# Circulation et hélicité cinétique sous la photosphère solaire et leur relation avec l'activité magnétique de surface

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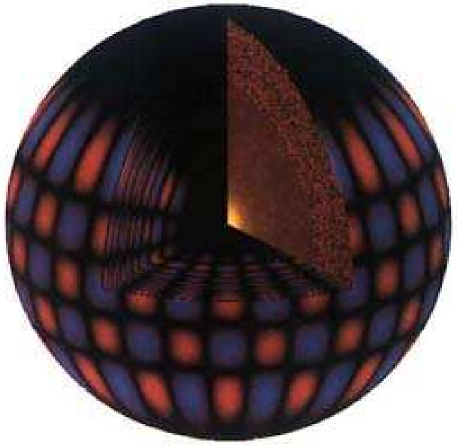


# Global Helioseismology

**Internal Rotation breaks spherical symmetry**

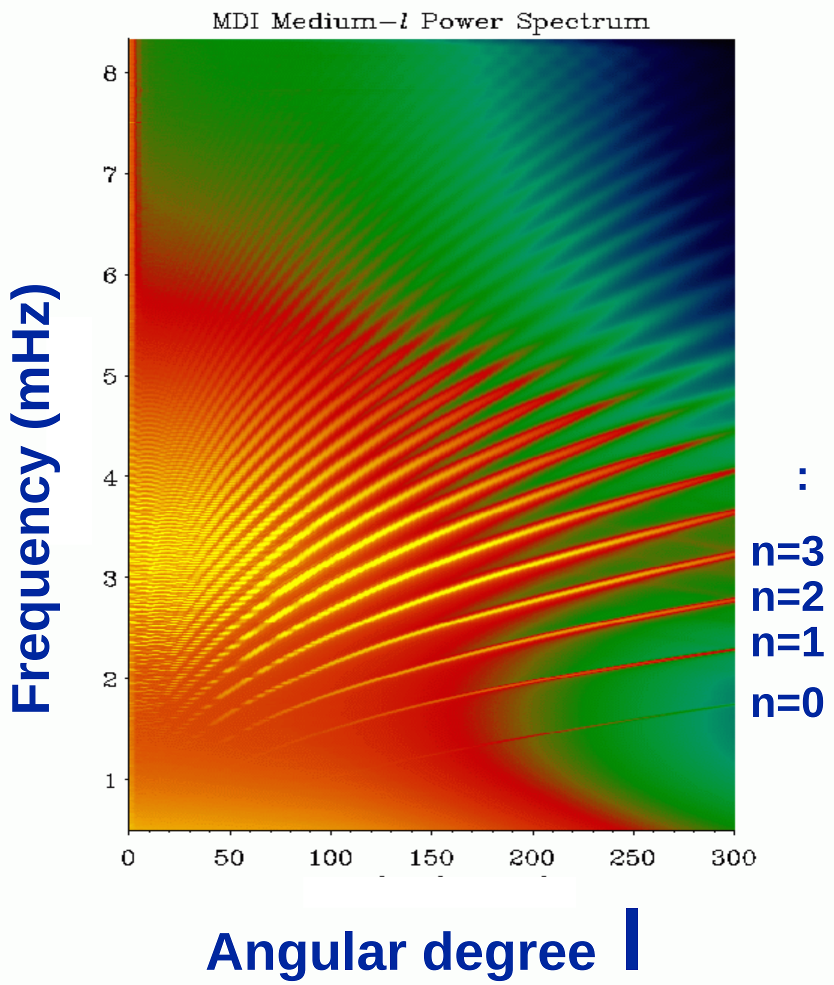
**=> Multiplets of 2l+1 frequencies**

$$\frac{\omega_{nl\text{-}m} - \omega_{nlm}}{m} = \iint K_{nlm}(r,\theta)\,\Omega(r,\theta)\, dr d\theta$$

**Unknown**

**observed** **Standard Solar Model**

**=> 2D Inverse Problem**



# Global Helioseismology
## Limitations

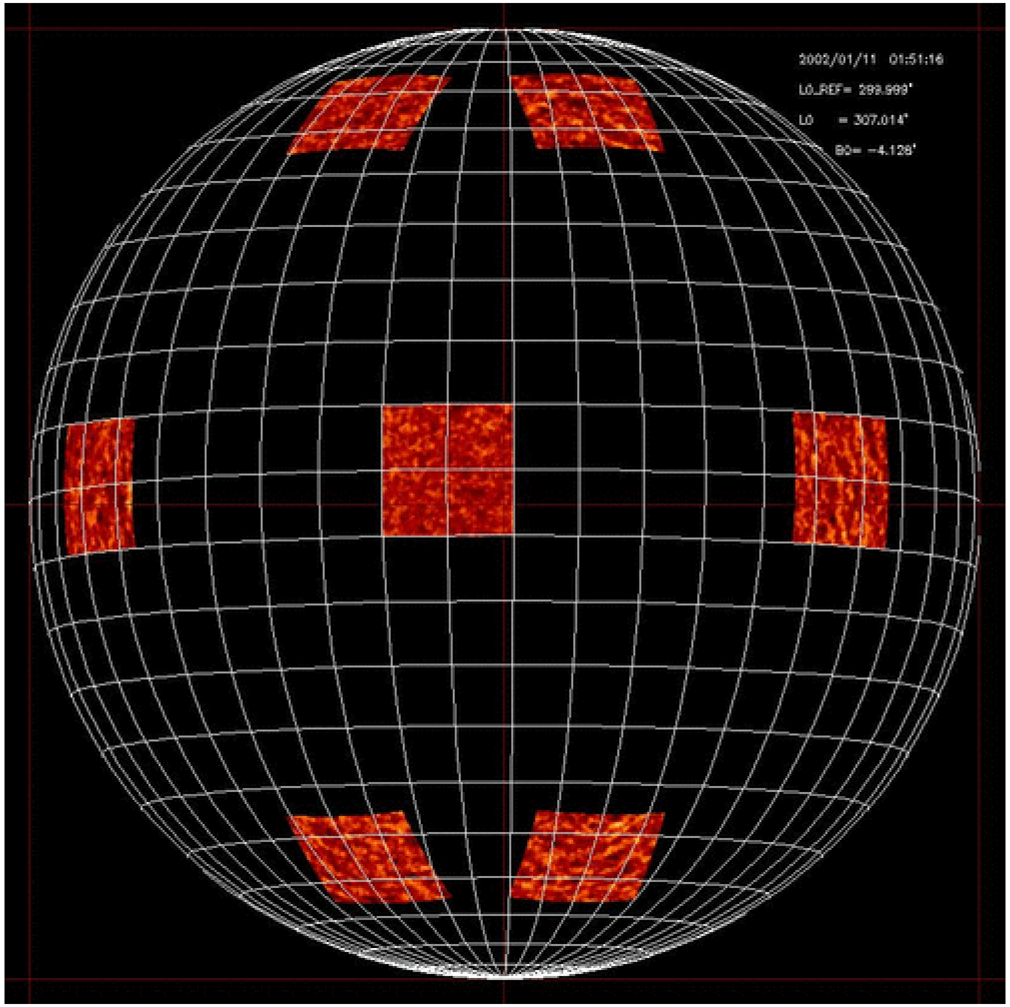
- Sensitive only to the part of the rotation that is symmetric about the equator.

- Kernels Independent of longitude (e.g. cannot detect effect of active region on rotation)

- Limited access to the polar zone

- Impossible to separate the spherically asymmetric effects other than rotation (meridional circulation, magnetic fields, structural asphericity)

# Local Helioseismology
# Analysis Principles




- Small areas (16ºx16º) are tracked (typically between 8hrs and 28hrs)over the solar disk at a rate depending on the latitude of their center.

- These areas are remapped using a Postel or transverse cylindrical projection that tend to preserve the distance along great circles.

- => Data cubes
  (Latitude – Longitude – time)

# Local Helioseismology
# Main Methods

Based on the local observation of global acoustic modes.

1. **Ring-Diagram analysis (Fourier domain)**
   **(Gough & Toomre 1983; Hill 1988)**

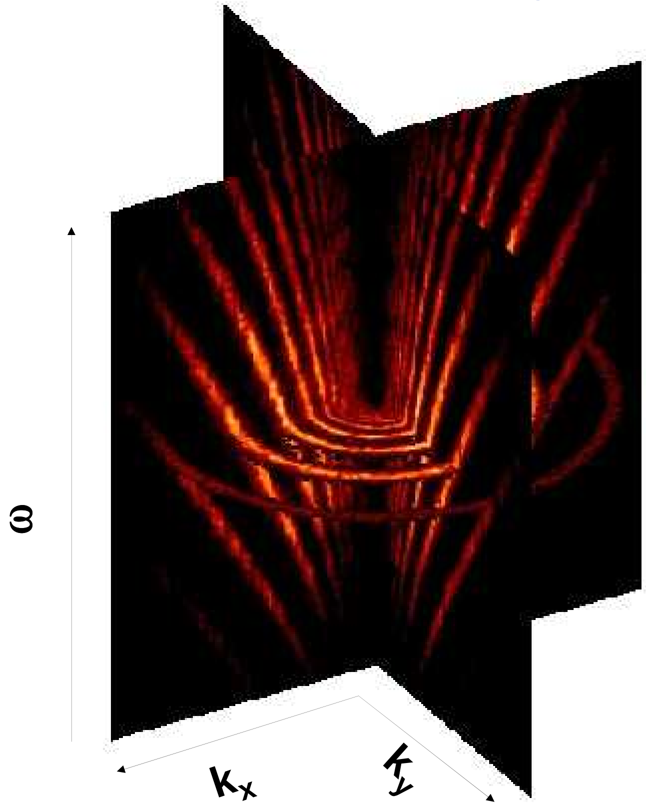
2. **Time-distance analysis (Time domain)**
   **(Duvall et al. 1993, 1996)**

