Magnetic Activity on the Sun Revealed by Hinode/SOT

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Observational MHD from SOT

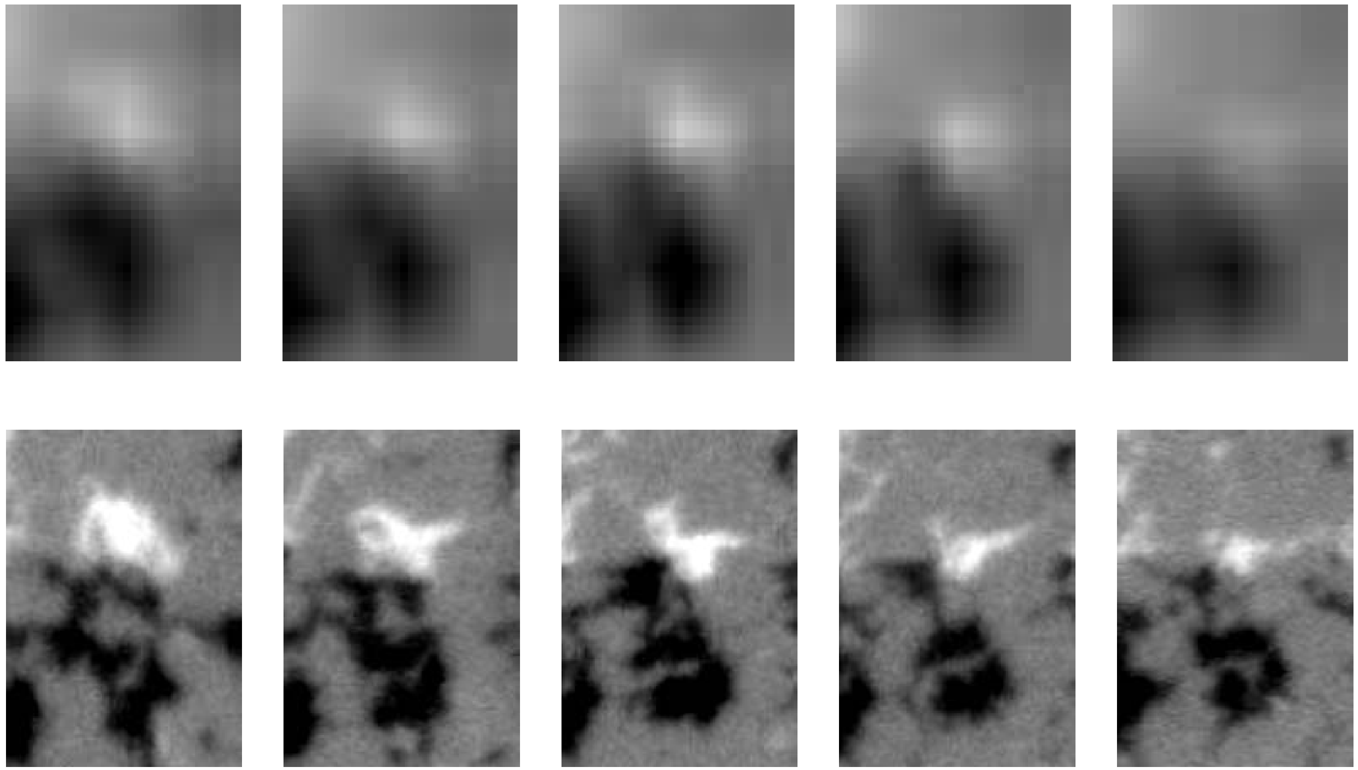
- Entering a new era of observational MHD
  - Seeing-free, high resolution
  - Stability and durability
  - Polarization-optimized design
- Observational MHD is to precisely measure
  - Magnetic fields $\boldsymbol{B}$
  - Velocity fields $\boldsymbol{v}$
  - at different atmospheric levels
- Better understand magnetic activity

What to talk about

1. SOT measurement of magnetic flux and physics of canceling magnetic features
2. SOT measurements of transverse velocity fields and physics of turbulent magnetic diffusivity
3. SOT observations of flows in a prominence and physics of plasma support: dynamic or magnetic?

1. SOT measurement of magnetic flux and physics of canceling magnetic features

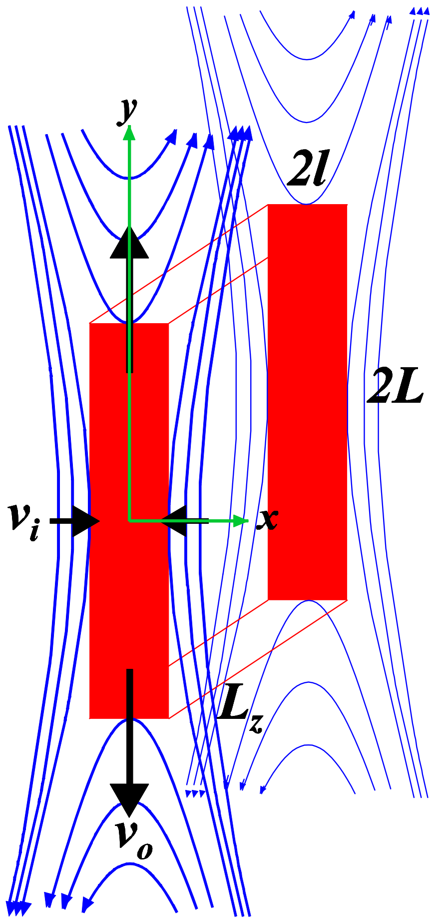
Canceling Magnetic Features



[MDI]

[SOT/NFI]

Rates of flux cancellation

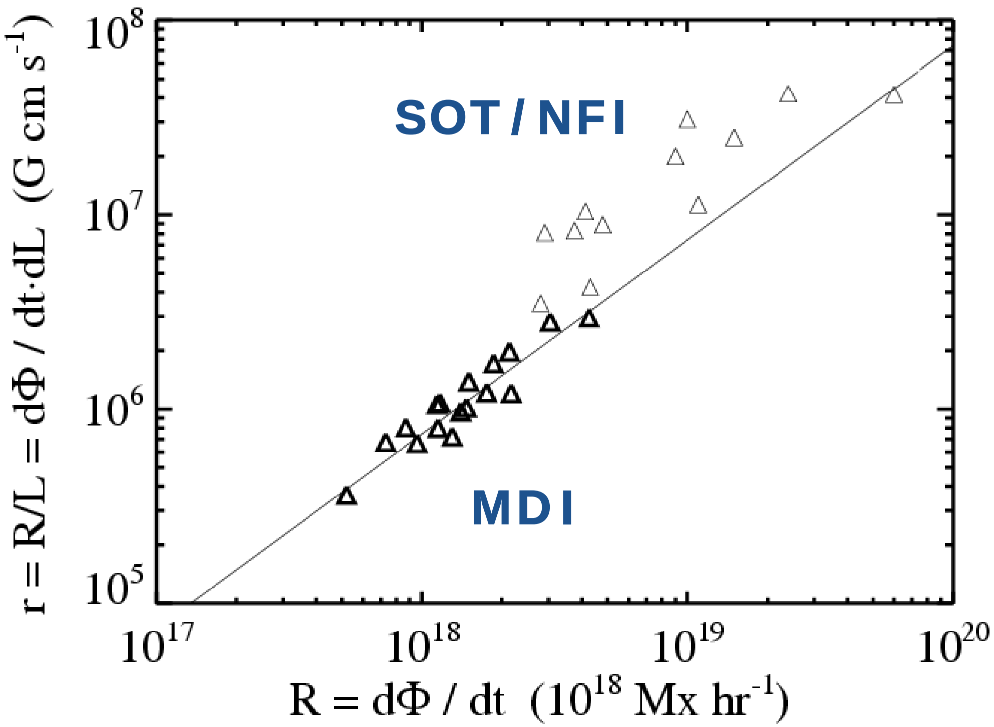


- Rate of flux cancellation: R
- Specific rate of flux cancellation: r

$$R \equiv \frac{d\Phi}{dt} = L_z v_i B_i = L_z cE$$

$$r \equiv \frac{d\Phi}{L_z dt} = v_i B_i = v_o B_o = cE$$

Rates of flux cancellation



- Median values of ***R***
  - MDI: $1.5\ 10^{18}$ Mx hr^{-1}
  - NFI: $9.0\ 10^{18}$ Mx hr^{-1}
- Median values of ***r***
  - MDI: 10^{6} G cm s^{-1}
  - NFI: 10^{7} G cm s^{-1}

