Understanding Solar Eruptions with *SDO*/HMI

Measuring Photospheric Flows, Testing Models, and Steps Towards Forecasting Solar Eruptions
Work Supported by: LWS Tools & Methods, LWS TR&T Strategic Capability, and HGI

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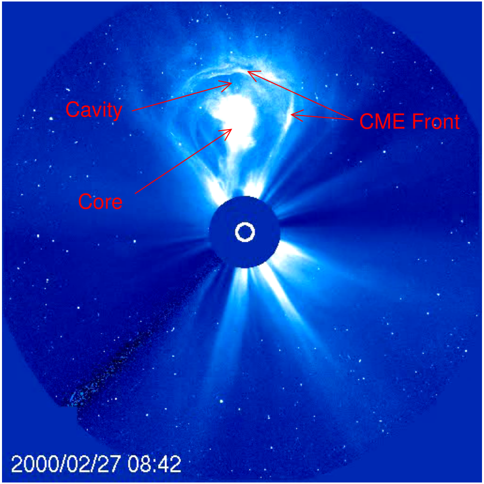
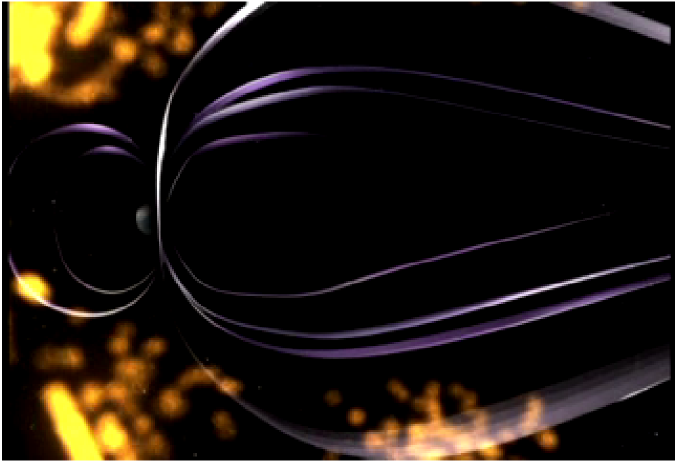


CME Energetics

- Mass: $10^{13} - 10^{17}$ g of plasma
- Kinetic: $10^{27} - 10^{32}$ ergs
- Magnetic: $10^{27} - 10^{32}$ ergs
- Solar Energetic Particles (SEPs): $1 - 10\%$ of KE
- Associated Flare (sometimes) similar to KE

CMEs and Space Weather
CMEs impact Earth



www.nasa.gov/mpg/160602main_what_is_a_cme_NASA%20WebV_1.mpg

Civilian Infrastructure:

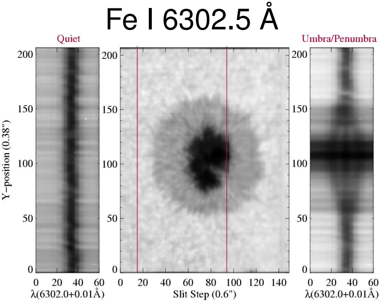
- Electrical power grids, oil pipelines, polar aviation routes, satellite- and long-line communication systems, space tracking, navigation systems, and satellite operations
- Direct economic consequences $200-400 million dollars a year (Horne, 2003)

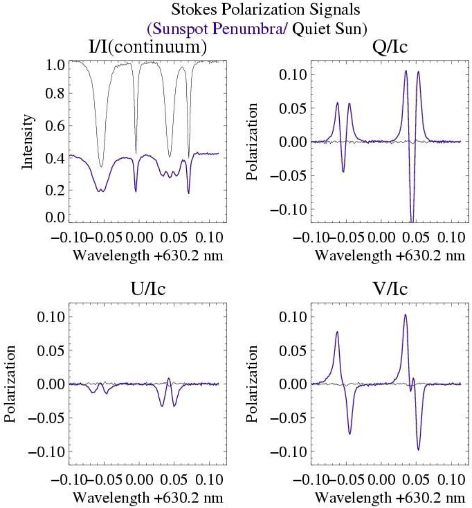
NASA Operations:

- Space Shuttle, satellite, and International Space Station (ISS) operations
- Dangers and unpredictability of solar eruptions operationally constrain a manned mission to Mars (Foullon et al., 2005)

Solar Magnetic Fields: Magnetograms

- Widely accepted that energy stored in the coronal magnetic field drives CMEs and flares.
  - Vector measurements of the coronal magnetic field? Rare and uncertain
- State of the photospheric magnetic field provides limited predictive capabilities (Leka & Barnes, 2007)
  - Examined 1200 photospheric vector magnetograms
  - "[W]e conclude that the state of the photospheric magnetic field at any given time has limited bearing on whether that region will be flare productive"
- Dynamics and time-history of the photospheric magnetic field key to understanding the energization and initiation of solar eruptions
  - Plasma flow properties
  - Poynting flux - energy budget of the corona

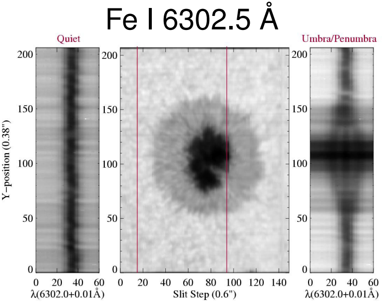


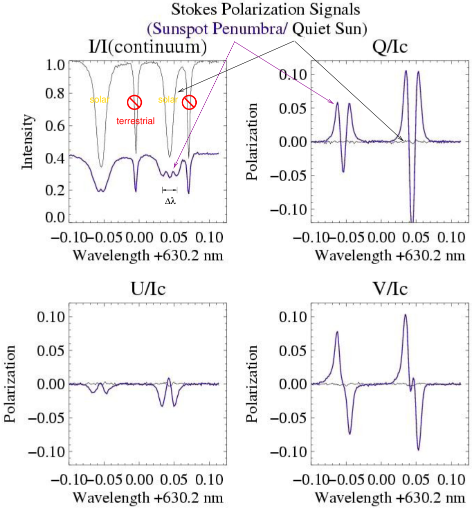


- Zeeman effect: magnetic field induces energy level splitting and polarization to magnetically sensitive lines
- Splitting proportional to $|\boldsymbol{B}|$

Solar Magnetic Fields: Magnetograms

How are Vector Magnetograms Measured?: Adapted from Leka *et al.* (2009)





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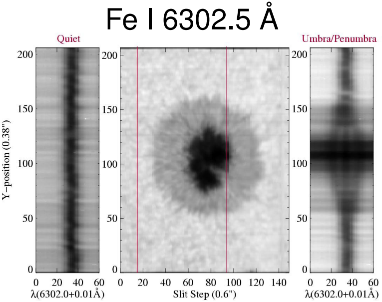
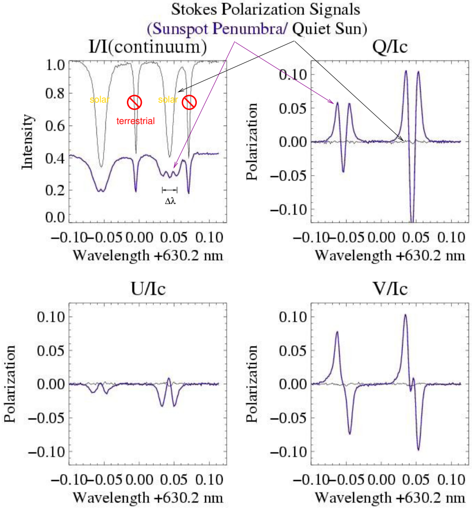
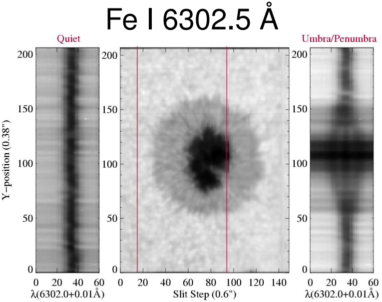
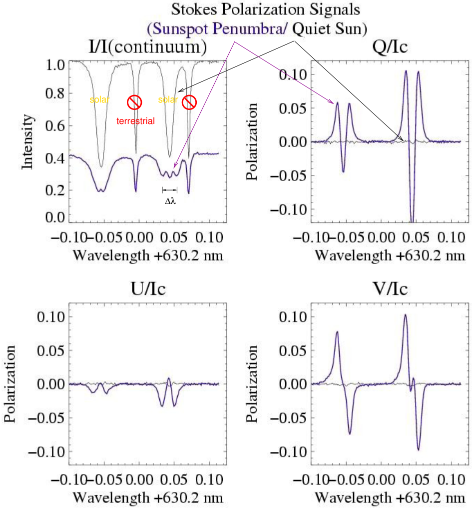




Weak field approximations:

- $B_{\|} \propto V$
- $B_{\perp} \propto \sqrt{Q^2 + U^2}$
- $\Phi \approx n\pi + \tan^{-1}(U/Q)$ (azimuthal ambiguity)
- $\gamma = \tan^{-1}\left(B_{\|}/B_{\perp}\right)$ (inclination)



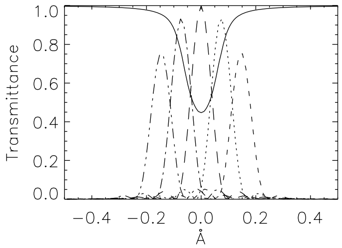


General:

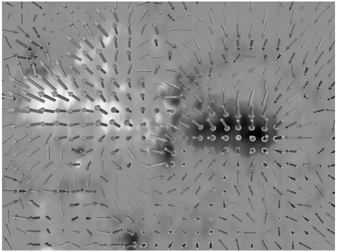
- Spectra fit to a Milne-Eddington atmosphere to determine $B_{||}$ and $B_{\perp}$ (Borrero et al., 2007)
- 180° ambiguity in $\boldsymbol{B}_{\perp}$ resolved by minimizing currents and $\nabla \cdot \boldsymbol{B}$ via simulated annealing (Metcalf et al., 2006; Leka et al., 2009)

Solar Magnetic Fields: Magnetograms
Solar Dynamics Observatory/Helioseismic Magnetic Imager

- HMI will sample 5-6 points along the Stokes profiles I, Q U, V of the Ni I 6768 absorption line
- Cadence of science quality ambiguity resolved vector magnetograms $10 - 15$ minutes (available after 24 hours)
- full disk 4096×4096 pixels or 1" resolution

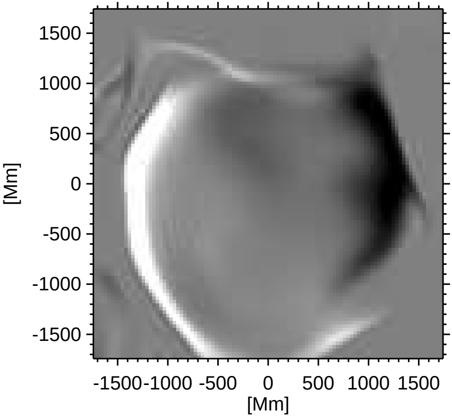


(Norton et al., 2006)



(Keller et al., 2008)

Synthetic Magnetogram of the Vertical Magnetic Field



- White/Black positive/negative vertical flux
- Green neutral line ($B_z = 0$)
- *Sometimes* we get vector fields: $\boldsymbol{B} = \boldsymbol{B}_h + B_z \hat{z}$

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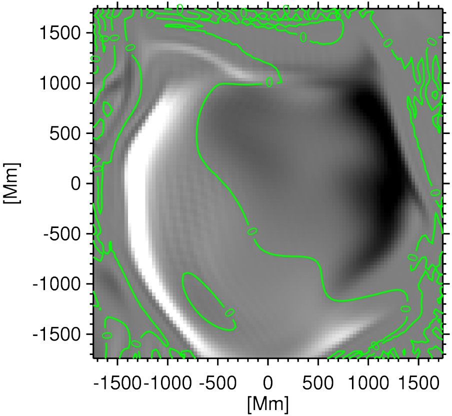

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Solar Magnetic Fields: Magnetograms

What is a "Neutral-Line?"

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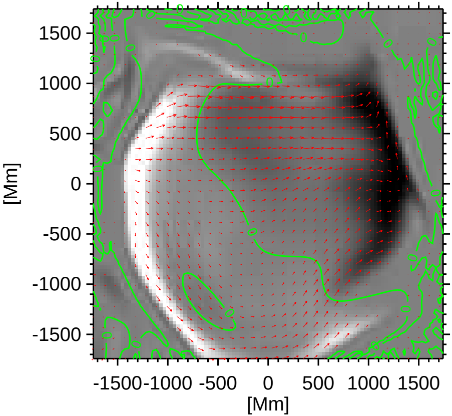

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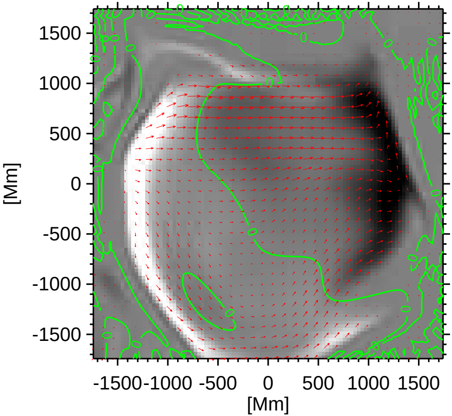
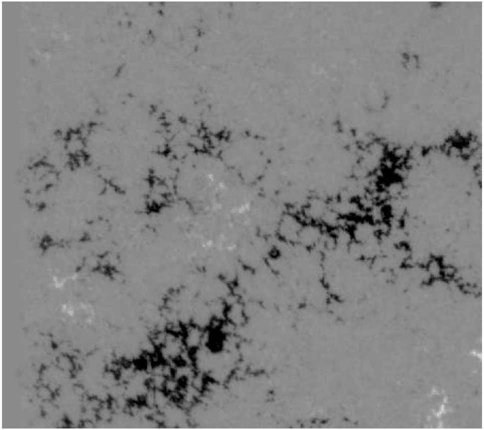


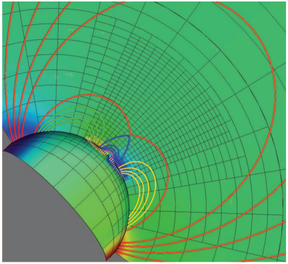
Flux Emergence (Hinode/SOT)

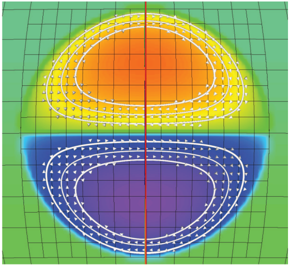


Photospheric Flows: Why are They Important?

Photospheric plasma flows estimated from a sequence of vector magnetograms can be used to:

1. Test CME initiation models that require neutral line magnetic footpoint shearing in the photosphere
   - Major open questions in Solar Physics:
     "How, why, and when do CMEs and flares erupt?"
2. Quantify the magnitude and timing of Poynting and helicity fluxes in active regions – free energy and structure in the corona
3. Provide boundary conditions for MHD simulations of the corona evolution — first principles predictive space weather models



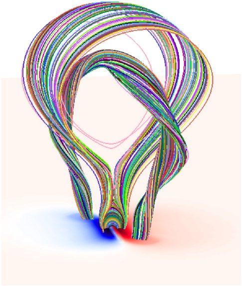


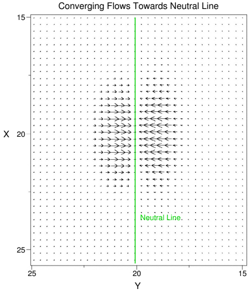
(DeVore & Antiochos, 2008)

Breakout Model

- Magnetic topology: Quadrapole: Dipolar active region in the Sun's dipolar magnetic field
- Unsigned Flux: constant (no emergence/submergence/cancelation)
- Flows parallel to the magnetic neutral line (twisting)
- Shears across the neutral line

(Antiochos, 1998; Antiochos et al., 1999)

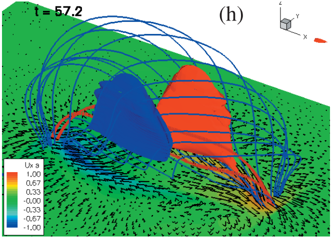




Flux-Cancellation Model

- Magnetic topology: Dipole or Quadrapole
- Driving:
  - Phase#1 Energize corona with twisting (like Breakout)
  - Phase#2 Initiation:
    - Unsigned Flux: decreasing (cancellation)
    - Converging flows towards the neutral line

(Amari et al., 2003)



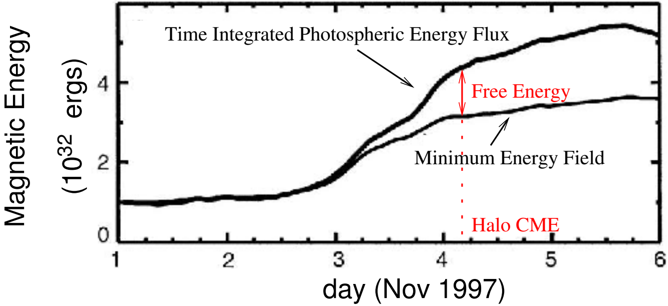
Flux-Emergence Model

- Magnetic topology: Dipole
- Unsigned Flux: increasing (emergence)
- Diverging flows away from the neutral line

(Manchester, 2001; Manchester et al., 2004)

Coronal Energy Budget

- $\frac{d\Delta E}{dt} = \int_{S_p} d^2x\,(\boldsymbol{v}_h\, B_z - v_z\, \boldsymbol{B}_h) \cdot \boldsymbol{B}_h / (4\,\pi)$
- Compare to minimum energy corona: current free "potential" field $\boldsymbol{B} = -\nabla\Phi$ consistent with *just* the observed photospheric B_z
- CME energy budget $\sim 10^{32}$ ergs



(Kusano et al., 2002)

Welsch et al. (2009) examine a large number of metrics that quantified the line-of-sight magnetograms $B \simeq B_z$ and horizontal plasma velocities in 46 active regions derived from two velocity estimation algorithms: FLCT and DAVE.

Some Phenomenological Results:

- Small active regions are the most dynamic, but least likely to flare
- Big active regions that <u>evolve</u> are most likely to flare

Quantitative Results: Most strongly associated with flaring

- Quasi-Poynting flux proxy $S = \int d^2x \; |\boldsymbol{v}_h| \; B_z^2$
  Assumes $\boldsymbol{v}_h B_z^2 \sim (\boldsymbol{v}_h B_z - v_z \boldsymbol{B}_h) \cdot \boldsymbol{B}_h$, $B_z \propto \boldsymbol{B}_h$
- Unsigned flux near the neutral line $R = \Sigma W_{\mathrm{NL}} \, |B_z|^2$

How Can We Estimate Photospheric Flows?

1. Doppler measurements (spectroscopy)
   - Provides line of sight velocity
   - Mixture of flows parallel and perpendicular to the photospheric magnetic field except near the neutral line where $\boldsymbol{B} = \boldsymbol{B}_h$
2. Optical flow methods (LCT, MEF, DAVE, DAVE4VM), etc, solve inverse problem: given time-history of $\boldsymbol{B}$ calculate $\boldsymbol{v}$
   - Assume a motion model: For example the magnetic induction equation with the ideal Ohm's law $\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B}/c$

$$\partial_t B_z = -\boldsymbol{\nabla} \cdot (\boldsymbol{v}_h B_z - v_z \boldsymbol{B}_h)$$

   - Ancillary assumption: Additional information about the local flow structure or global flow properties is required to resolve motion ambiguity
   - Answer depends on assumed model and ancillary assumptions

REPEAT: All optical flow methods involve a motion model and ancillary assumptions, including local correlation tracking (LCT)!

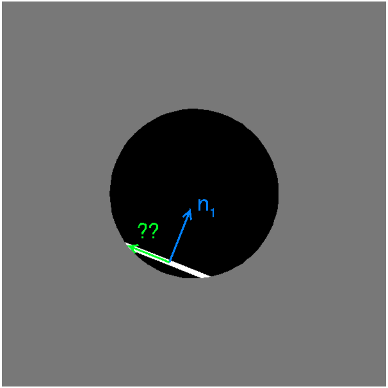
Edge Moving in an Aperture

1. Assume a motion model:

   $$\partial_t B_z = -\boldsymbol{v}_h \cdot \boldsymbol{\nabla}_h B_z \text{ (advection)}$$

   Two unknowns: $\boldsymbol{v}_h$
2. Assume local velocity profile: $\boldsymbol{v}_h = \boldsymbol{v}_0$ (rigid motion)
3. Correlate location of edge to infer motion from frame to frame

Aperture Problem



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- These are the assumptions underlying local correlation tracking (Schuck, 2005, 2006)

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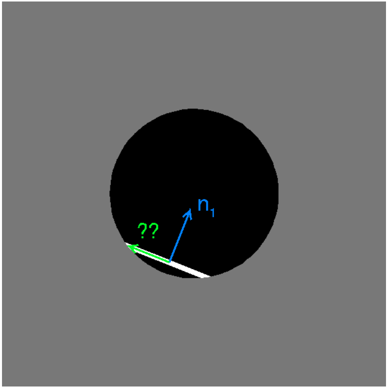

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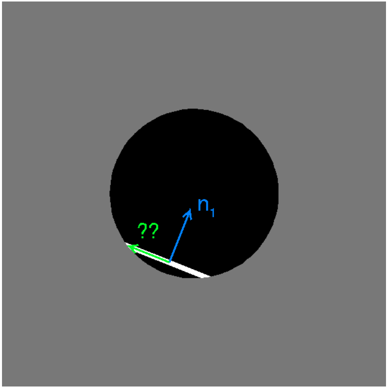

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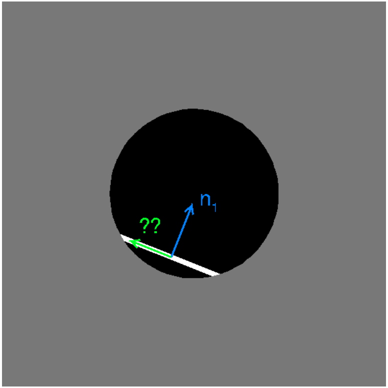

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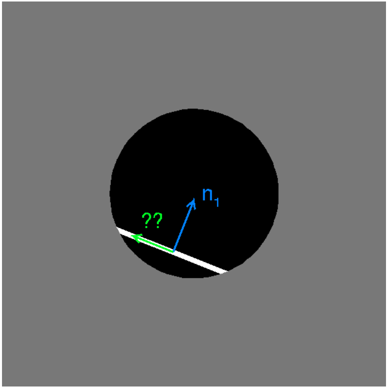

How Can We Estimate Photospheric Flows?

