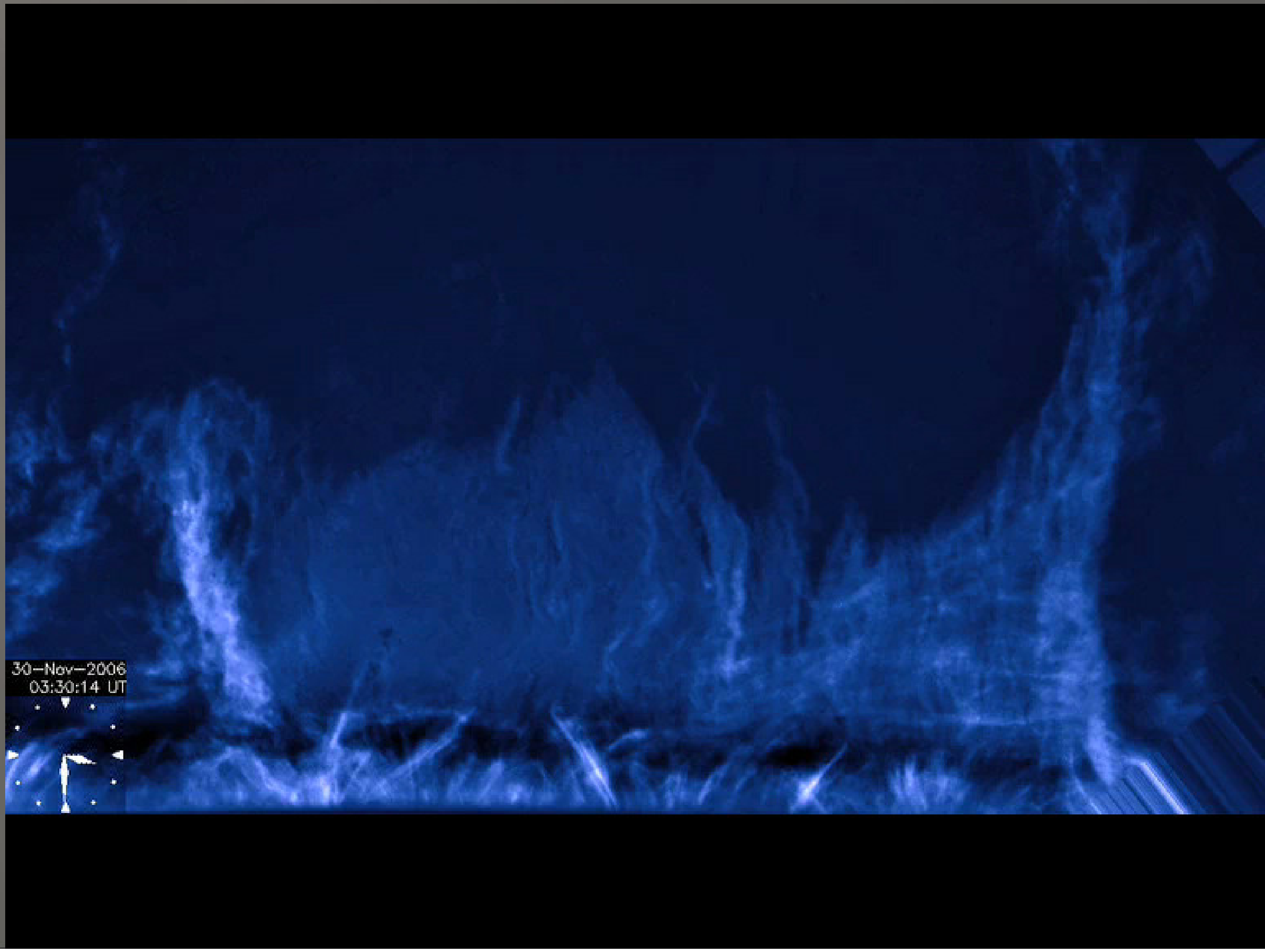
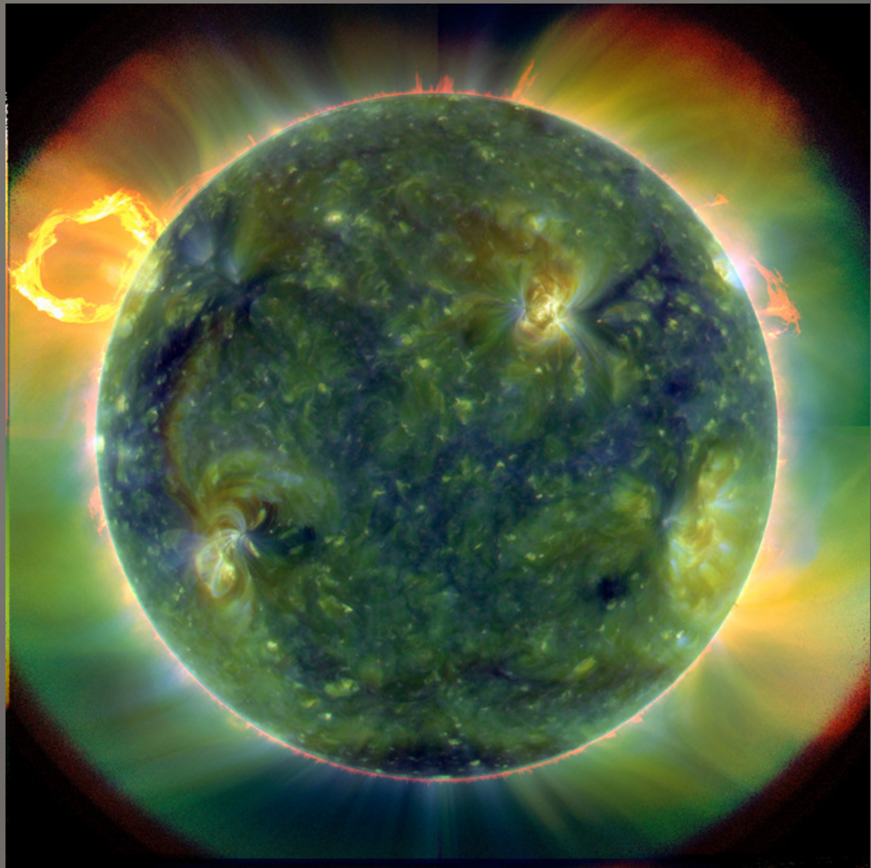
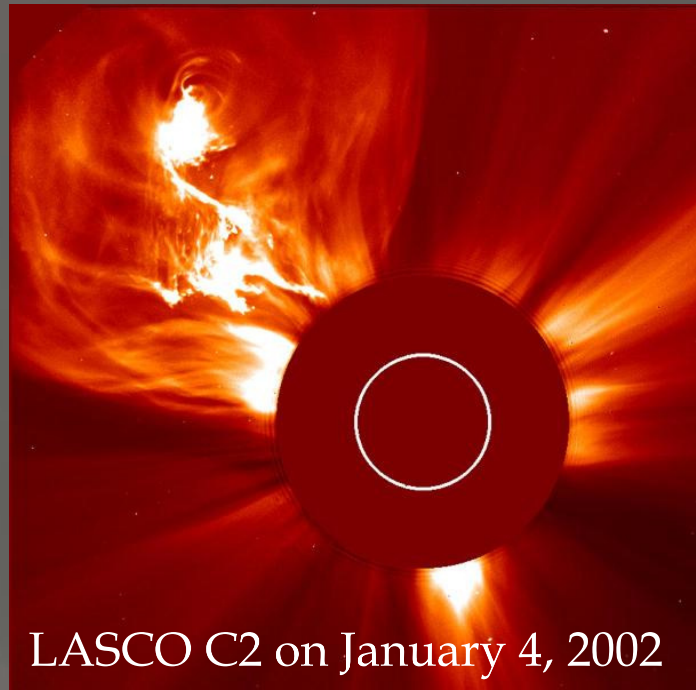
Ion-neutral Coupling in Solar Prominences