Rates of flux cancellation

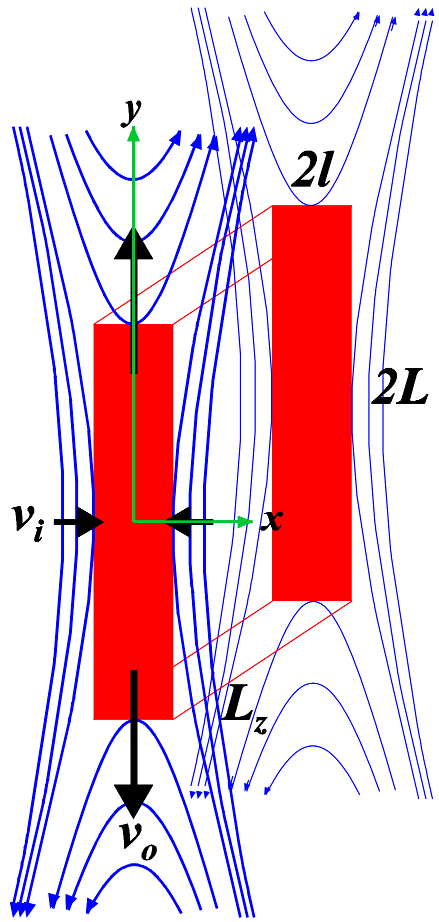
- Adiabatic current sheet model (Chae et al. 2003)

$$v_i = r^{1/3} f^{1/3} \eta_c^{1/3} (4\pi\rho_i)^{-1/3} L^{-1/3}$$

$$B_i = r^{2/3} f^{-1/3} \eta_c^{-1/3} (4\pi\rho_i)^{1/3} L^{1/3}$$

$$M_{Ai} = r^{-1/3} f^{2/3} \eta_c^{2/3} (4\pi\rho_i)^{1/6} L^{-2/3}$$

- Higher values of r requests us to reconsider the physics of reconnection



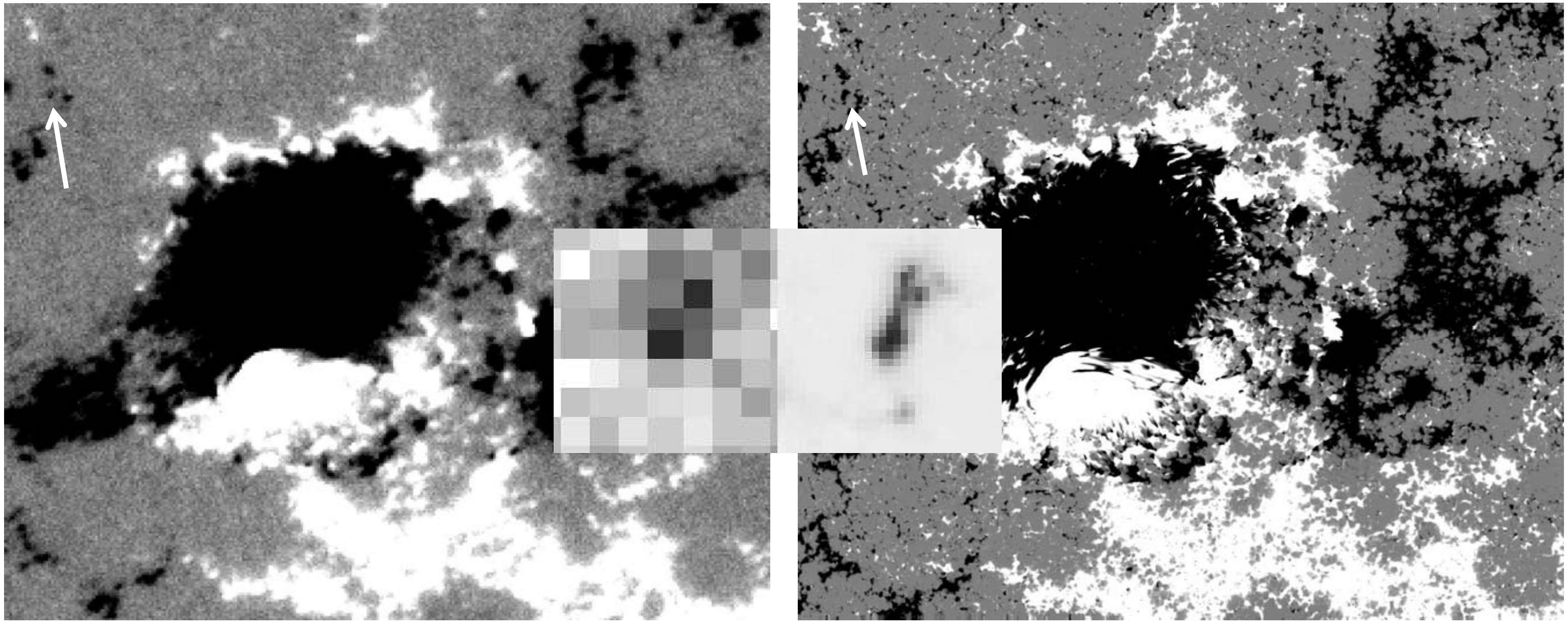
Why much higher than before?

- Sampling: 1.2
- Contact length measurement: 1.7
  - MDI length/SOT length = 10/6=1.7
- Flux measurement: 5
  - Flux density Calibration: 2.1=1.3x1.6
    - NFI data: cross-calibrated in reference to the COG calibration of SP data
    - SP(COG) value / SP(ME) value = 1.3
    - SP(ME) value / MDI value = 1.6
  - Spatial resolution and filling factor: affect field strength much, but little flux
  - Sensitivity: affect flux measurements