Simple illustration of motion ambiguity

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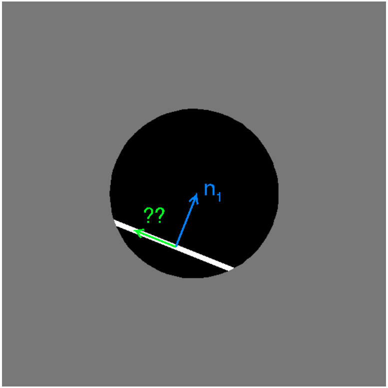

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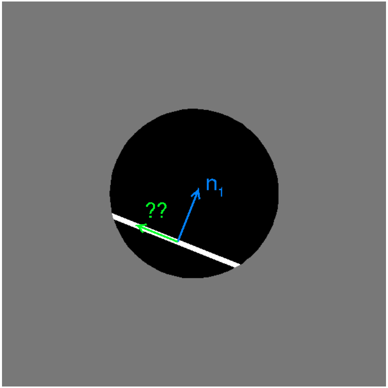

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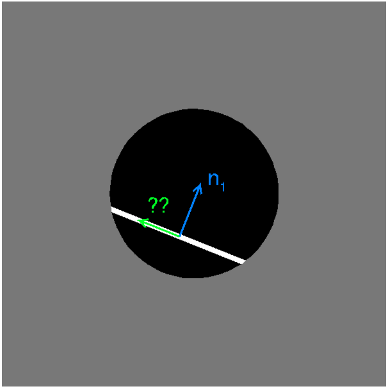

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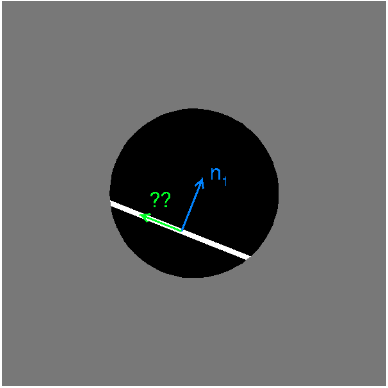

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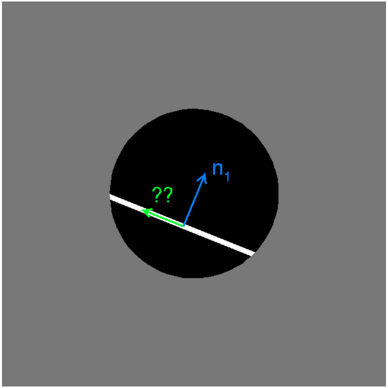

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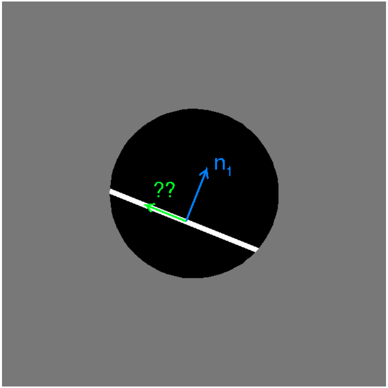

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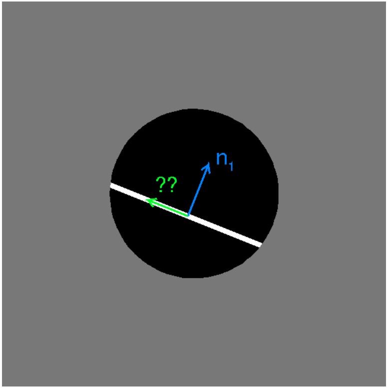

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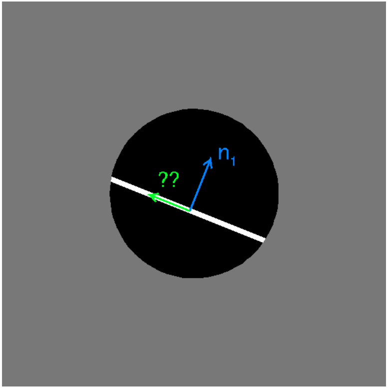

How Can We Estimate Photospheric Flows?

Simple illustration of motion ambiguity

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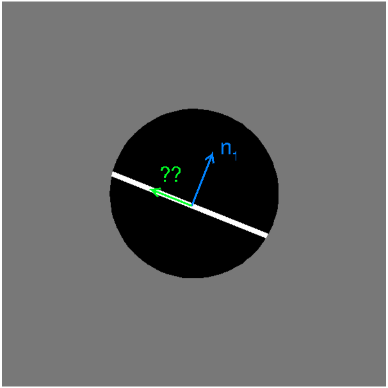

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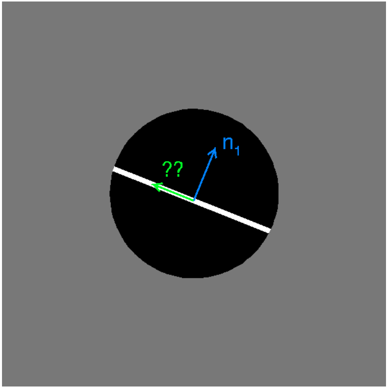

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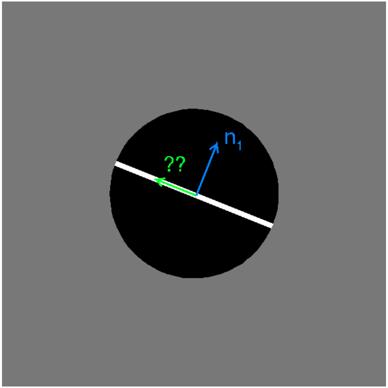

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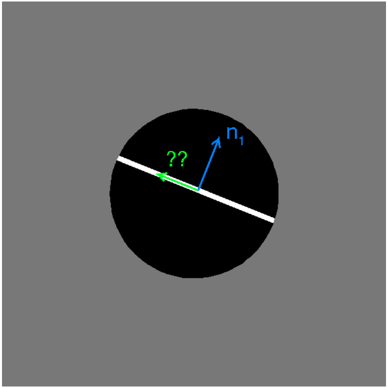

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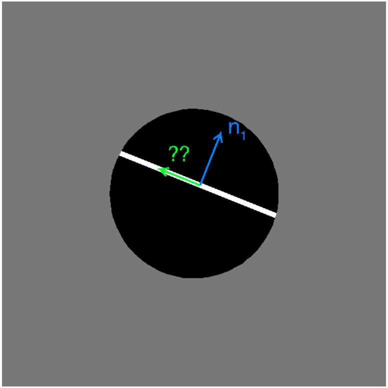

How Can We Estimate Photospheric Flows?

Simple illustration of motion ambiguity

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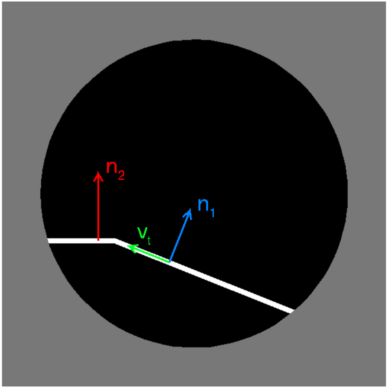

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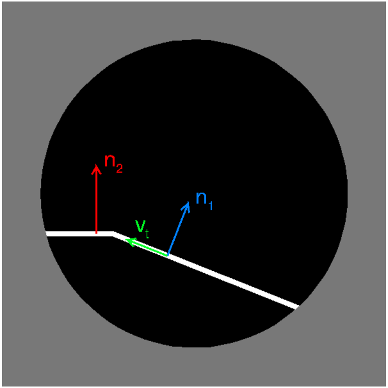

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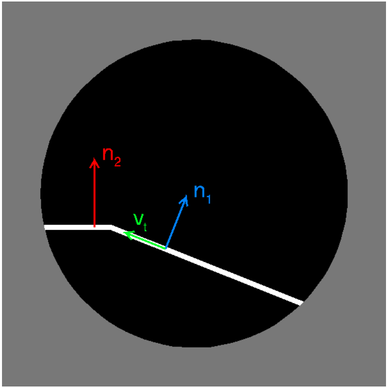

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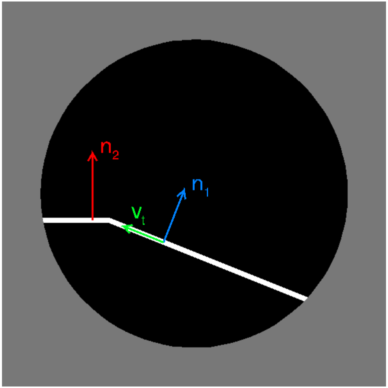

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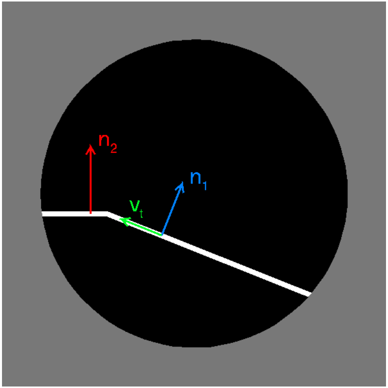

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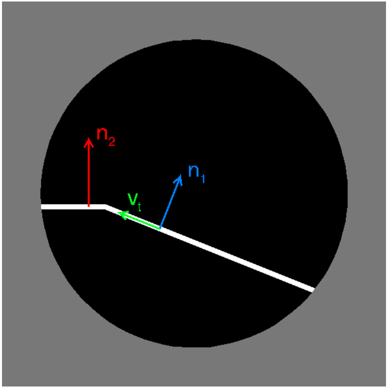

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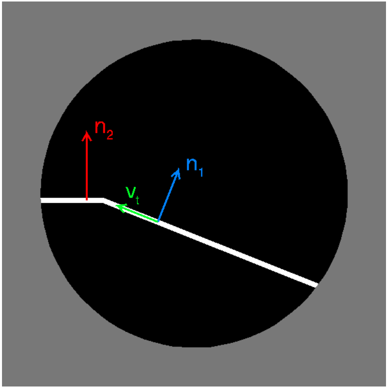

How Can We Estimate Photospheric Flows?

Simple illustration of motion ambiguity

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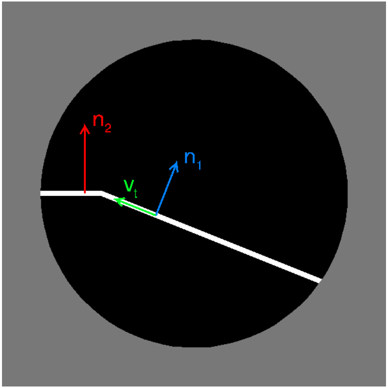

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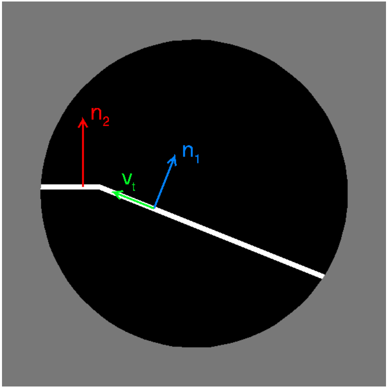

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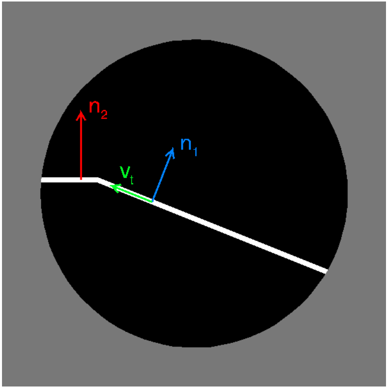

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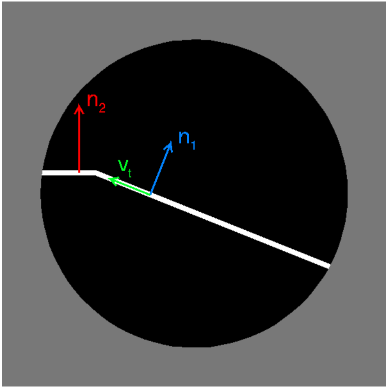

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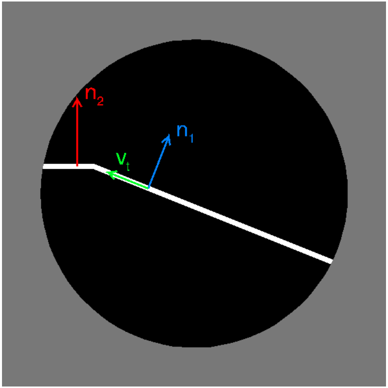

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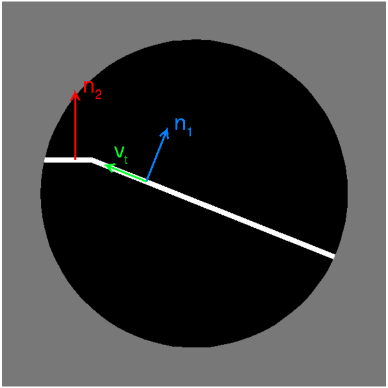

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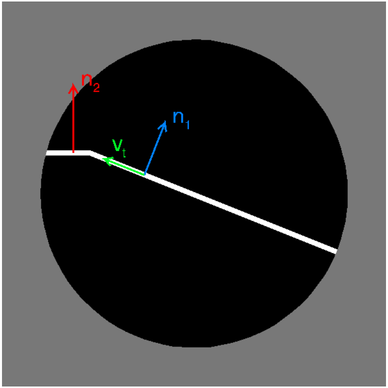

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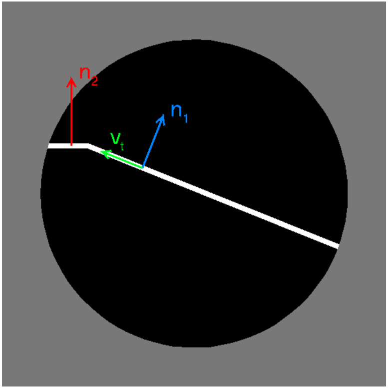

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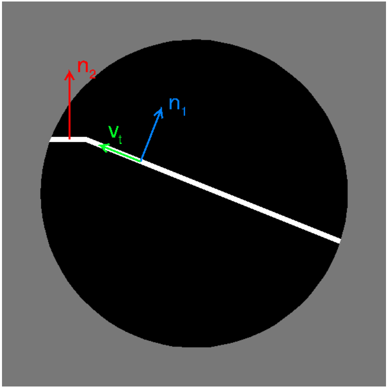
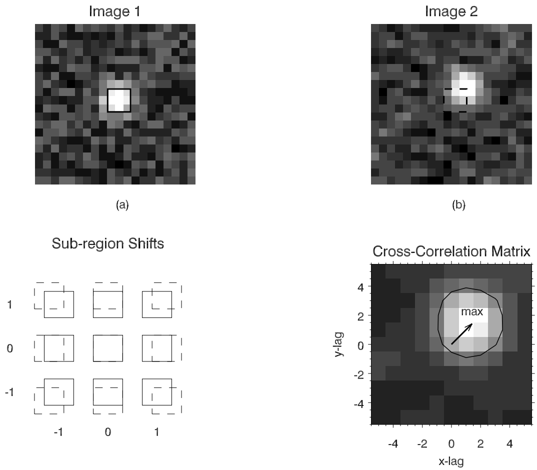


How Can We Estimate Photospheric Flows?
Local Correlation Tracking (LCT)

Template/Pattern Matching Algorithm



How does LCT work?

- Minimizes the functional:

$$C = \int d^2 x\, w\left(\boldsymbol{X_0} - \boldsymbol{x}\right)\left[B_n\left(\boldsymbol{x} + \boldsymbol{u}_0 \Delta t, t + \Delta t\right) - B_n\left(\boldsymbol{x}, t\right)\right]^2$$

- First order Taylor expansion:

$$C \approx \Delta t^2 \int d^2 x\, \overbrace{w\left(\boldsymbol{X_0} - \boldsymbol{x}\right)}^{\text{Aperture}} \left[\overbrace{\partial_t B_n\left(\boldsymbol{x}, t\right) + \boldsymbol{u}_0 \cdot \nabla B_n\left(\boldsymbol{x}, t\right)}^{\text{Advection Equation}}\right]^2 \approx 0$$

- LCT attempts to find the velocity $\boldsymbol{u}$ that minimizes the **advection operator** in the apodizing window. — **Not Induction Equation!**

Geometrical Interpretation of the "Footpoint Velocity" $\boldsymbol{u}_{\mathrm{F}}$

$$B_z\,\boldsymbol{u}_{\mathrm{F}} = B_z\,\boldsymbol{v}_h - v_z\,\boldsymbol{B}_h$$

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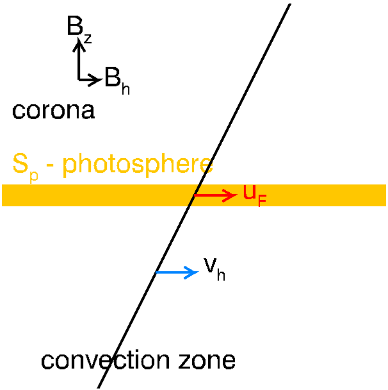
Implies footpoint velocity $\boldsymbol{u}_{\mathrm{F}}$ may be accurately estimated from the line-of-sight magnetic field B_z.

Horizontal Plasma Motion



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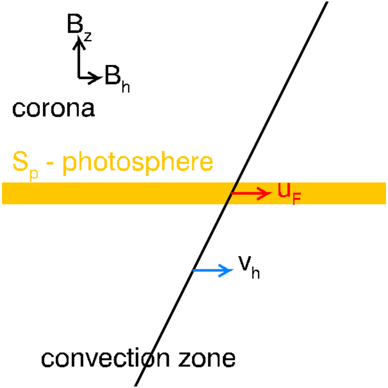

How Can We Estimate Photospheric Flows?

Démoulin & Berger Conjecture (2003)

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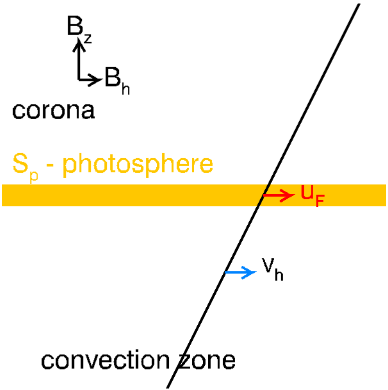

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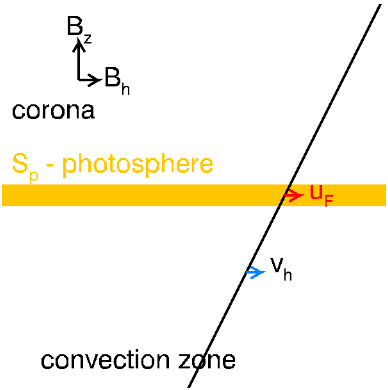

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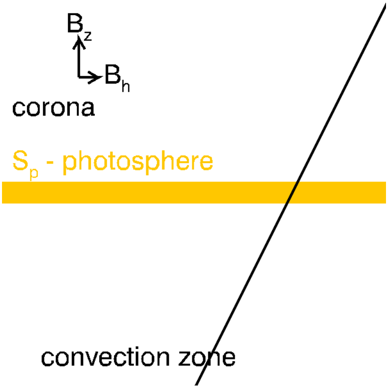

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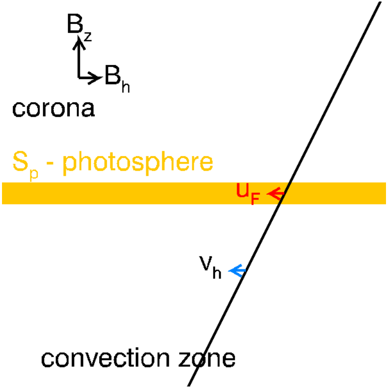

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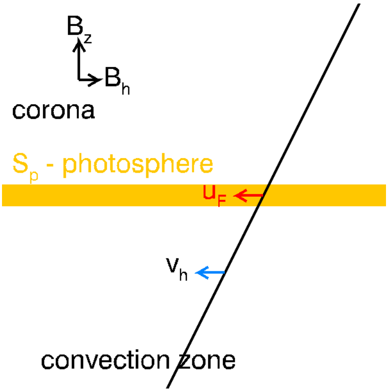

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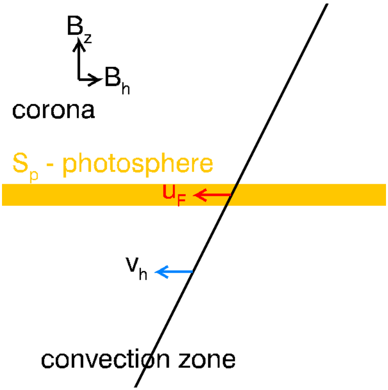

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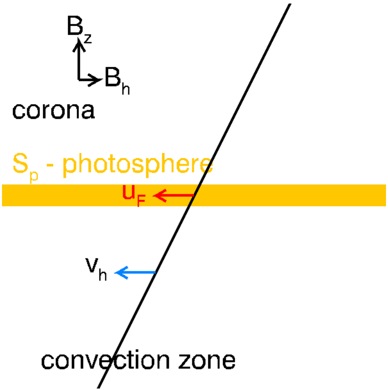

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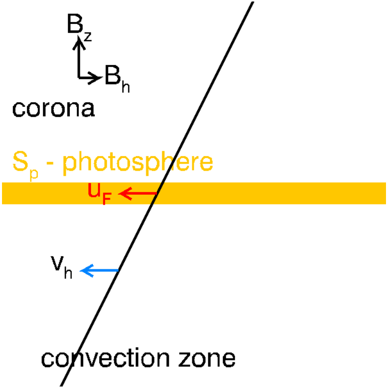

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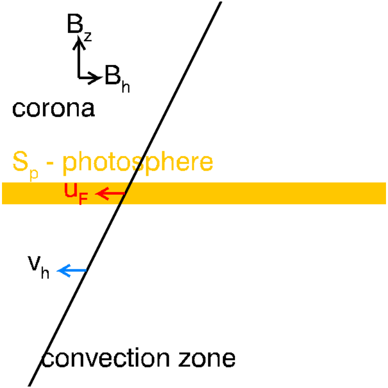

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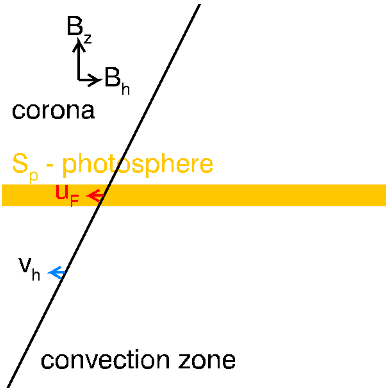

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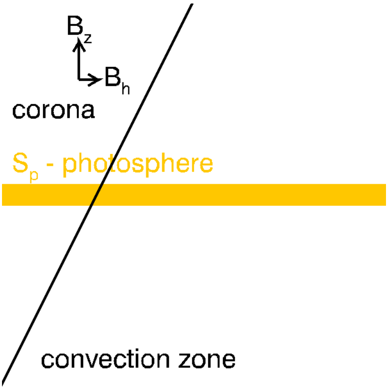

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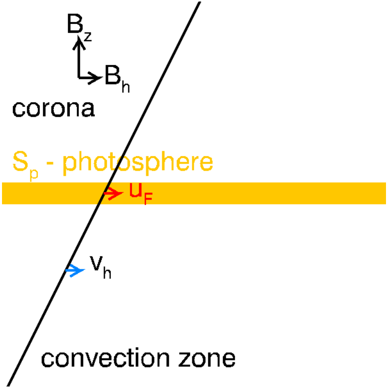

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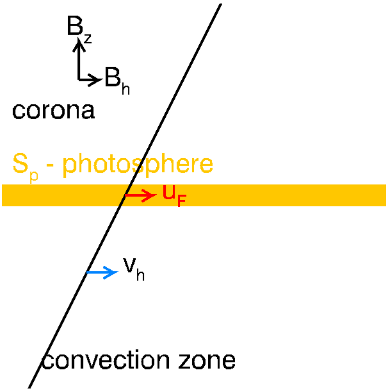

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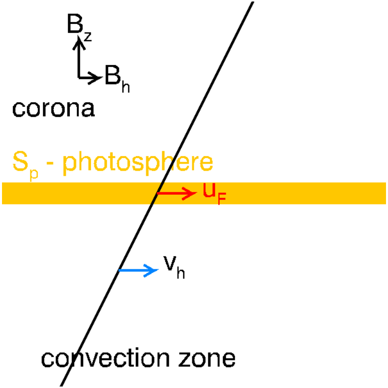

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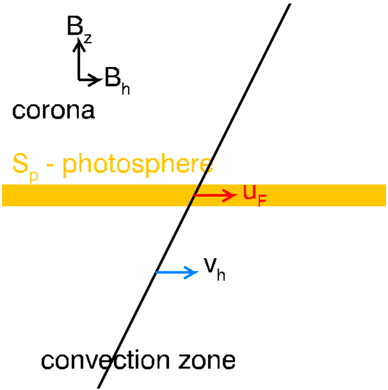

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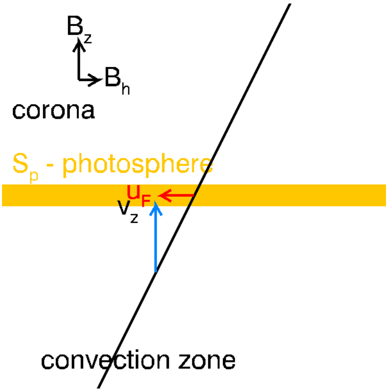

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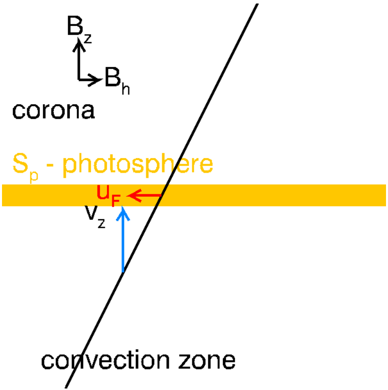