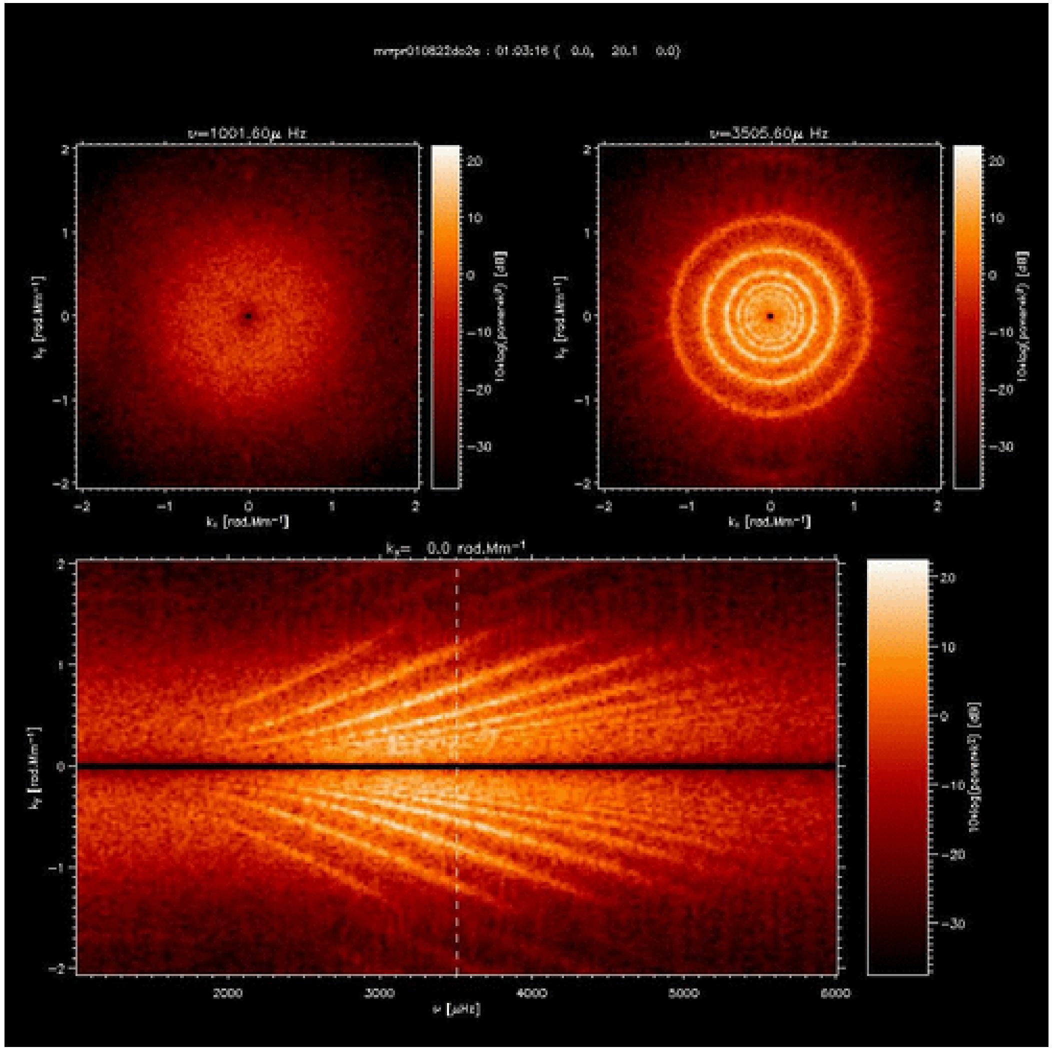
3. **Acoustic Holography (Phase sensitive)**
   **(Lindsey & Braun, 1990, 1997)**

# Ring Diagram Analysis

**3D FFT**

$(\theta,\varphi,t) \rightarrow (k_x,k_y,\omega)$

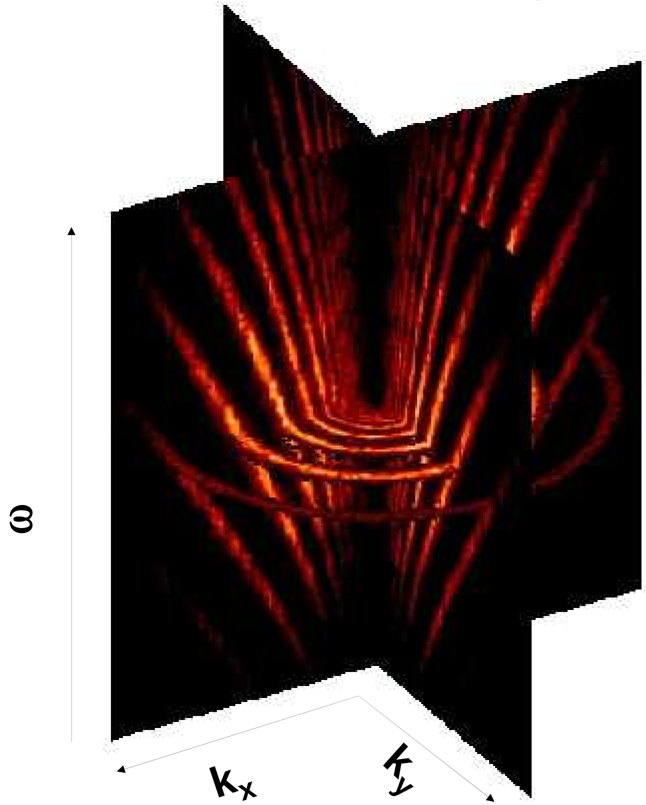


# Ring Diagram Analysis

**3D FFT** → **3D Power spectra Fitting**

**$(\theta,\varphi,t) \rightarrow (k_x,k_y,\omega)$**



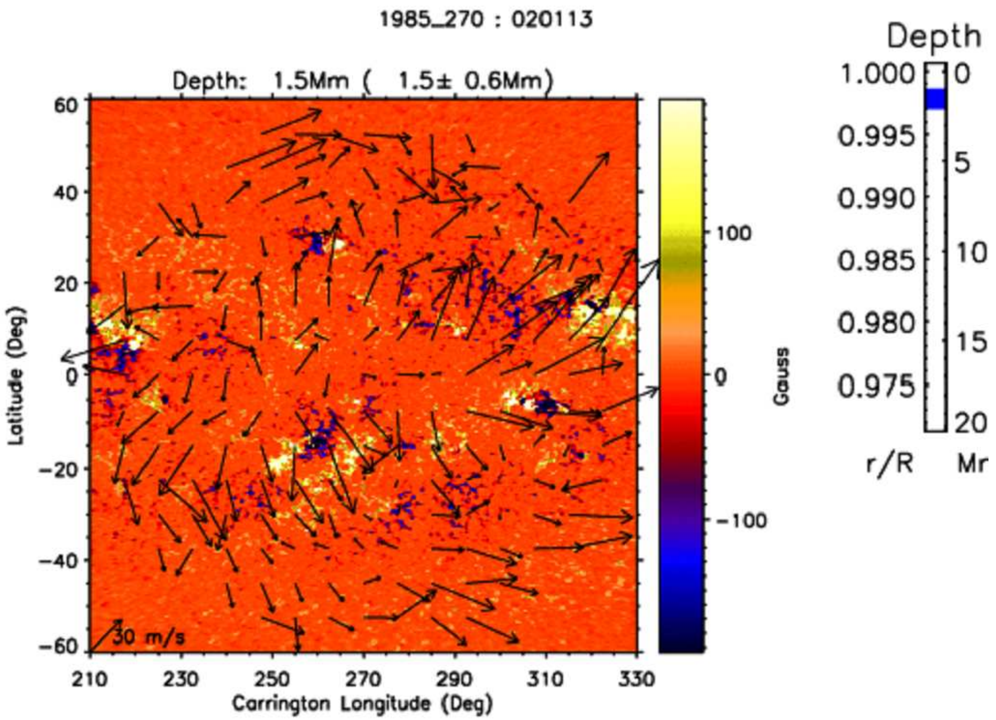

$$P = \frac{A}{(\omega - \omega_0 + k_x U_x + k_y U_y)^2 + \Gamma^2} + \frac{b_0}{k^3}$$

