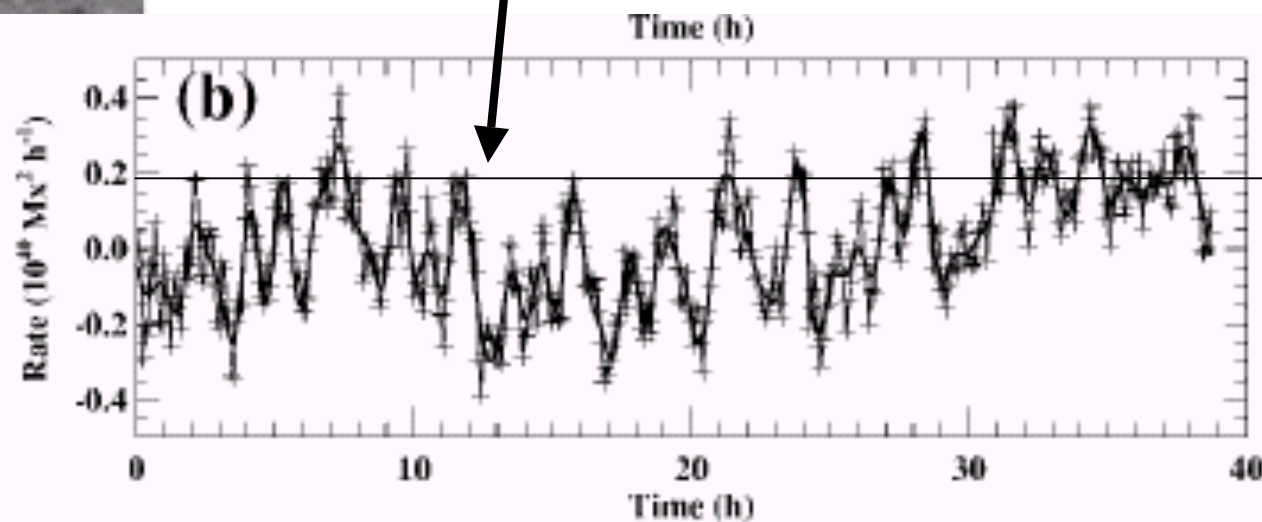


(Chae 2001)