MDI and SP Flux measurements

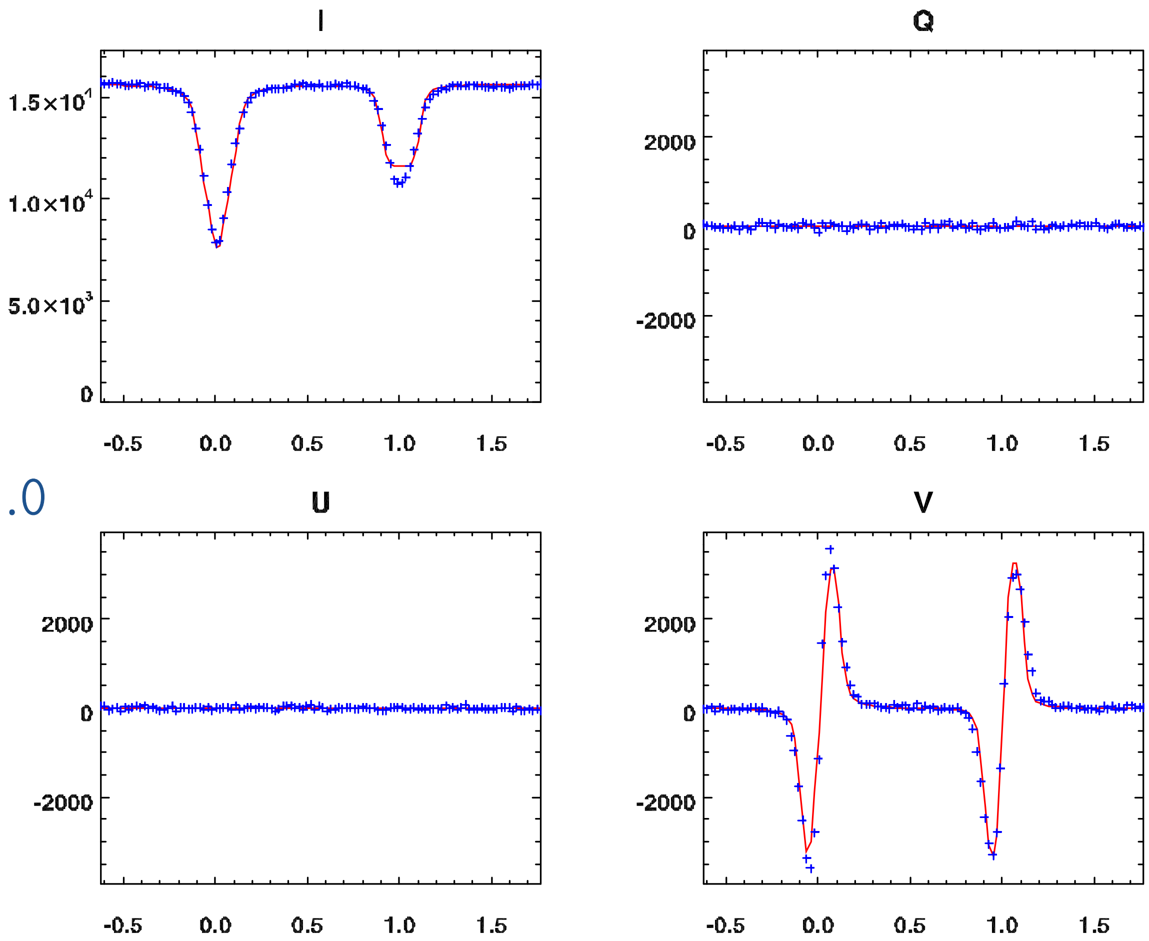
MDI HR

SOT / SP

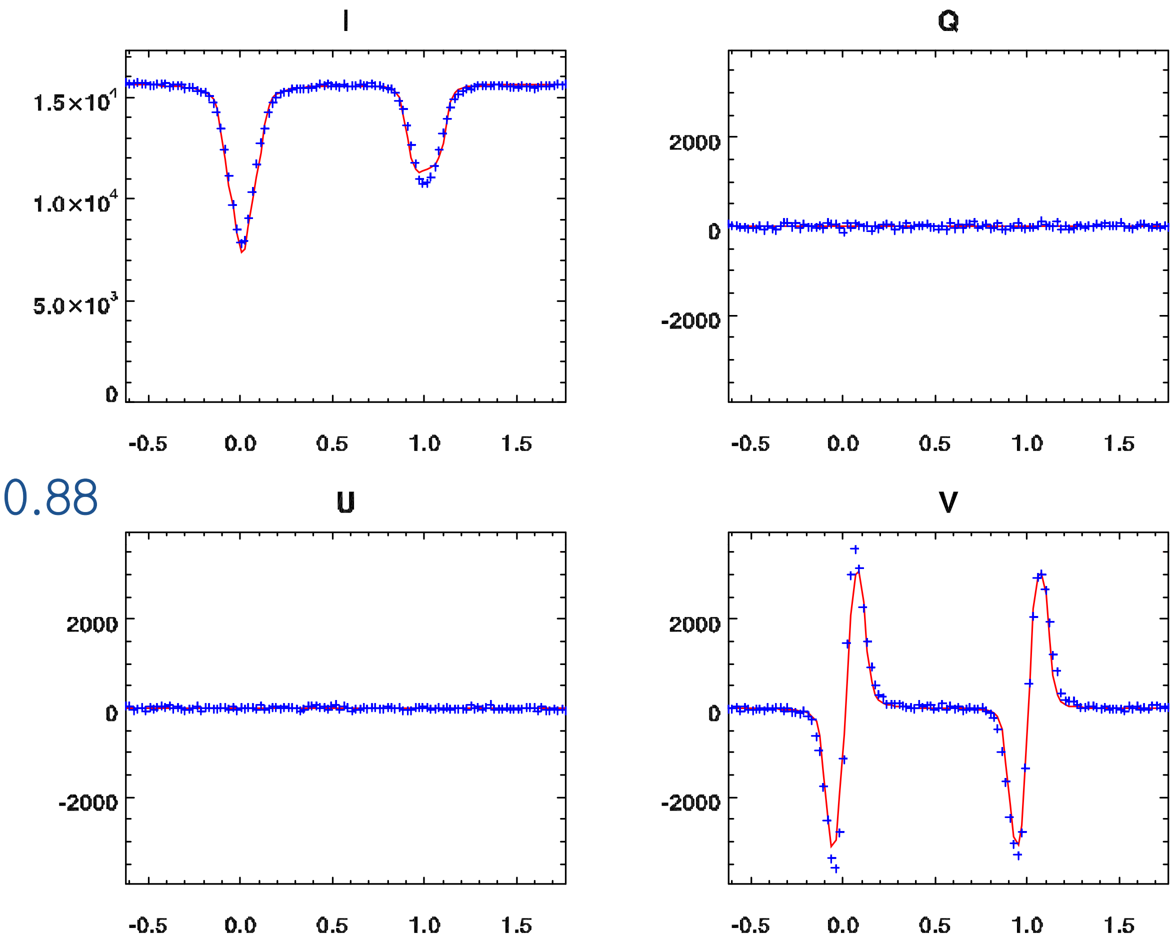


ta

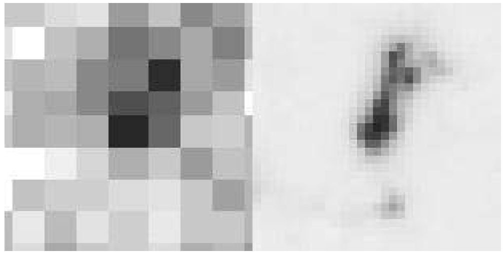
Bl = −1153 G, f=1.0

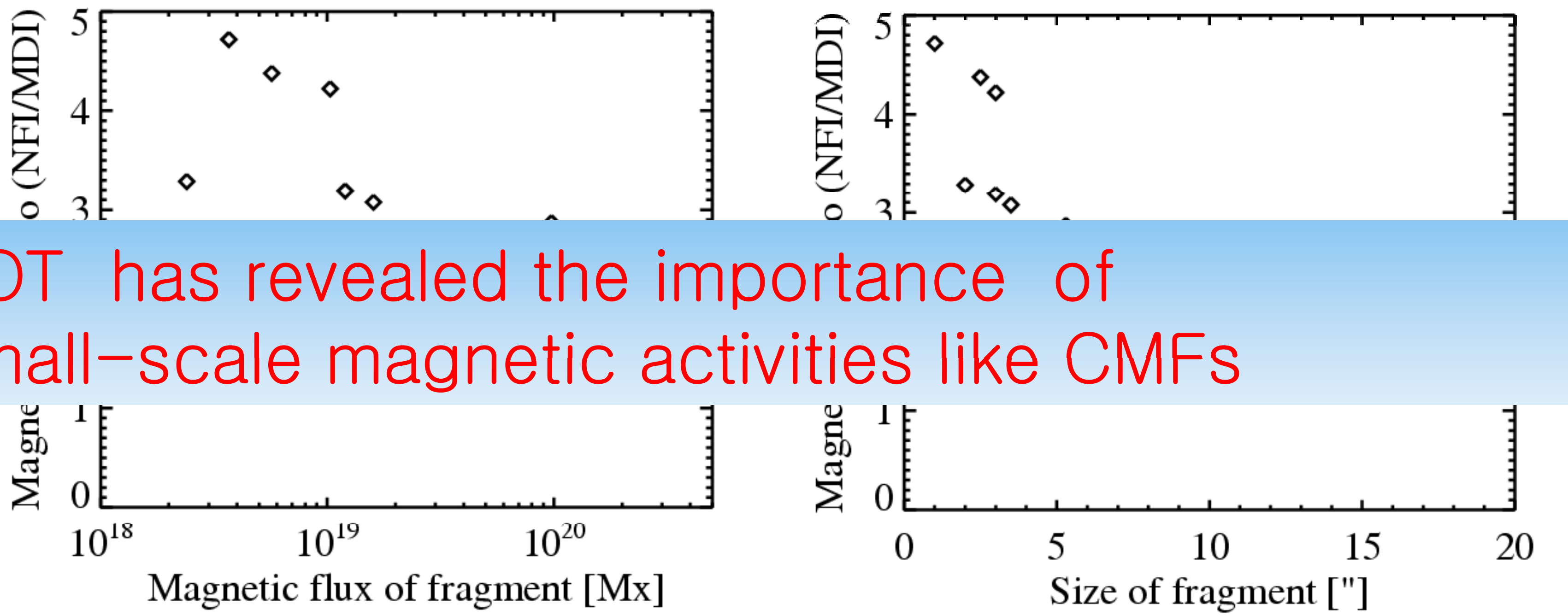


Bl = −1262 G, f=0.88



- Peak line-of-sight field strength
  - MDI HR: -86 G
  - SOT/SP: -1153 G (ME without filling factor), -1226 G (ME with filling factor), -1320 G (COG)
- Negative magnetic flux
  - MDI HR: -3 10^{18} Mx
  - SOT/SP: -9 10^{18} Mx (ME without filling factor), -12 10^{18} Mx (COG)