Holly Gilbert: NASA GSFC

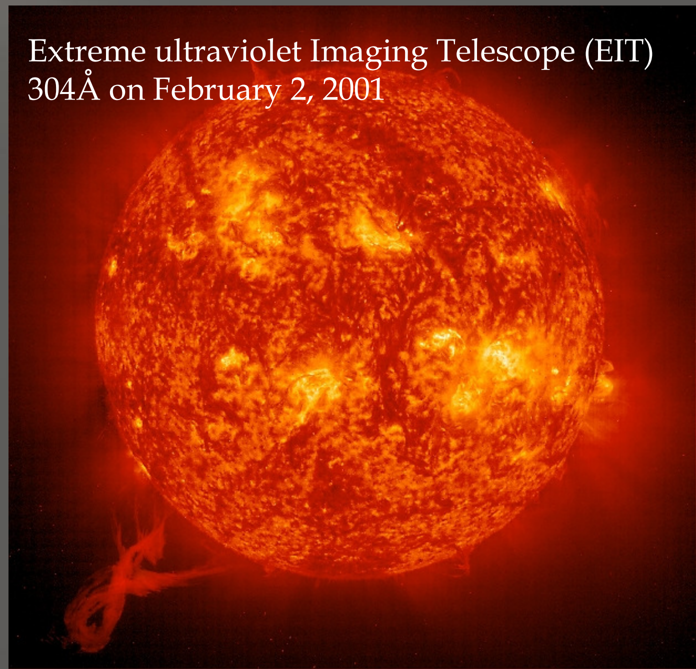




SDO AIA composite made from three of the AIA wavelength bands, corresponding to temperatures from .7 to 2 million degrees (hotter = red, cooler = blue).

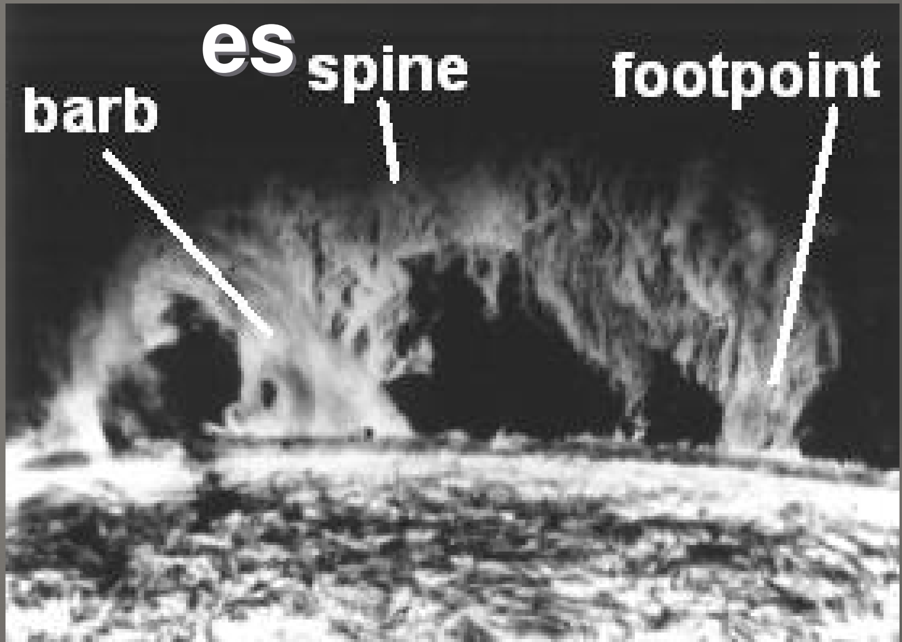


LASCO C2 on January 4, 2002

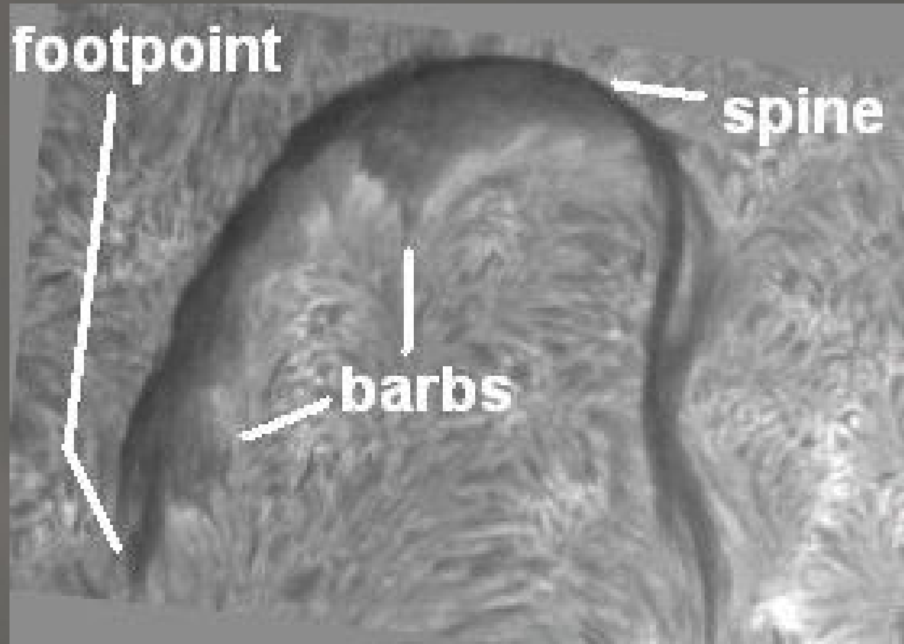


Extreme ultraviolet Imaging Telescope (EIT) 304Å on February 2, 2001

Prominences



Filaments



- Length ~ 10 - 1000 Mm, Height ~ 1 - 100 Mm, Width ~ 1 - 10 Mm *(1 Mm = 1000 km = 10^8 cm)*
- Lifetime ~ hours - months
- $T < 10^4$ K, $N \sim 10^{10}$ cm^{-3}, $M \sim 10^{15}$ gm
- $V \sim 5$ - 100 km s^{-1}

Some fundamental questions

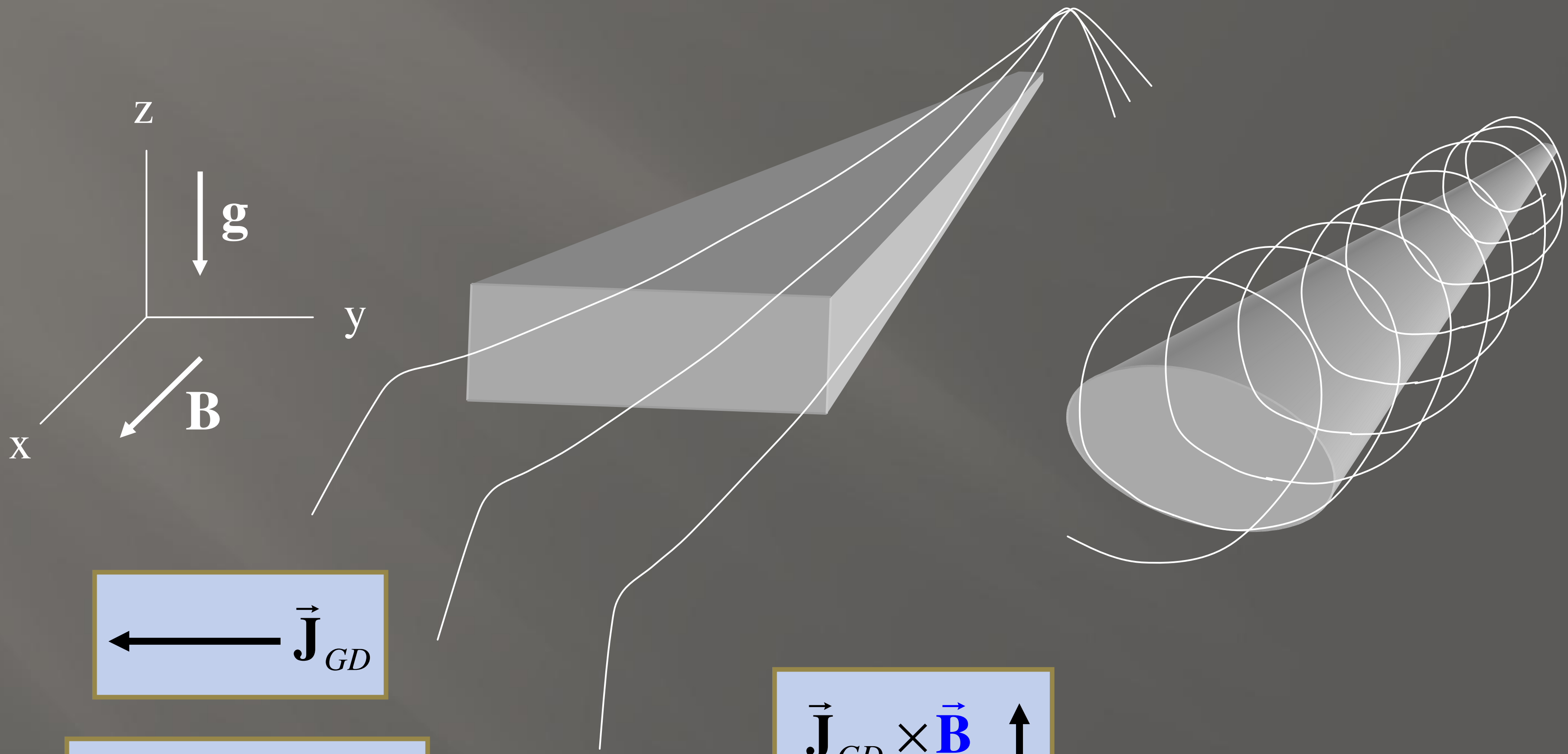
- How are prominences formed?
- Are there fundamental differences between the various types (active region vs. quiescent)?
- What drives prominence evolution?
- What causes eruption?
- Does prominence density, magnetic structure, & pre-eruptive dynamics tell us something fundamental about the magnetic structure and available energy