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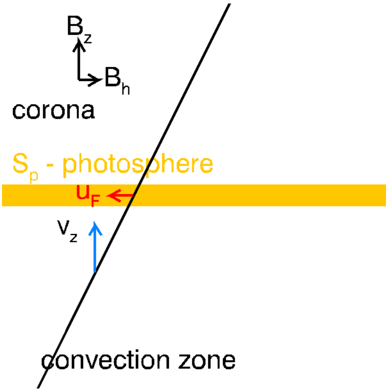

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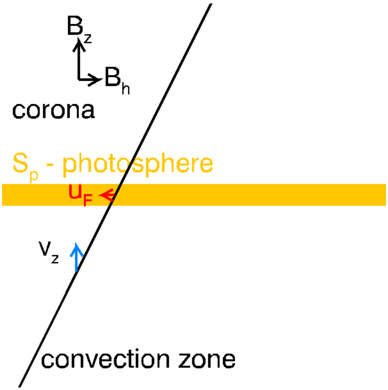

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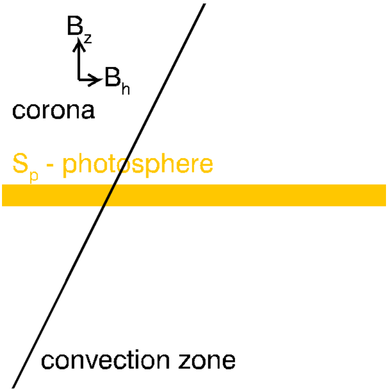

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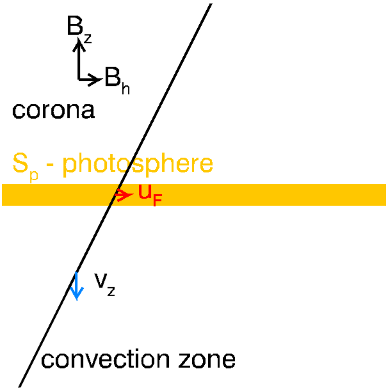

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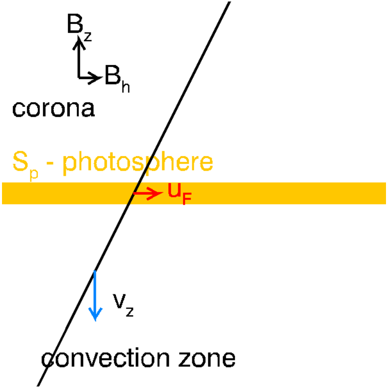

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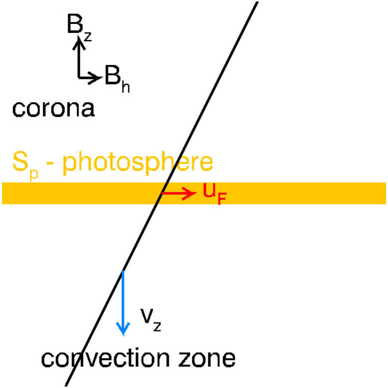

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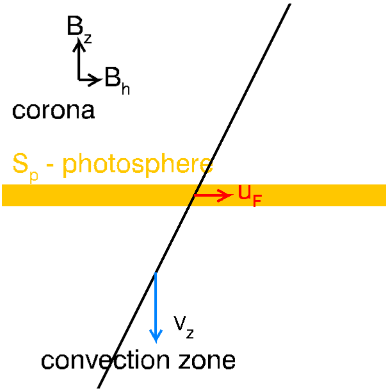

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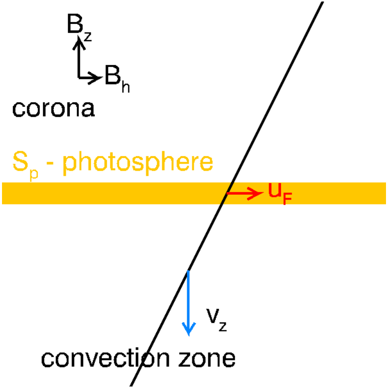

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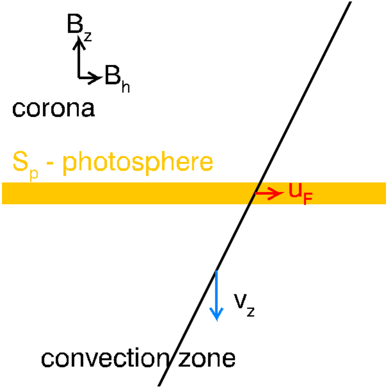

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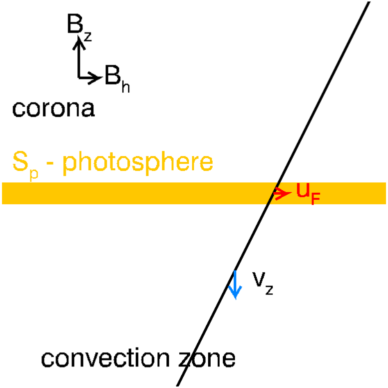

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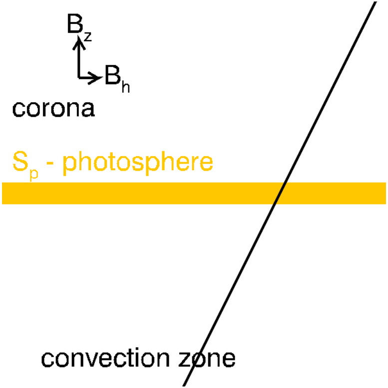

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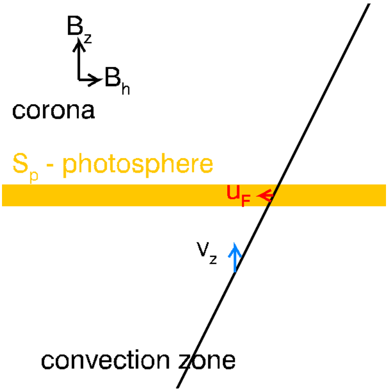

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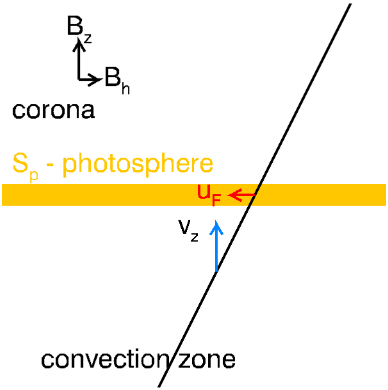

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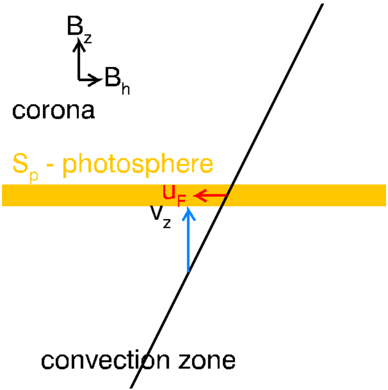
Vertical Plasma Motion



How Can We Estimate Photospheric Flows?

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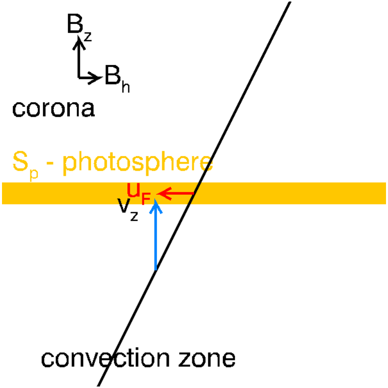

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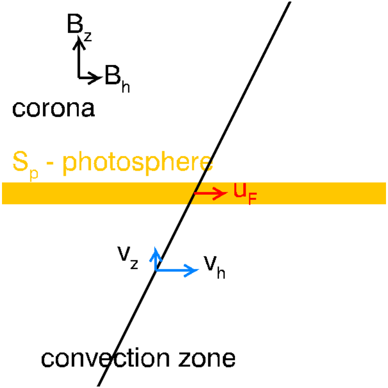

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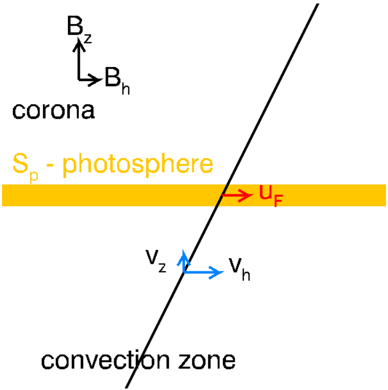

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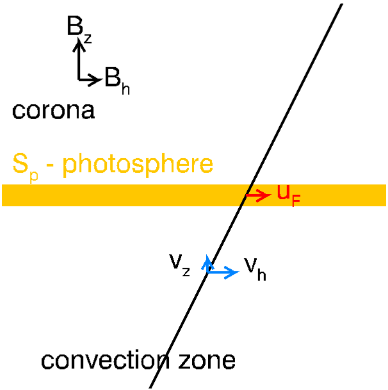

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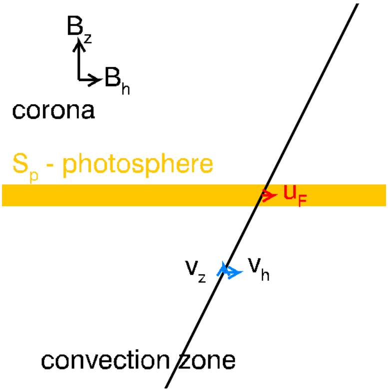

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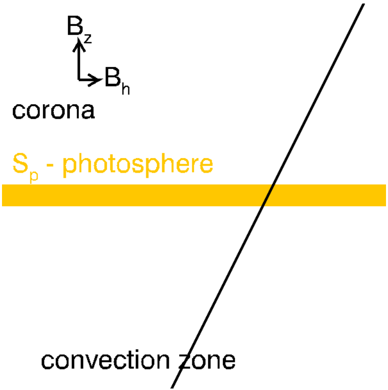

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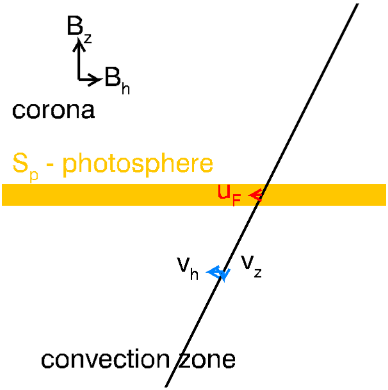

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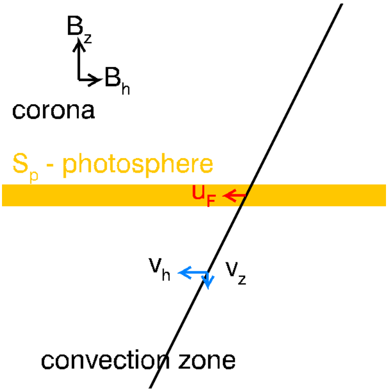

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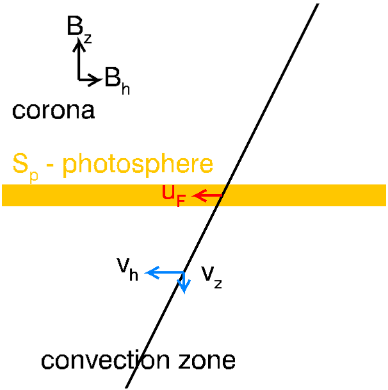

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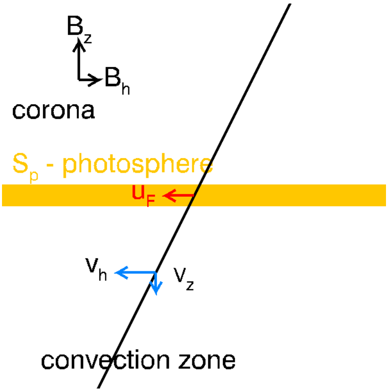

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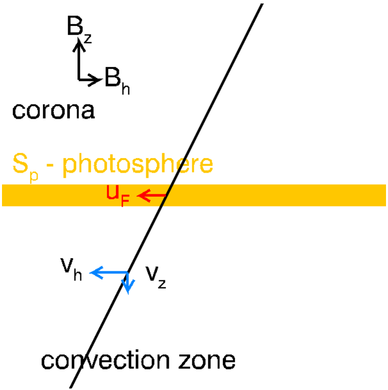

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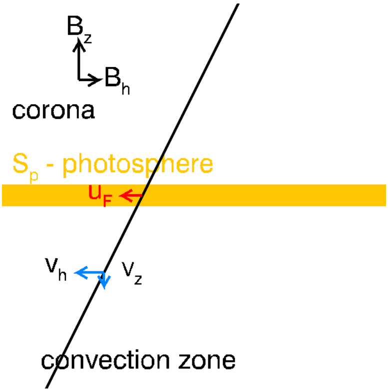

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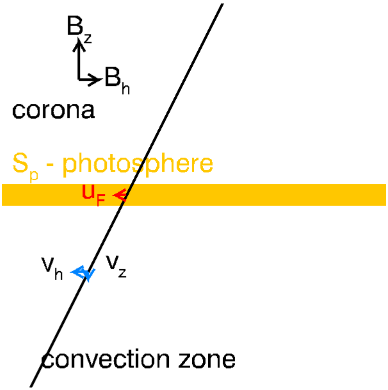

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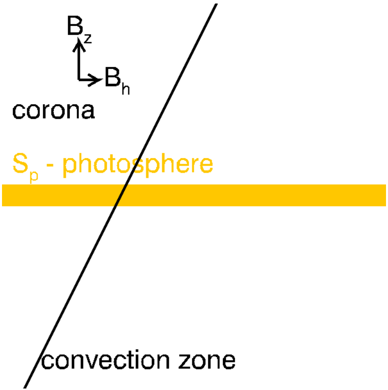

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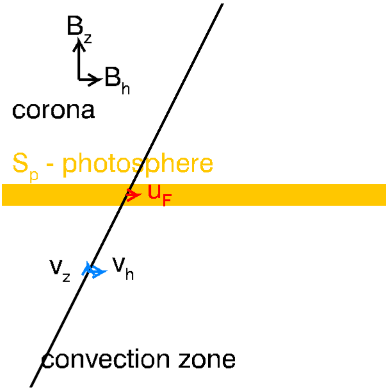

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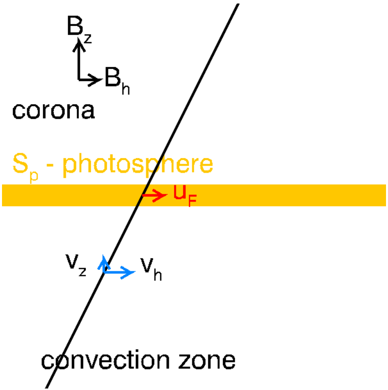

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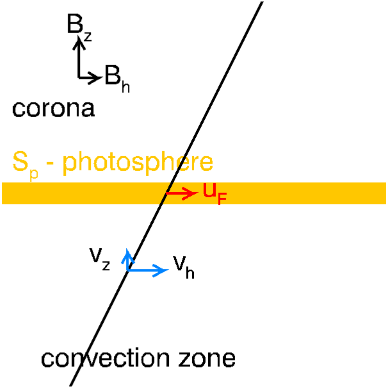

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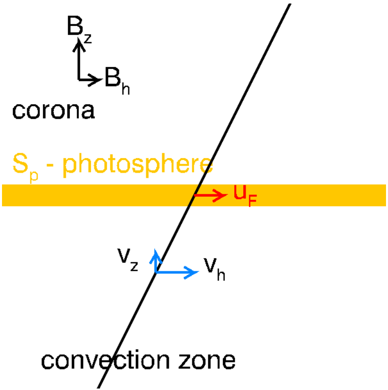

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Conjecture can be tested by comparing DAVE4VM and DAVE estimates against "ground truth" from MHD simulations

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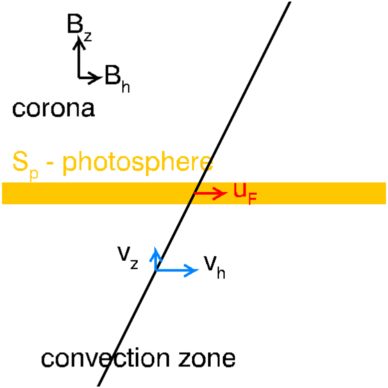


How Can We Estimate Photospheric Flows?

Differential Affine Velocity Estimator (DAVE)

$$C \approx \int dx^2\, w(\boldsymbol{x} - \boldsymbol{X_0}) \left\{ \partial_t B_z(\boldsymbol{x}, t) + \boldsymbol{\nabla}_h \cdot \left[B_z(\boldsymbol{x}, t)\, \widehat{\boldsymbol{u}}_{\mathrm{F}} \right] \right\}^2$$

$$\widehat{\boldsymbol{u}}_{\mathrm{F}} = \begin{pmatrix} u_0 \\ v_0 \end{pmatrix} + \begin{pmatrix} \widehat{u}_x & \widehat{u}_y \\ \widehat{v}_x & \widehat{v}_y \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \qquad \boldsymbol{\nabla}_h = (\partial_x, \partial_y)$$

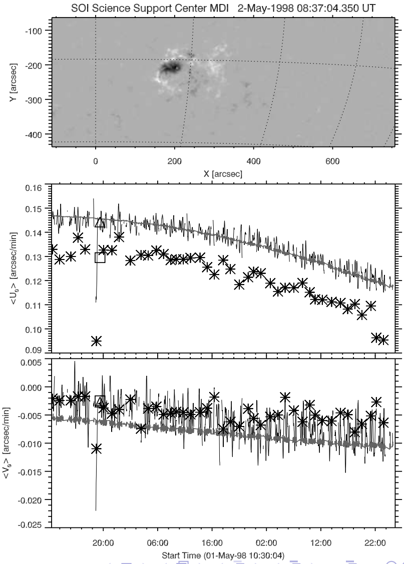
- Incorporates only vertical magnetic field component (line-of-sight)
- No explicit vertical flows
- Motivated by Démoulin & Berger's 2003 incorrect conjecture that the $\boldsymbol{u}_{\mathrm{F}}$ is the "magnetic footpoint velocity"
- Actually biased estimate of the horizontal plasma velocity $\boldsymbol{u}_{\mathrm{F}}=\boldsymbol{v}_h$

Schuck (2006)

How Can We Estimate Photospheric Flows?

Application to MDI data AR8210

- 2600 MDI magnetograms (1-minute cadence)
- Velocities estimated for $|B_{\rm LOS}| > 60$ G
- Mean V_x and V_y of the active region
- Thick line - Mean *synodic* differential velocity of the active region computed from Howard et al. (1990) and projected into the image plane.



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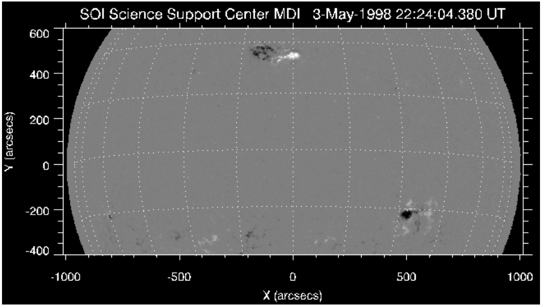

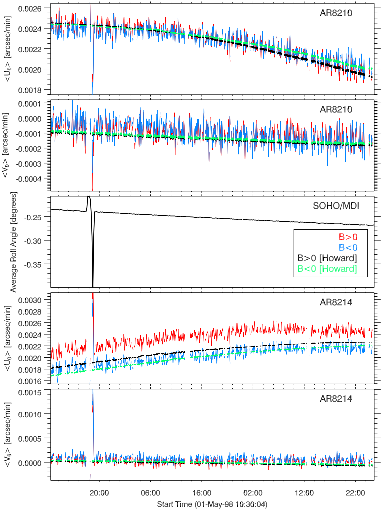

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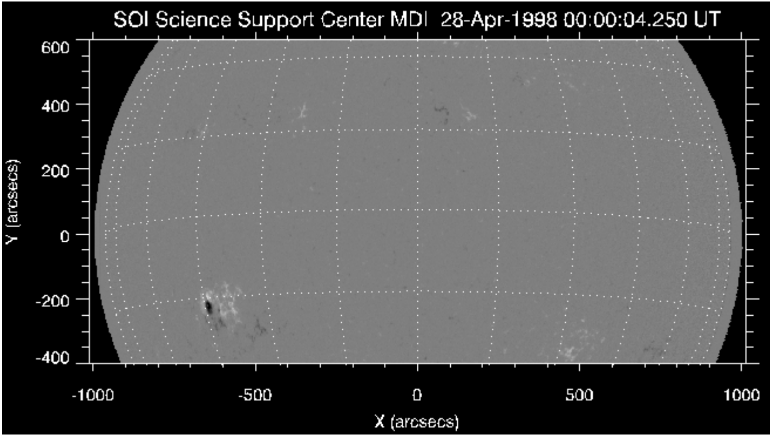

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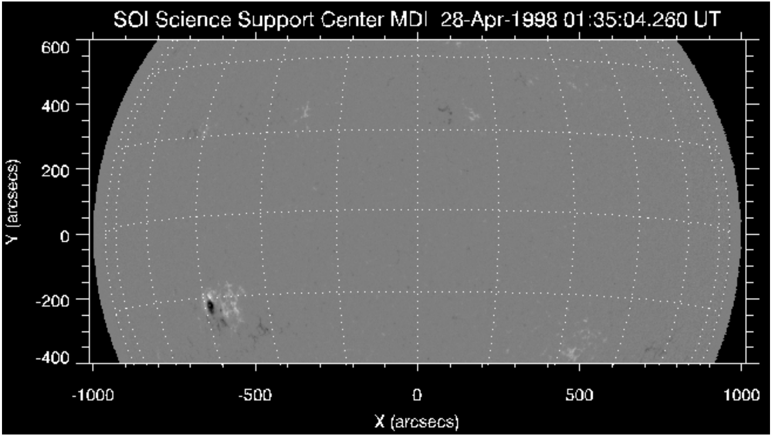

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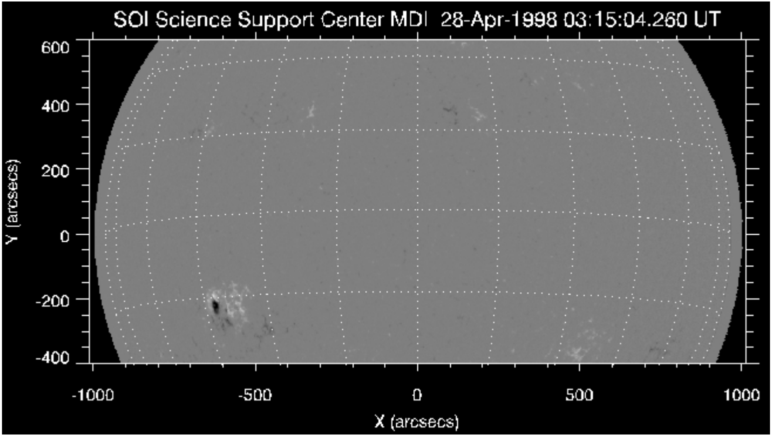

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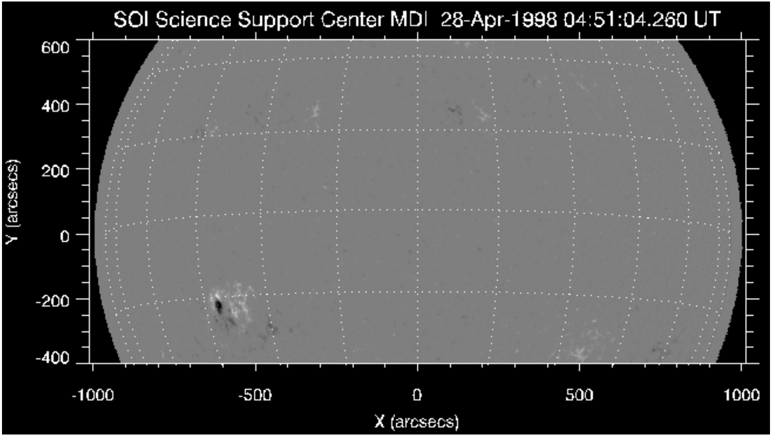