$$\frac{dH_R}{dt} = -2 \int_{z=0} (\mathbf{U} \cdot \mathbf{A}_0) B_z ds$$

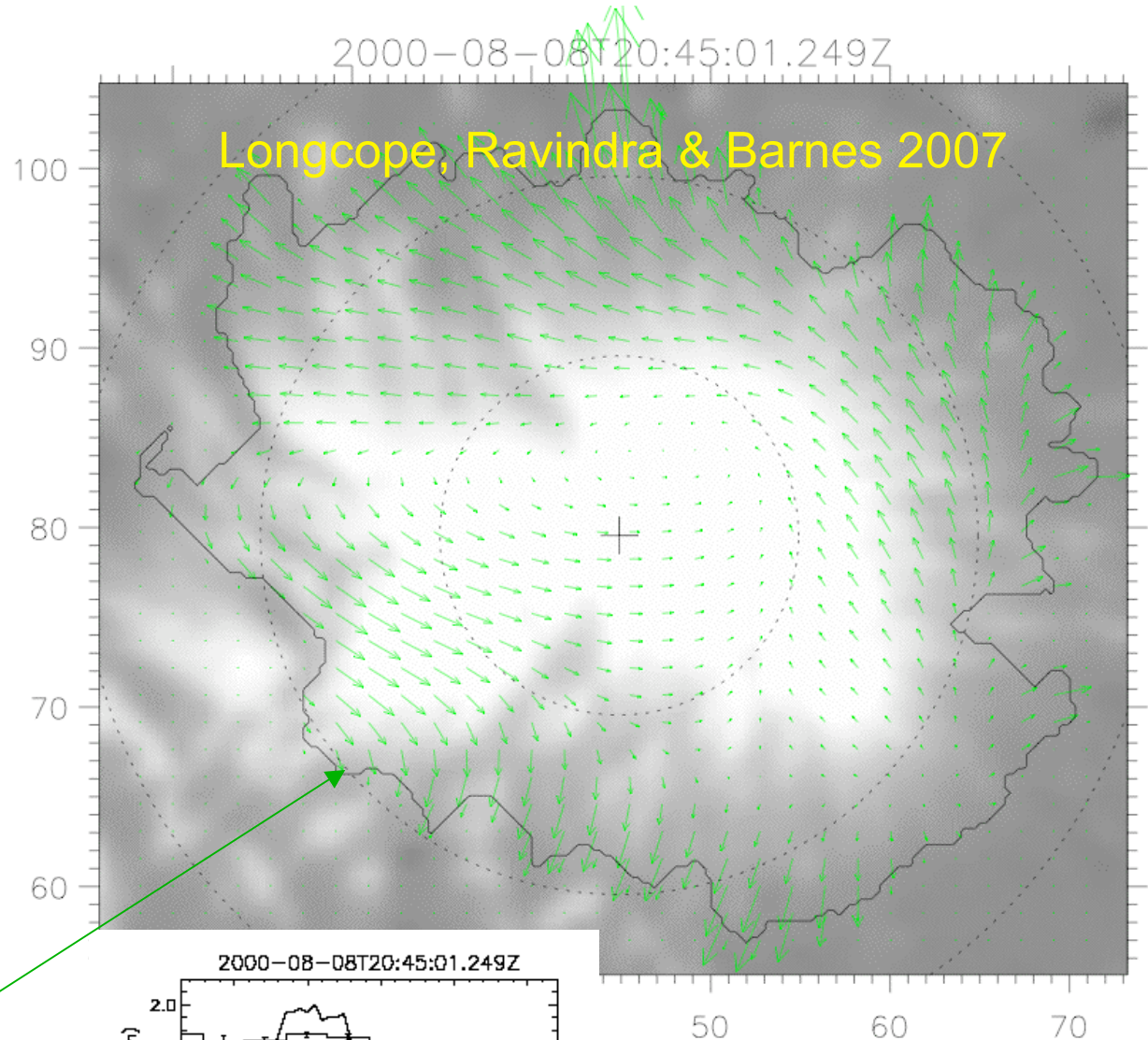
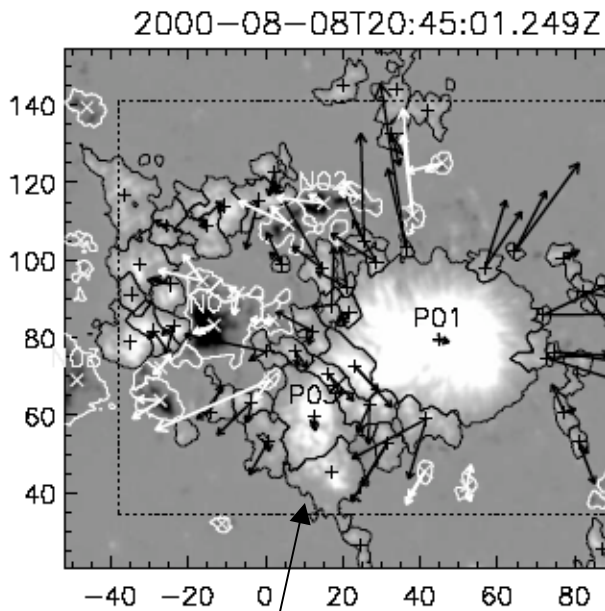
$$= +3 \times 10^{40} \text{ Mx}^2/\text{day}$$

$$= \Phi^2 10^{-2}/\text{day}$$



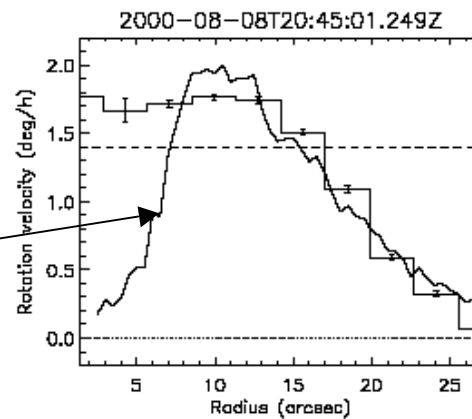


# Measuring Spin



- partition m-gram
- $\mathbf{v}(\mathbf{x})$  from LCT
- cf WL rotation from Brown *et al.* 2003