Motivation:

- Understanding prominence support
- Understanding prominence mass loss

- Observations of vertical flows: do ion-neutral interactions play a role?
- By understanding the ion-neutral coupling what can we infer about the

Mass loss via. Cross field diffusion *(Gilbert et al. 2002; 2007)*



$$\longleftarrow \vec{\mathbf{J}}_{GD}$$

$$\vec{\mathbf{J}}_{GD} \times \vec{\mathbf{B}} \uparrow$$

$$\vec{\mathbf{J}}_{GD} \approx \frac{\rho_i \, \vec{\mathbf{g}} \times \vec{\mathbf{B}}}{B^2}$$

Force Balance in a Multi-Constituent Prominence Plasma

General Momentum Balance Equation (j^{th} particle species)

$$\cancel{\frac{\partial}{\partial t}\left(\rho_j \mathbf{u}_j\right)} + \cancel{\nabla\cdot\left(\rho_j \mathbf{u}_j \mathbf{u}_j\right)} = \cancel{-\nabla p_j} - \cancel{\nabla\cdot\overleftrightarrow{\tau}_j} + n_j e Z_j \left(\cancel{\mathbf{E}} + \boxed{\mathbf{u}_j \times \mathbf{B}}\right) - \boxed{\rho_j \frac{GM_{\odot}}{r^2}\hat{\mathbf{e}}_r}$$

$$+\boxed{\rho_j \sum_k \nu_{jk}\left(\mathbf{u}_k - \mathbf{u}_j\right)} + \cancel{F}_{Rj} + \cancel{F}_{Tj} + m_j \cancel{\left[\sum_k \mathsf{P}_{jk}\mathbf{u}_k - \mathsf{L}_j \mathbf{u}_j\right]}$$

Other assumptions:

- Neglect flows along the magnetic field
- Constant density and temperature throughout system
- Collision frequencies appropriate for subsonic flow speeds (our calculated flow speeds are less than 0.1 km s^{-1})
- Local magnetic field is exactly horizontal to the (locally flat) solar surface

EXAMPLE: Proton Force Balance

z-component:
$$u_{py} = -g/\Omega_p + \Omega_p^{-1}\Big[\nu_{pe}\left(u_{ez} - u_{pz}\right) + \nu_{pH}\left(u_{Hz} - u_{pz}\right)$$
$$+\nu_{pHe}\left(u_{Hez} - u_{pz}\right) + \nu_{pHe^+}\left(u_{He^+z} - u_{pz}\right)\Big]$$

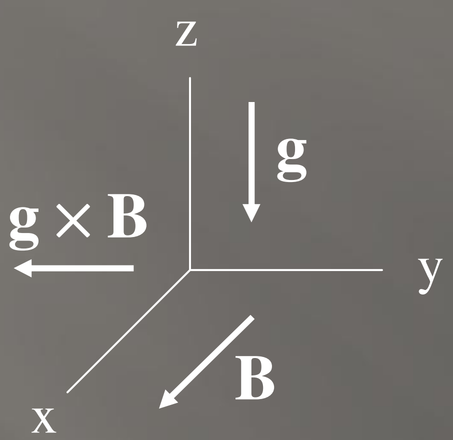
y-component:
$$u_{pz} = \Omega_p^{-1}\Big[\nu_{pe}\left(u_{ey} - u_{py}\right) + \nu_{pH}\left(u_{Hy} - u_{py}\right)$$
$$+\nu_{pHe}\left(u_{Hey} - u_{py}\right) + \nu_{pHe^+}\left(u_{He^+y} - u_{py}\right)\Big]$$

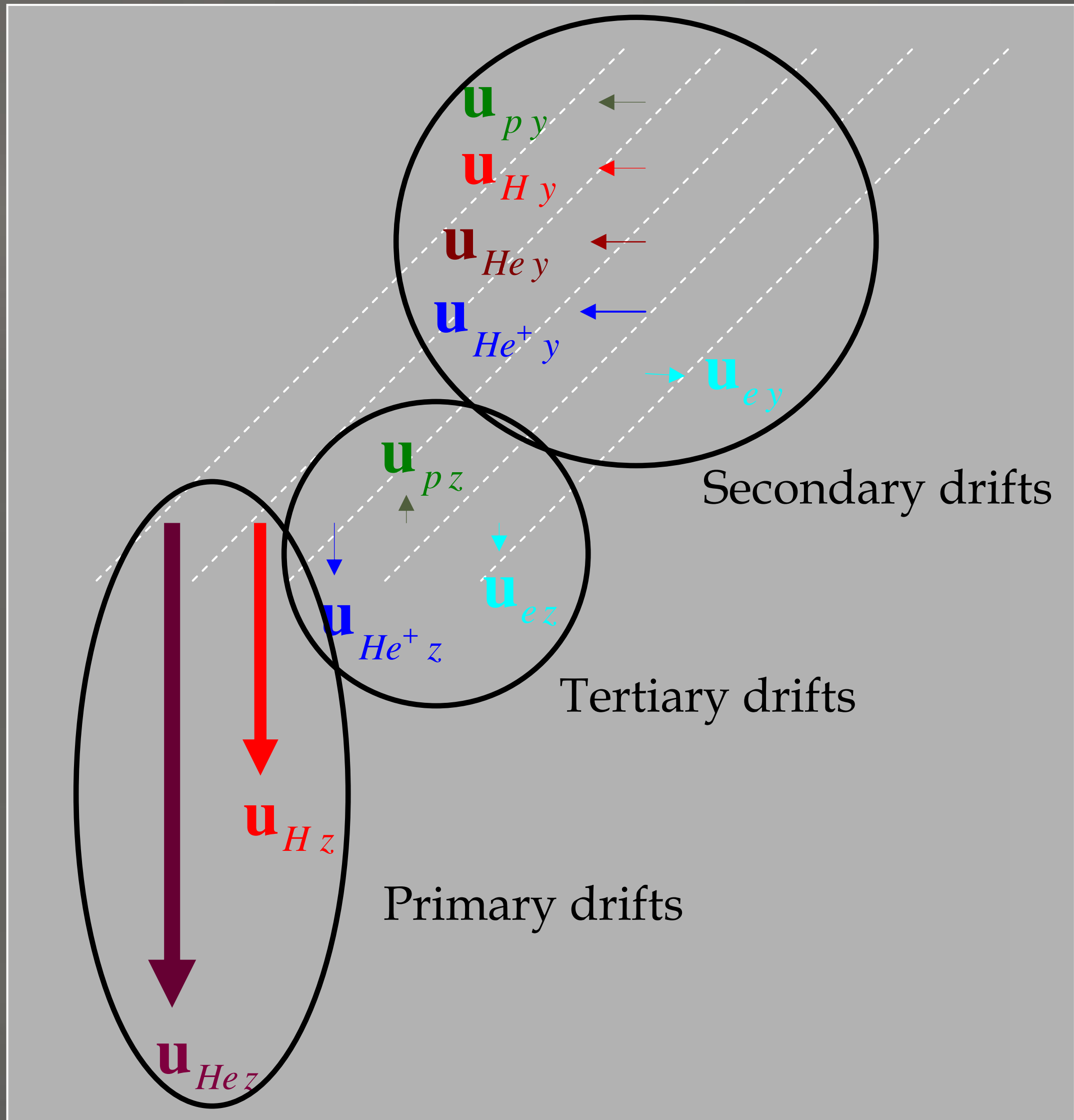
$\mathbf{B} = B\hat{\mathbf{e}}_{\mathbf{x}}$