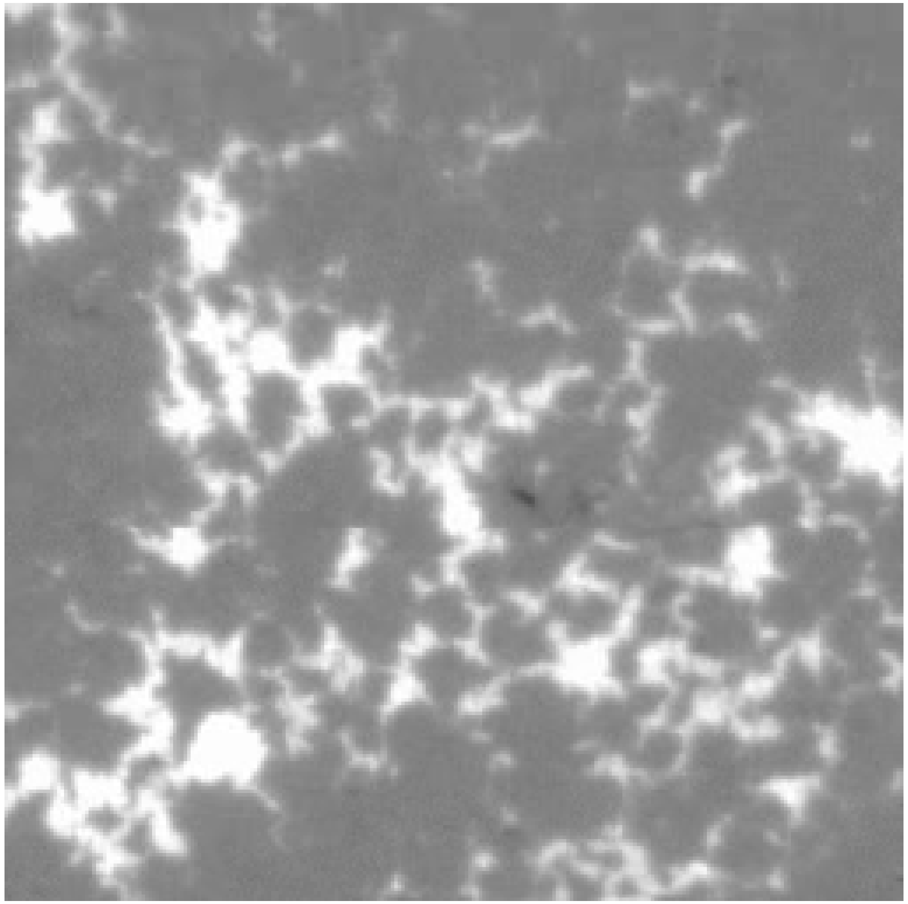




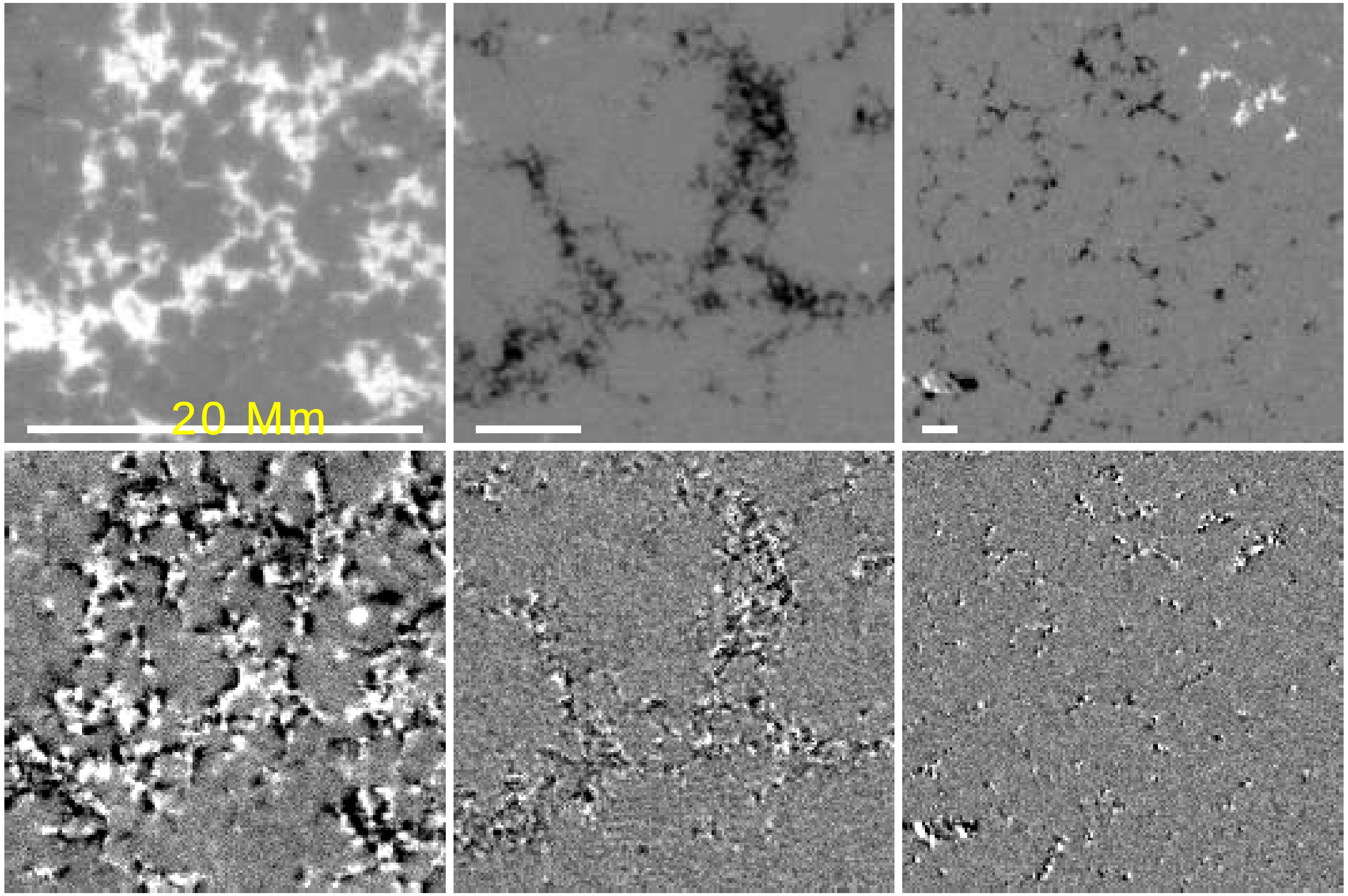
SOT has revealed the importance of small-scale magnetic activities like CMFs

* NFI data were cross-calibrated in reference to the COG calibration of SP data

2. SOT measurements of transverse velocity fields and physics of turbulent magnetic diffusivity



Introduction



Hinode SOT
(0.16”, 10min)

MDI HR
(0.61”,20min)

MDI FD
(2.0”, 96min)

Modeling of magnetic field change

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B} - \eta \nabla \times \boldsymbol{B})$$

$$\frac{\partial B_n}{\partial t} + \nabla_t \cdot (\boldsymbol{u} B_n) = \eta \nabla_t^2 B_n$$

$$\boldsymbol{u} B_n = \boldsymbol{v}_t B_n - v_n \boldsymbol{B}_t$$

- Both $\boldsymbol{v}$ (or $\boldsymbol{u}$) and η represents plasma motion
  - $\boldsymbol{v}$ (or $\boldsymbol{u}$) ~ resolved motion, η ~ diffusion due to unresolved random motion
  - Practical definitions of these depend on a chosen length scale

Optical flow technique: NAVE

- Model equations
  - Induction equation

$$\frac{\partial B_n}{\partial t} + \nabla_t \cdot (\boldsymbol{u} B_n) = \eta \nabla_t^2 B_n$$

  - Affine velocity model

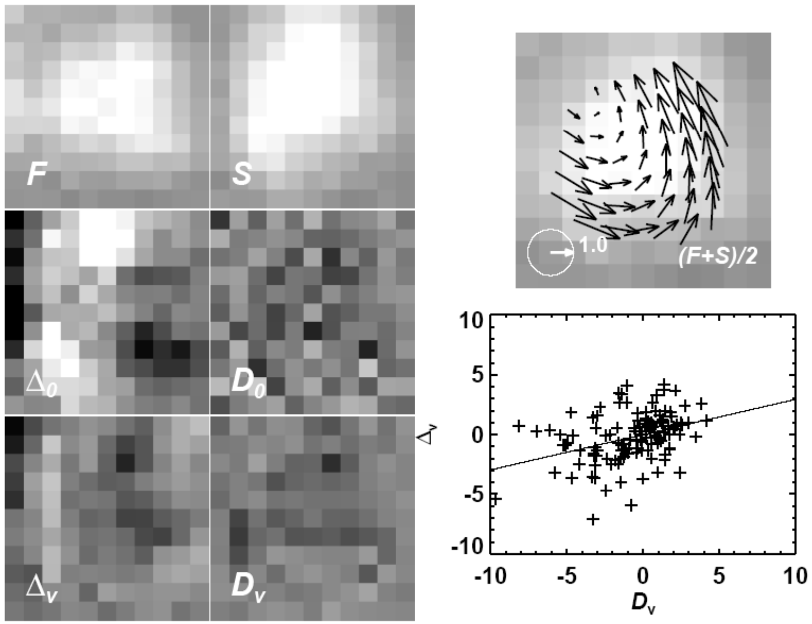
$$\begin{aligned} u_x &= U_0 + U_x \cdot (x - x_0) + U_y \cdot (y - y_0) \\ u_y &= V_0 + V_x \cdot (x - x_0) + V_y \cdot (y - y_0) \end{aligned}$$