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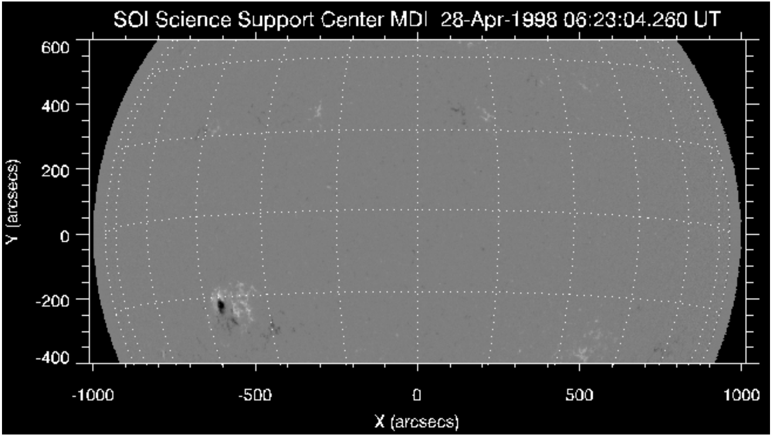

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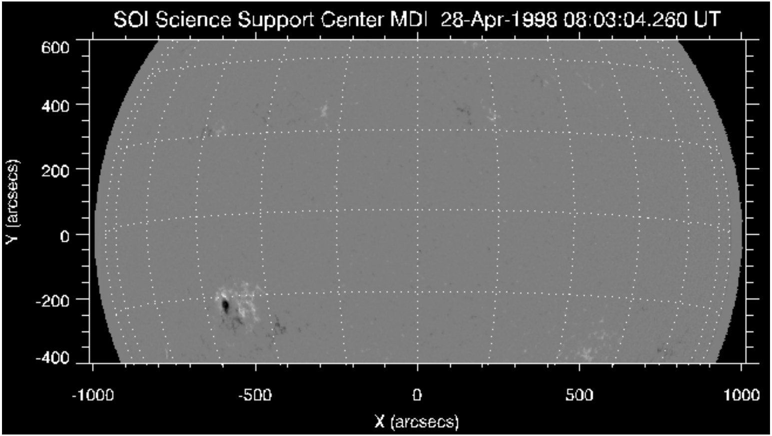

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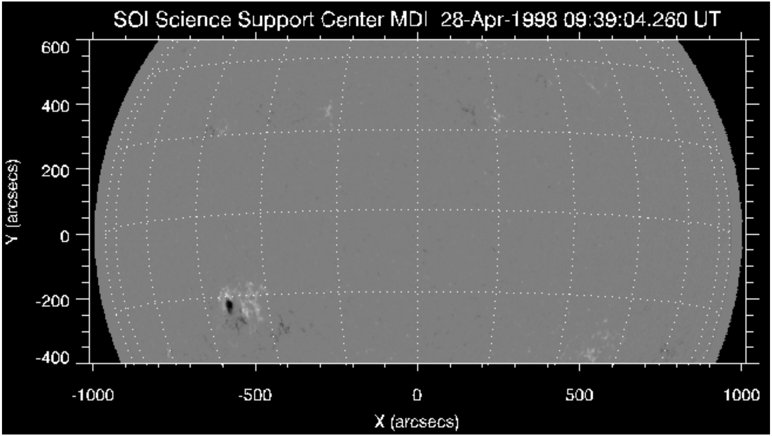

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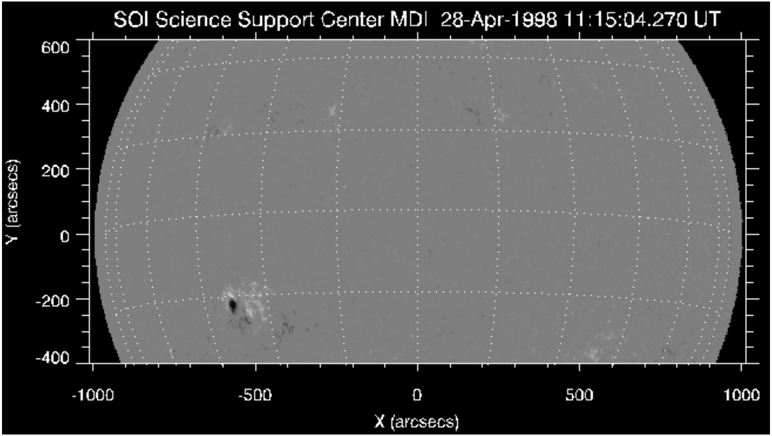

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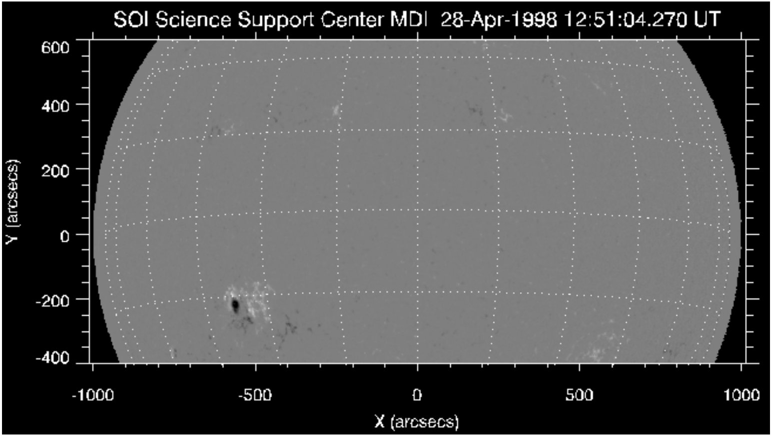

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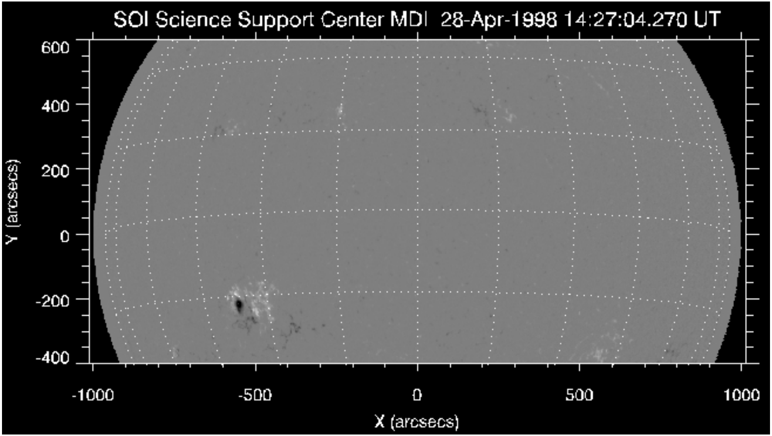
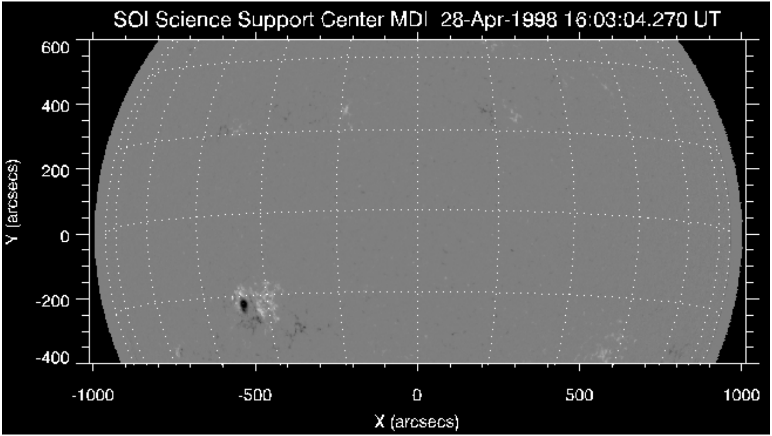


How Can We Estimate Photospheric Flows?

Application to MDI data AR8210



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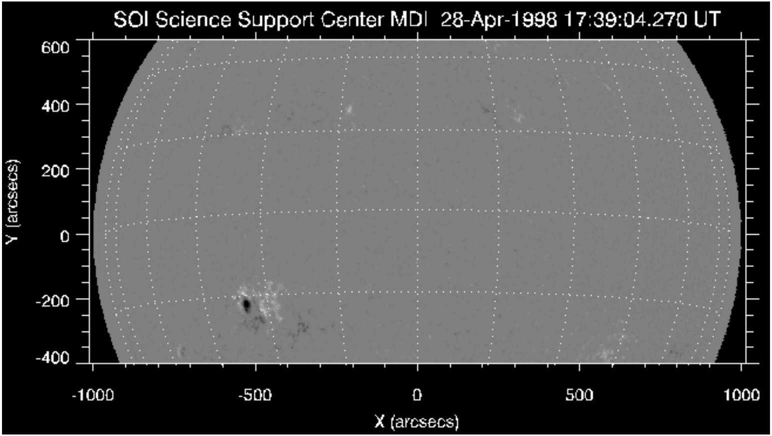

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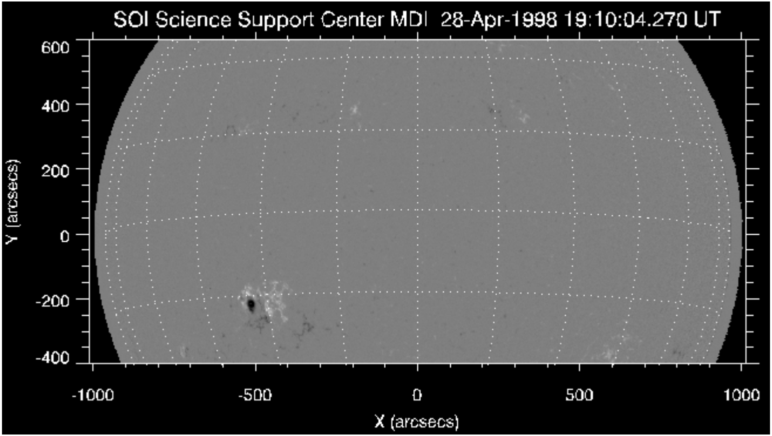
Application to MDI data AR8210



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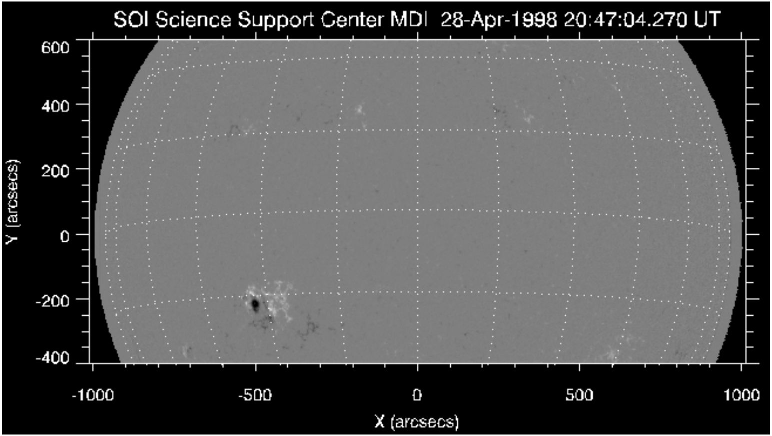

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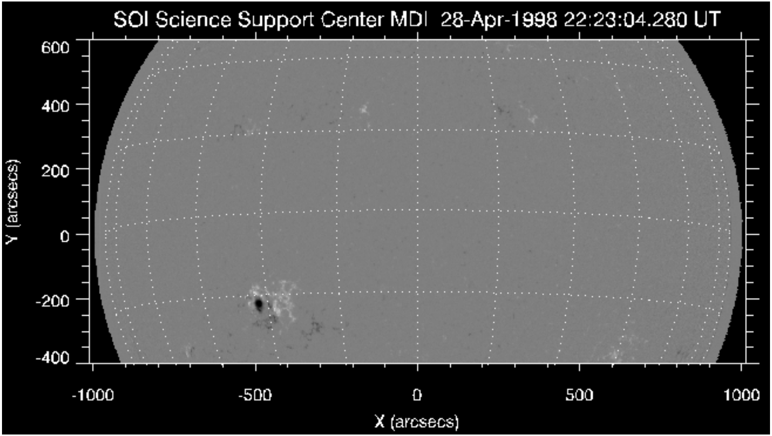

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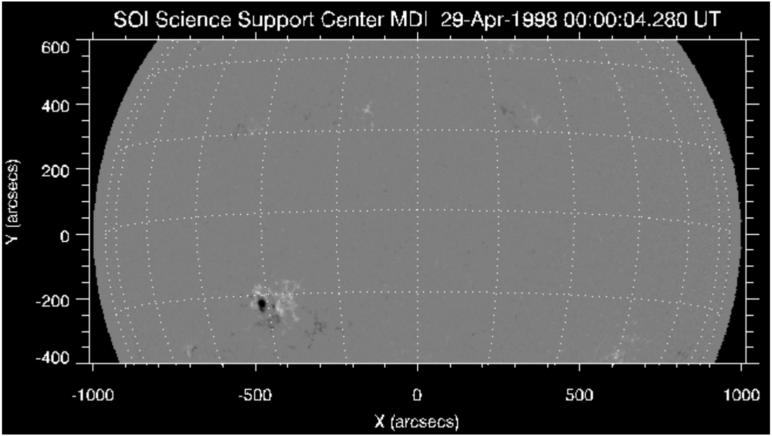

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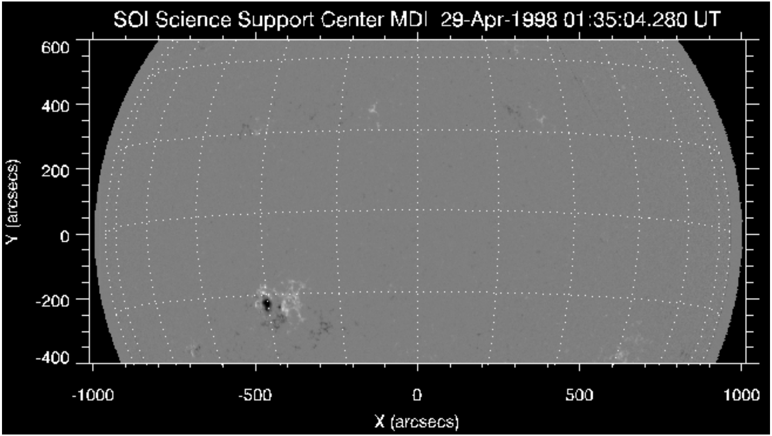

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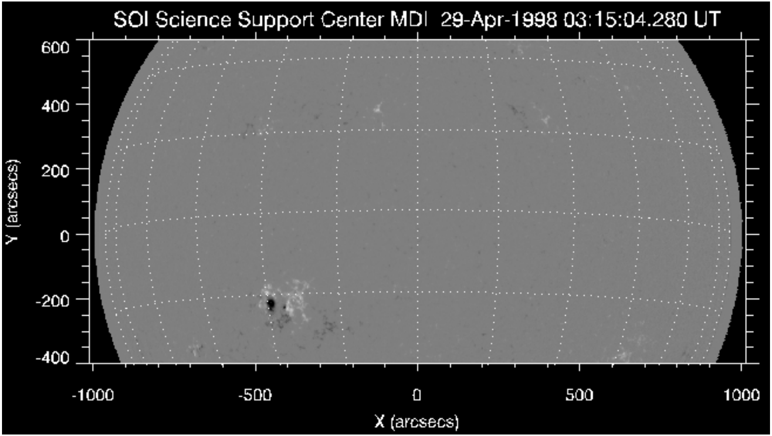

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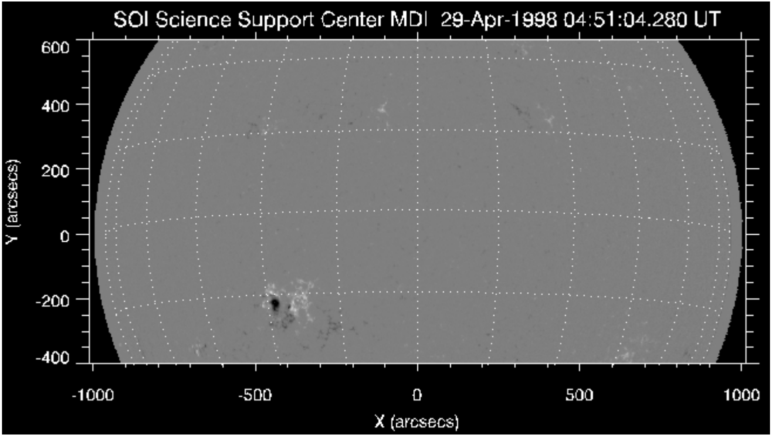

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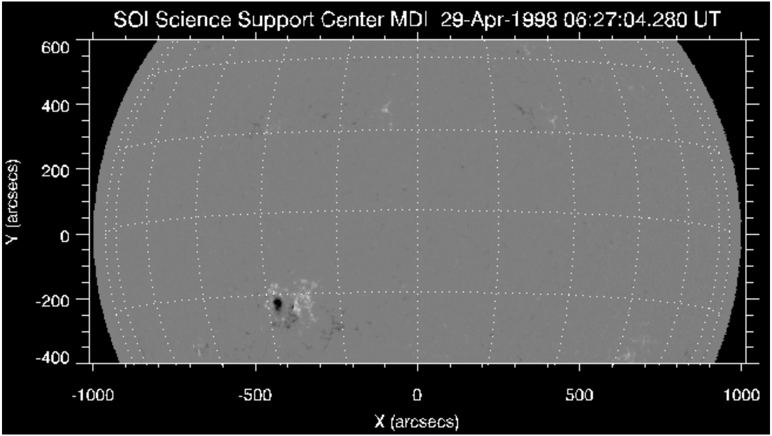

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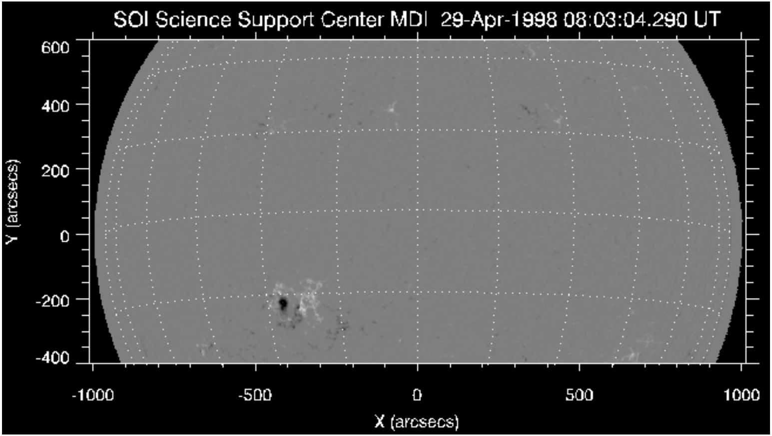

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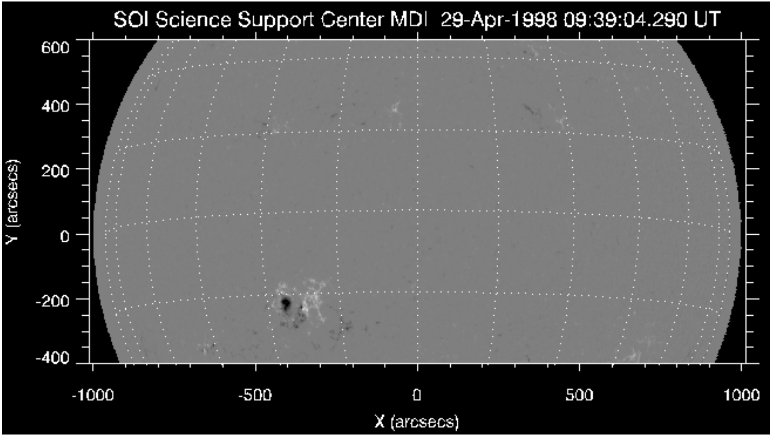

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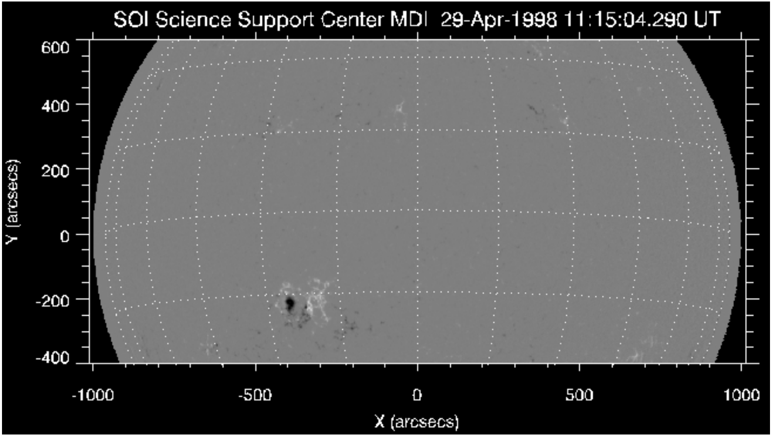

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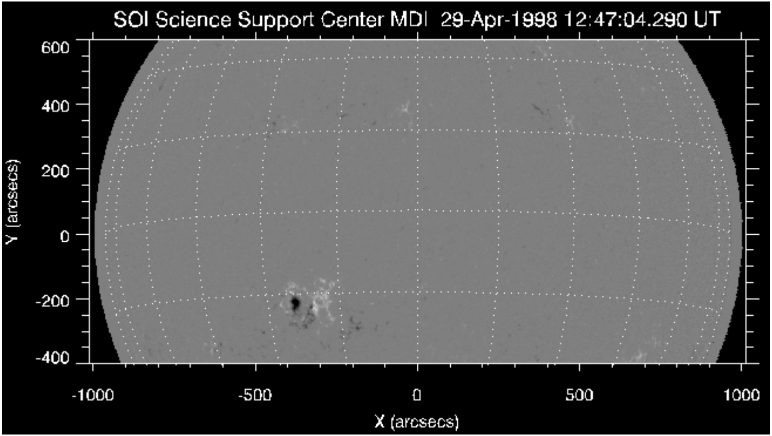

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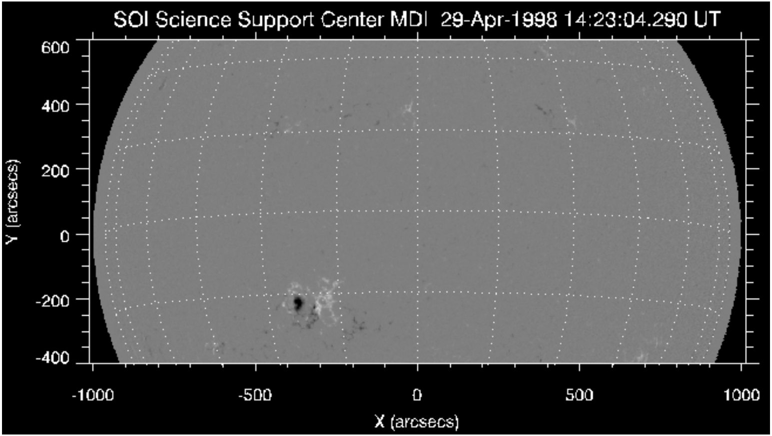

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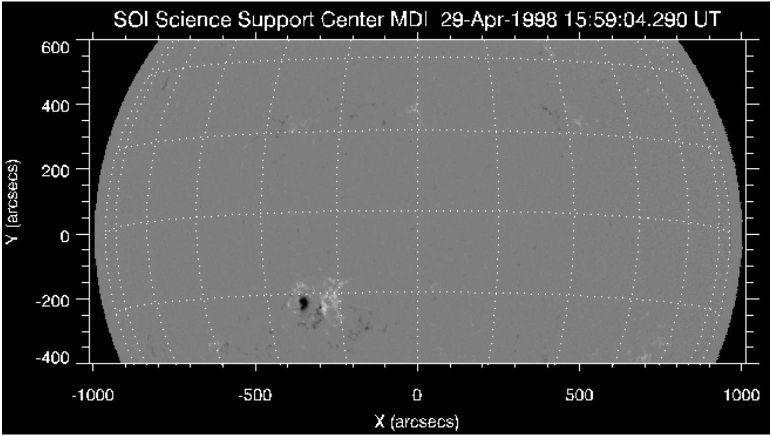

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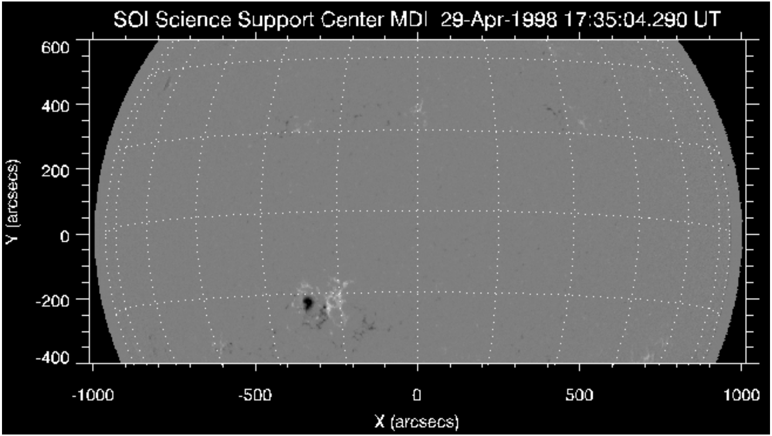