**2 x 1D Inversions**

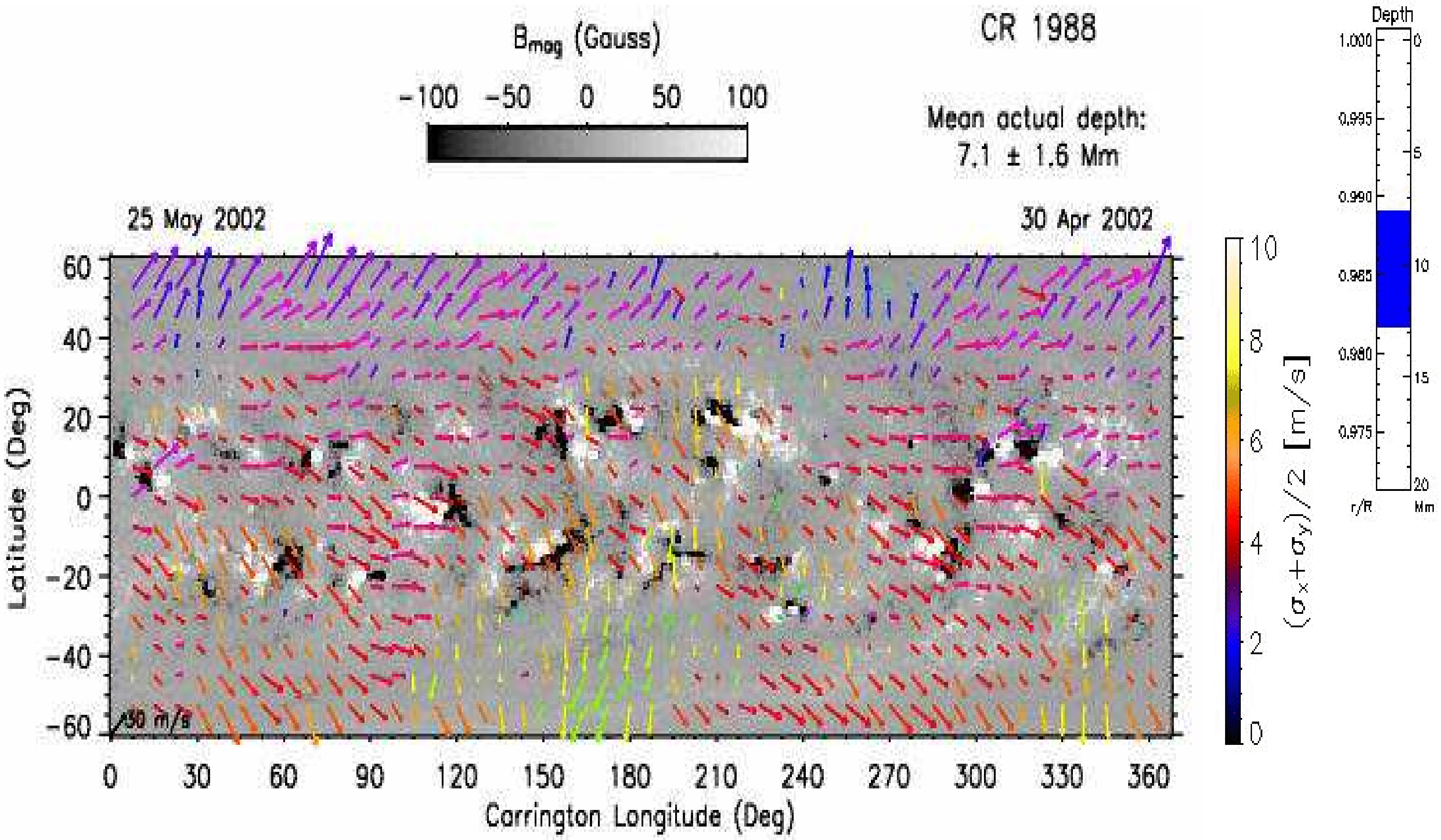
$$U_{x,y}(\omega_o, k_h) = \int K(\omega_o, k_h, z)\, v_{x,y}(z)\, dz$$

**$V_z$ may then be computed using the divergence of the horizontal flow and assuming mass conservation.**
***(Komm, Corbard et al. 2004)***

# 1664 mn « days » flow maps

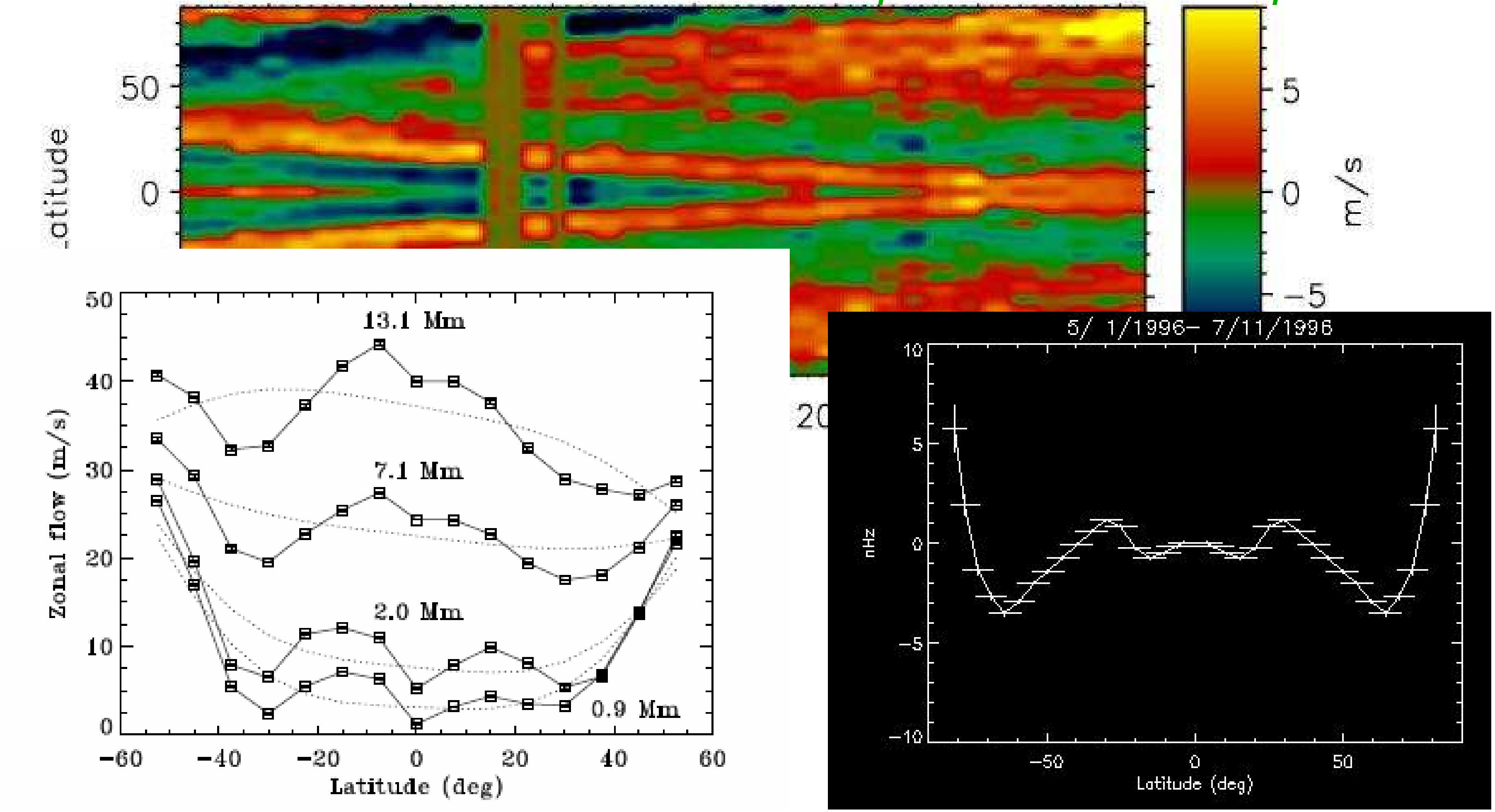


# Ring Diagram Analysis
# Synoptic Flow Maps



# Averaged Zonal Flow residuals:
# Torsional Oscillations

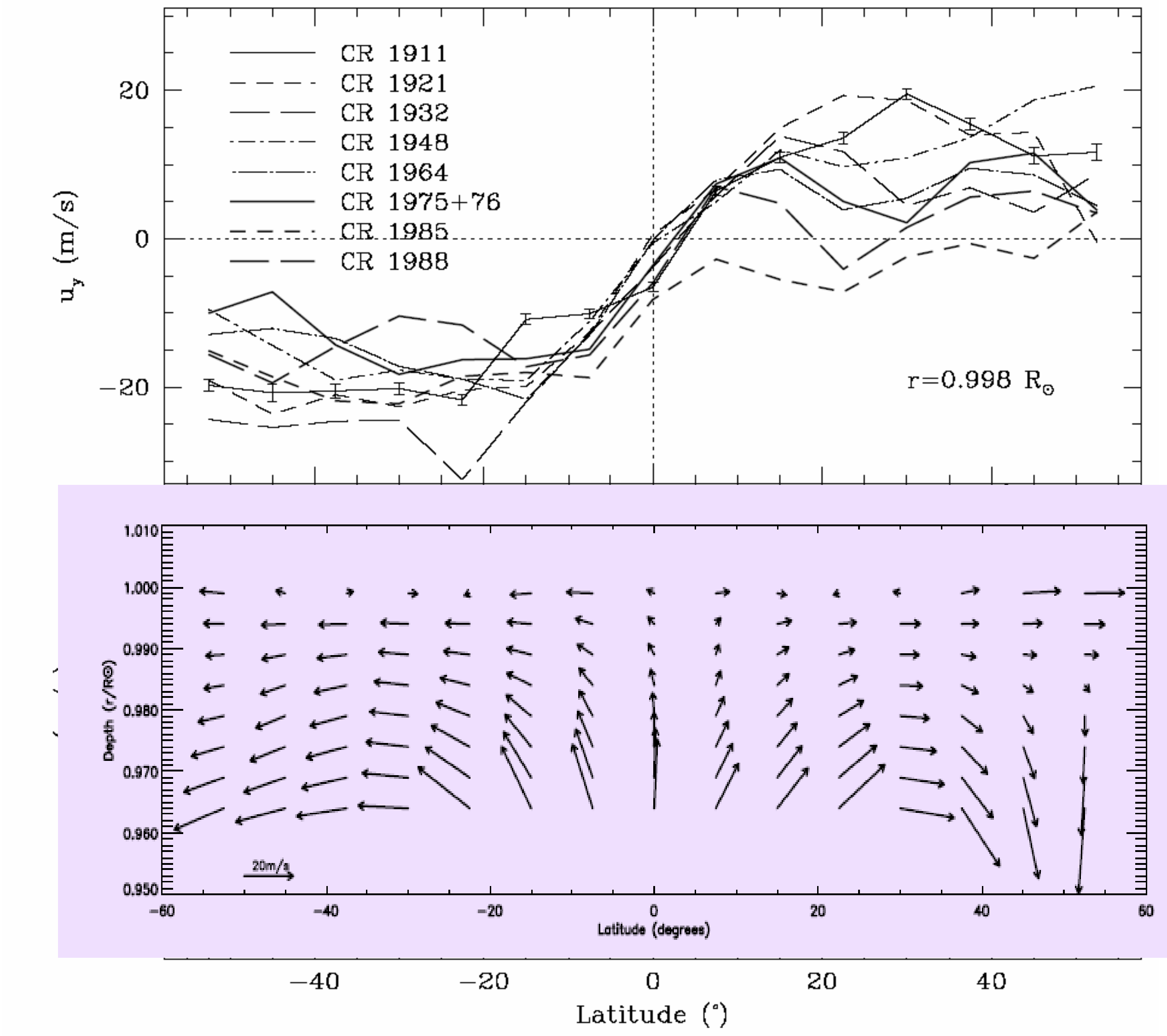
*Adapted from Corbard & Thompson 2001*



# Time and depth variations of Meridional Flows

*Basu & Antia 2002*

*Gonzalez Hernandez et al. 2004*

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# Some fluid descriptors

From the daily flow maps, we calculate the divergence of the horizontal flow components and the vertical vorticity component

$$\boxed{\mathrm{div}\, v = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y}} \quad (1)$$

$$\boxed{\mathrm{vort}\, v = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}} \quad (2)$$

where $v_x$ is the zonal and $v_y$ is the meridional flow component. We use $\mathrm{div}\, v$ and $\mathrm{vort}\, v$ to distinguish the components from the complete divergence $(\nabla \vec{v})$ and vorticity $(\nabla \times \vec{v})$. We then calculate synoptic maps of these quantities in the same way as for the velocities. In addition, we calculate the vertical gradients, $\partial v_x / \partial z$ and $\partial v_y / \partial z$, of the horizontal flow components and the corresponding synoptic maps. All quantities are functions of latitude, longitude, and depth.