- Seven free parameters

Non-linear Affine Veloicty Estimatro (NAVE)

$$e^{-\nu/2}S(\boldsymbol{x}+\frac{1}{2}\boldsymbol{d})-e^{\nu/2}F(\boldsymbol{x}-\frac{1}{2}\boldsymbol{d})=\frac{1}{2}\eta\left[e^{-\nu/2}\nabla_t^2 S(\boldsymbol{x}+\frac{1}{2}\boldsymbol{d})+e^{\nu/2}\nabla_t^2 F(\boldsymbol{x}-\frac{1}{2}\boldsymbol{d})\right]$$

$$\boldsymbol{d}=[U_0+U_x\cdot(x-x_0)+U_y\cdot(y-y_0),V_0+V_x\cdot(x-x_0)+V_y\cdot(y-y_0)]$$



(NAVE; Chae et al. 2008a, b)

$$\Delta_0 \equiv S(\boldsymbol{x})-F(\boldsymbol{x})$$

$$D_0 \equiv \frac{1}{2}[\nabla_t^2 S(\boldsymbol{x})+\nabla_t^2 F(\boldsymbol{x})]$$

$$\Delta_v \equiv e^{-\nu/2}S(\boldsymbol{x}+\frac{1}{2}\boldsymbol{d})-e^{\nu/2}F(\boldsymbol{x}-\frac{1}{2}\boldsymbol{d})$$

$$D_v \equiv \frac{1}{2}\left[e^{-\nu/2}\nabla_t^2 S(\boldsymbol{x}+\frac{1}{2}\boldsymbol{d})+e^{\nu/2}\nabla_t^2 F(\boldsymbol{x}-\frac{1}{2}\boldsymbol{d})\right]$$

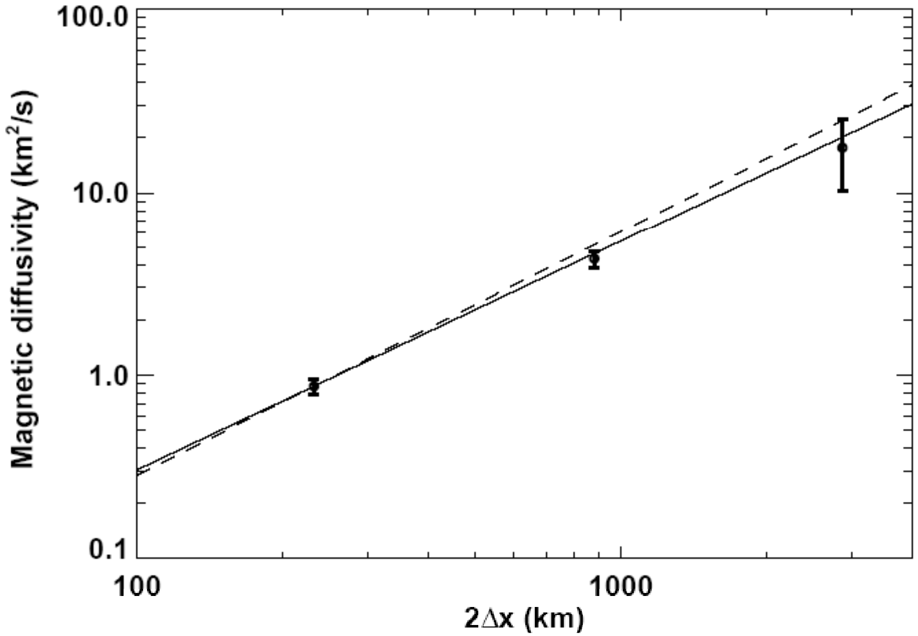
$$\eta = 0.30 \text{ pixel}^2/\text{step} = 6.6 \text{ km}^2 \text{ s}^{-1}$$

Results

Method / Data	Diffusivity $km^2 s^{-1}$	Scale	Ref.
Ohmic value	0.07	MHD scale	Kubat & Karlicky (1986)
Hinode SOT	0.87	0.23 Mm	Present study
MDI High Res.	4.4	0.88 Mm	Present study
MDI Full-disk	18	2.8 Mm	Present study
Random walk	60	>granule	Berger et al.(1998)
Random walk	200	>supergranule	Schrijver & Zwan (2000)
Large-scale Pattern	600	Hemisphere	Sheeley (1992)

Results

- Turbulent diffusivity



  - Kolmogorov model

$$\eta_t \simeq \epsilon^{1/3} l^{4/3}$$

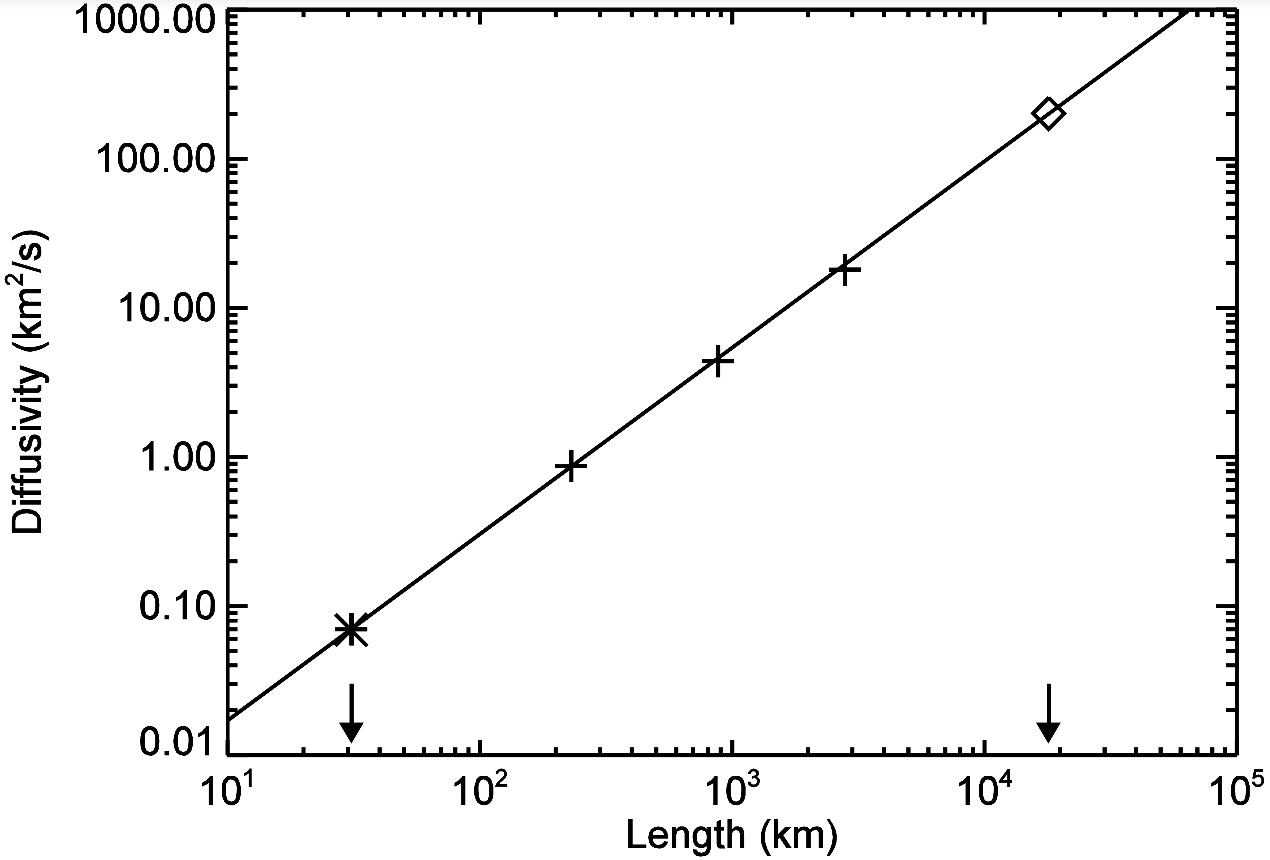
  - Iroshnikov-Kraichnan model

$$\eta_t \simeq (\epsilon v_A)^{1/4} l^{5/4}$$

$$\eta \simeq \left(\frac{l}{260\ \mathrm{km}}\right)^{5/4} \mathrm{km}^2\ \mathrm{s}^{-1}$$

$$\tau = \frac{l^2}{\eta} \approx 20\left(\frac{l}{260\ \mathrm{km}}\right)^{3/4}\ \mathrm{hr}$$