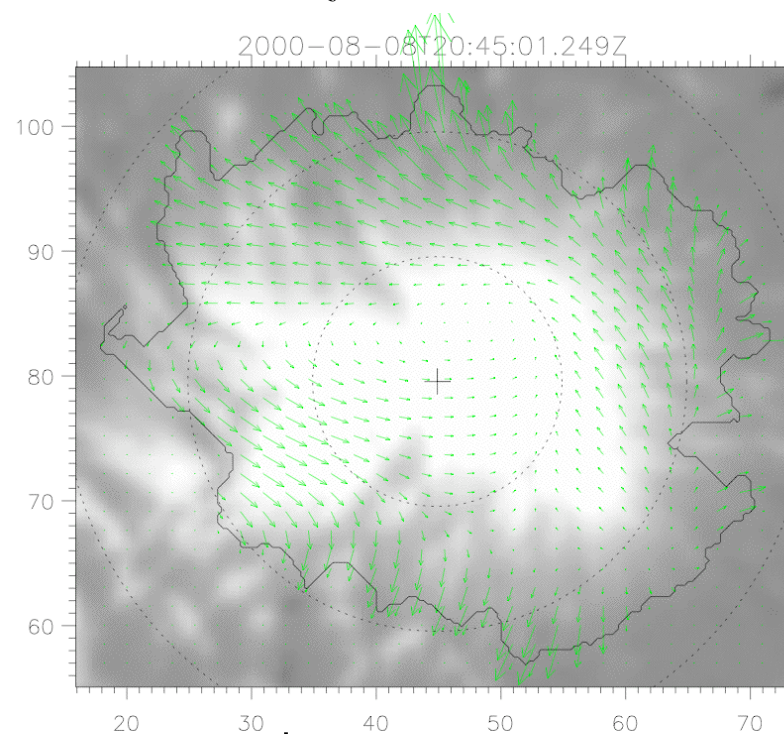
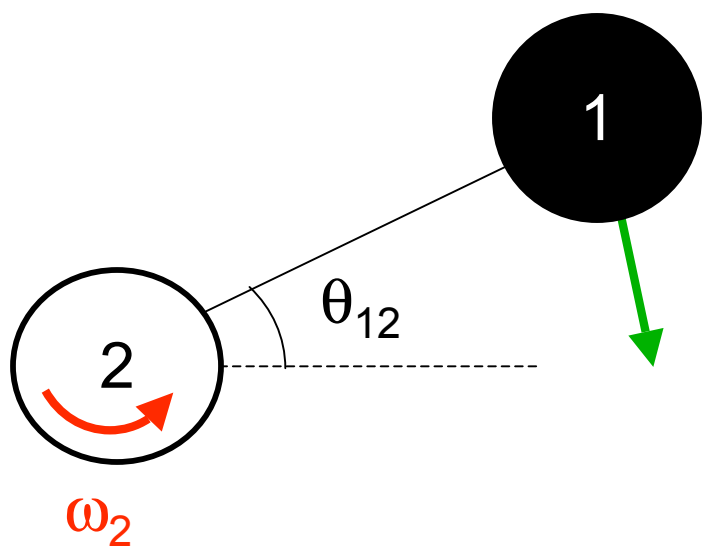
Dec. 2, 2008  
Bangalore, India