# Kinetic Helicity

The kinetic helicity of a fluid flow is the integrated scalar product of the velocity field, $\vec{v}$, and the vorticity field, $\nabla \times \vec{v}$ (Moffatt & Tsinober 1992):

$$\mathcal{H} = \int \vec{v} \cdot \nabla \times \vec{v} \; dV \tag{7}$$

where $\vec{v} \cdot \nabla \times \vec{v}$ is called the helicity density of the flow. The kinetic helicity and its density are pseudoscalar quantities. If the vorticity is a stationary random quantity (for example, homogeneous turbulence), one can define the mean helicity

$$H = \langle \vec{v} \cdot \nabla \times \vec{v} \rangle \tag{8}$$

# Computing Vz using the continuity equation

Using the continuity equation (representing mass conservation), we estimate the vertical velocity component from the measured divergence of the horizontal flow (Scorer 1978; Holton 1979). The continuity equation can be written as follows

$$\cancel{\frac{\partial \rho}{\partial t}} + \nabla \rho \cdot \vec{v} + \rho \cdot \nabla \vec{v} = 0 \tag{3}$$

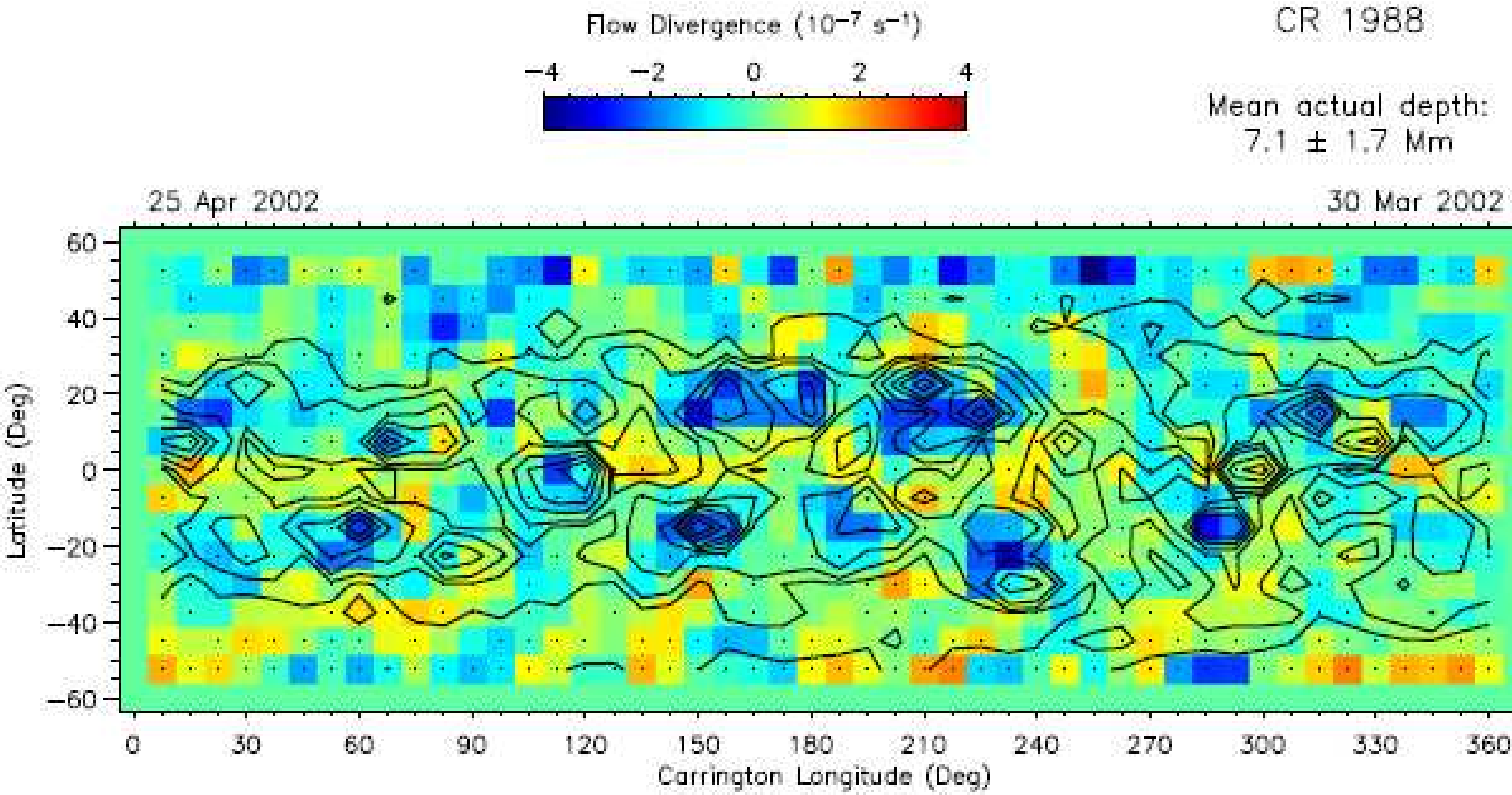
where $\rho$ is the density and $\vec{v}$ is the 3-dimensional velocity vector. Since each data point represents an average over 1664 minutes, we neglect the term of the temporal density fluctuations. In addition, we assume that any horizontal density variations average out over the area of a dense-pack patch. The density is simply a function of radius. The continuity equation can then be simplified to

$$\frac{\partial v_z}{\partial z} + \left(\frac{1}{\rho}\frac{\partial \rho}{\partial z}\right) v_z + \mathrm{div}\, v = 0 \tag{4}$$

where div $v$ is the horizontal flow divergence (Equation 1). This equation has the following solution:

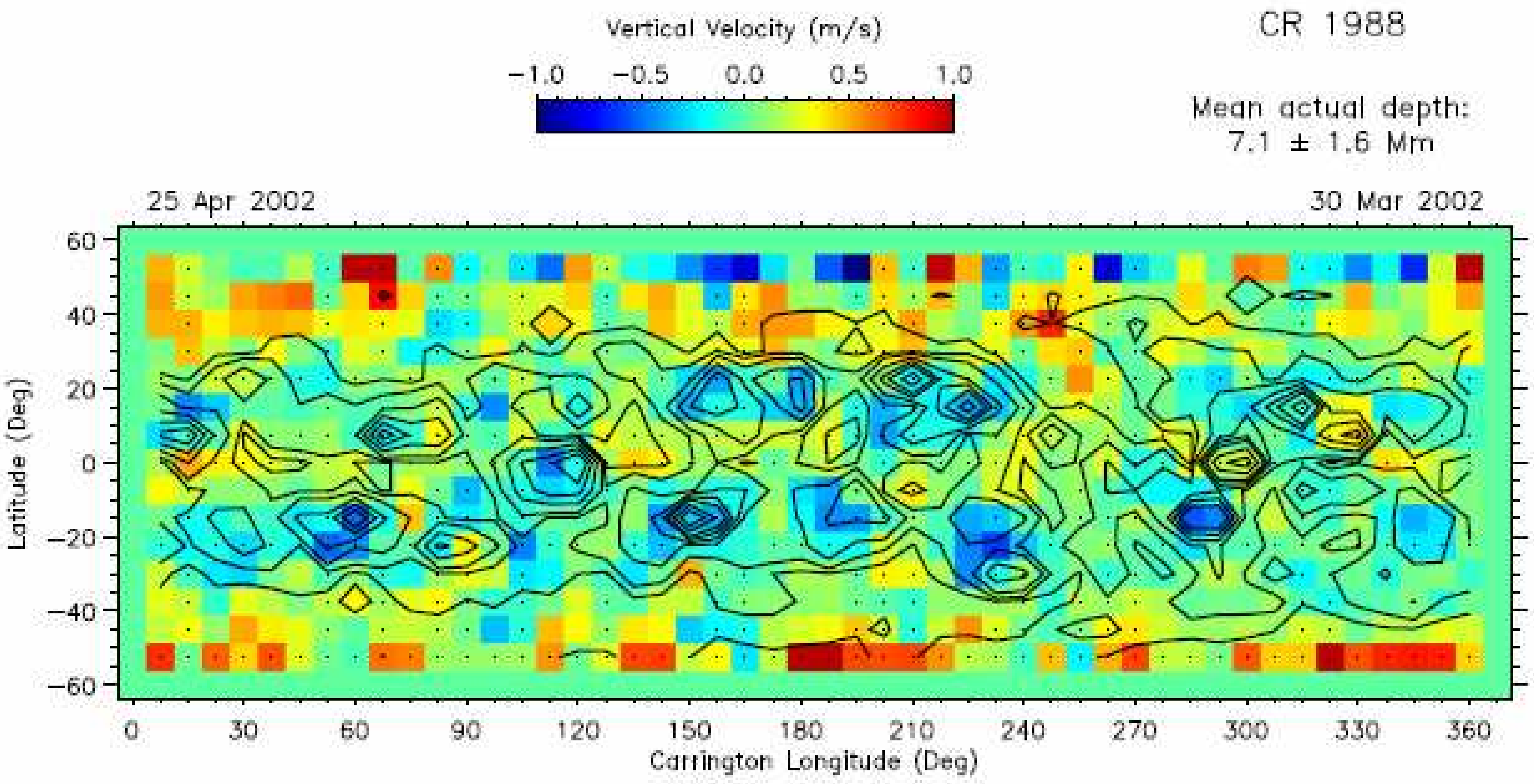
$$v_z(d) = -\frac{1}{\rho}\int_{R_\odot}^{R_\odot - d} \rho\, \mathrm{div}\, v\, \mathrm{d}z + \cancel{v_\odot \frac{\rho_\odot}{\rho}} \tag{5}$$