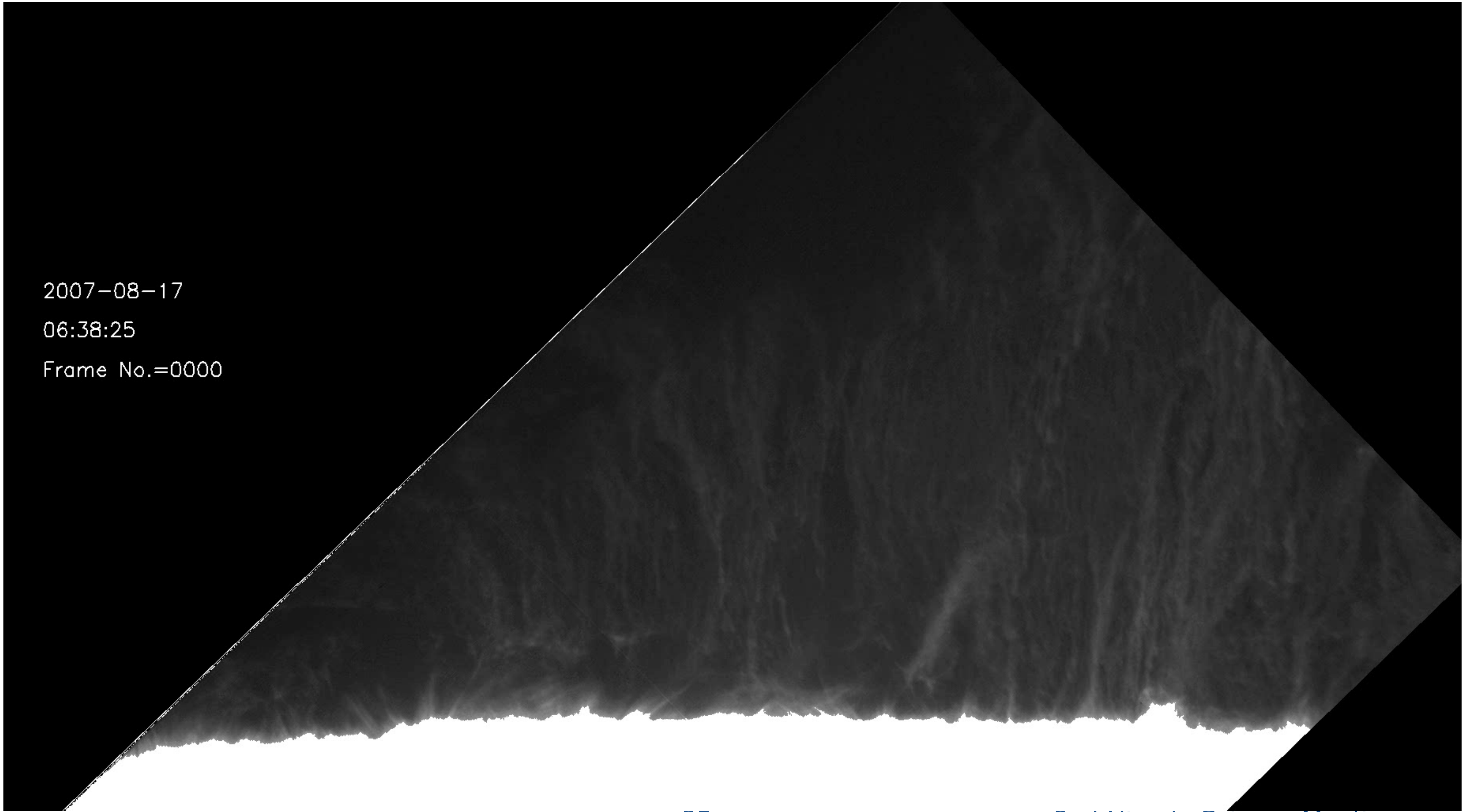
Extrapolation of the spectrum



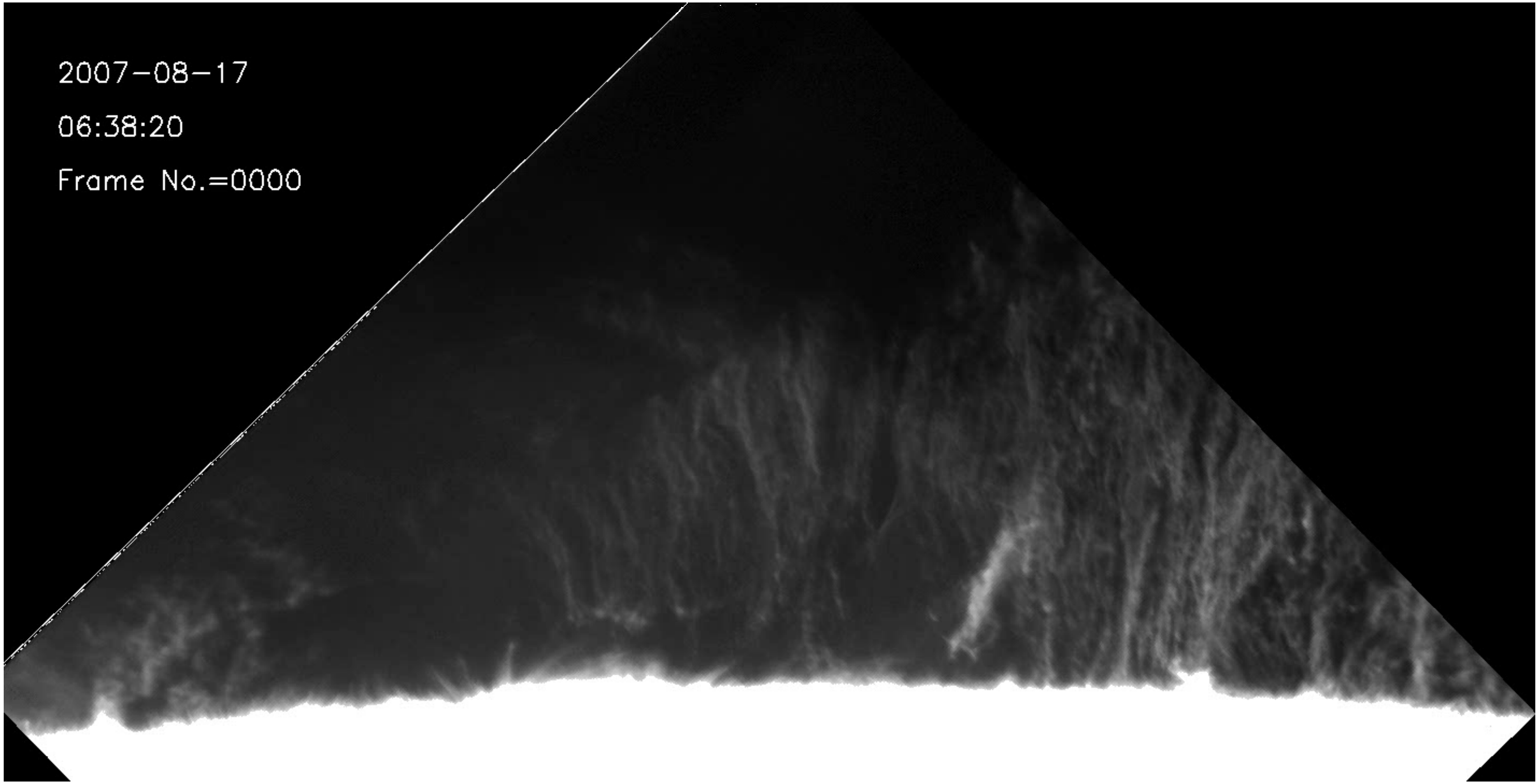
→ Determine decay time of magnetic features at different scales