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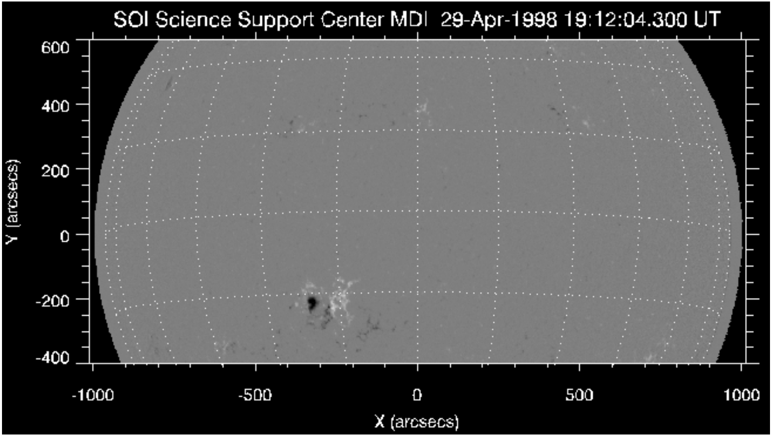

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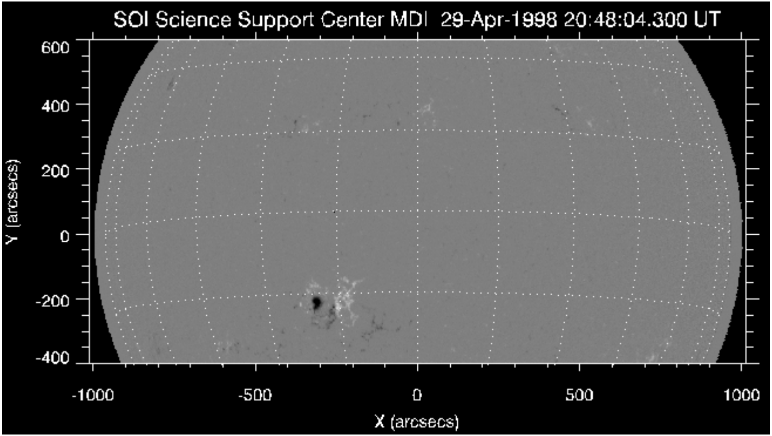

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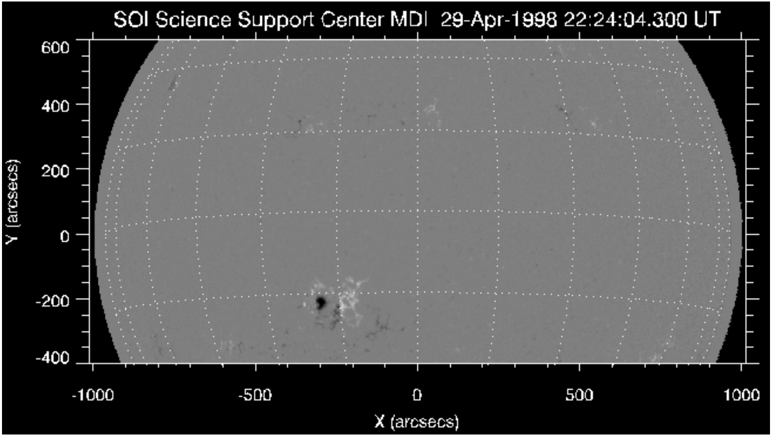

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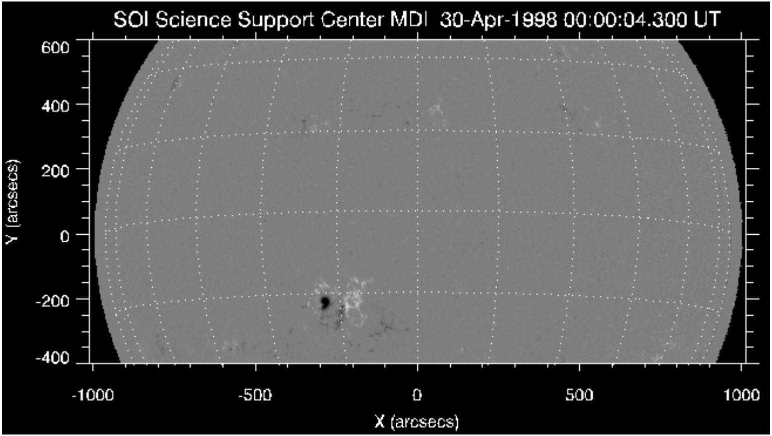

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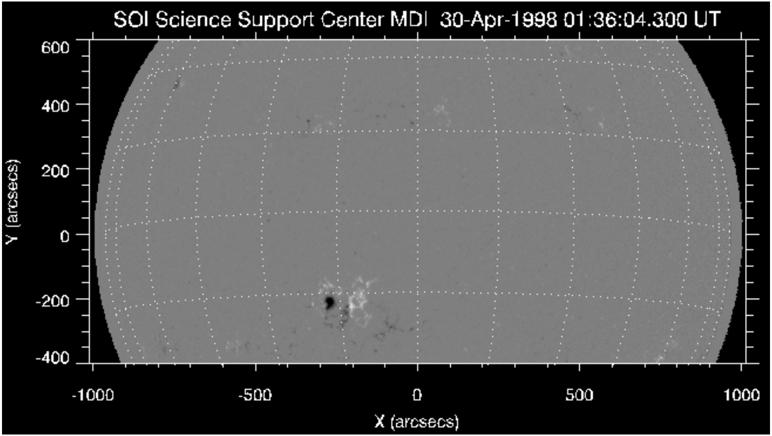

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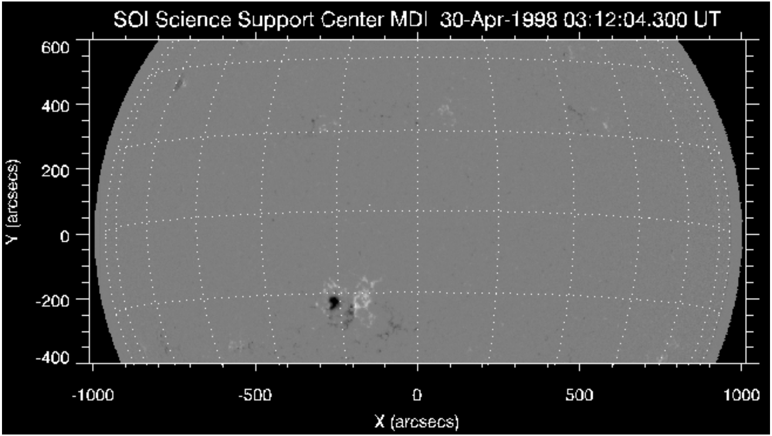

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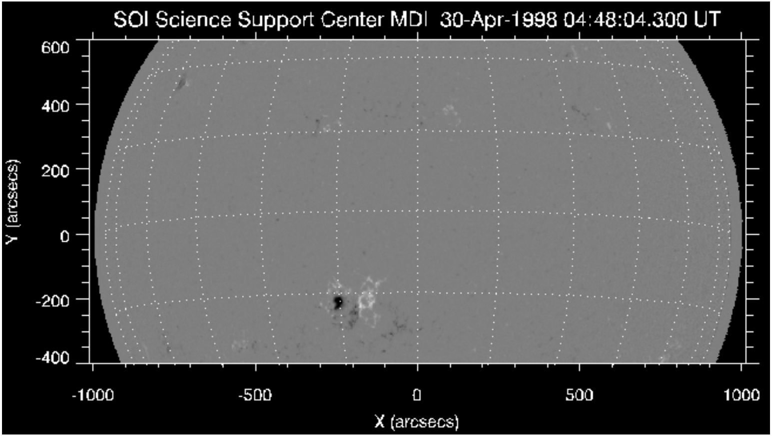

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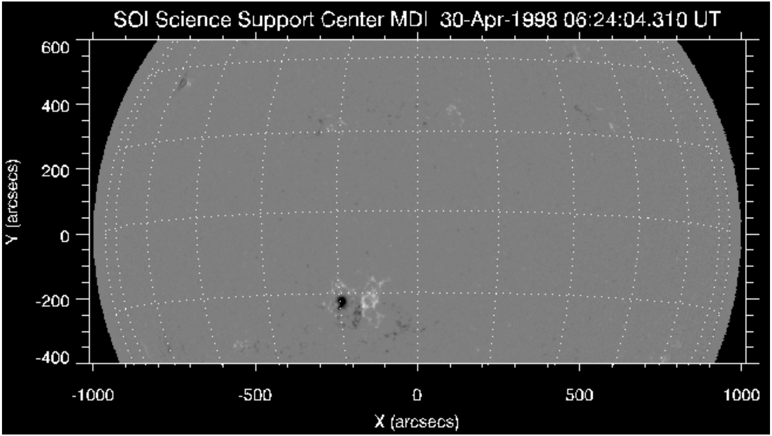

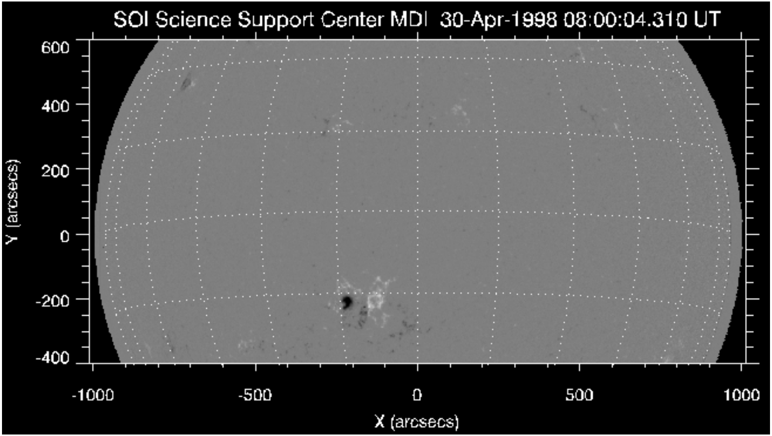
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How Can We Estimate Photospheric Flows?

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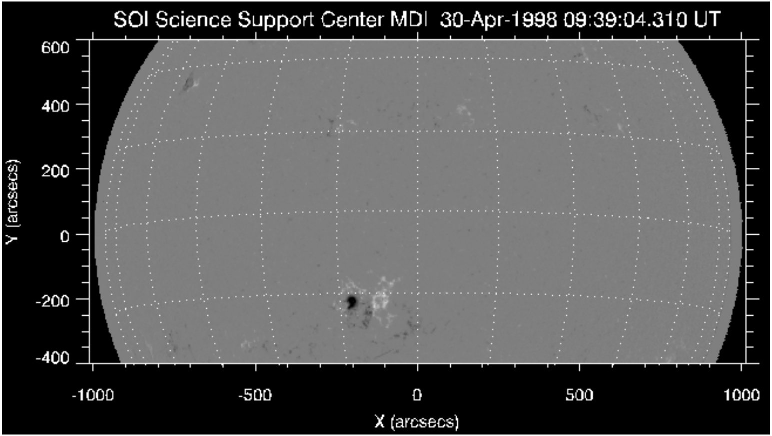

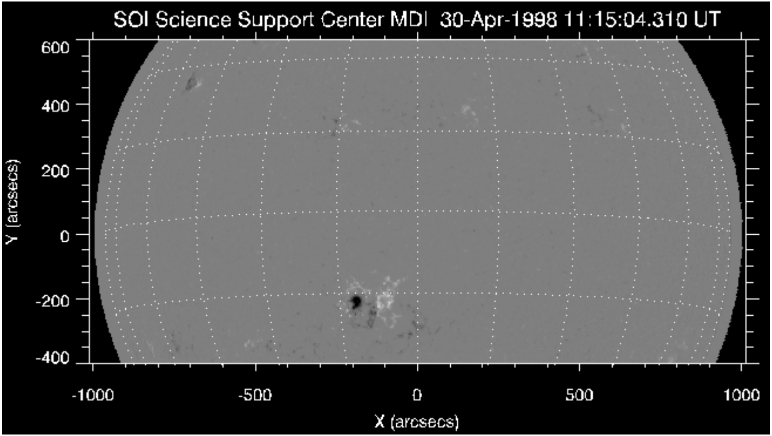

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How Can We Estimate Photospheric Flows?

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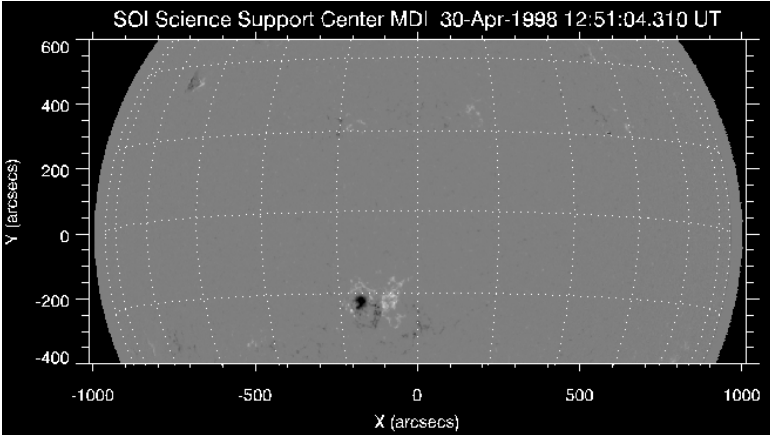

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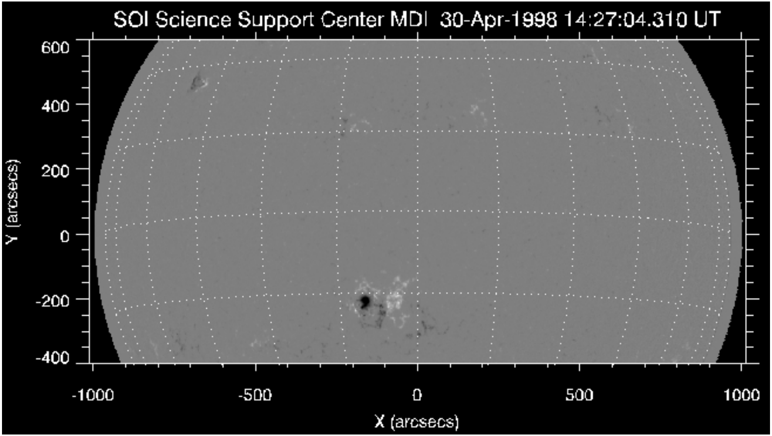

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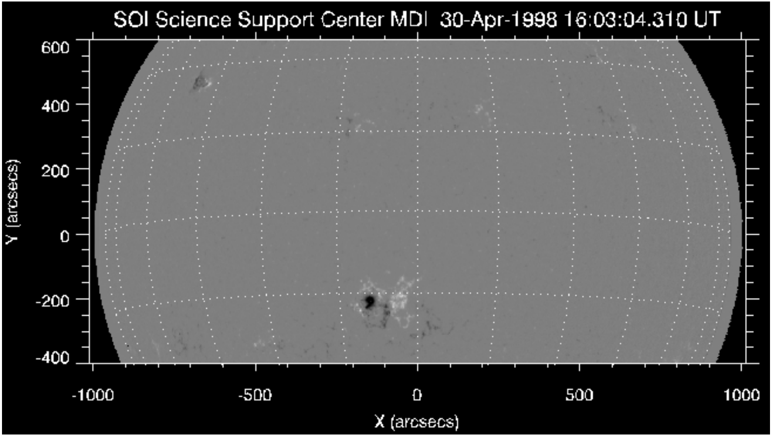

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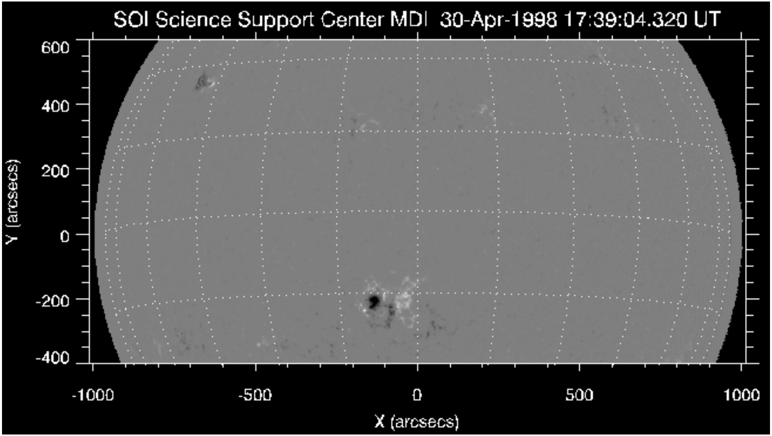

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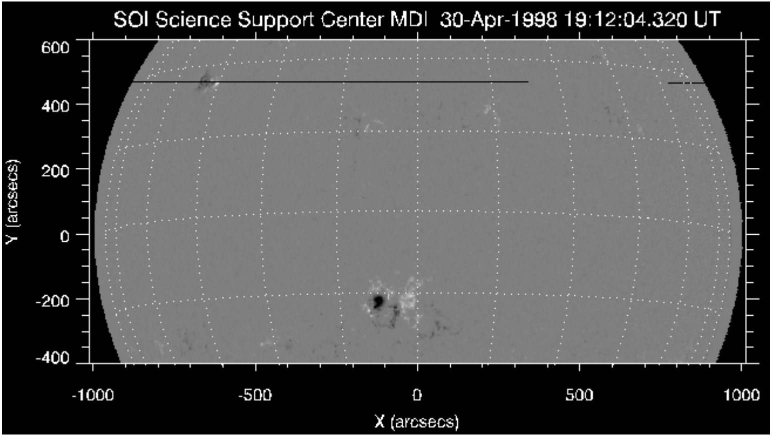

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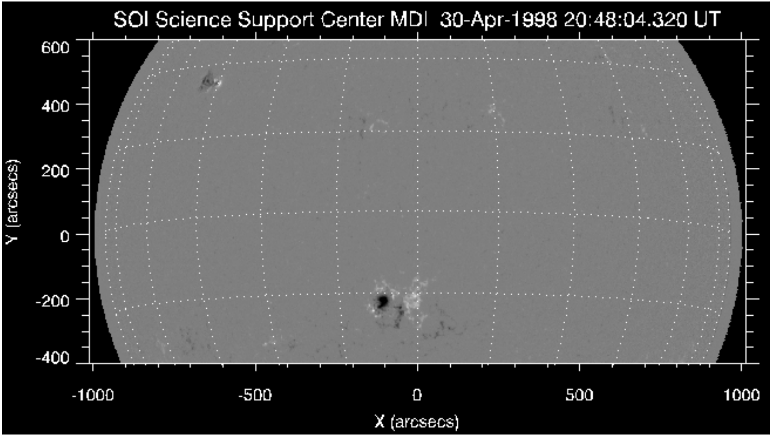

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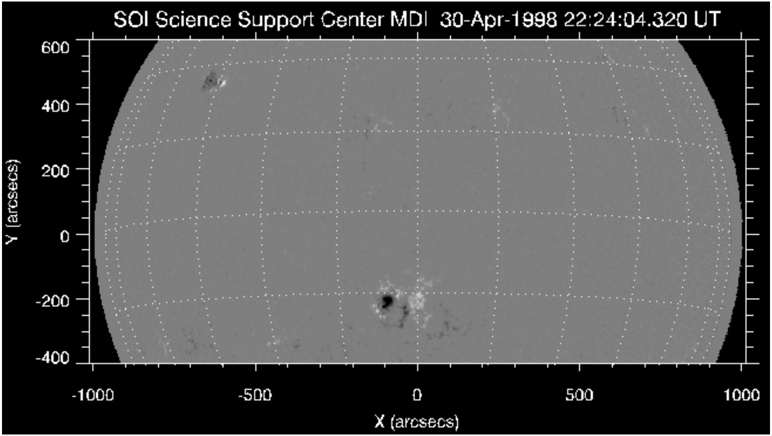

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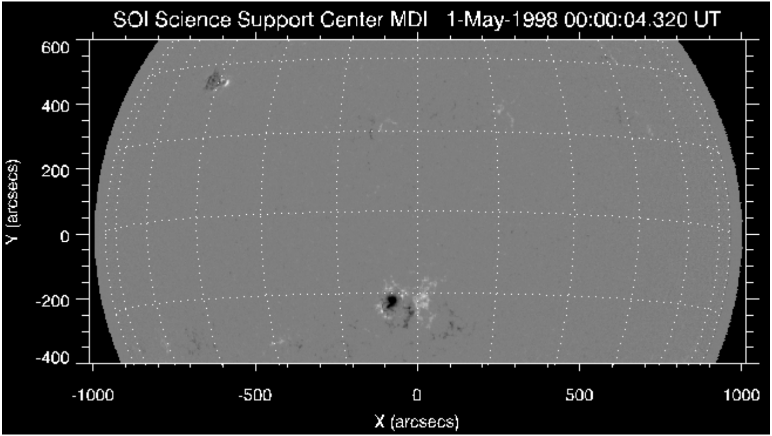

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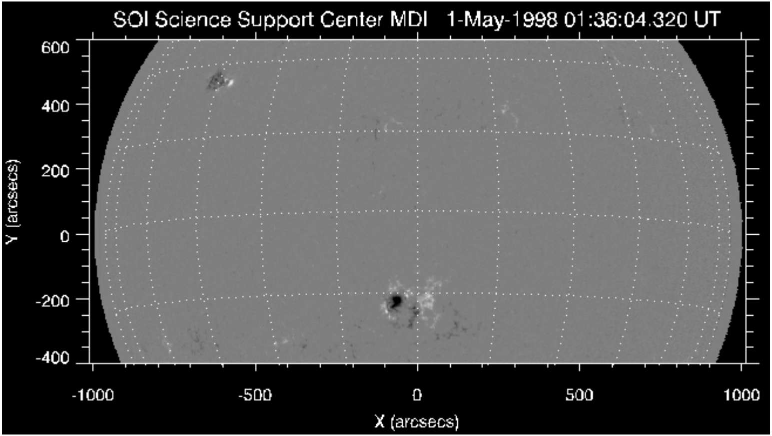

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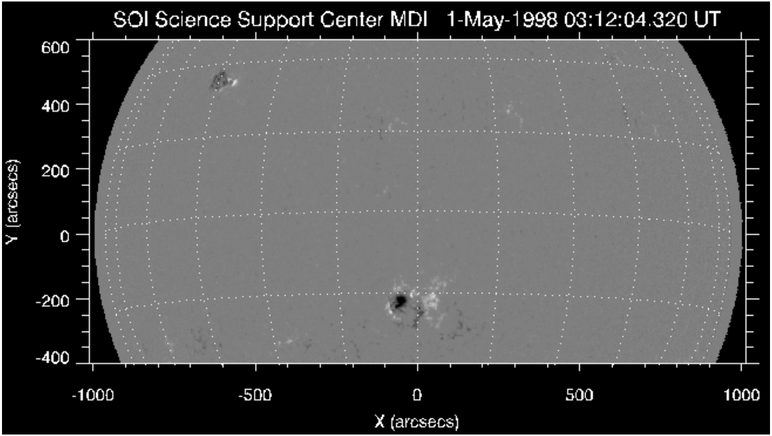

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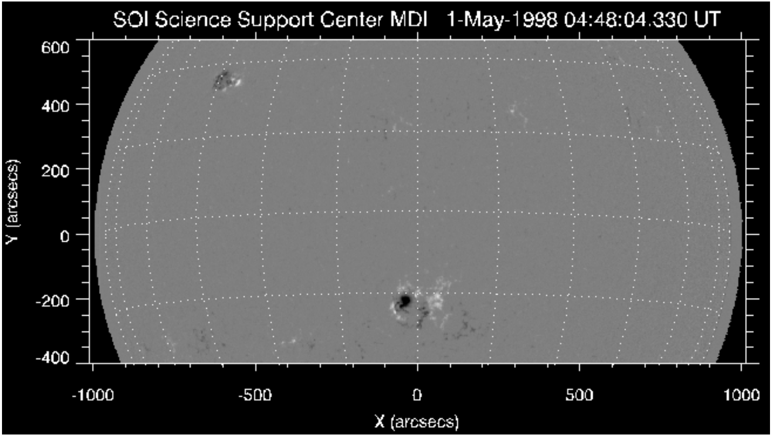