$\mathbf{g} = -\hat{\mathbf{e}}_{\mathbf{z}}GM/r^2$

$\boldsymbol{\Omega}_j = Z_j\, eB/m_j$

Perpendicular Flow in a H-He Prominence Plas

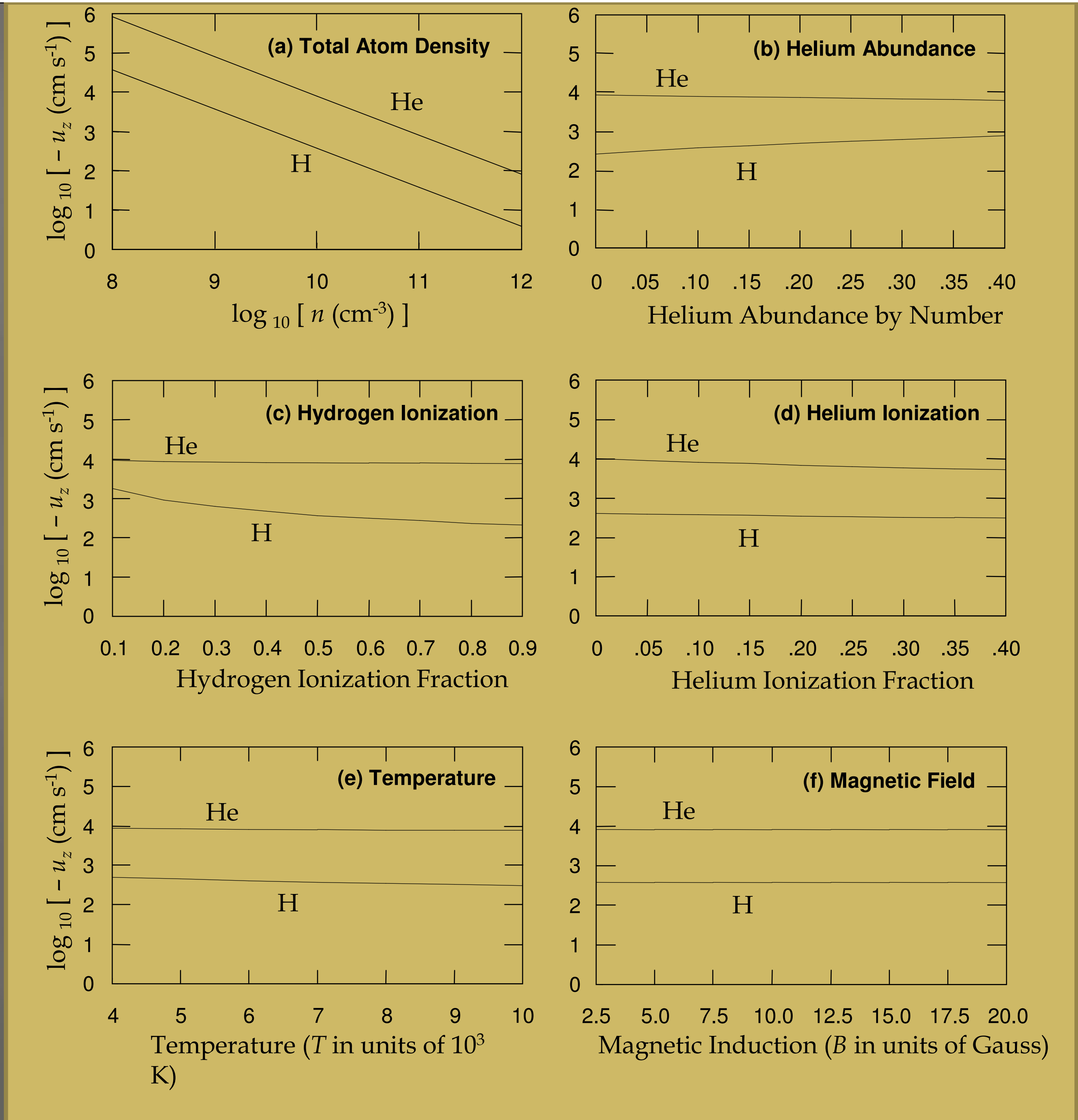




Parameter Study

Considered dependence of particle velocities on variation of several parameters (reference values in parentheses):

- Total atom density (10^{10} cm^{-3})
- Helium abundance by number (0.1)
- H and He ionization fractions (0.5 and 0.1)
- Temperature (7×10^{3} K)
- Magnetic field (10 G)



(a) Total Atom Density
He
H
$\log_{10} [-u_z \, (\mathrm{cm\ s^{-1}})]$
$\log_{10} [n \, (\mathrm{cm^{-3}})]$
(b) Helium Abundance
He
H
Helium Abundance by Number
(c) Hydrogen Ionization
He
H
$\log_{10} [-u_z \, (\mathrm{cm\ s^{-1}})]$
Hydrogen Ionization Fraction
(d) Helium Ionization
He
H
Helium Ionization Fraction
(e) Temperature
He
H
$\log_{10} [-u_z \, (\mathrm{cm\ s^{-1}})]$
Temperature (T in units of 10^3 K)
(f) Magnetic Field
He
H
Magnetic Induction (B in units of Gauss)

Time Scales for Neutral Atom Loss

$$|u_{He}| \approx 10^4 \left[\frac{10^{10}\,\mathrm{cm}^{-3}}{n\left(\mathrm{cm}^{-3}\right)}\right] \mathrm{cm\ s}^{-1} \qquad |u_H| \approx 5\times10^2 \left[\frac{10^{10}\,\mathrm{cm}^{-3}}{n\left(\mathrm{cm}^{-3}\right)}\right] \mathrm{cm\ s}^{-1}$$