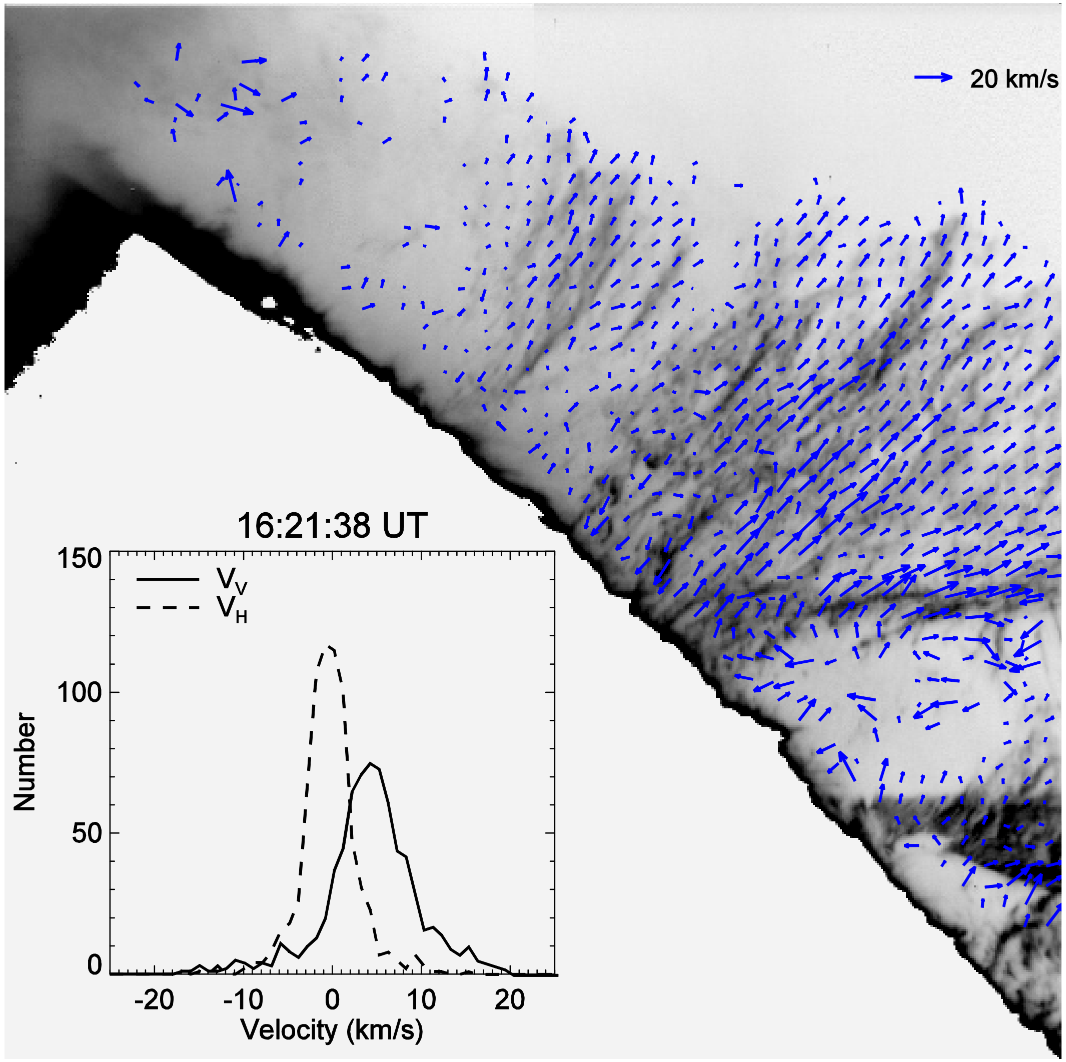
3. SOT observations of flows in a prominence and physics of plasma support: dynamic or magnetic?