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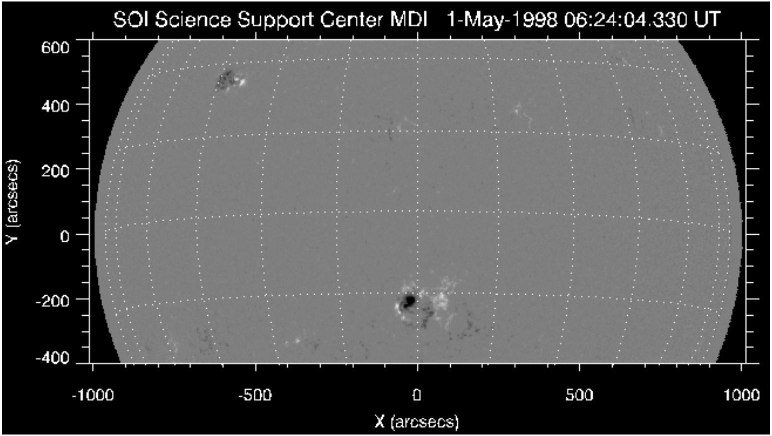

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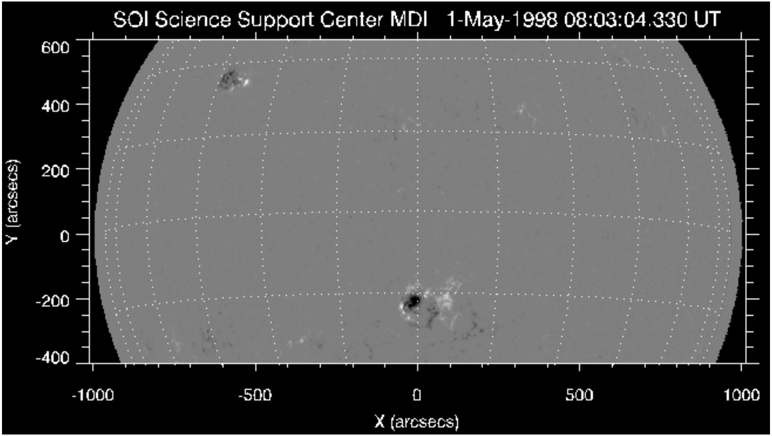

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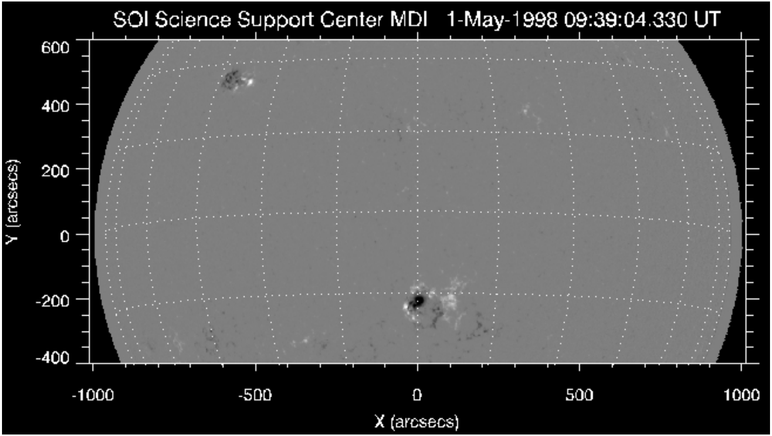

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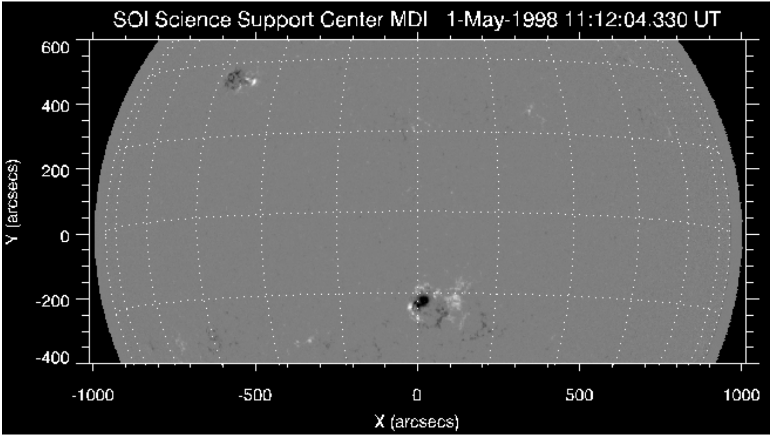

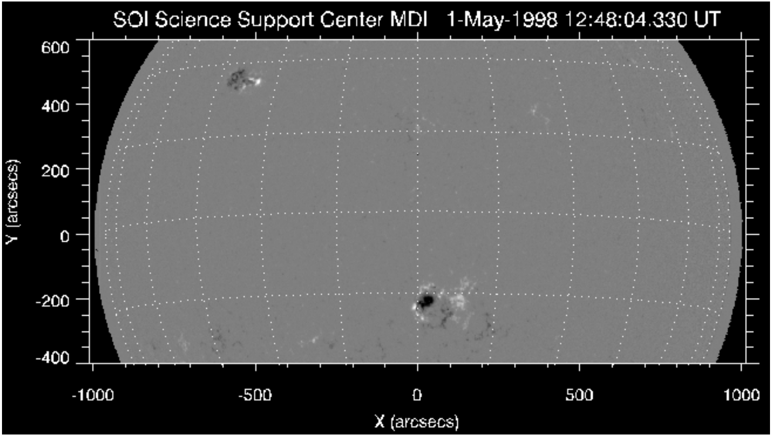

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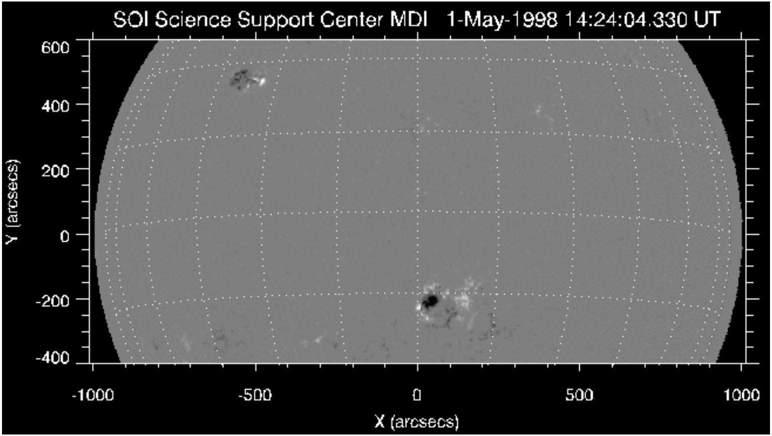
How Can We Estimate Photospheric Flows?

Application to MDI data AR8210



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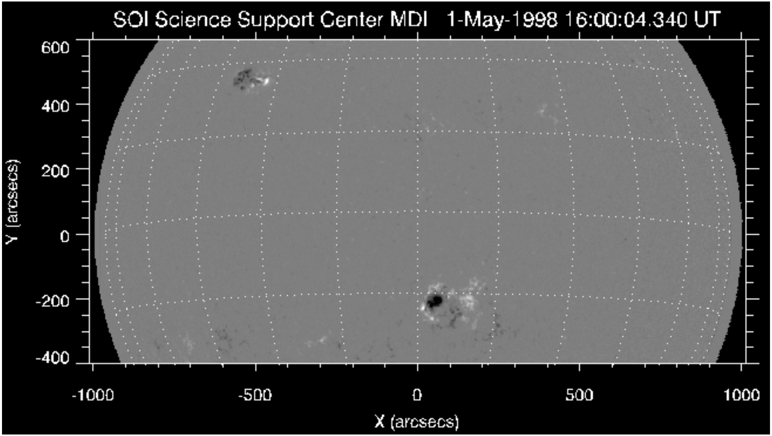

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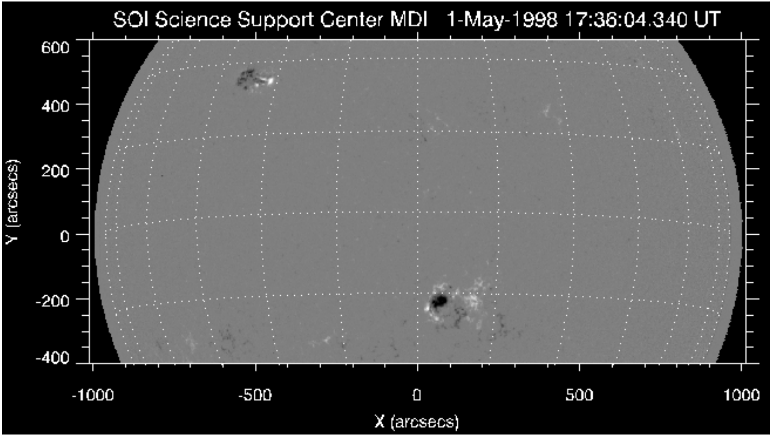

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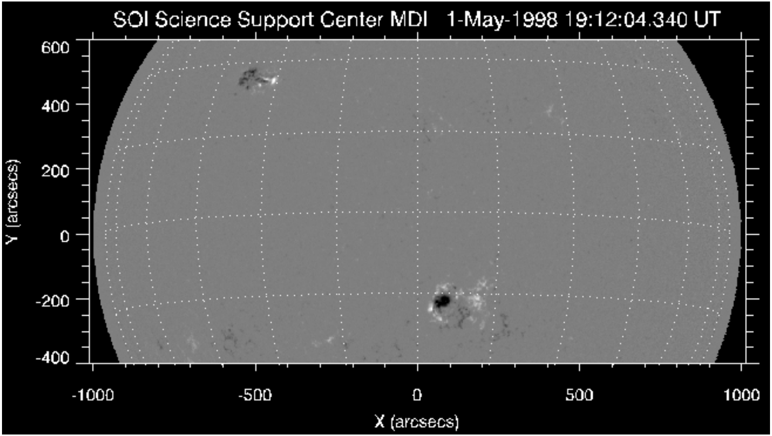

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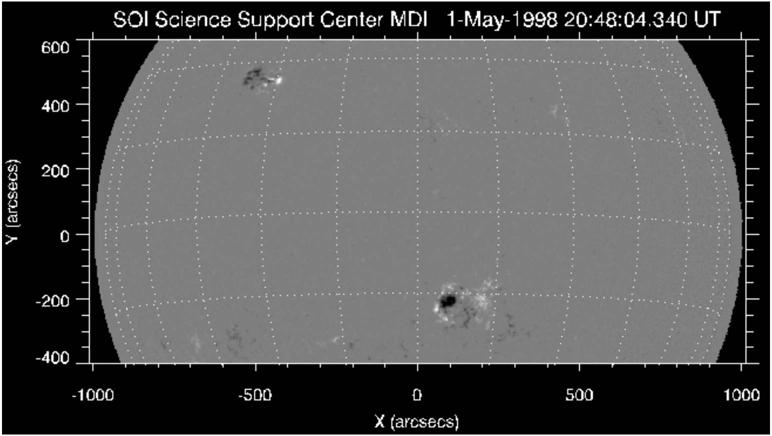

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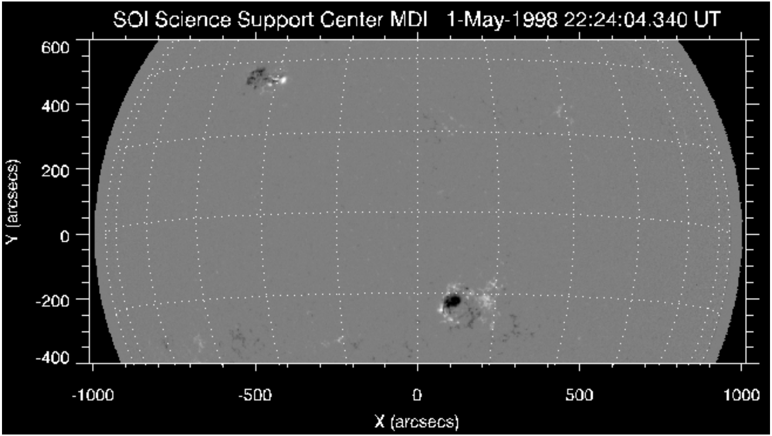

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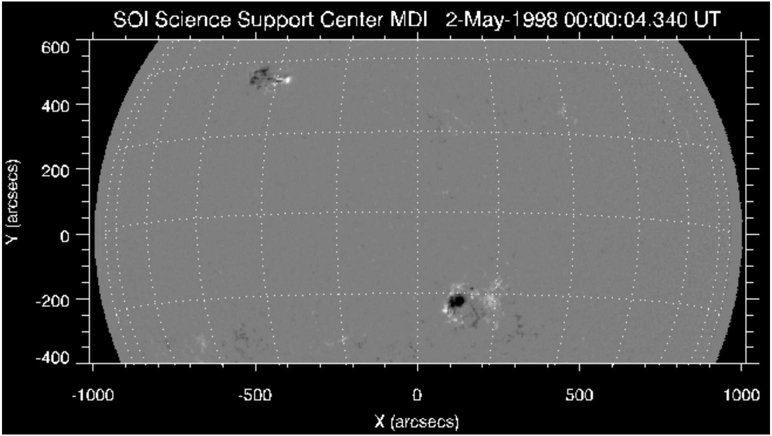

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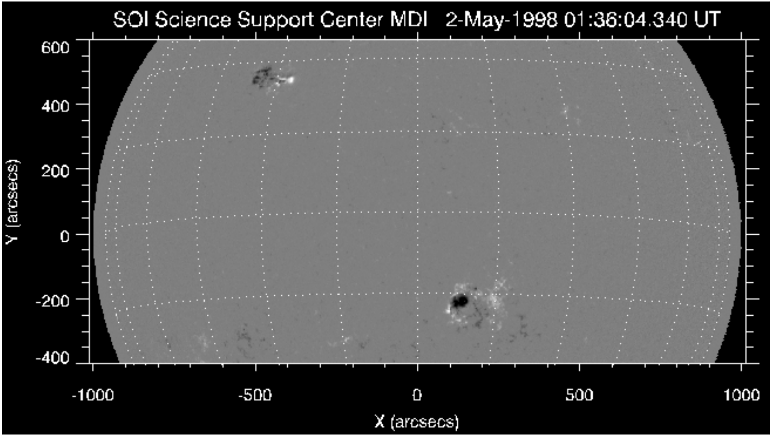

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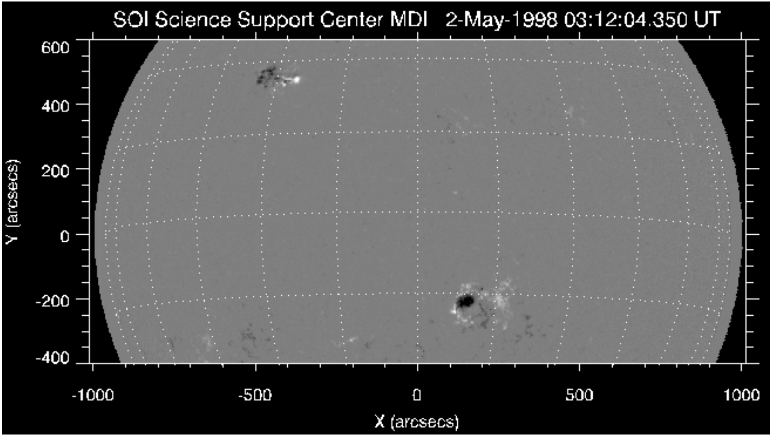

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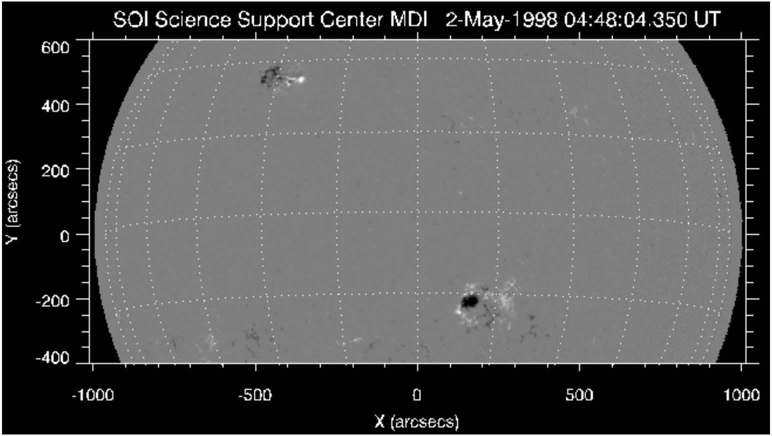

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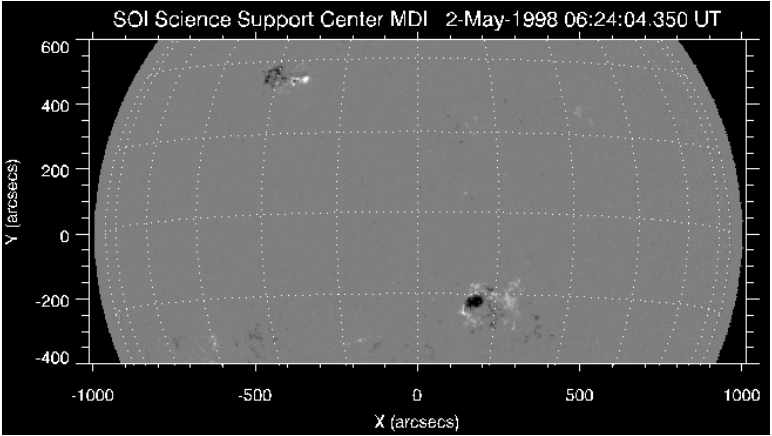

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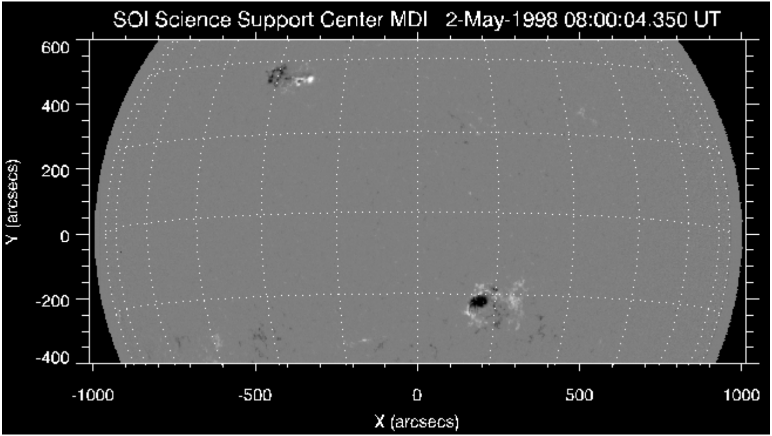

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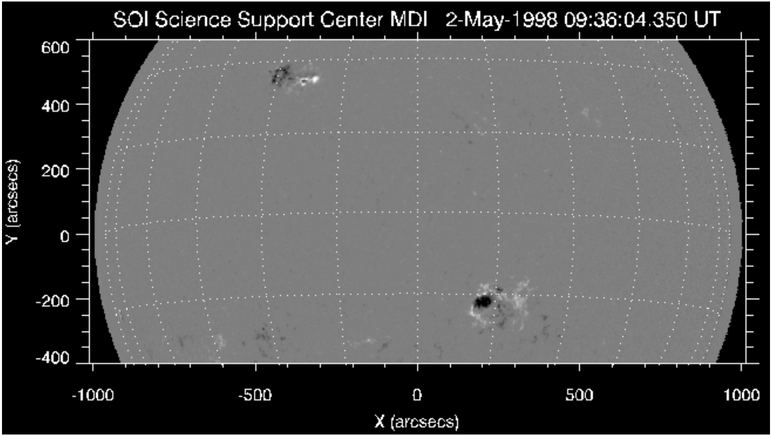

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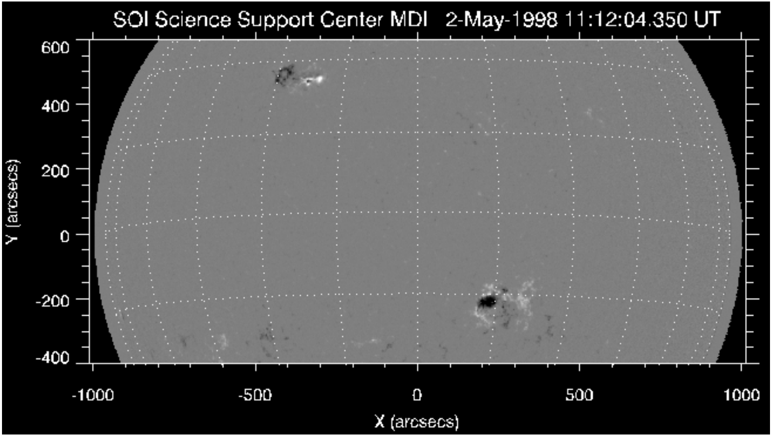

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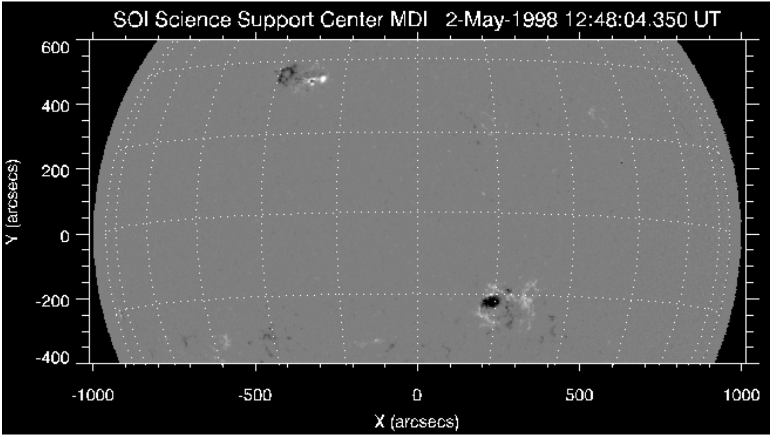

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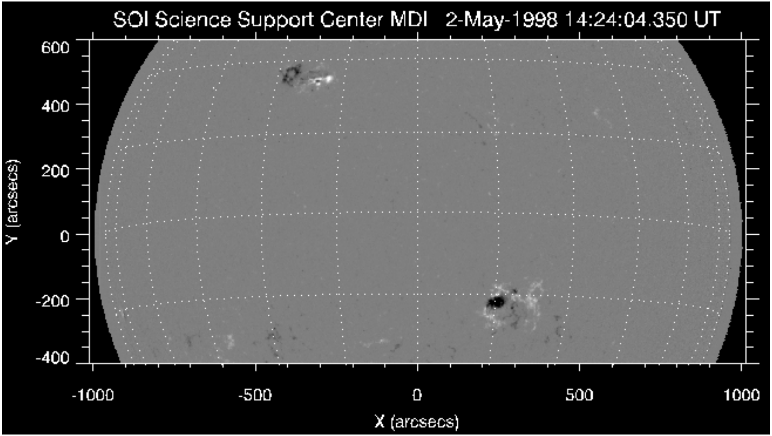

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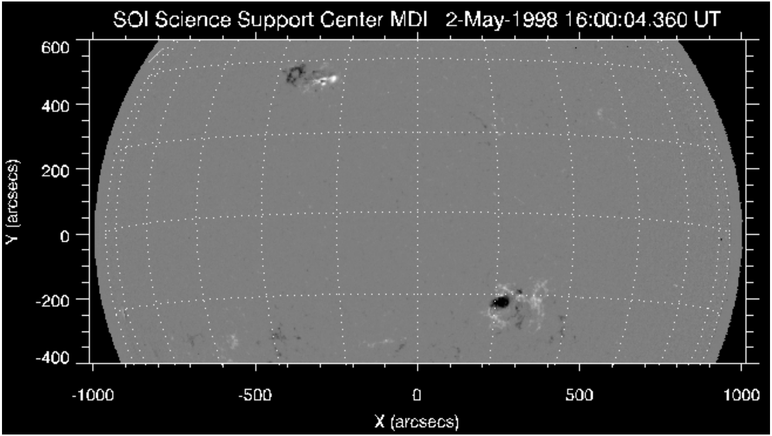

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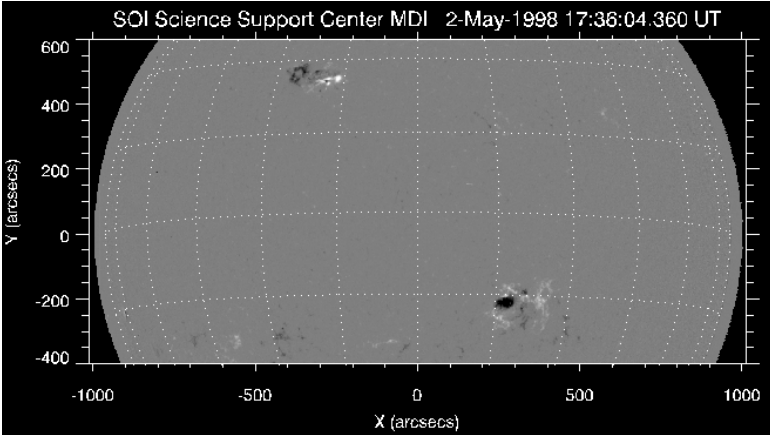
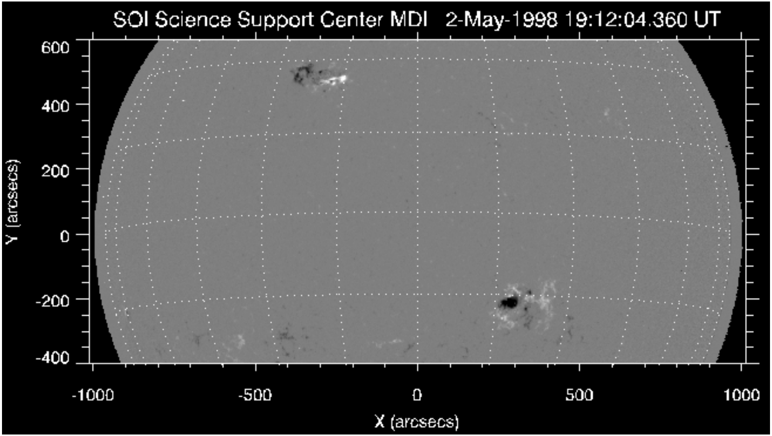


How Can We Estimate Photospheric Flows?