# Divergence of horizontal flow  (div v)



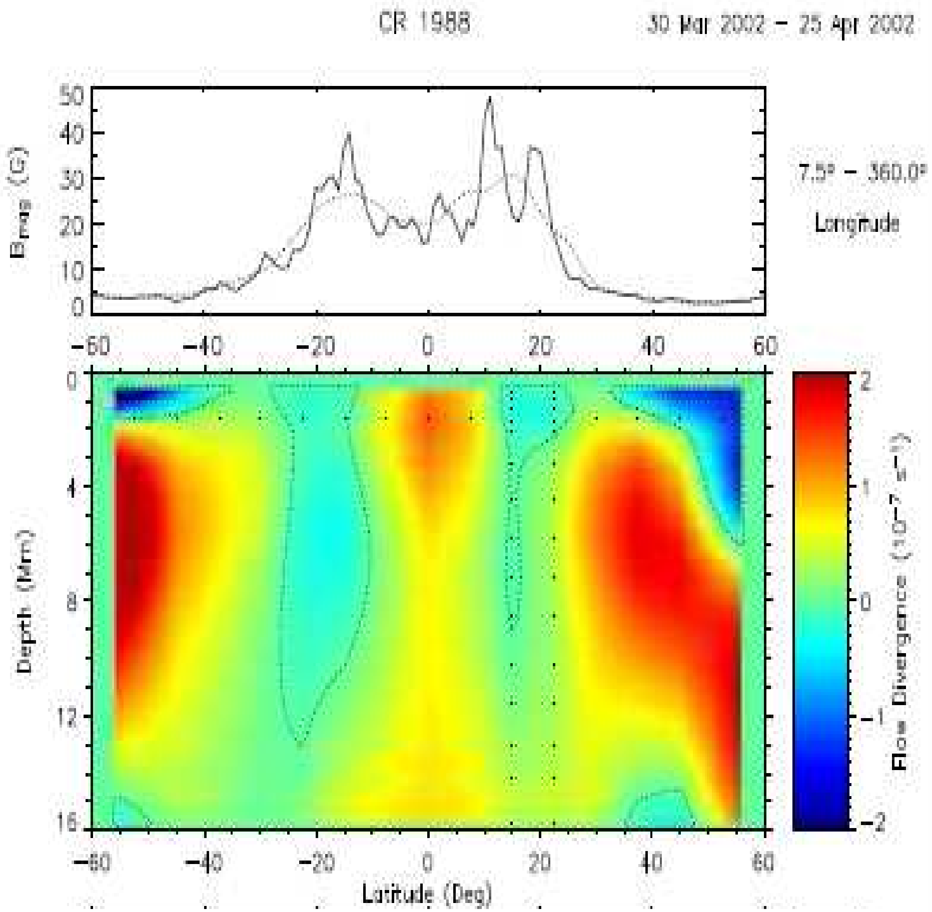

*Komm, Corbard et al. 2004 (ring diagrams)*

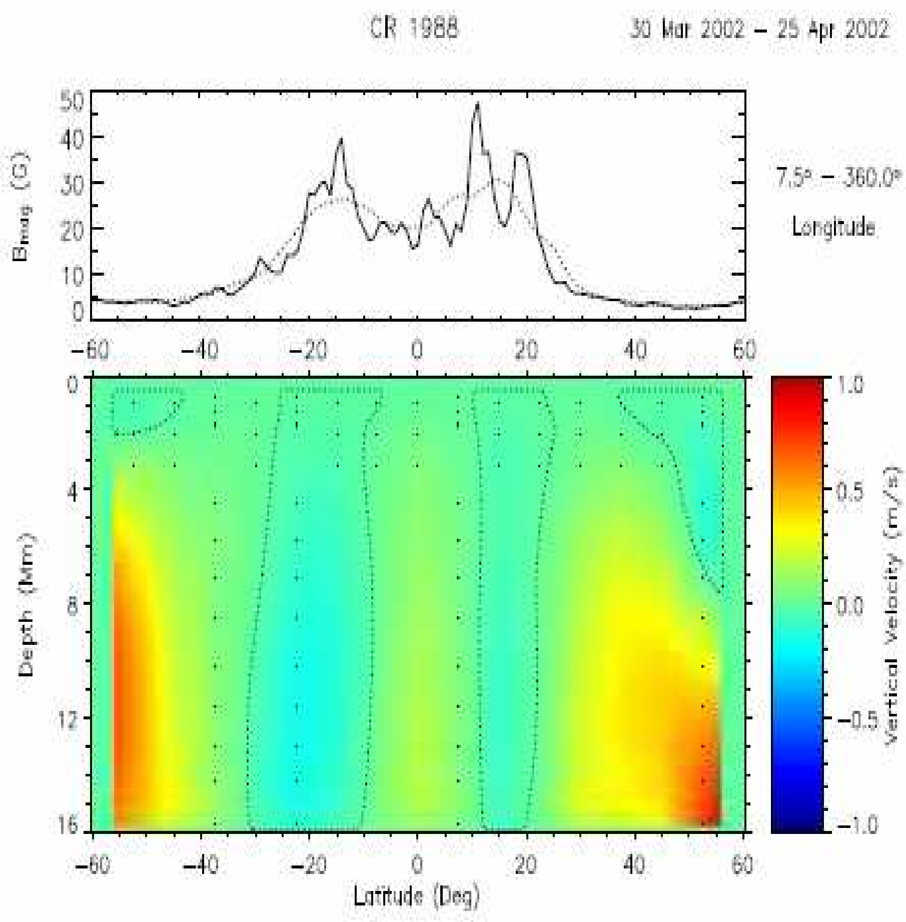
# Vertical Velocity (Vz)