Ca II H movie



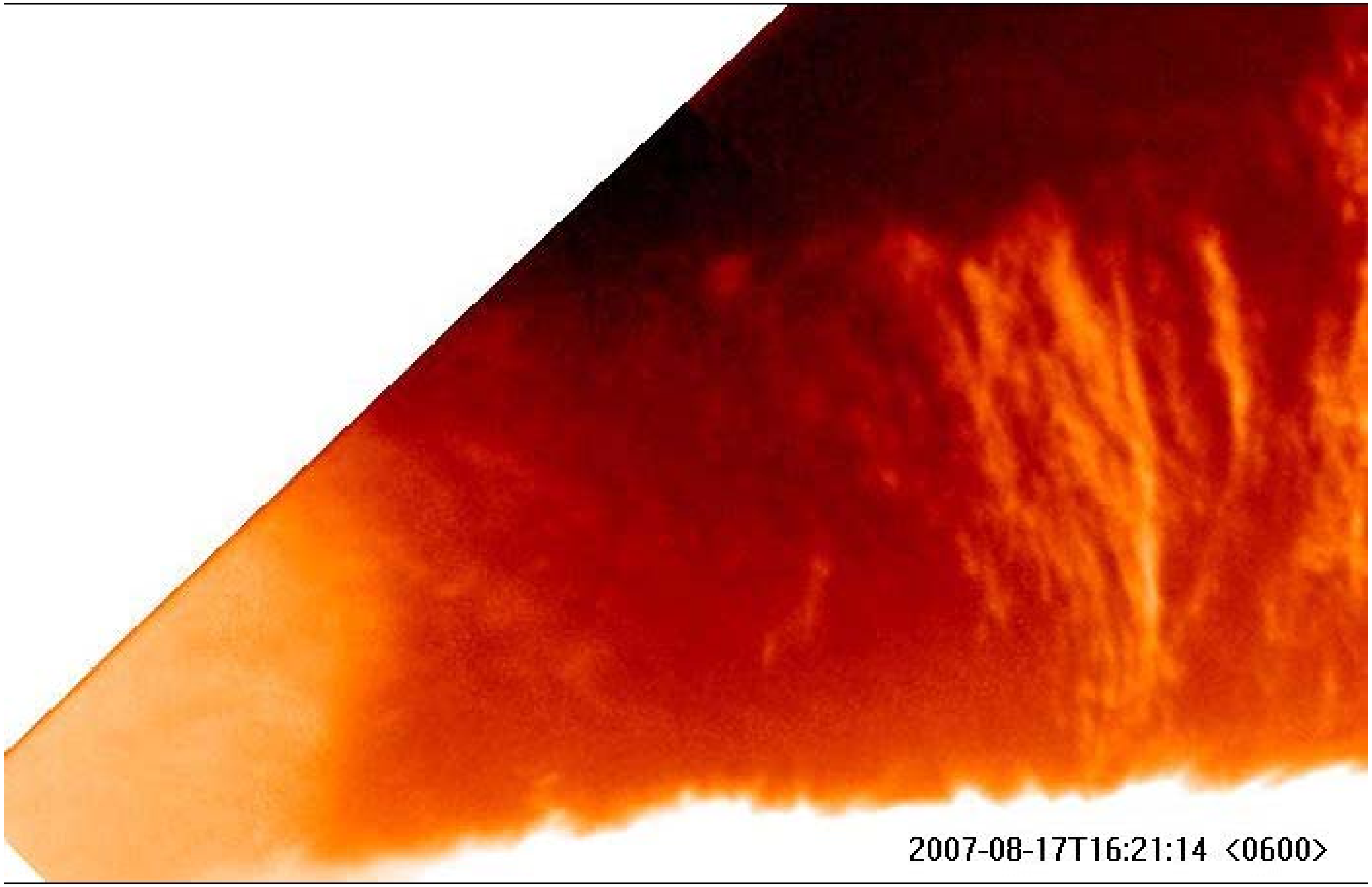
Hα movie



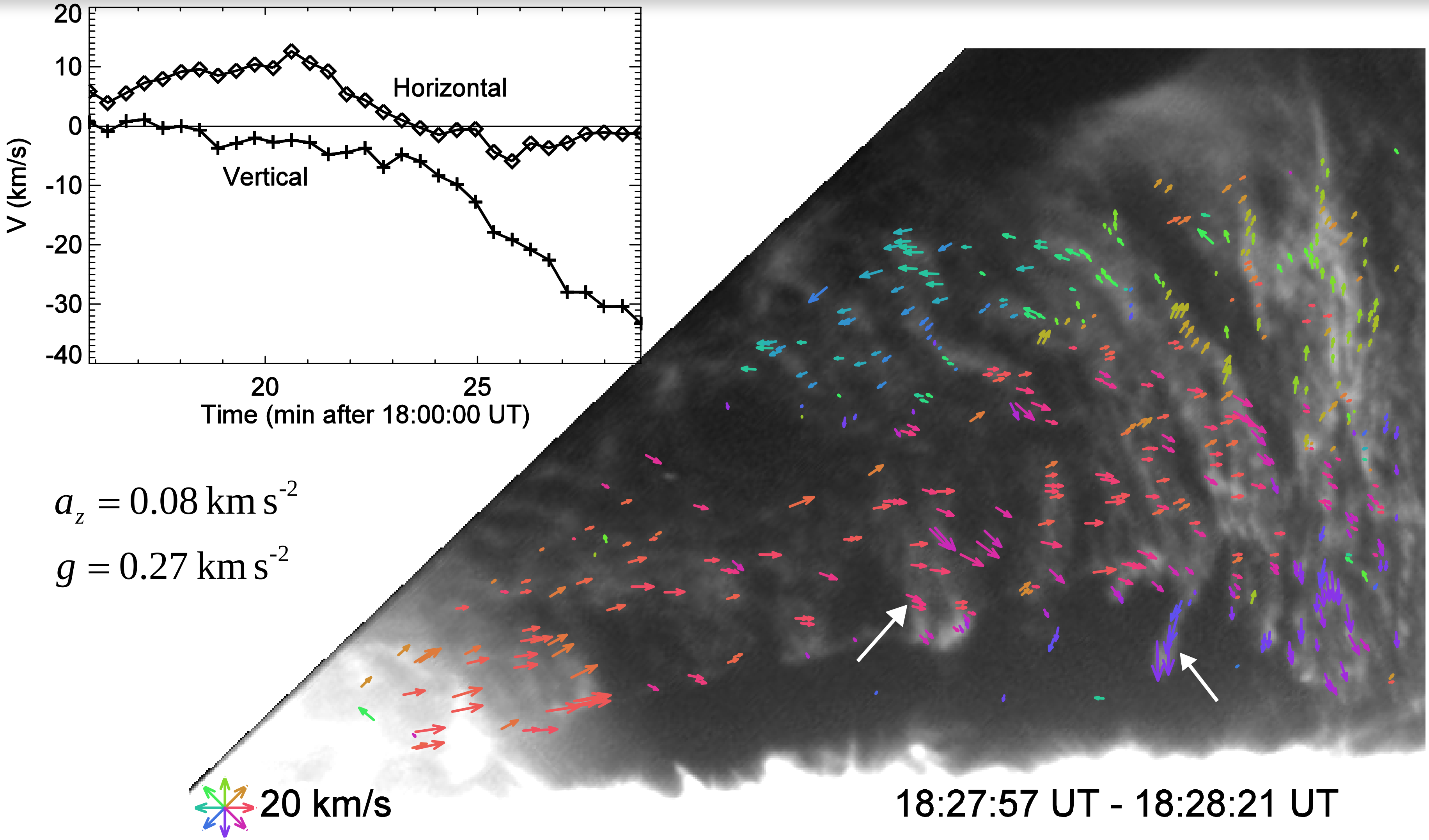

20 km/s
16:21:38 UT
150
100
50
0
Number
V_V
V_H
-20
-10
0
10
20
Velocity (km/s)

- A variety of flows exist: horizontal flows, downflows, upflows, vortex flows,...
- Dynamic support? Probably not.
  - The flow speeds are usually lower than 20 km/s.
  - The acceleration is usually much lower than gravity.
- Magnetic support? Probably yes.
  - There exist long-distance reaching horizontal flows which often make column-like structures or shed plasma blobs downward.

Hα movie (subview)



Flows



$$a_z = 0.08\,\mathrm{km\,s^{-2}}$$

$$g = 0.27\,\mathrm{km\,s^{-2}}$$

Gravity-induced magnetic dip

– Acceleration of plasma

$$a_z = \frac{Dv_z}{Dt} = -g + \frac{B_x}{4\pi\rho}\frac{\partial B_z}{\partial x} - \frac{\partial}{\partial z}(p + \frac{B_x^{\ 2}}{8\pi}) \approx 0$$

– Models of gravity-induced magnetic dip

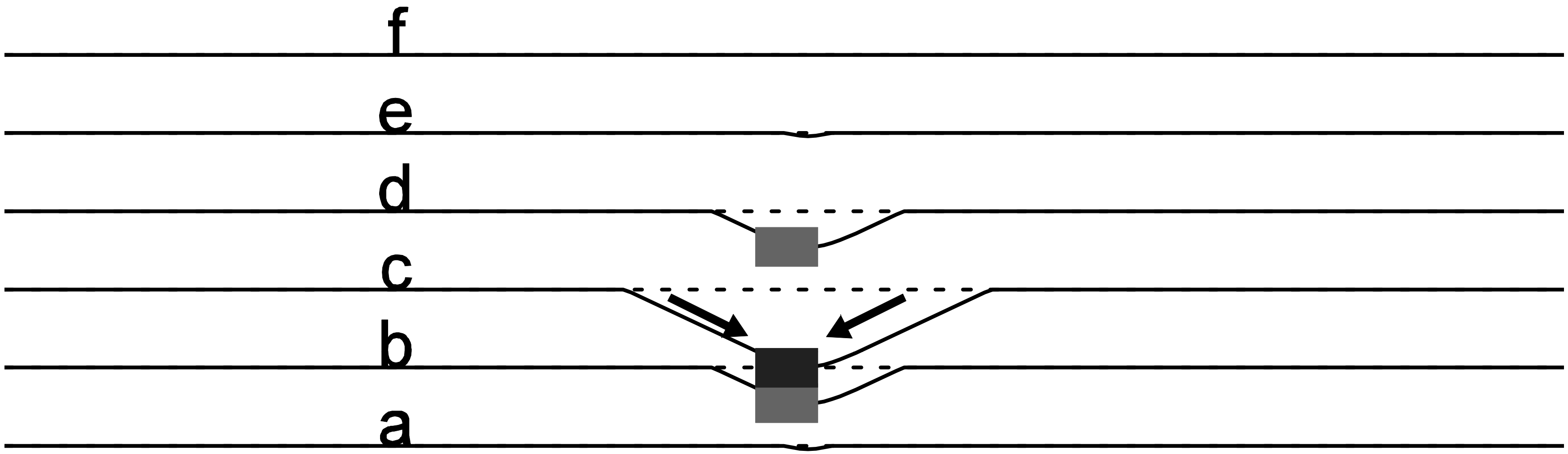
- Kippenhan & Schleuter 1957, Heinzel & Anzer 2001, Low & Petrie 2005

$$-g + \frac{B_x}{4\pi\rho}\frac{\partial B_z}{\partial x} = 0$$

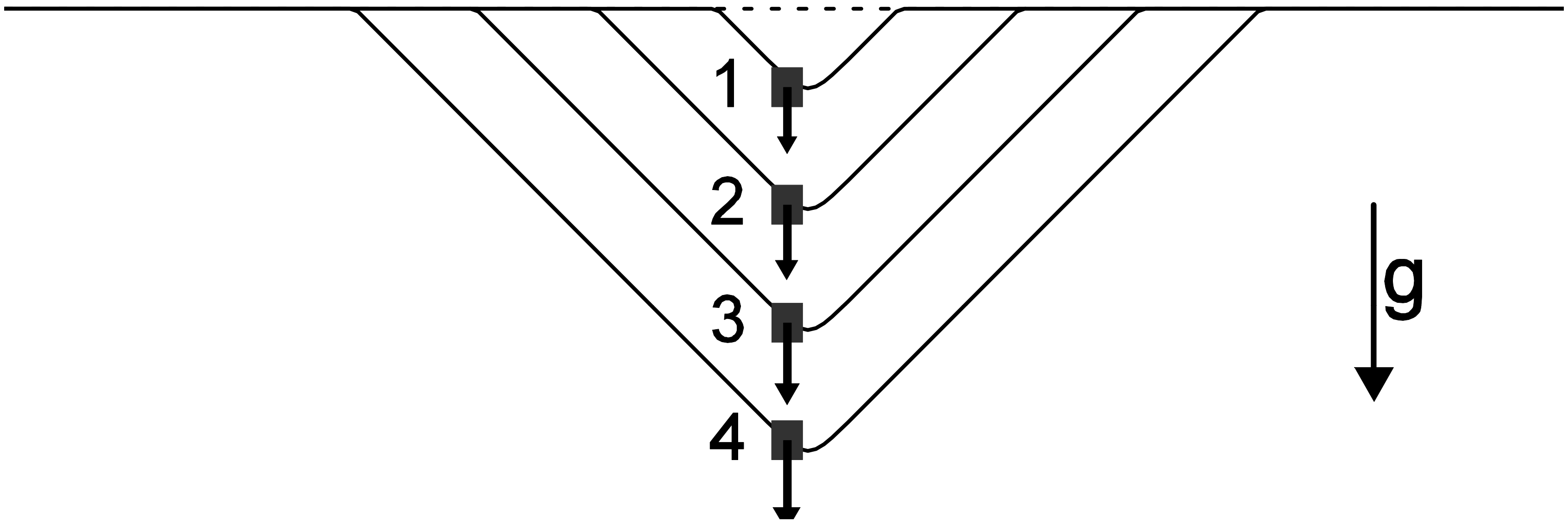
$$B_z = 2\pi g \frac{M}{B_x}$$

$$w = 4\frac{B_x}{B_z}H_p = \frac{2B_x^{\ 2}}{\pi g M}H_p$$

Formation of vertical threads



Fall of plasma blobs



Why do quiescent prominences look so odd?

- Because magnetic field is weak.
  - →allow to form high beta plasma blobs
  - →gravity-induced magnetic dips
  - →thin vertical threads and non free-fall, non-field-aligned downflows
- Active region prominences have strong fields.
  - →Low beta plasma
  - →Force-free induced magnetic dips
  - →Horizontal threads with field-aligned flows

Summary

1. Magnetic fluxes of small-scale magnetic activities such as CMFs seem to be much larger than previously reported
   - need to reconsider the physics and role of small-scale magnetic activities
2. Magnetic diffusivities at different scales seem to follow the scaling relation of MHD turbulence.
3. Quiescent prominences look dynamic, but may not be far from a magnetically-supported quasi-static configuration.