Application to MDI data AR8210



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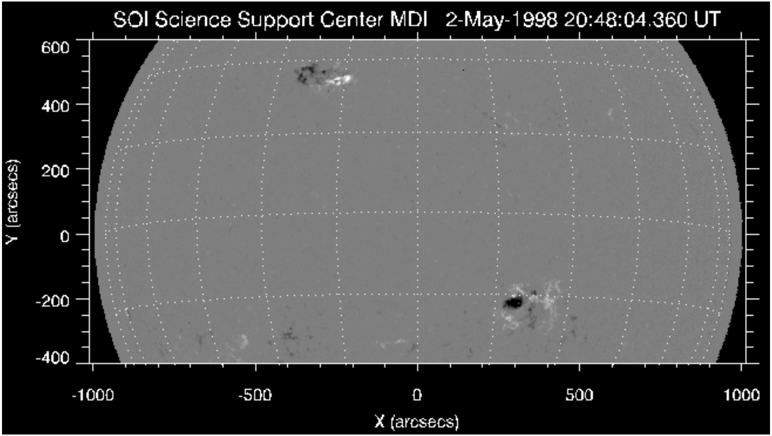

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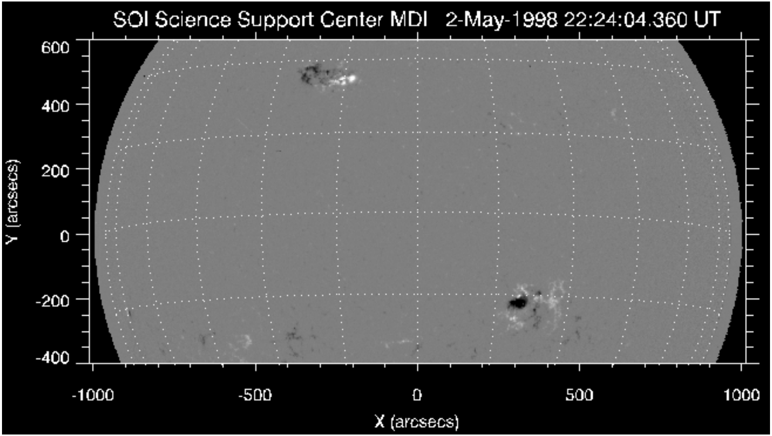

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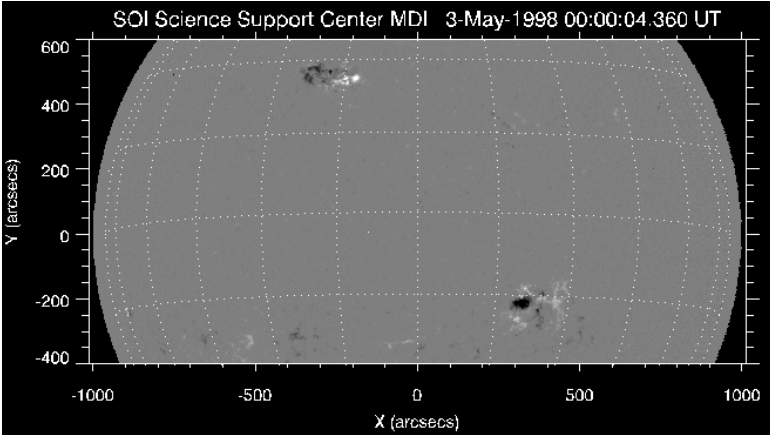

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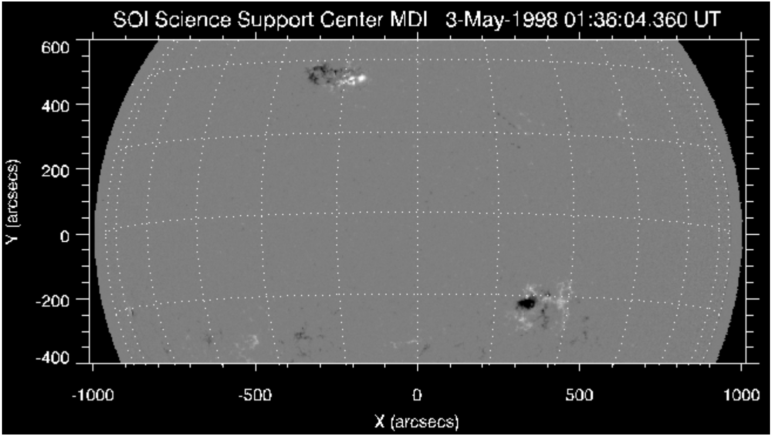

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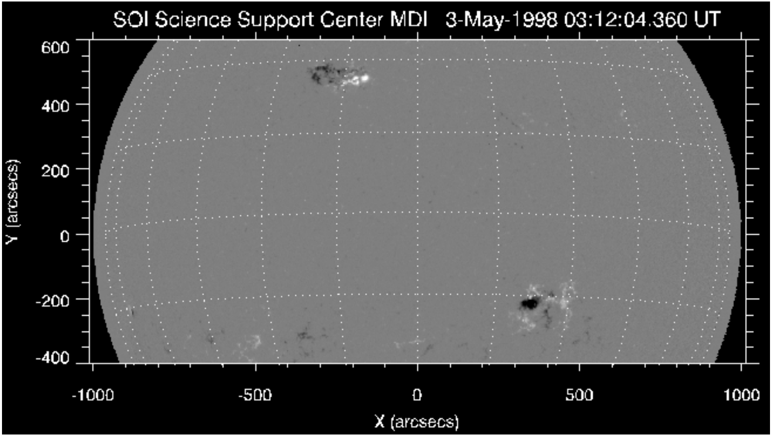

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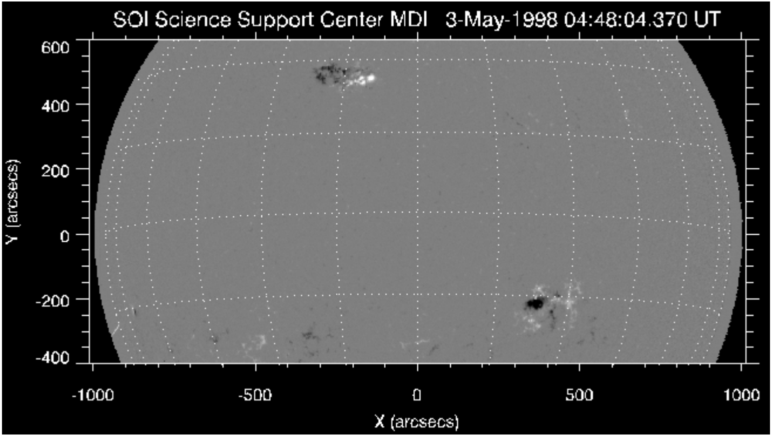

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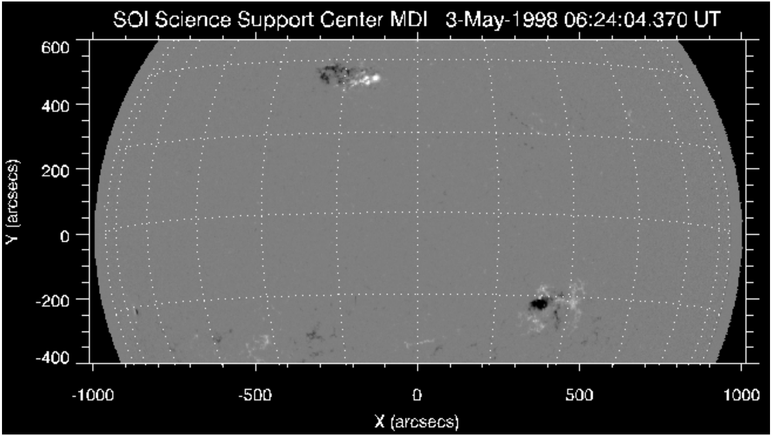

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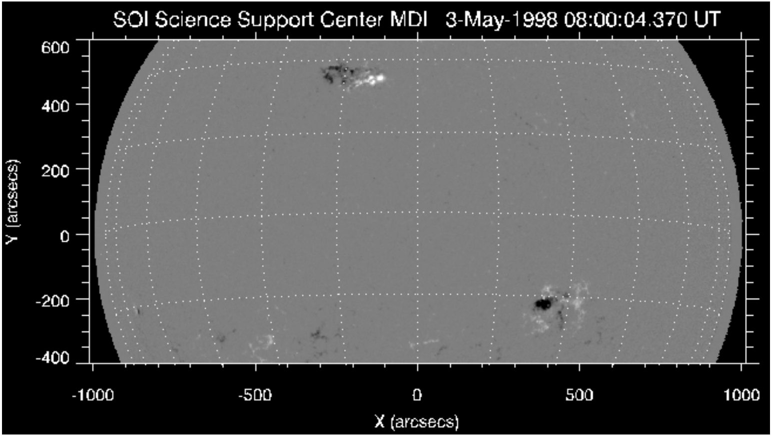
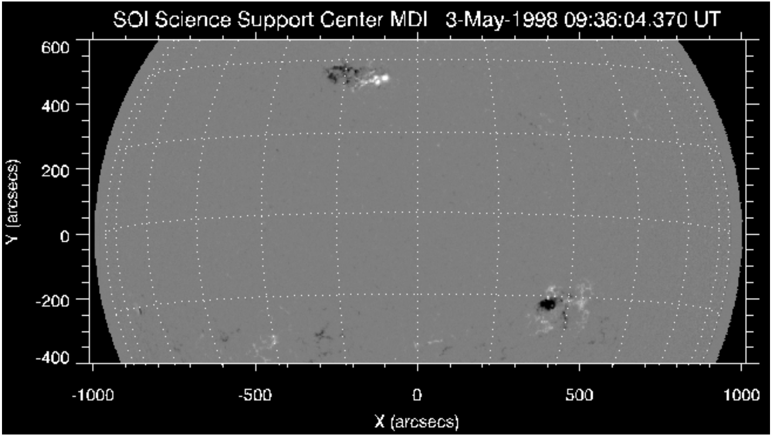


How Can We Estimate Photospheric Flows?
Application to MDI data AR8210



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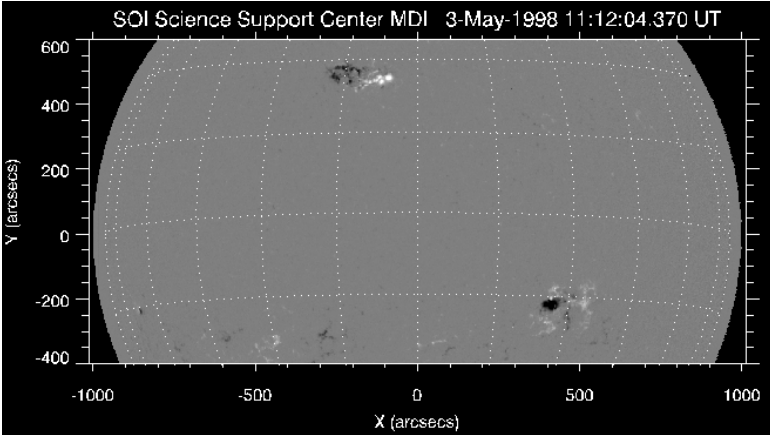
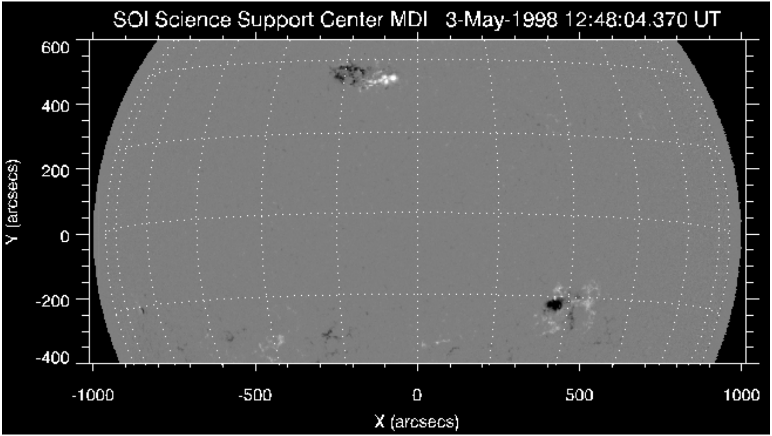
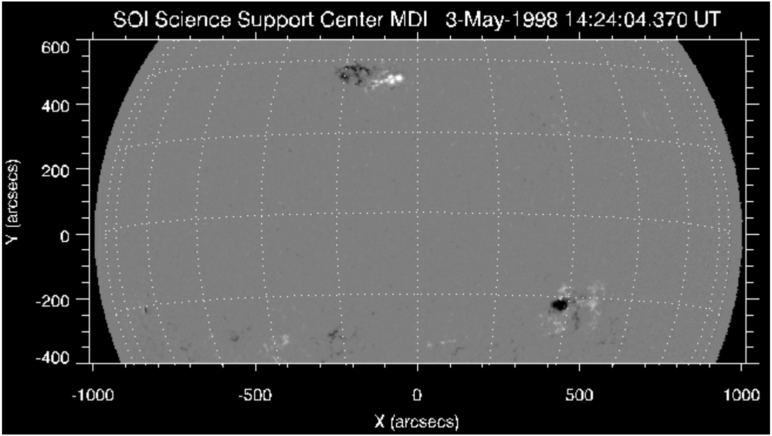
Application to MDI data AR8210



How Can We Estimate Photospheric Flows?

Application to MDI data AR8210





SOI Science Support Center MDI 3-May-1998 14:24:04.370 UT
Y (arcsecs)
600
400
200
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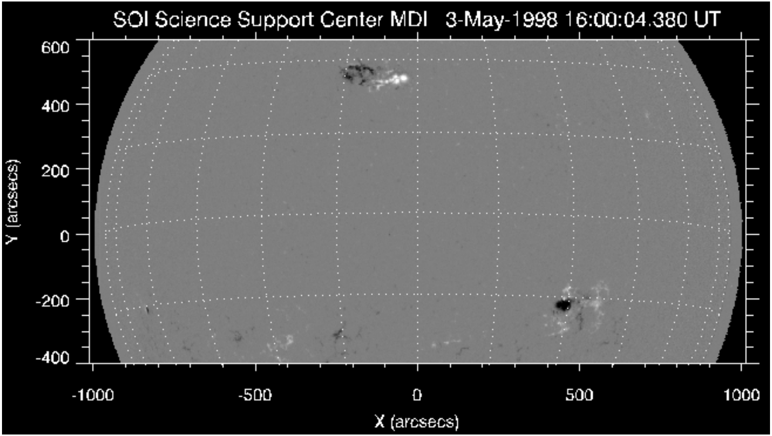
-200
-400
-1000
-500
0
500
1000
X (arcsecs)

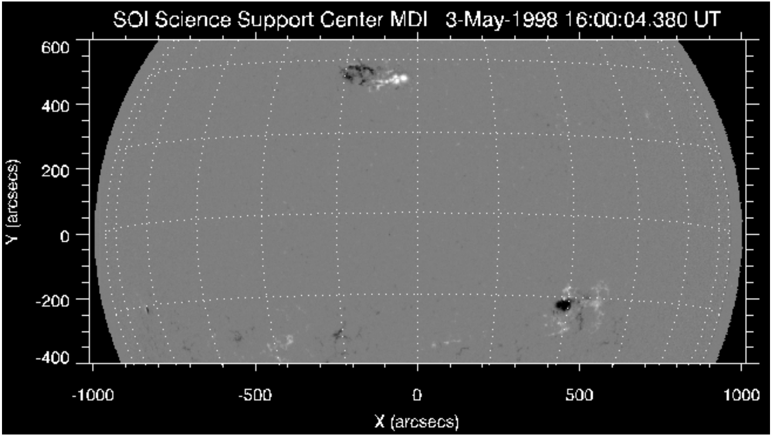
How Can We Estimate Photospheric Flows?

Application to MDI data AR8210



How Can We Estimate Photospheric Flows?

Application to MDI data AR8210



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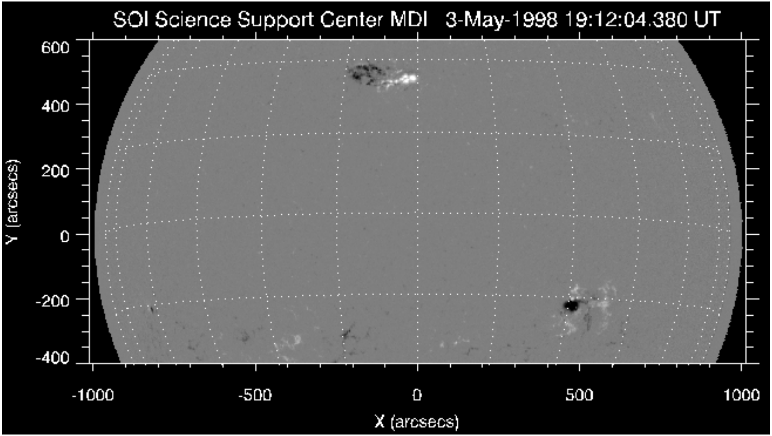

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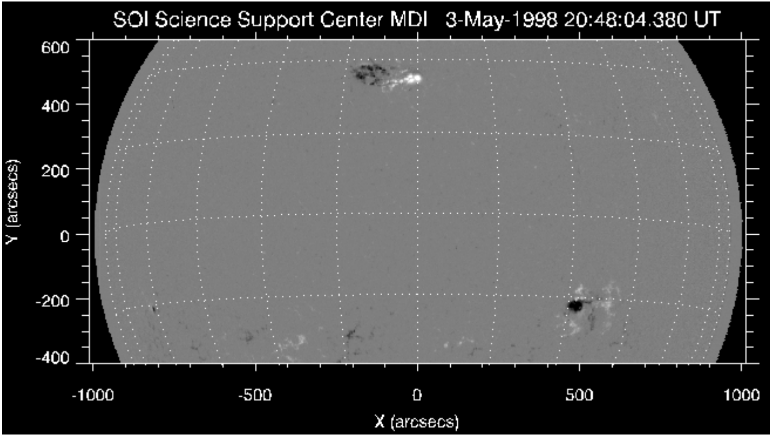

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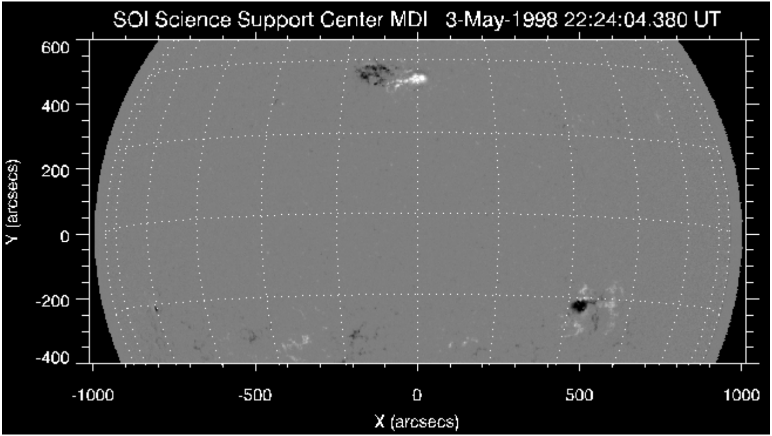


How Can We Estimate Photospheric Flows?

Differential Affine Velocity Estimator for Vector Magnetograms (DAVE4VM)

$$C \approx \int dx^2 \, w\left(\boldsymbol{x} - \boldsymbol{X}_0\right) \left\{ \partial_t B_z\left(\boldsymbol{x}, t\right) + \boldsymbol{\nabla}_h \cdot \left[B_z\left(\boldsymbol{x}, t\right) \widehat{\boldsymbol{v}}_h - \widehat{v}_z \boldsymbol{B}_h\left(\boldsymbol{x}, t\right) \right] \right\}^2$$

$$\widehat{\boldsymbol{v}} = \begin{pmatrix} u_0 \\ v_0 \\ w_0 \end{pmatrix} + \begin{pmatrix} \widehat{u}_x & \widehat{u}_y \\ \widehat{v}_x & \widehat{v}_y \\ \widehat{w}_x & \widehat{w}_y \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \qquad \boldsymbol{\nabla}_h = \left(\partial_x, \partial_y\right)$$

- Incorporates both vertical and horizontal magnetic field components
- 3D photospheric plasma velocities: explicit vertical flows
- Variational principle results in a least squares/total least squares estimator
  - Can incorporate magnetic field covariance matrices (uncertainties)

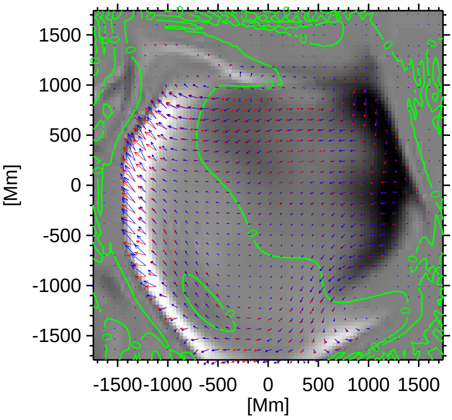
Schuck (2008)

- Analastic Magnetohydrodynamics (ANMHD) (Fan et al., 1999; Abbett et al., 2000)
  CCMC `http://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=ANMHD`
- Simulation of a twisted flux rope rising through the turbulent convection zone
- Magnetic Reynolds Number: $Re_{\mathrm{M}} \equiv 3500$ much more resistive than the photosphere $R_{\mathrm{M}} \sim 10^5 - 10^6$
- Provides ground truth plasma velocities to compare with DAVE4VM and DAVE

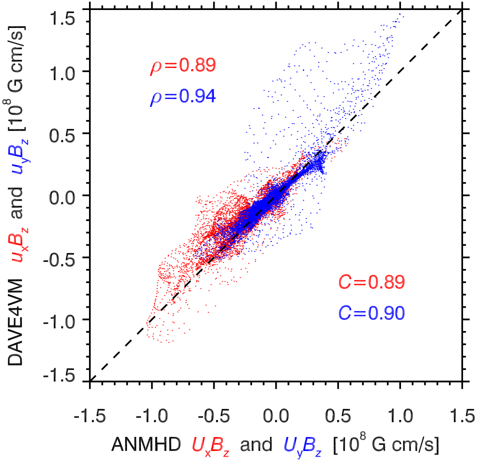
How Can We Estimate Photospheric Flows?