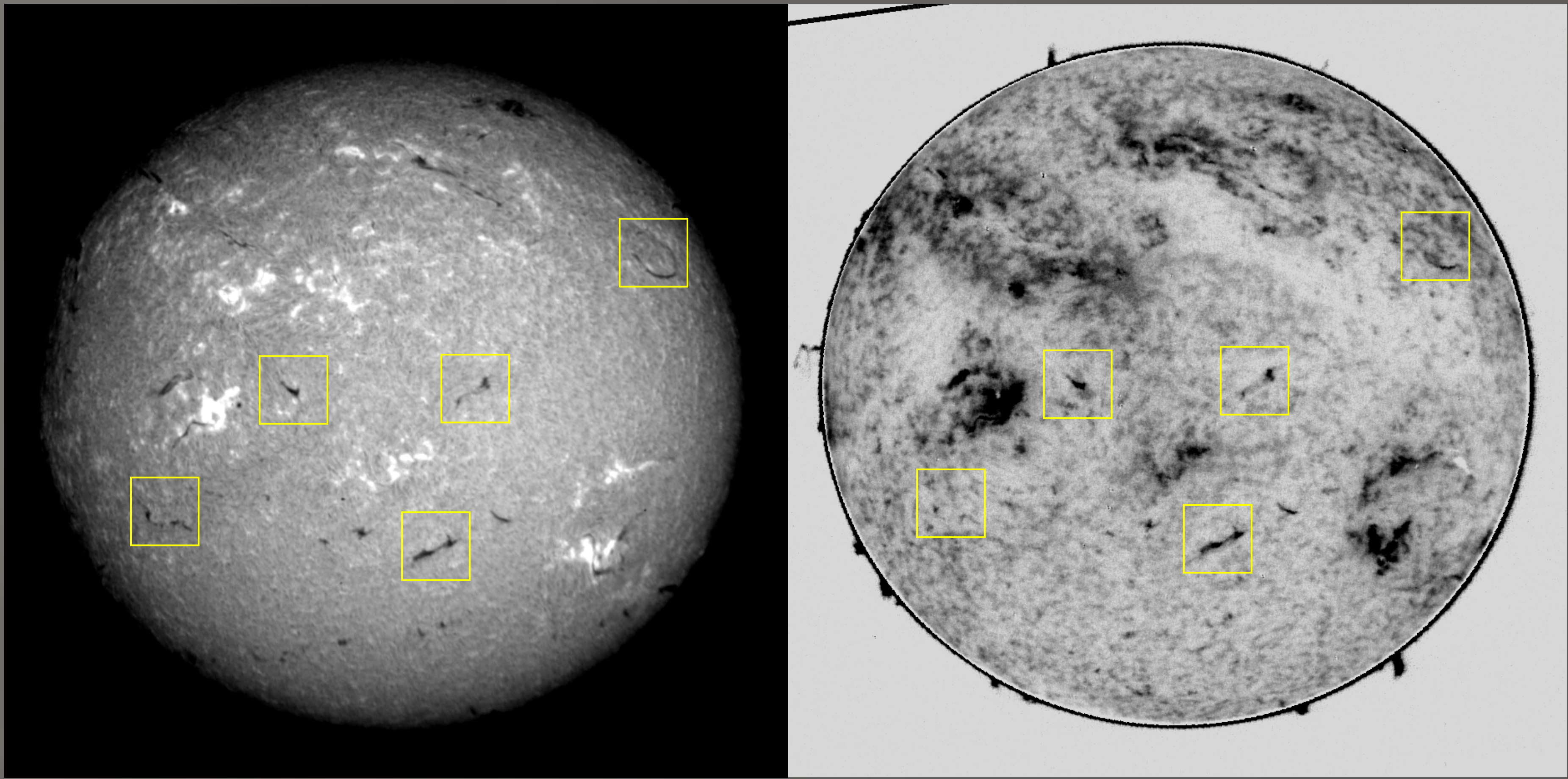
$$\tau_{He} \approx h_{prom} / |u_{He}| \qquad \tau_H \approx h_{prom} / |u_H|$$

(h_{prom} = vertical prominence dimension)

Loss Times for Helium and Hydrogen

Helium: $$\tau_{He} \approx 24 \left[\frac{h_{prom}\left(\mathrm{R_{sun}}\right)}{0.01\ \mathrm{R_{sun}}}\right] \left[\frac{n\left(\mathrm{cm}^{-3}\right)}{10^{10}\,\mathrm{cm}^{-3}}\right] \text{hours}$$ ~ 1 day

Hydrogen: $$\tau_H \approx 520 \left[\frac{h_{prom}\left(\mathrm{R_{sun}}\right)}{0.01\ \mathrm{R_{sun}}}\right] \left[\frac{n\left(\mathrm{cm}^{-3}\right)}{10^{10}\,\mathrm{cm}^{-3}}\right] \text{hours}$$ ~ 22 days

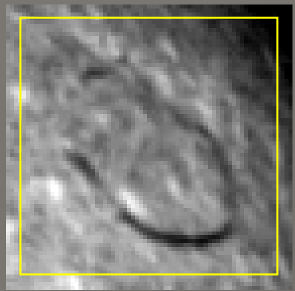


Hα (λ=656 nm)
January 30, 2000, 20:11:22 UT

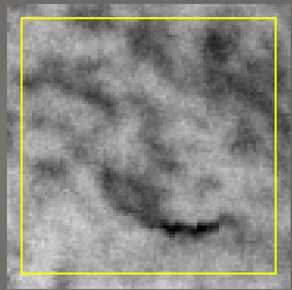
He I (λ=1083 nm)
January 30, 2000, 20:10:15 UT

Both Images from the HAO Mauna Loa Solar Observatory

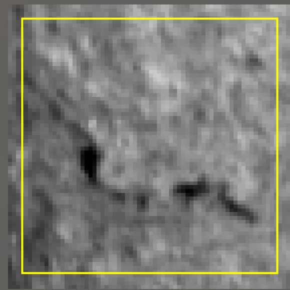
Initial Comparison of H and He Observat



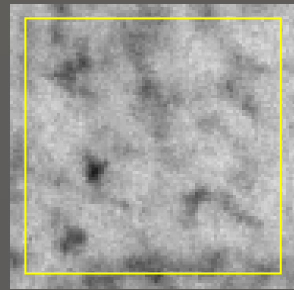
Hα (λ=656 nm)



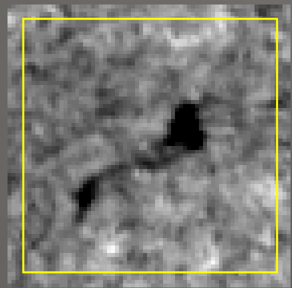
He I (λ=1083 nm)



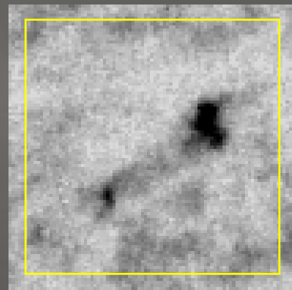
Hα (λ=656 nm)



He I (λ=1083 nm)



Hα (λ=656 nm)



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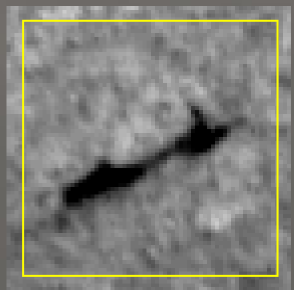
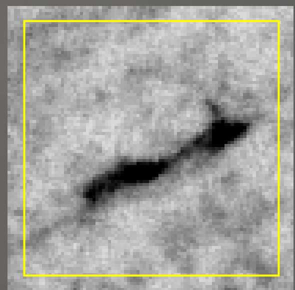
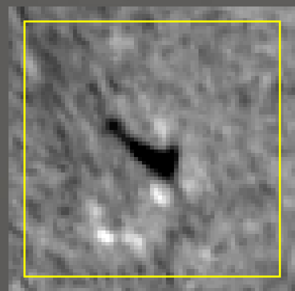


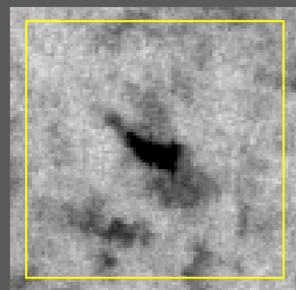
Hα (λ=656 nm)



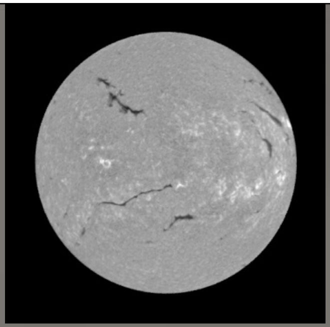
He I (λ=1083 nm)



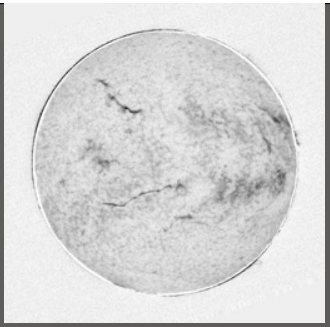
Hα (λ=656 nm)