*Komm, Corbard et al. 2004 (ring diagrams)*

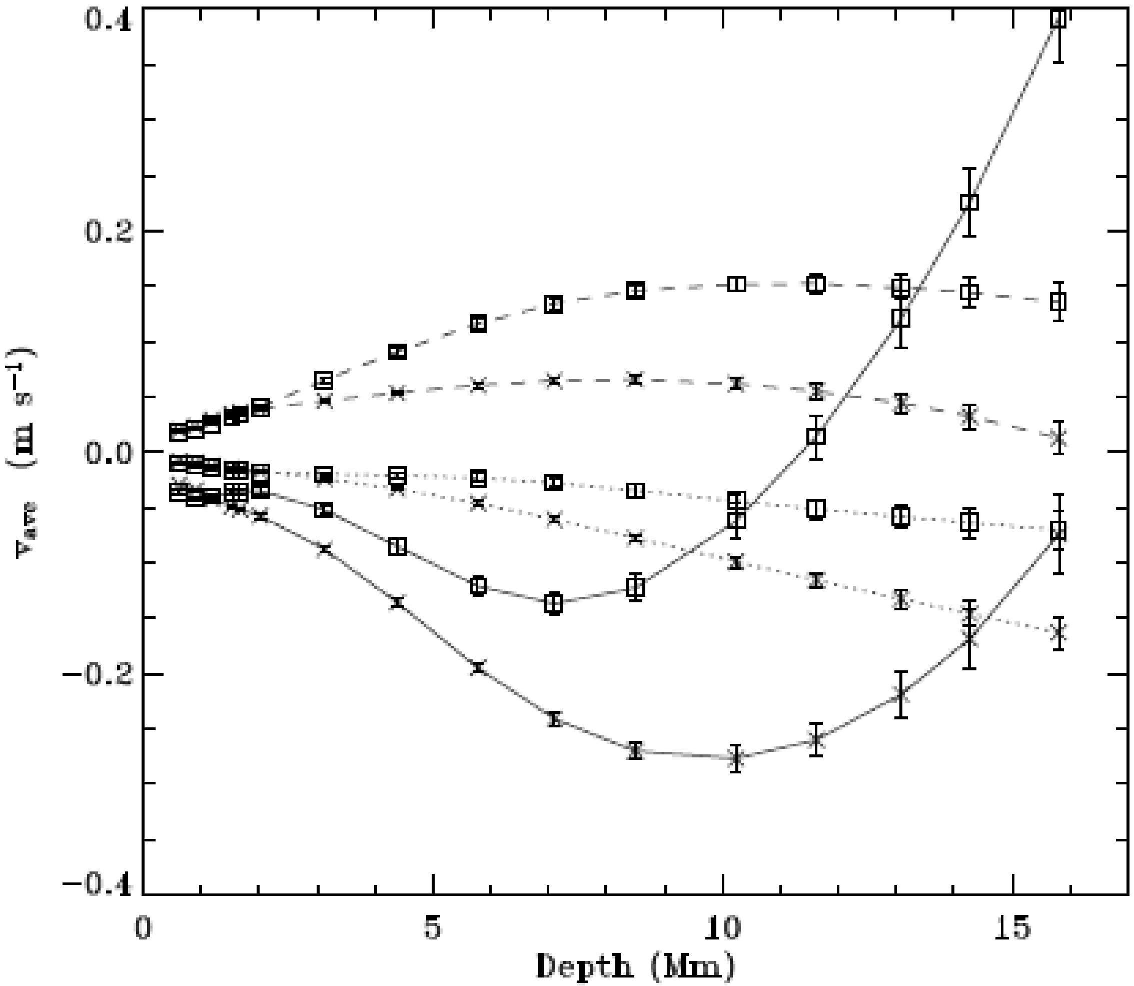
# Div v / Vz as a function of depth




*Komm, Corbard et al. 2004 (ring diagrams)*

# Vertical Velocity as a function of depth for 3 levels of magnetic activity




- Low B => up flows
- Medium B => Down flows
- High B => Down flows <10Mm

Up flows >10Mm

# Selection of areas with different magnetic flux levels over 14 Carrington Rotations

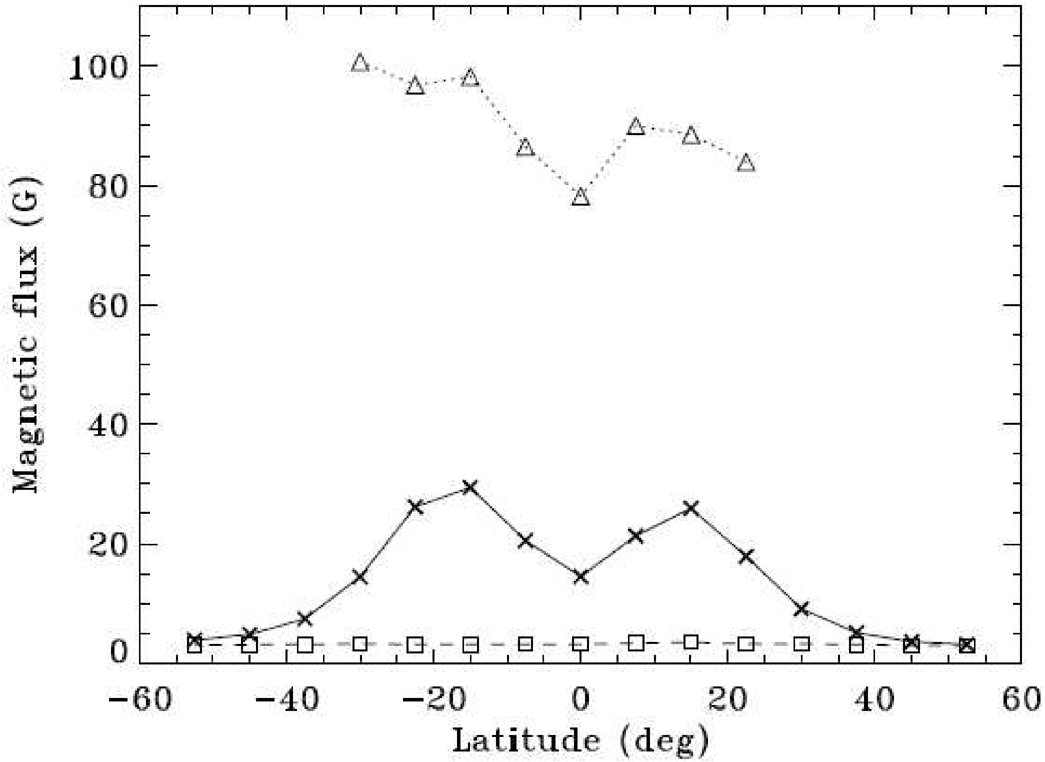
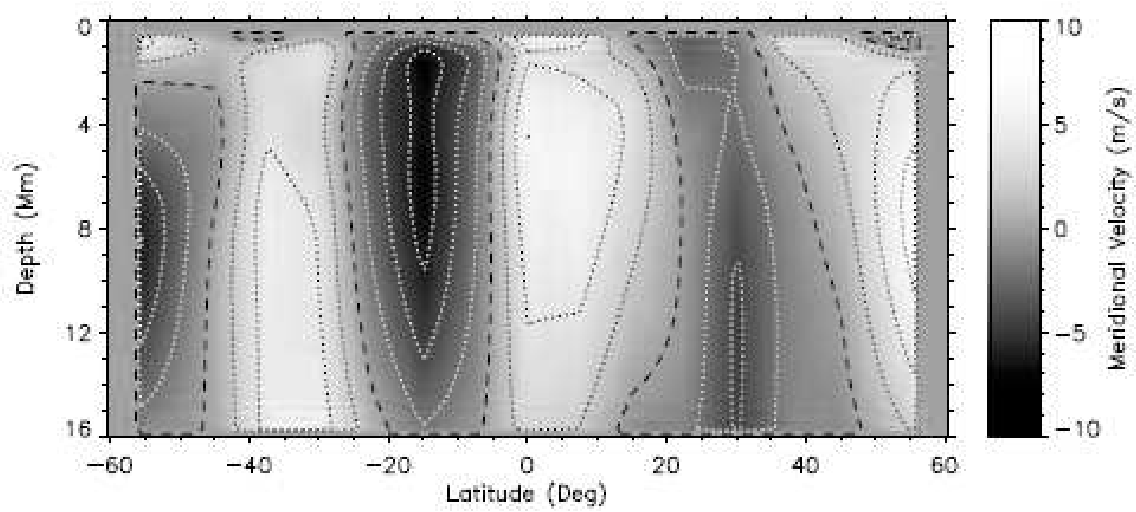
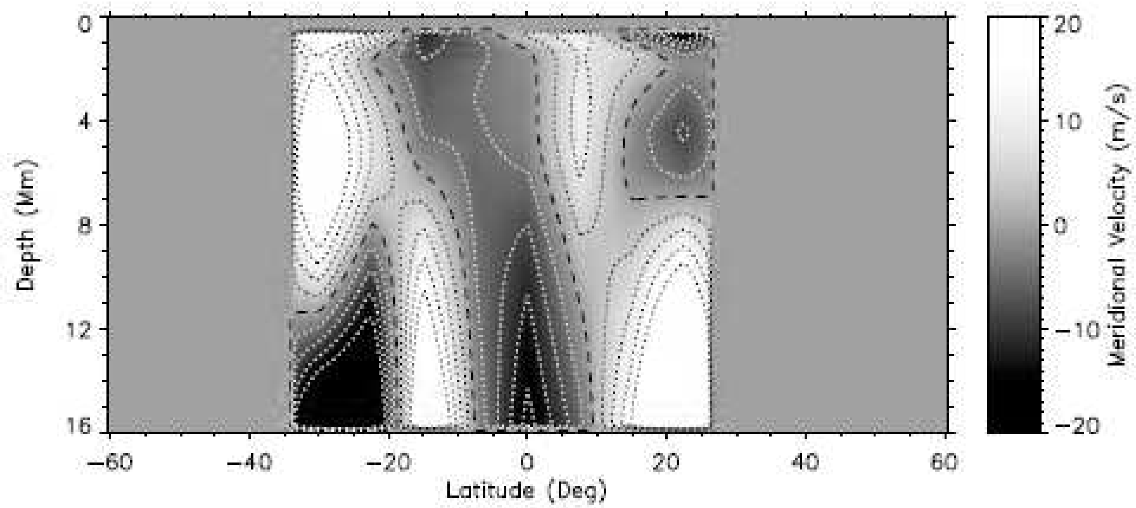



Fig. 1.— The magnetic flux as a function of latitude (solid line, cross symbols) averaged in longitude over CR 1979–1992 (2001, July 27 – 2002, Aug 12). The triangle symbols (dotted line) indicate the average over all locations with magnetic flux greater 71 G and the square symbols (dashed line) indicate the average over 25% of locations with the lowest flux.