# Measuring Spin

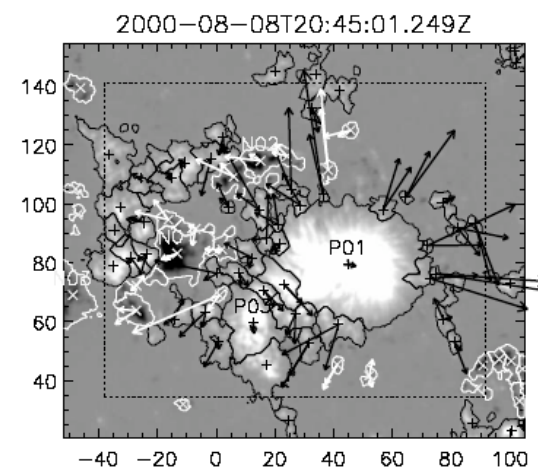
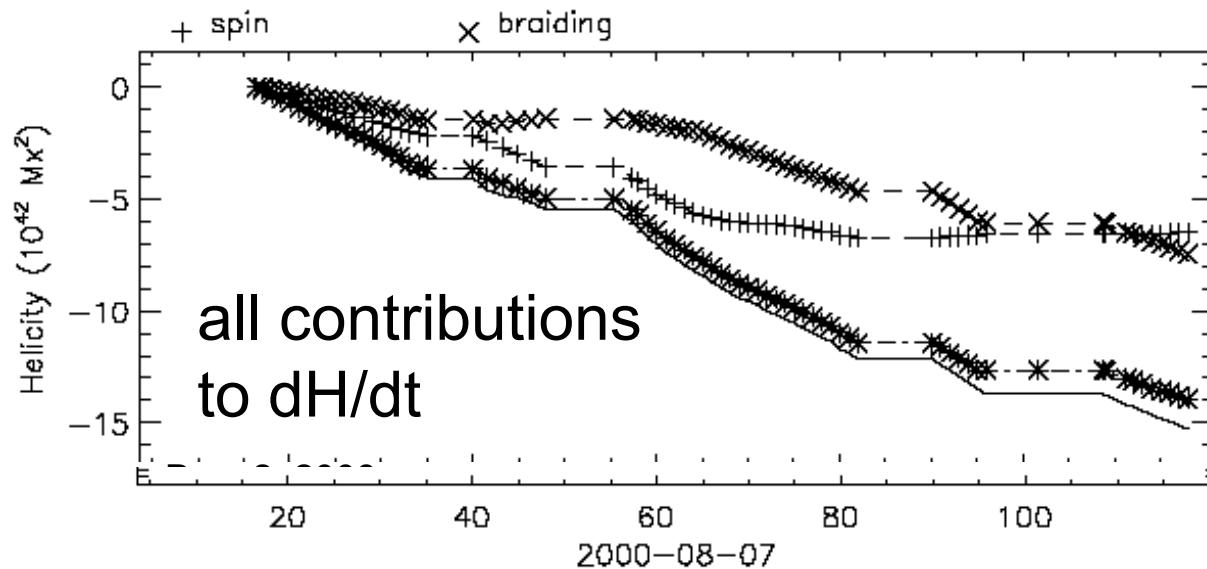
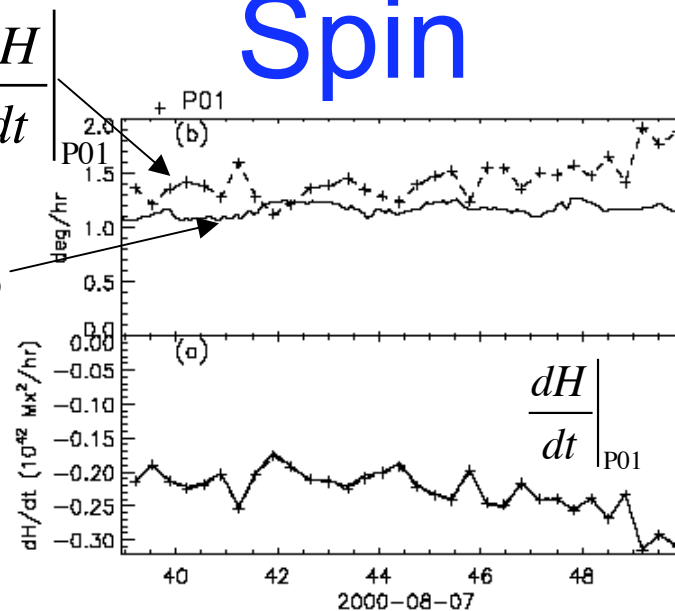
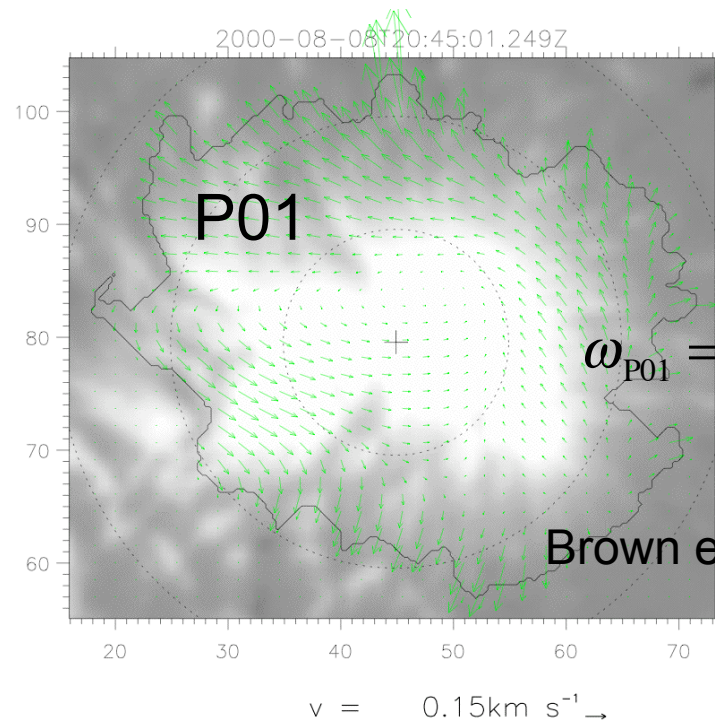
$$\frac{dH}{dt} = \underbrace{\sum_a \left( -\frac{\Phi_a^2}{2\pi} \omega_a \right)}_{\text{spin}} - \underbrace{\sum_{a,b} \frac{\Phi_a \Phi_b}{2\pi} \frac{d\theta_{ab}}{dt}}_{\text{braiding}}$$