He I (λ=1083 nm)



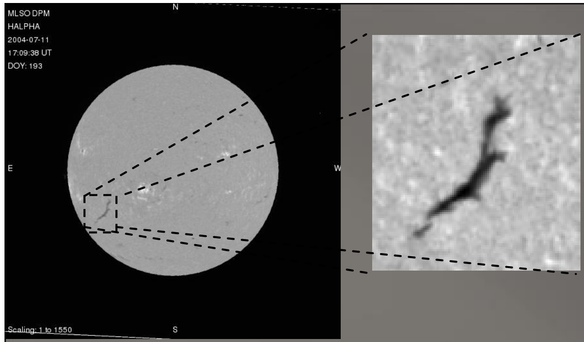
Quantitative Analysis



Gilbert, Kilper, & Alexander, ApJ 671, 2007

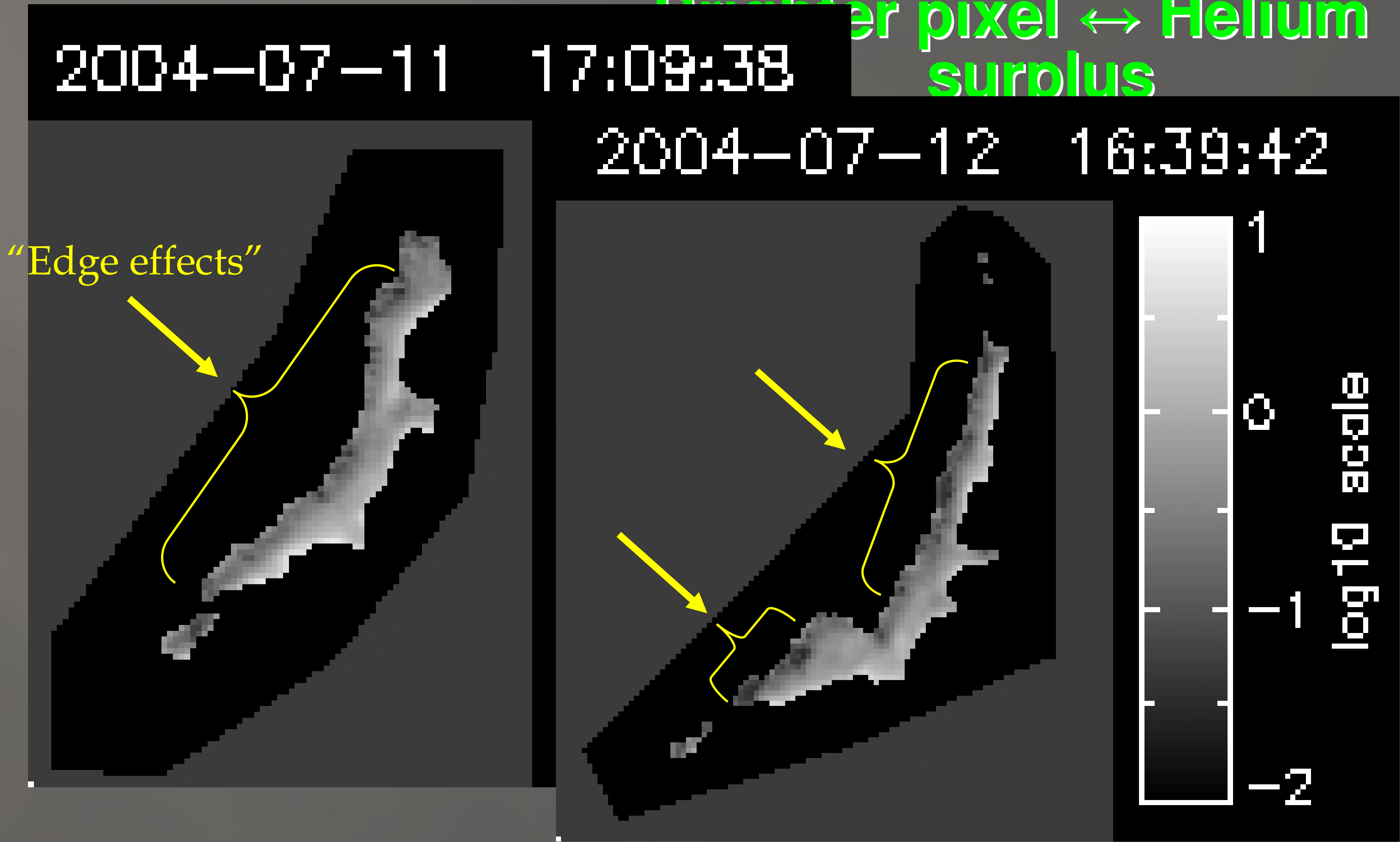
- Study temporal and spatial Changes in the relative H and He in filaments via the absorption and He I / Hα absorption ratio
  - Chose large/stable and small/stable filaments that could be followed across the solar disk
- Used co-temporal Hα (6563 Å) and He I (10830 Å) images from the Mauna Loa Solar Observatory in 2004
- Kilper (Master's thesis) Developed an IDL code that scales and aligns each pair of images, selects the filament, and calculates the absorption ratio at every pixel