# Residual Meridional Flow $V_y$ averaged over 14 CR

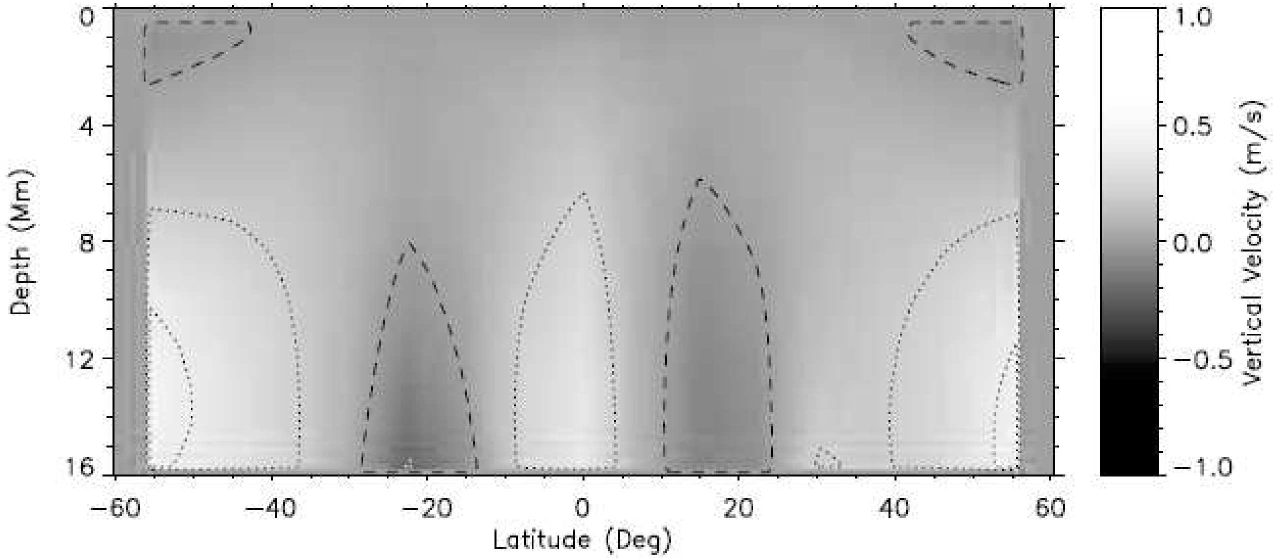



**Low activity set**

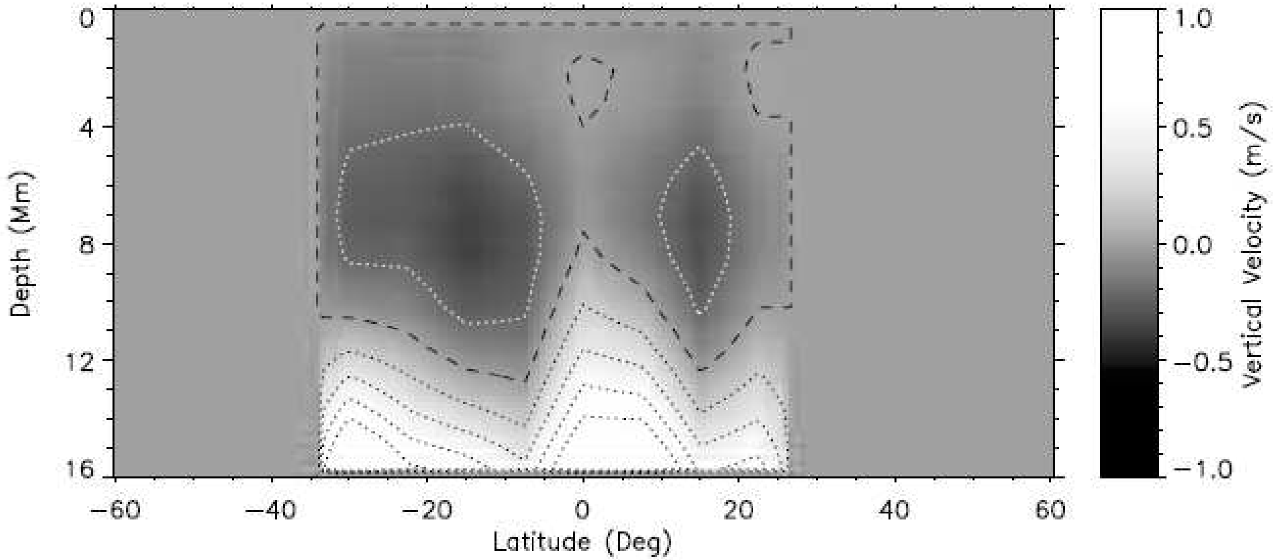



**High activity set**
**B> 71 G**

# $V_z$ averaged over 14 CR

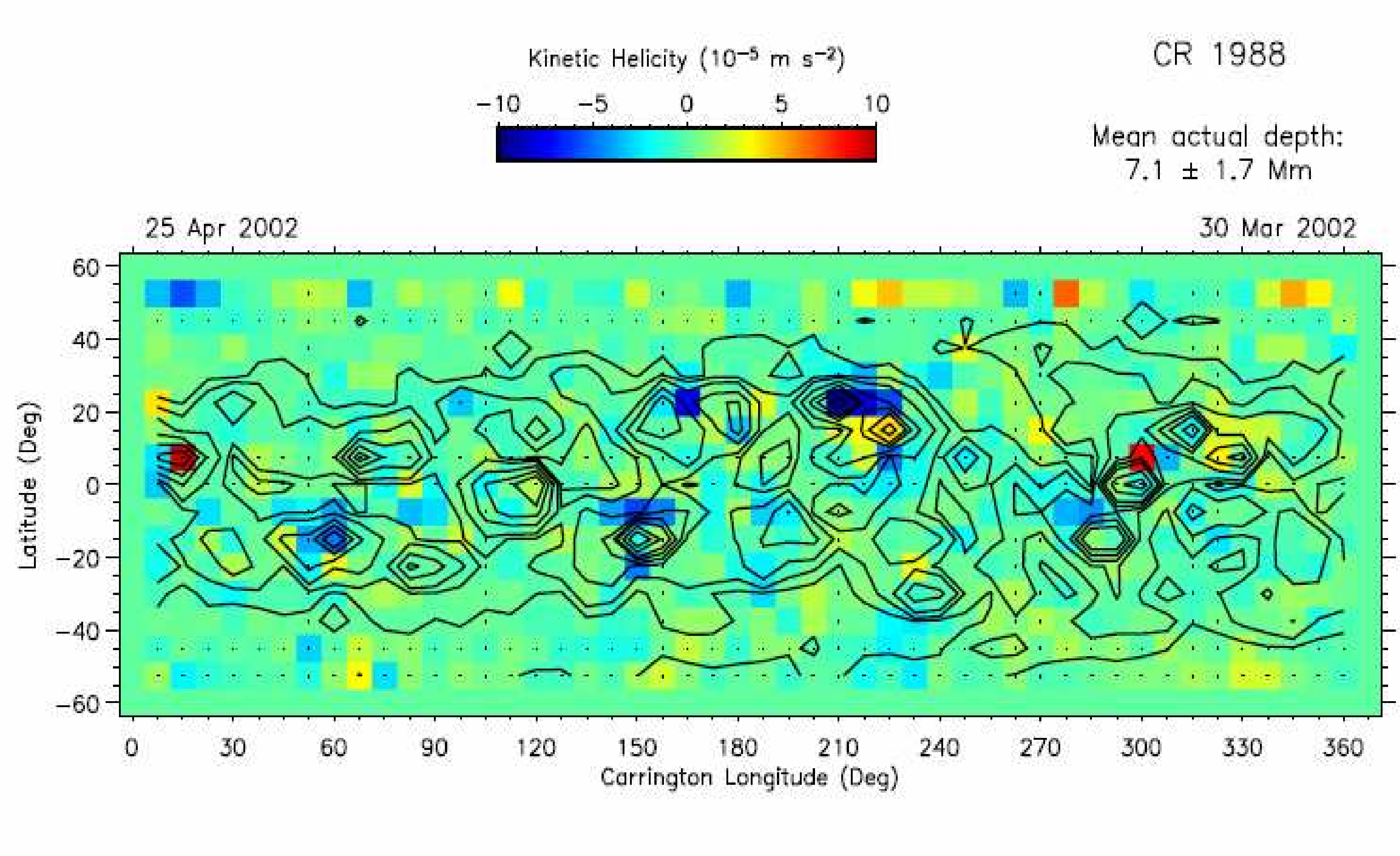



**Low activity set**

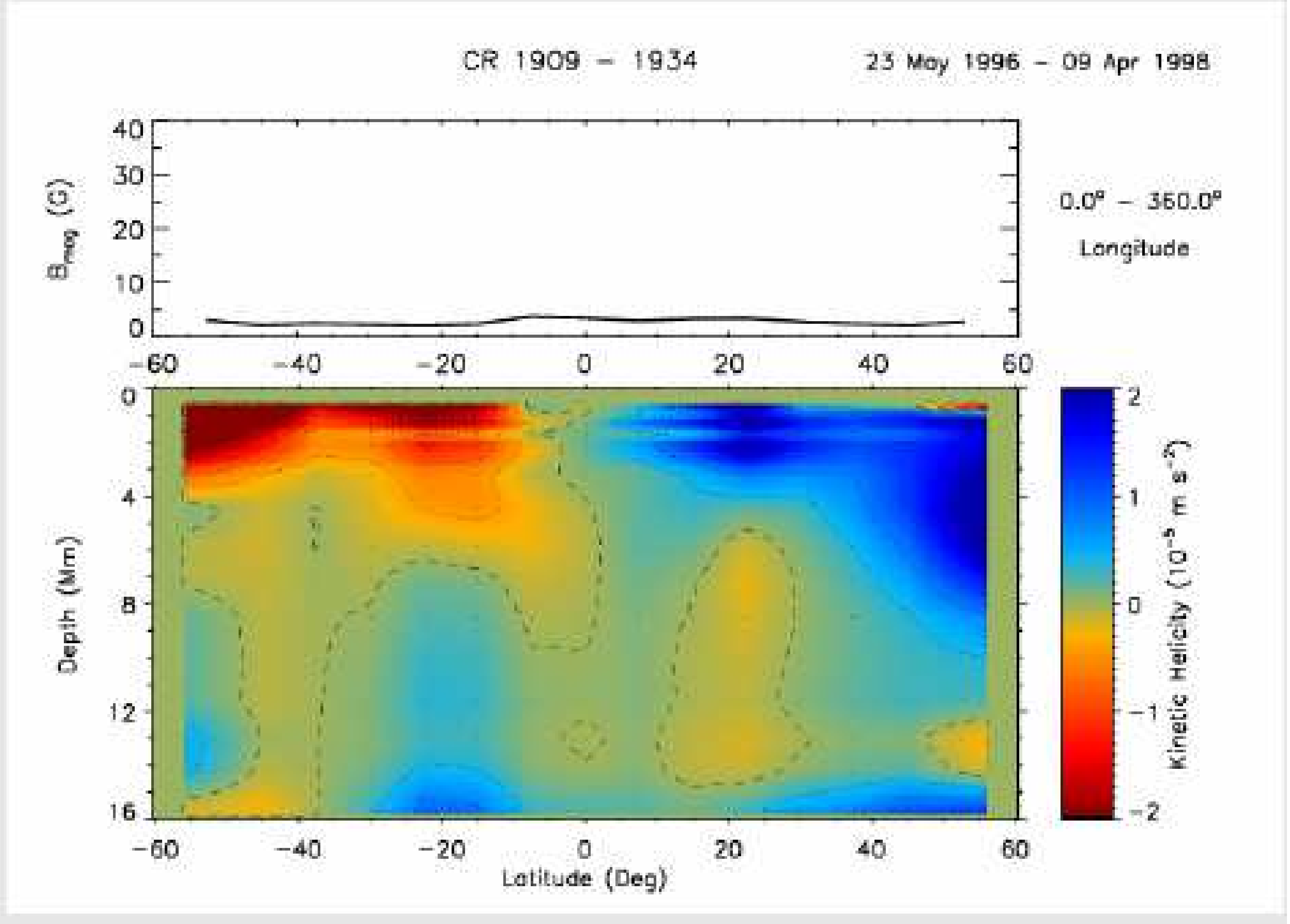



**High activity set**
**B> 71 G**

# Synoptic Maps of Kinetic Helicity



# Kinetic Helicity at low activity level

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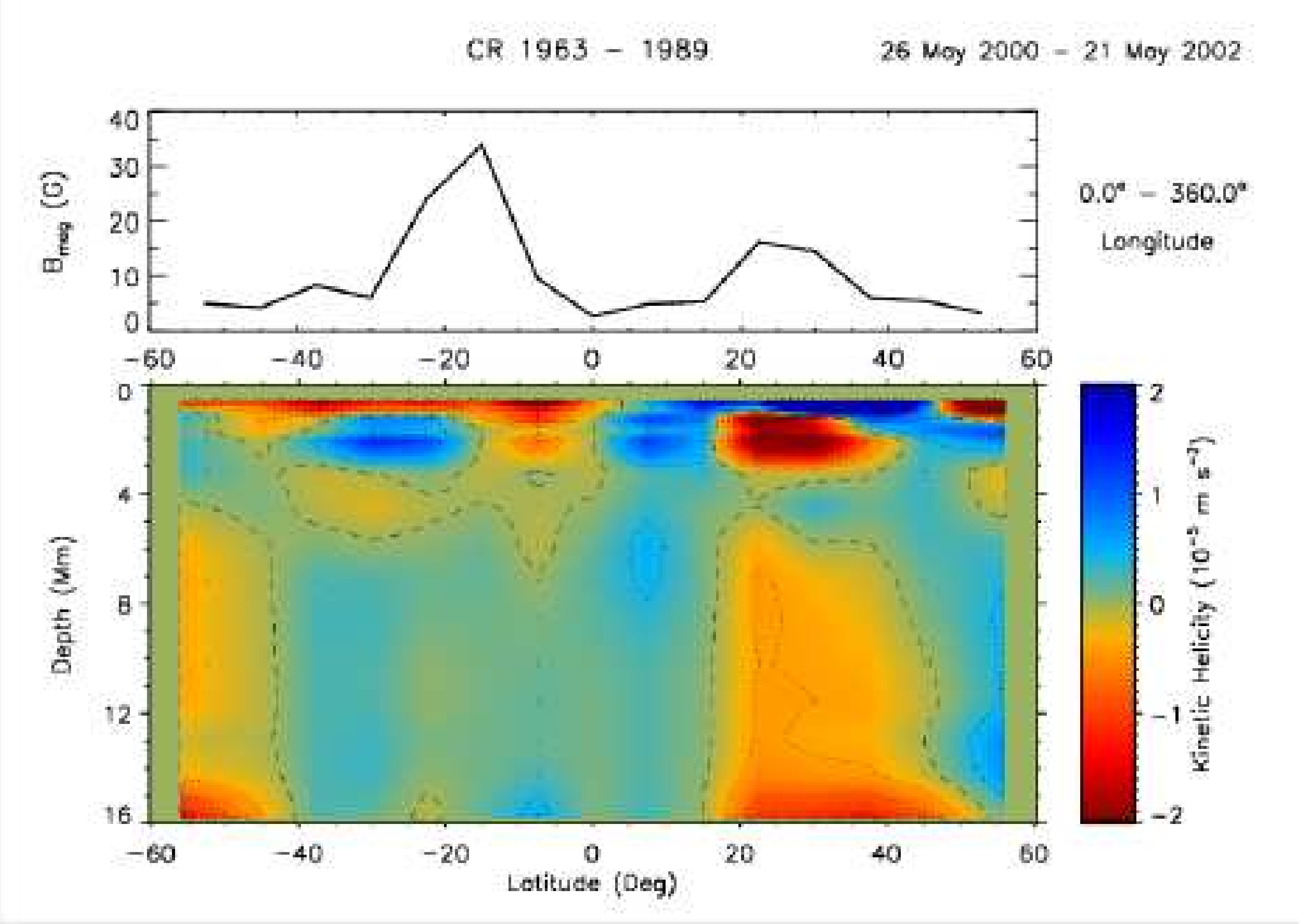
# Kinetic Helicity at high activity level



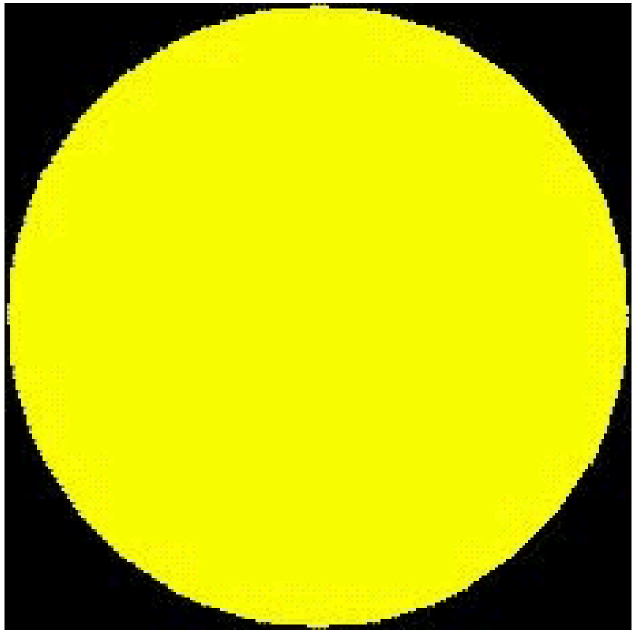
# Time-distance helioseismology
# Principles

- First developed by *Duvall 1993*

- Employs waves travel times observed between different surface location on the Sun.

- These travel times are then “inverted” to deduce:
  - Flow speed and direction,
  - Sound speed perturbations
  - [Magnetic field perturbations]