$$\frac{dH}{dt} = -2 \int_{z=0} (\mathbf{v} \cdot \mathbf{A}_0) B_z dx dy$$

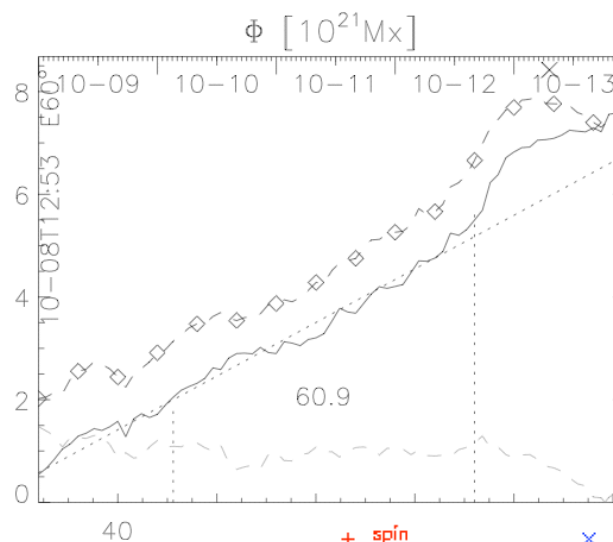
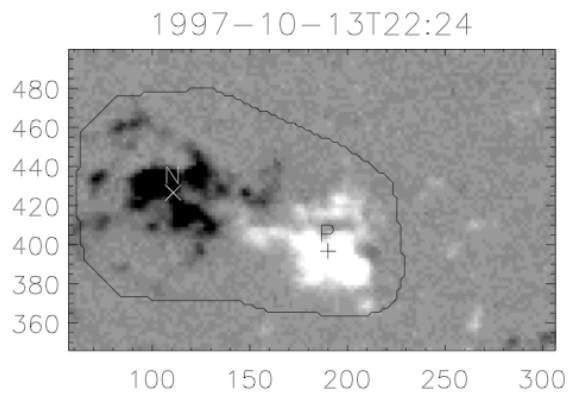


$$\omega_a = - \left. \frac{2\pi}{\Phi_a^2} \frac{dH}{dt} \right|_a \quad v = 0.15 \text{ km s}^{-1} \rightarrow$$