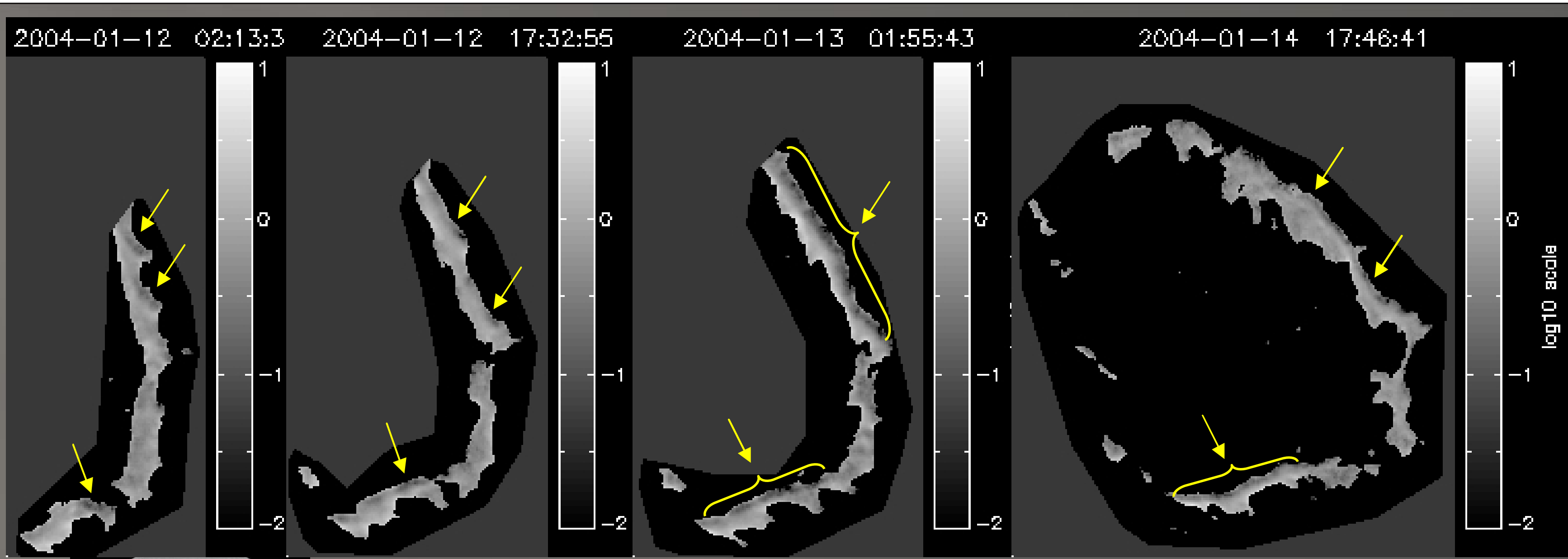
He/H absorption

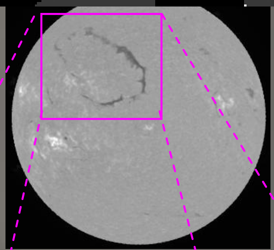


Darker pixel ↔ Helium deficit

Brighter pixel ↔ Helium surplus

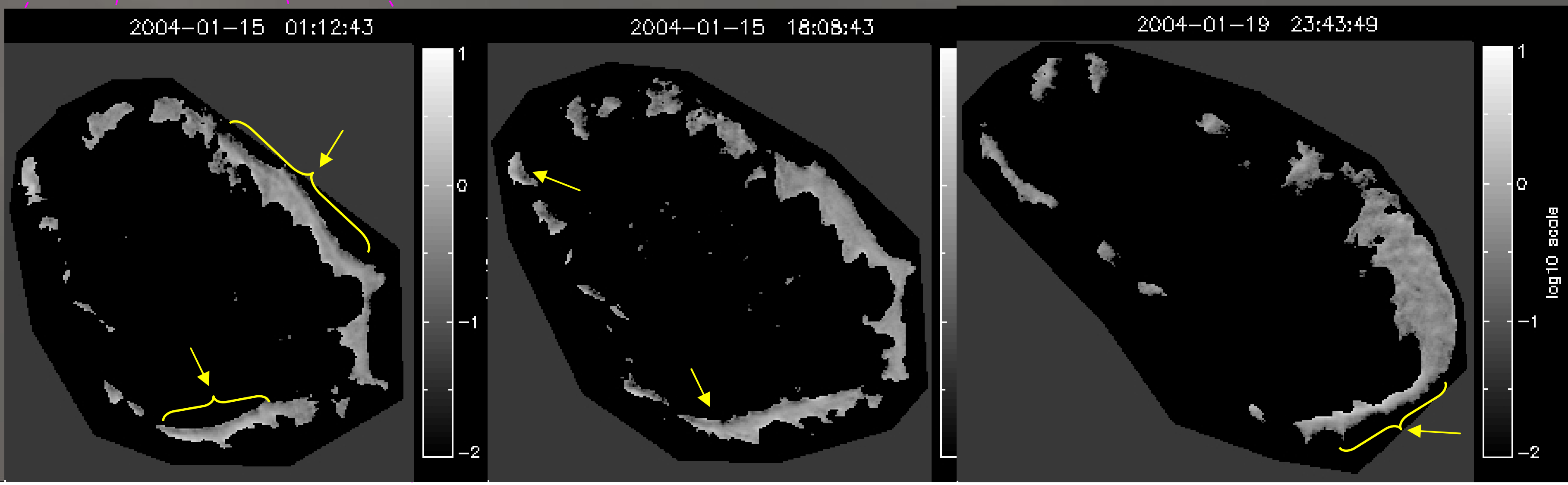






January 2004

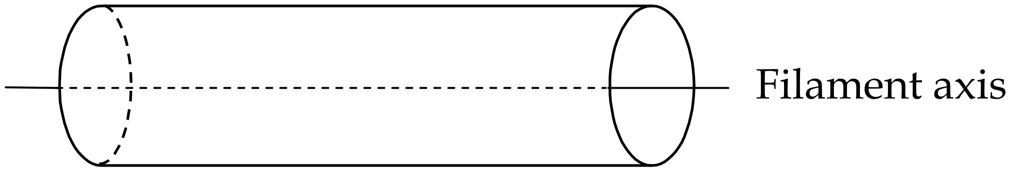
"Large & stable"



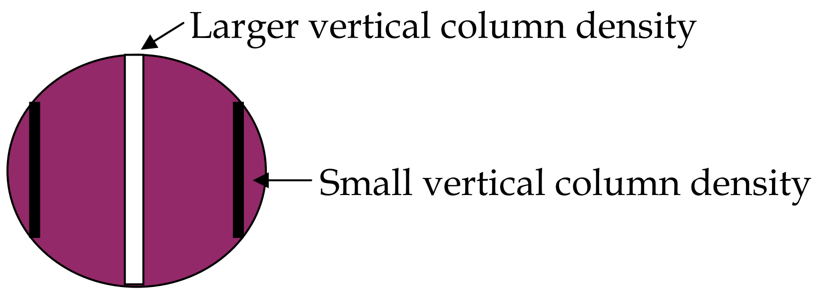
What do we expect??