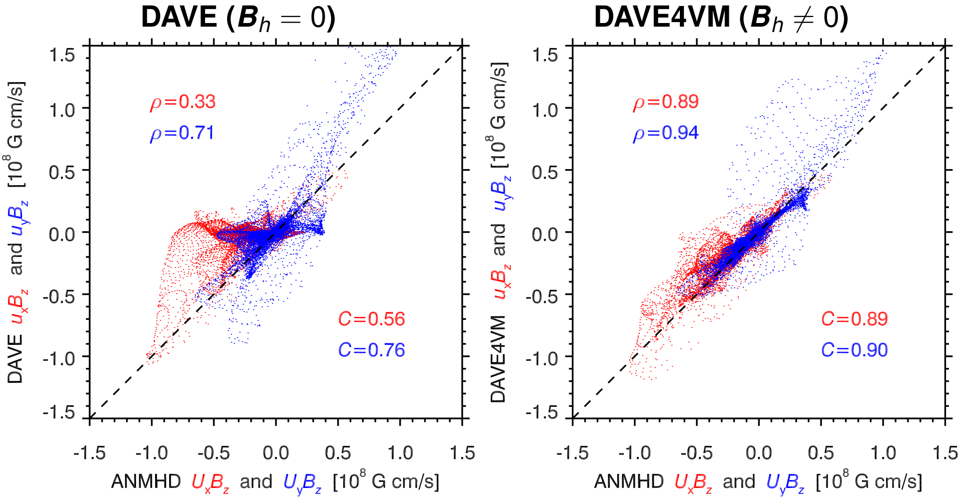
Validating DAVE4VM with an ANMHD Simulation

DAVE4VM $\boldsymbol{u}\, B_z$ & **ANMHD** $\boldsymbol{U}\, B_z$



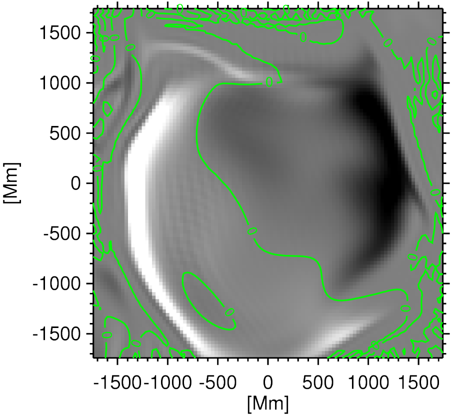
DAVE4VM ($\boldsymbol{B}_h \neq 0$)



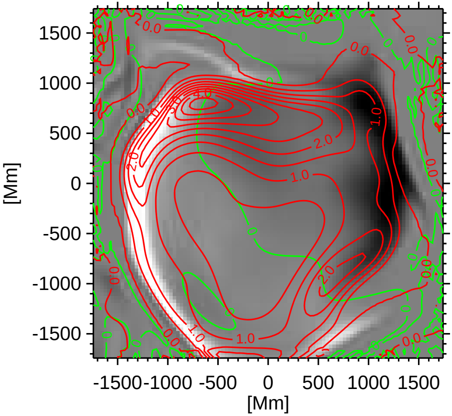


DAVE ($B_h = 0$)
DAVE4VM ($B_h \neq 0$)
ρ=0.33
ρ=0.71
C=0.56
C=0.76
ρ=0.89
ρ=0.94
C=0.89
C=0.90
DAVE u_xB_z and u_yB_z [10^8 G cm/s]
DAVE4VM u_xB_z and u_yB_z [10^8 G cm/s]
ANMHD U_xB_z and U_yB_z [10^8 G cm/s]
-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5

Neutral Line

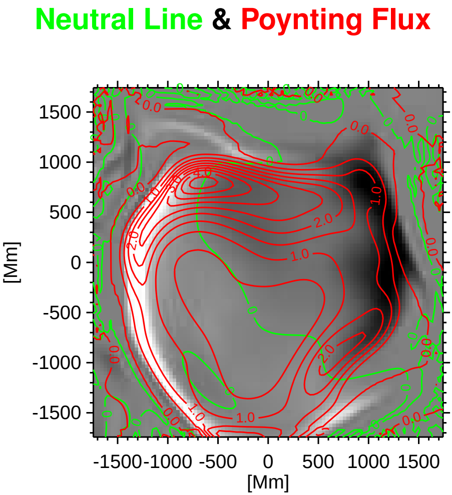


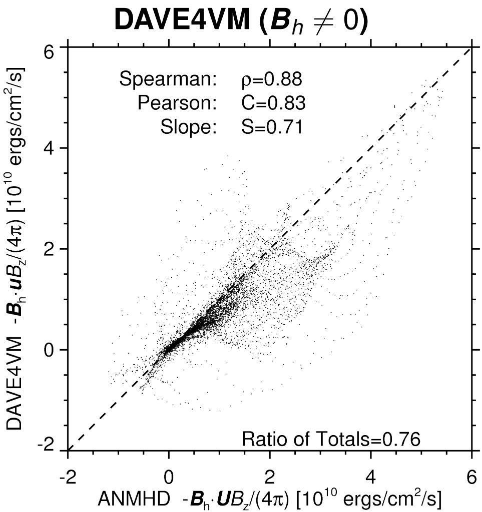
Neutral Line & Poynting Flux



How Can We Estimate Photospheric Flows?

Validating DAVE4VM with an ANMHD Simulation





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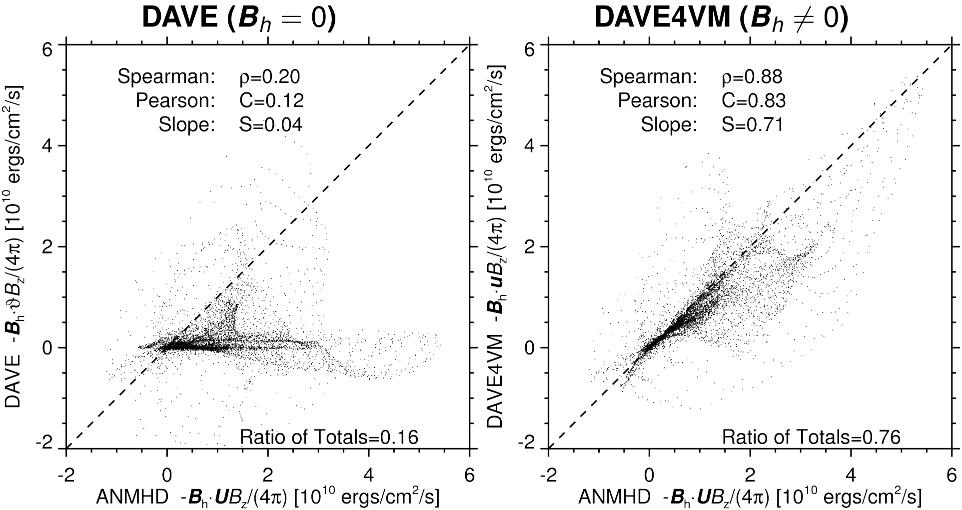
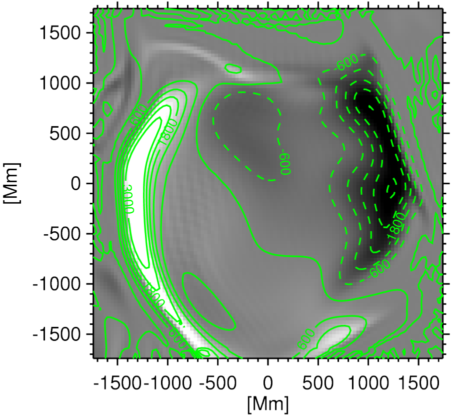
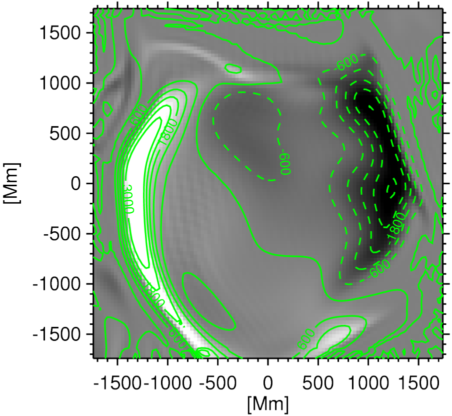
Validating DAVE4VM with an ANMHD Simulation



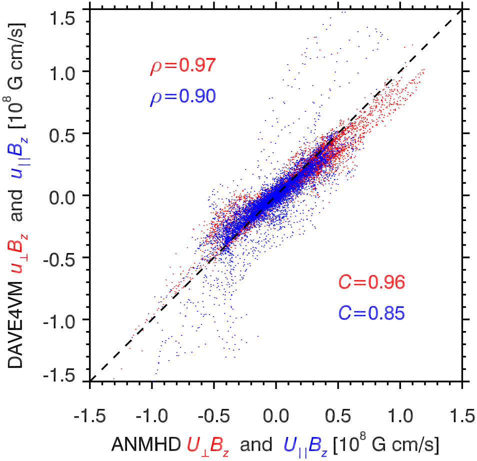
Flows $\parallel$ & $\perp$ to Neutral Lines



Flows $\parallel$ & $\perp$ to Neutral Lines



DAVE4VM ($B_h \neq 0$)



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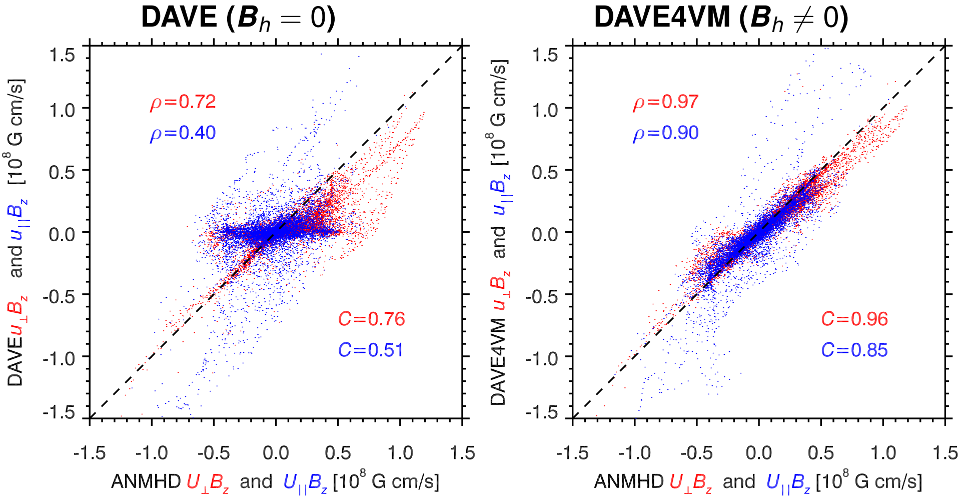
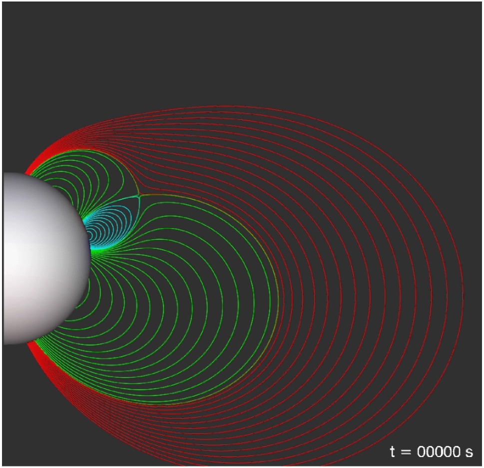


Challenges!

1. Must be able to produce an eruption in 3D spherical geometry
2. Must be able to reproduce to properties of a CME
3. Must be able to model the photosphere to the corona
4. Must be able to assimilate data

Data Driven Modeling of CMEs

ARMS can reproduce eruptions 3D spherical geometry

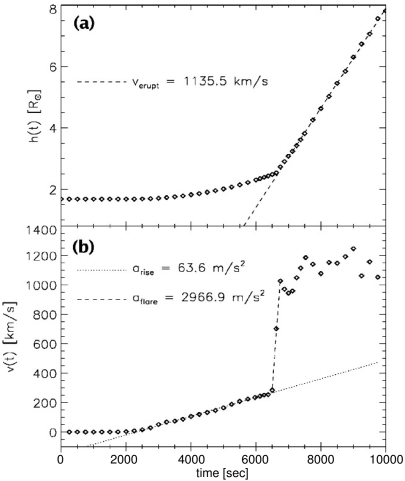


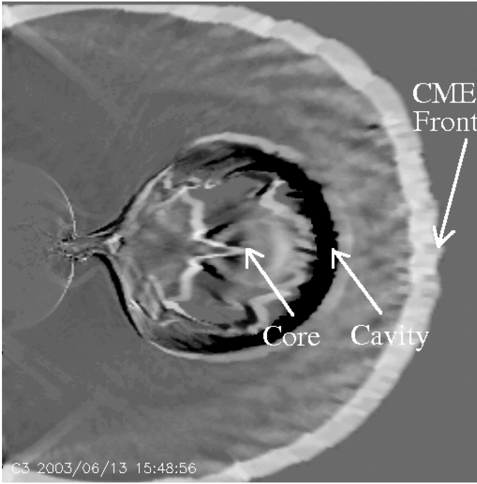
Lynch et al. (2008)

- ARMS - Adaptively Refined Magnetohydrodynamic Solver
- Flux corrected transport
- Highly Parallelized

Data Driven Modeling of CMEs

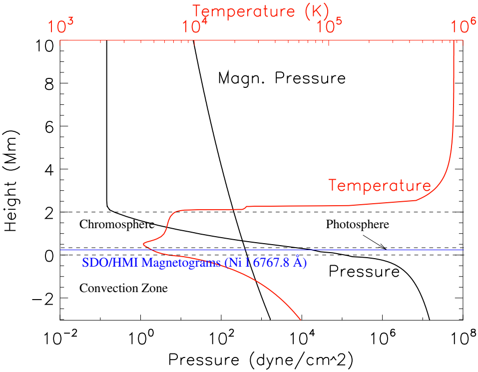
ARMS can reproduce a fast CME with a 3 three part structure





(Lynch et al., 2004)

VAL-C Model of the Solar Atmosphere



(Vernazza et al., 1981)

- Plasma Pressure drops by 10^8
- Temperature increases by 10^3
- Magnetic Pressure drops by 15
- Plasma β indicates dominate forces

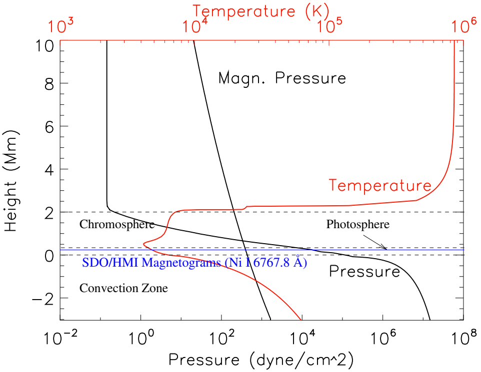
$$\beta \equiv \frac{4\pi P}{B^2}$$

- $\beta \gg 1$ plasma pressure dominant
- $\beta \ll 1$ magnetic forces dominant

Data Driven Modeling of CMEs

ARMS can model the photosphere to the corona

VAL-C Model of the Solar Atmosphere



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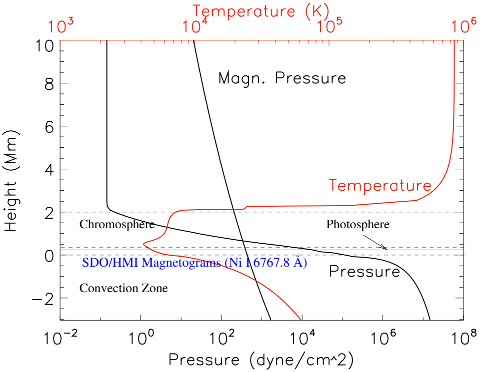
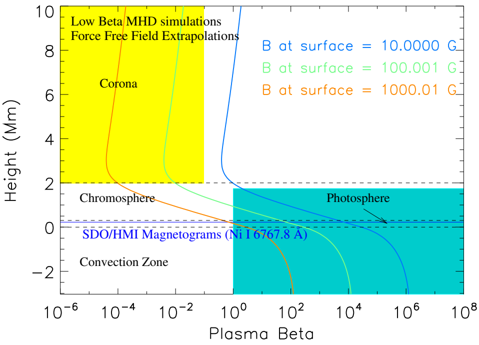


(Vernazza et al., 1981)

Plasma β



Data Driven Modeling of CMEs

ARMS can model the photosphere to the corona

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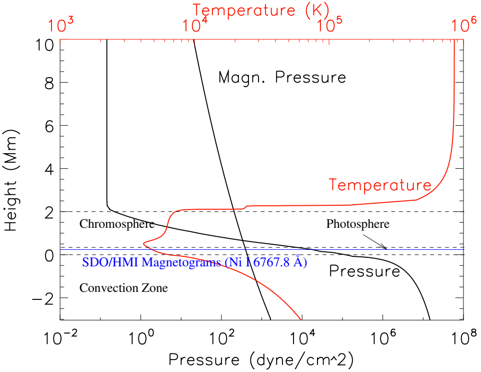
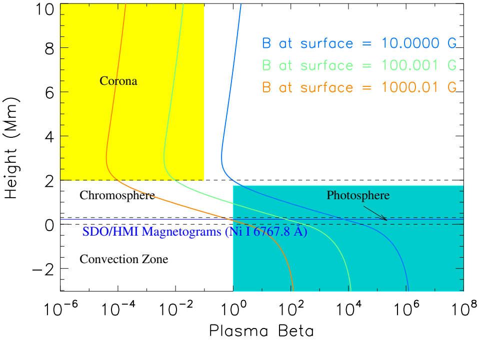


(Vernazza et al., 1981)

Plasma β



ARMS can model the photosphere to the corona

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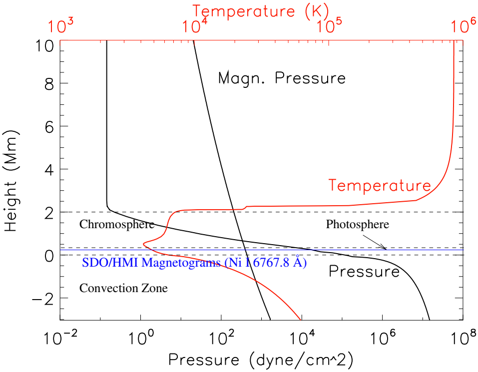
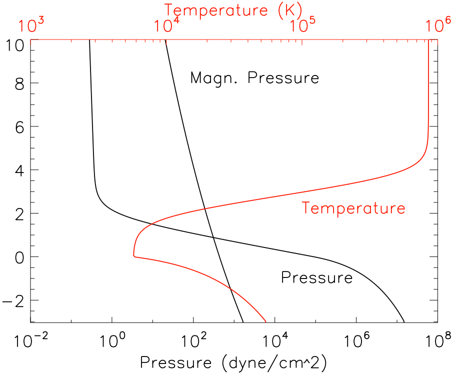


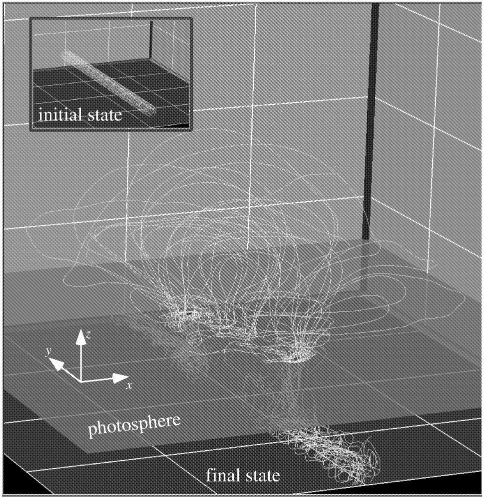
(Vernazza et al., 1981)

ARMS Model of the Solar Atmosphere



Data Driven Modeling of CMEs

ARMS simulation of flux emergence in a stratified atmosphere



.... And here we have a simulation using the ARMS model of the solar atmosphere!

- Magnetic flux rope emerging from the low β convection zone into the high β corona
- During emergence the flux rope expands and shear motions occur in the photosphere

(Magara et al., 2005)

- Putting in all together: The pieces all work (3D eruption, CME properties, highly stratified solar atmosphere, DAVE4VM)
- Initializing the 3D simulation domain consistent with the vector magnetograms at the lower boundary (photosphere)
- Evolving the boundary consistent with the ideal magnetic induction equation and/or the numerical algorithms
- Merging observed magnetic fields and flows with quiet Sun and farside Sun

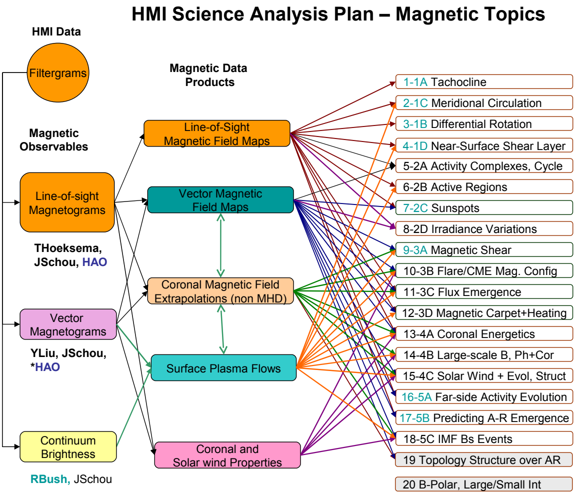
Despite the challenges, significant progress has been made!

- CME initiation theories have matured to the point that the first tests of these theories may be made with photospheric data.
- Optical flow techniques have matured to incorporate MHD.
  - DAVE4VM accurately estimates plasma velocities and Poynting flux from ANMHD synthetic vector magnetograms
- CME simulations have matured:
  - Produce fast CMEs with realistic properties.
  - Model the photosphere $\beta > 1$ to the corona $\beta \ll 1$.

Poised for progress LWS forecasting goals:
The next step beyond phenomenological prediction of eruptions will require assimilation of SDO/HMI or BBSO observations into the latest MHD simulations!

Summary

DAVE4VM Will Provide Critical Science Products for *SDO*/HMI



Courtesy of the HMI Team

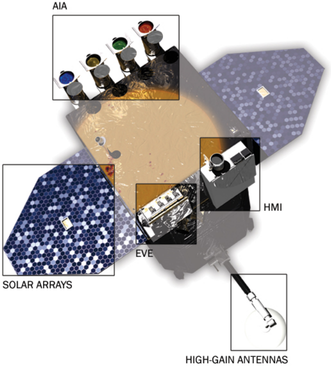
- IDL Codes: DAVE/DAVE4VM released with ancillary routines and turnkey code to produce examples/figures from article (Schuck, *ApJ*, **683**, 1134-1152, 2008)
  - Oldest: Archived with ApJ
    `www.iop.org/EJ/abstract/0004-637X/683/2/1134`
  - More recent archived at:
    - NRL `wwwppd.nrl.navy.mil/whatsnew/dave/index.html`
    - CCMC `http://ccmc.gsfc.nasa.gov/lwsrepository`
  - Latest: contact me at NASA/GSFC – peter.schuck@nasa.gov

- HMI Pipeline Codes: in production (Jacob Hageman GSFC/582), Intel Fortran with C-wrappers, and linked with Intel MKL math libraries with drop-in open source replacements (deliver final versions mid-February).

Summary

Planned Improvements in DAVE4VM

- Incorporate Doppler velocities to constrain vertical flows
- Incorporate HMI covariance matrices
- More verification tests on other MHD codes
- Consider spherical geometry
- *SDO*/HMI first light!



Six Publications:

P.W. Schuck, Tracking Vector Magnetograms with the Magnetic Induction Equation, *ApJ*, **683**, 1134-1152, 2008 doi: 10.1086/589434

B. T. Welsch, *et al.*, What is the Relationship Between Photospheric Flow Fields and Solar Flares?, *ApJ*, **705**, 821-843, 2009, doi: 10.1088/0004-637X/705/1/821

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Foreign and Domestic Patents

Filed: January 25, 2010. (United States Provisional Patent Application No. 61/146,808 filed on January 23, 2009)

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