# Measuring Spin

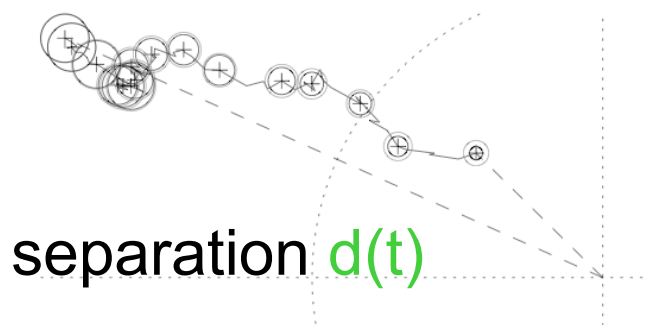




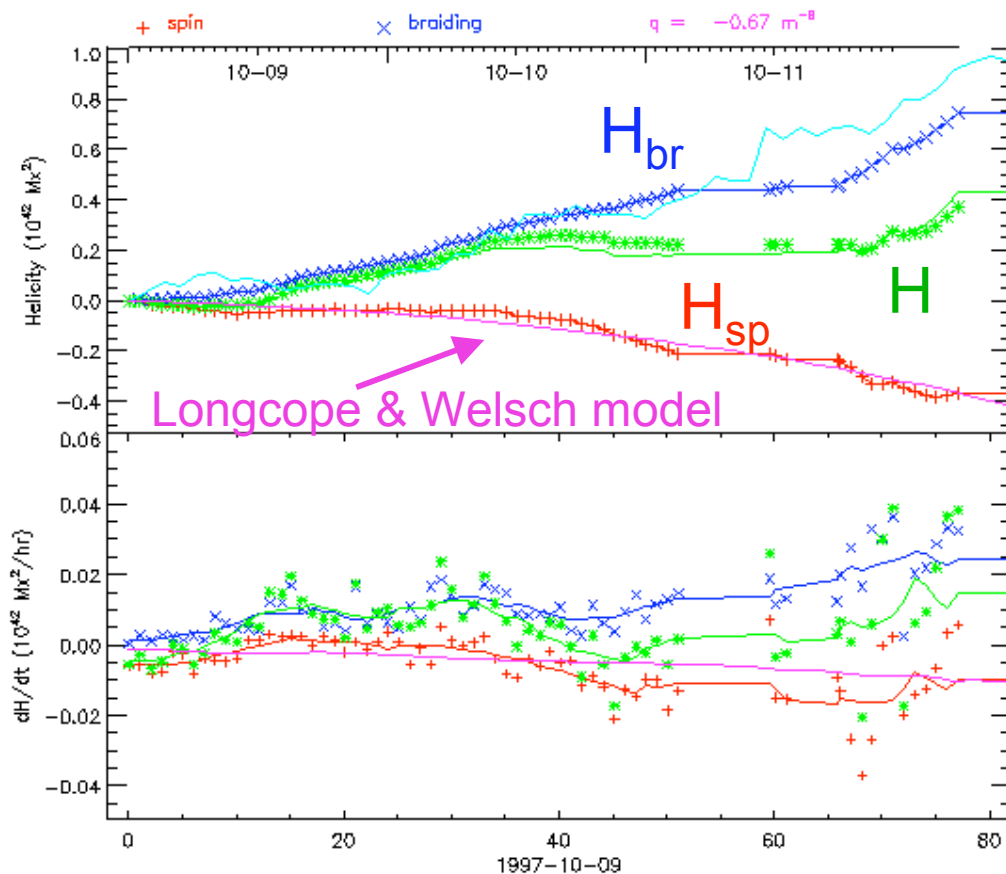


fit:

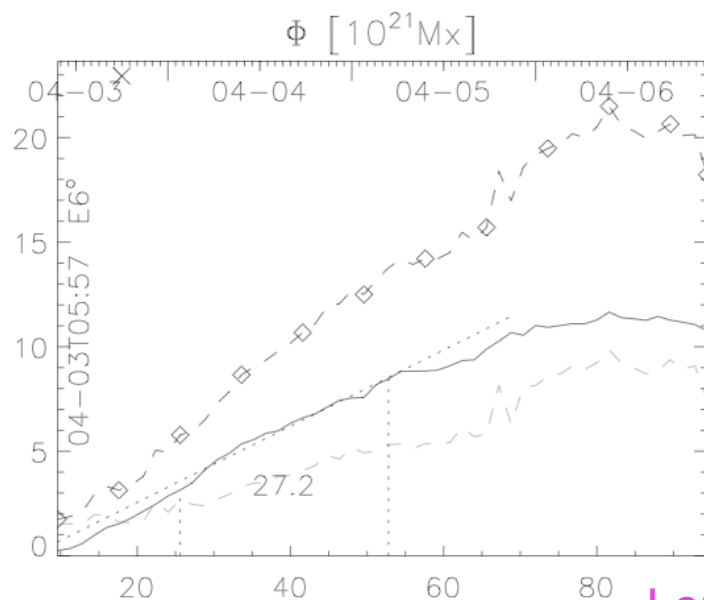
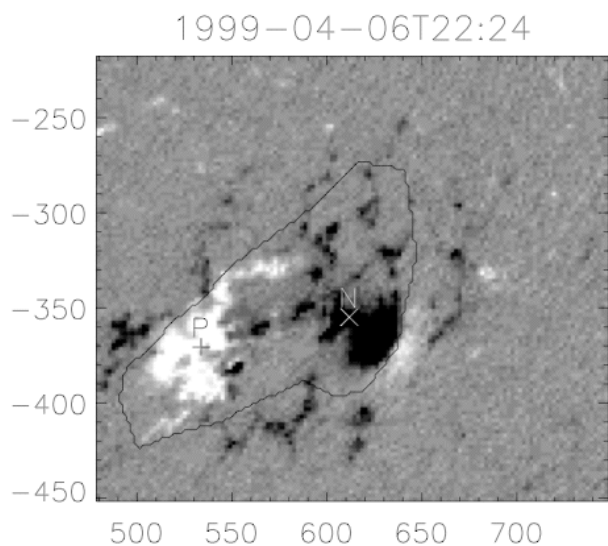
$$q = -0.67 \times 10^{-8} \text{ m}^{-1}$$