Geometrical considerations: the simplest pic

Cylindrical representation of a filament

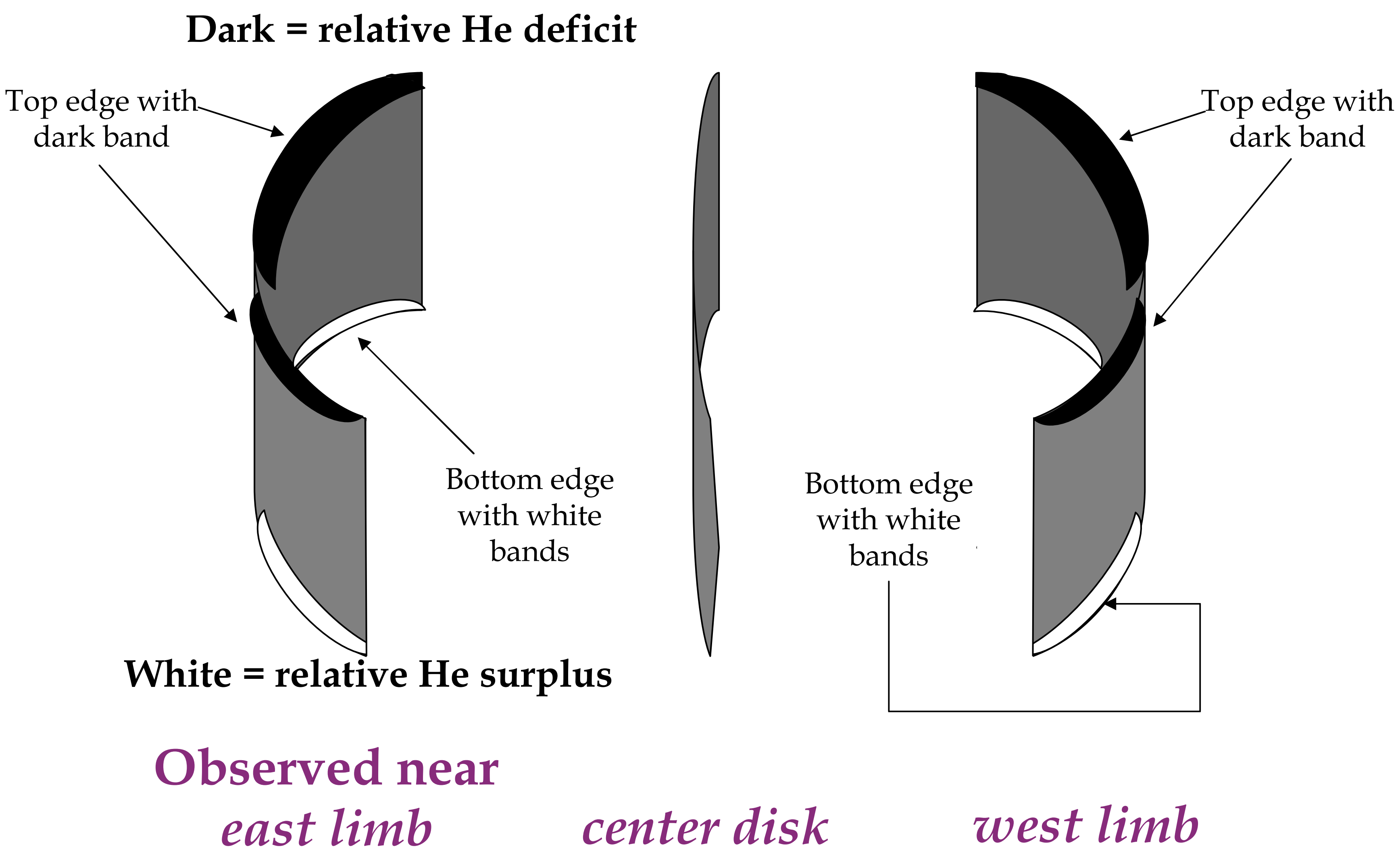


View along filament axis

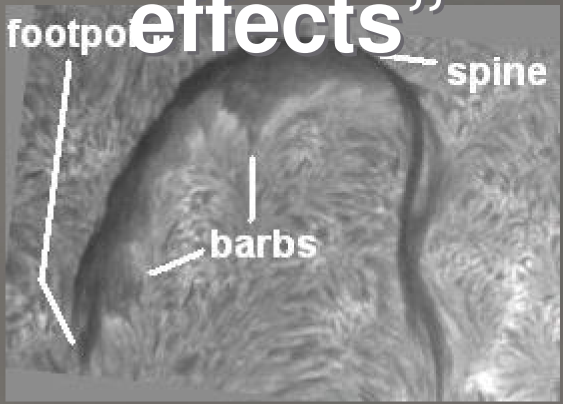


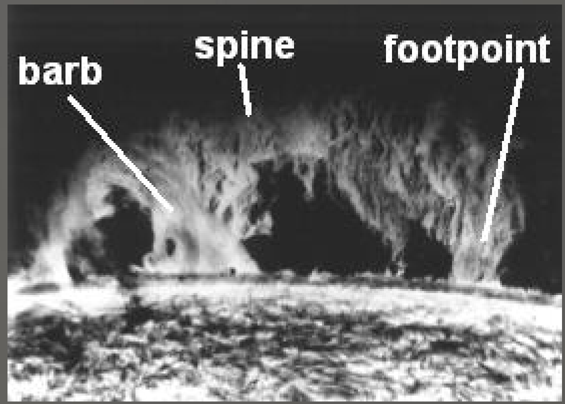
Top view at disk center

Somewhat more realistic geometry



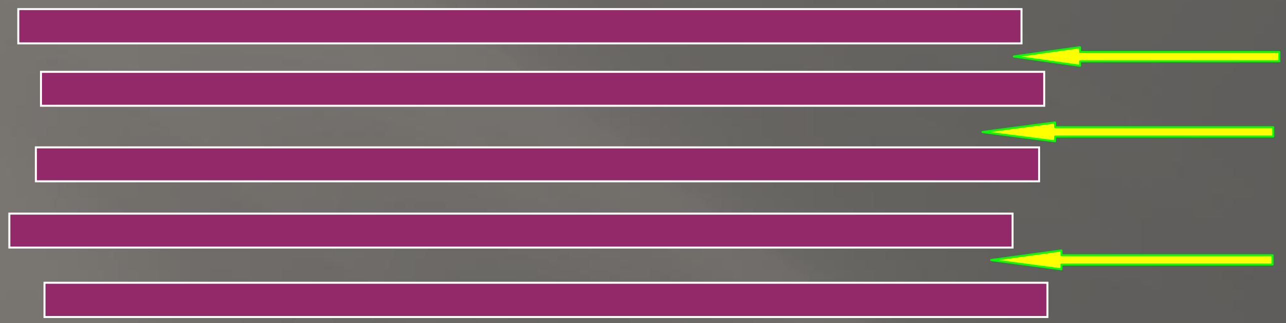
Interpretation of “Edge effects”





- **Far from disk center, one edge is at the top, and one at the bottom (where the barbs appear)**
- **In a relatively stable filament, He drains out of the top rapidly (*relative He deficit*)**
- **He draining out of bottom is replaced by He draining down from above (*no relative He deficit*)**

Diffusion timescales In the context of filament threads…..



Coronal plasma in between threads

Coronal plasma can readily ionize neutral material draining into it

$$\tau_{He} \approx 24\left[\frac{h_{prom}\left(\mathrm{R_{sun}}\right)}{0.01\ \mathrm{R_{sun}}}\right]\left[\frac{n\left(\mathrm{cm^{-3}}\right)}{10^{10}\,\mathrm{cm^{-3}}}\right]\ \mathrm{hours}$$

$$\tau_{H} \approx 520\left[\frac{h_{prom}\left(\mathrm{R_{sun}}\right)}{0.01\ \mathrm{R_{sun}}}\right]\left[\frac{n\left(\mathrm{cm^{-3}}\right)}{10^{10}\,\mathrm{cm^{-3}}}\right]\ \mathrm{hours}$$

Expect very short draining timescales…..

However……

For high density filament threads, draining timescale will not be too small– it depends on *vertical column*

Ongoing related work

LWS TR&T Focused Science Team on Plasma Neutral Gas Coupling

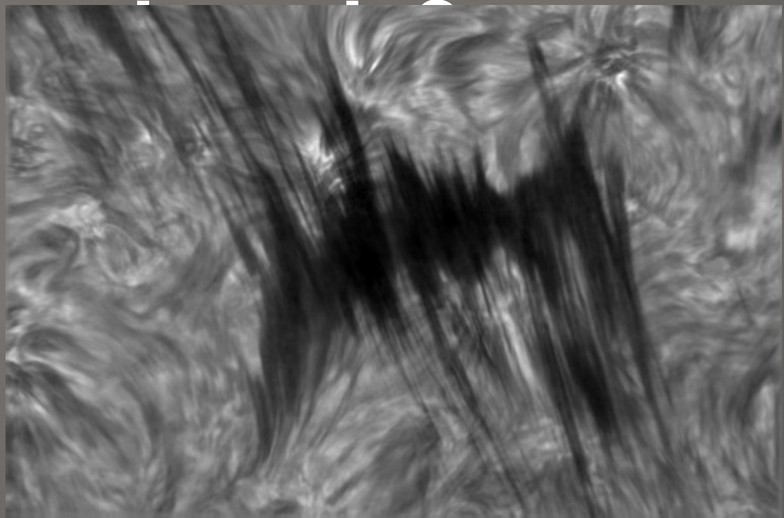
- Chromosphere component;
  - My team: prominences
  - Phil Judge: Thermal & magnetic models for ion-neutral chromospheric studies
  - James Leake: Modeling effects of ion-neutral coupling on reconnection & flux ememergence in chromosphere

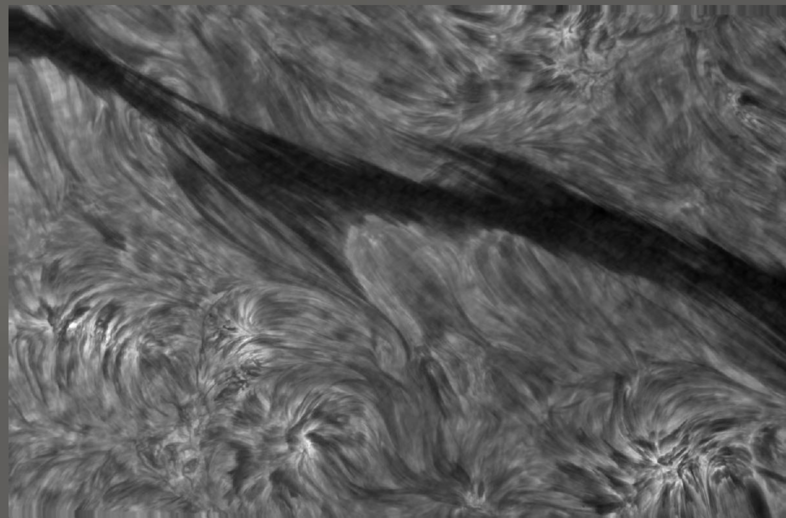
LWS TR&T Focused Science Team on Plasma Neutral Gas Coupling

- Ionosphere component;
  - Geoffrey Crowley: Thermosphere-ionosphere
  - Jiuhou Lei: Ion-neutral processes in the equatorial F-region
  - Wenbin Wang: Global ionospheric electric field variations

Key questions to be addressed

- What physical mechanism(s) set the cross-field scale of prominence





- Are ion-neutral interactions responsible for vertical flows and

Approach

Use idealized studies to develop physical insight into core processes:

- Cross-field diffusion
- Thermal nonequilibrium
- Rayleigh-Taylor instability

Advance to full multidimensional modeling

Utilize observations to guide and test new physical insights

Thank you