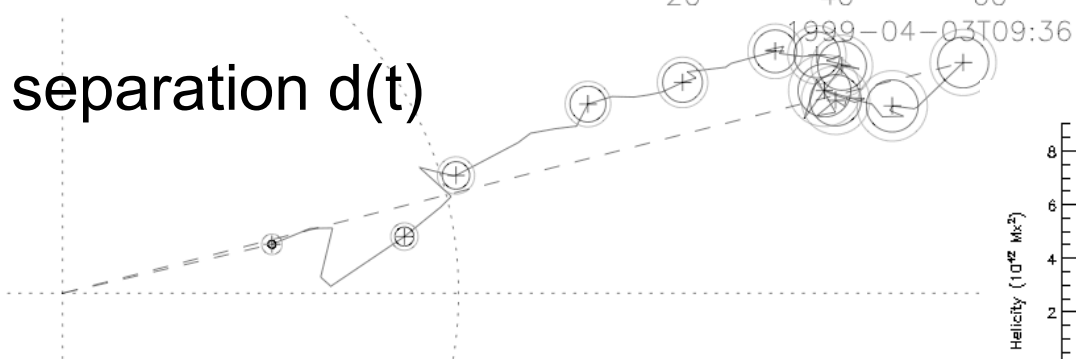
- Helicity dominated by braiding
- Northern AR:
  - $H > 0$
  - $H_{sp} < 0$



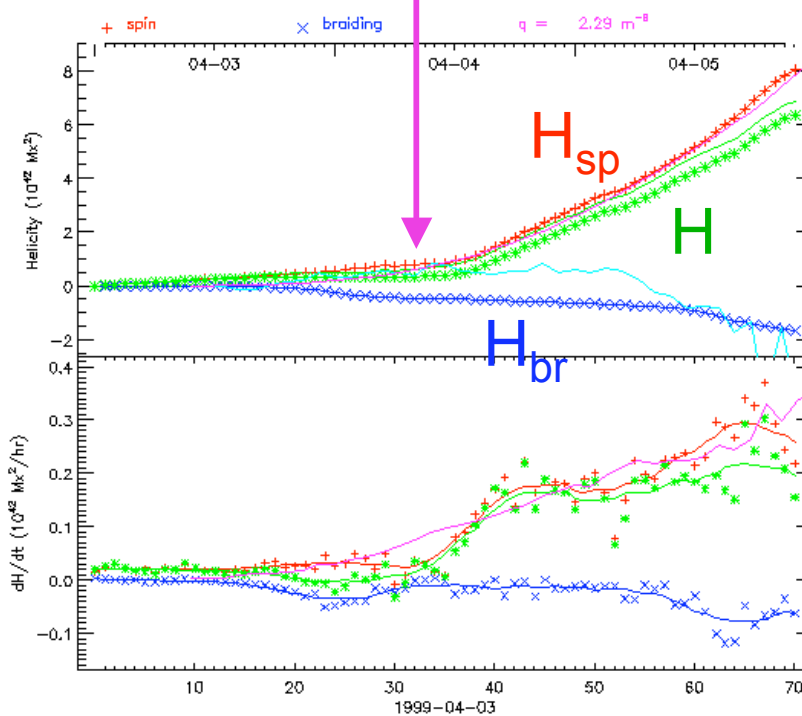
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Bangalore, India



fit:  
 $q = +2.3 \times 10^{-8} \text{ m}^{-1}$



Longcope & Welsch model



- Helicity dominated by spin

- Southern AR:

$$H > 0$$

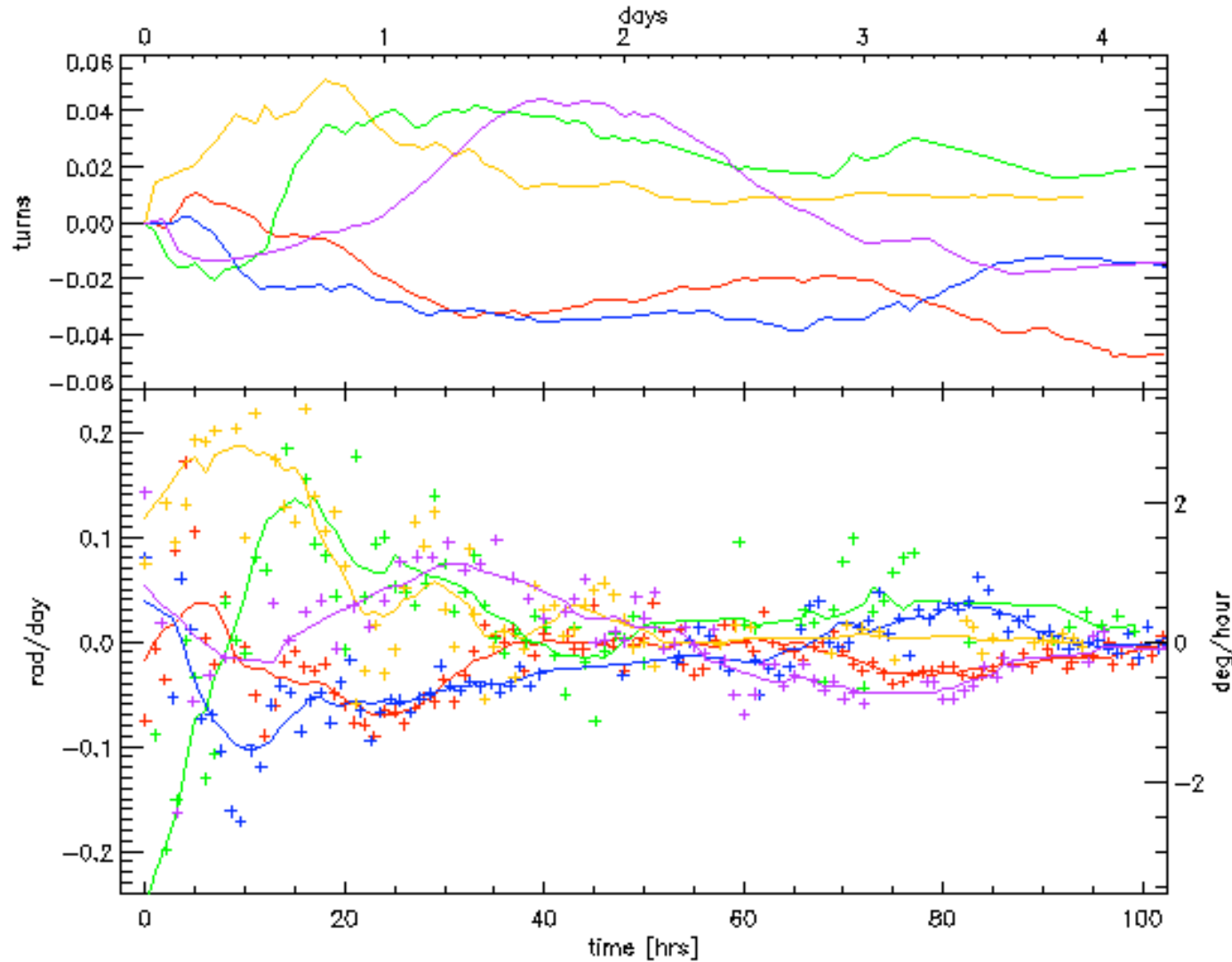
$$H_{sp} > 0$$

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# Helicity Injection



AR9139      AR8093      AR8968      AR8757      AR8582



Dec.  
Banç

# Long term helicity injection



AR	$\Delta t$ (hrs)	$\Delta H/\Phi^2$	$\langle dH/dt \rangle$ ( $10^{-2} \text{ day}^{-1}$ )	ref
8011	40	0.003	0.18	Chae (2001)
8100	120	0.02	0.4	Kusano et al. (2002)
8668	50	0.03	1.4	Chae et al. (2001)
9165	80	0.2	6.0	Nindos & Zhang (2002)
10365	120	0.05	1.0	Chae, Moon & Park (2004)
10696	132	0.02	0.4	Lim et al. (2007)

Dec. 2, 2008 (from van Driel-Gesztelyi, Demoulin & Mandrini, 2003)  
Bangalore, India

# Helicity Flux in ARs

$$\frac{dH}{dt} = \Omega \Phi^2 = \frac{\omega}{2\pi} \Phi^2$$

- Differential rotation:

- Th. (DeVore 2000):  $\Omega \sim 3 \times 10^{-3}/\text{day}$

- Obs. (Demoulin *et al* 2002)  $\Omega \sim 3 \times 10^{-4}$

- Proper motions: (observations)

- LCT (van Driel-Gesztelyi *et al.* 2003)  $\Omega \sim 10^{-2}$

- Sunspot rotation (Brown *et al* 2003)  $\Omega \sim 10^{-1}$

# Summary

- ARs created by emergence of flux tubes
- Tubes consist of twisted flux -- twisted by turbulence during rising ( $\Sigma$ -effect)
- Helicity of twist propagates into corona
- Observed proper motions (rotating sunspots) consistent with twist propagation