  Along the ray paths of the observed modes.



# Time-distance helioseismology
# Interpretation of travel time perturbations

## Dispersion relation:

*(Kosovichev et al. 1997)*

$$(\omega - \vec{\mathrm{k}}.\vec{\mathrm{v}})^2 = \omega_{ac}^2 + \frac{\mathrm{k}^2}{2}\left(c^2 + c_A^2 + \sqrt{(c^2 + c_A^2)^2 - 4c^2(\vec{k}.\vec{c}_A)^2 / k^2}\right)$$

**3D velocity field**

**Acoustic cut off frequency**

**Alvén velocity**

$$\vec{c}_A = \frac{\vec{B}}{\sqrt{4\pi\rho}}$$

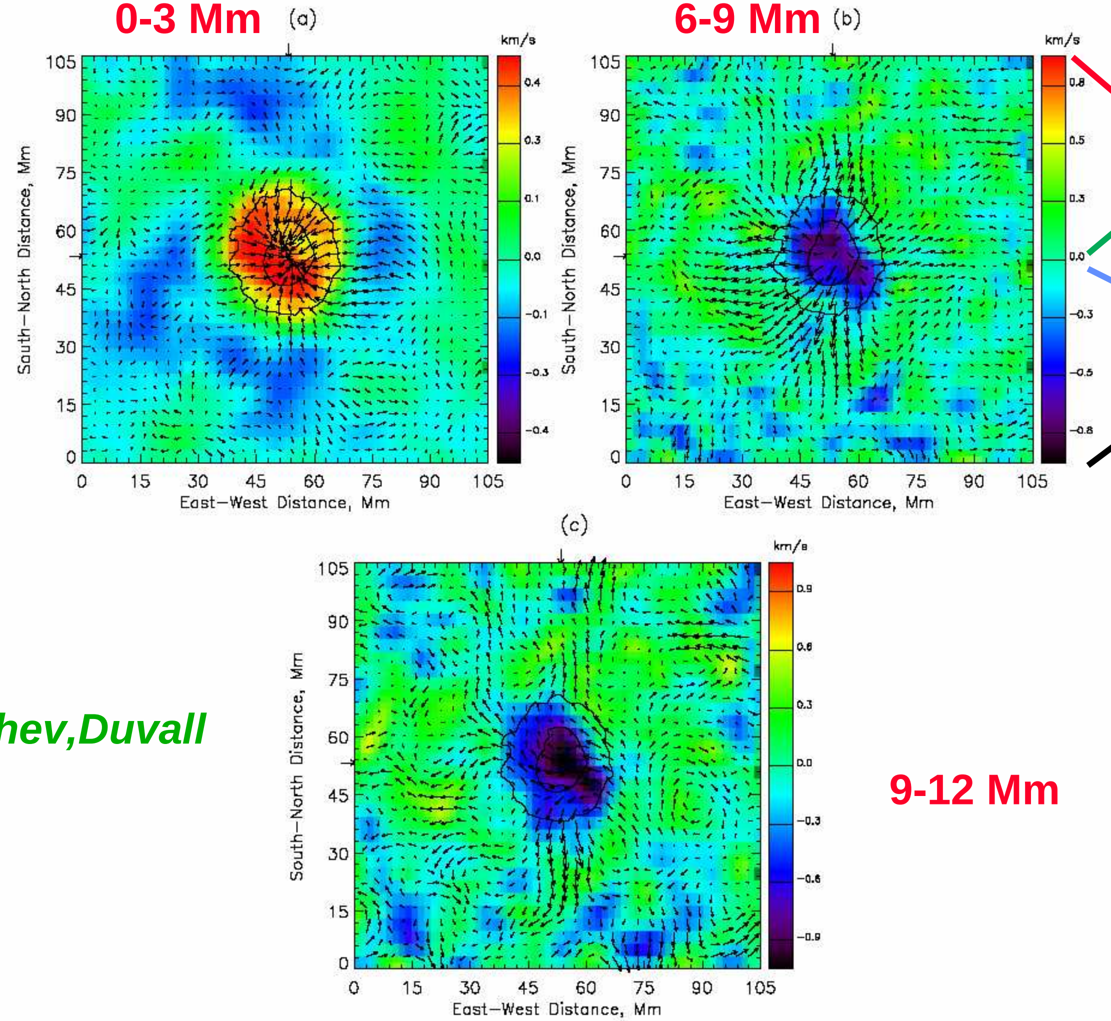
- Temperature perturbations => do not depend on the direction of propagation
- Flow perturbations => waves move faster along the flow
- Magnetic fields perturbations => waves traveling perpendicular to the field lines are the most sensitive to B (wave speed anisotropy not yet detected)

  *Ryutova & Scherrer 1998*

# Time-distance helioseismology
# Results: 3D Flows below sunspot

0-3 Mm

6-9 Mm




Downward flows

Upward flows

*Zhao, Kosovichev,Duvall 2001*

9-12 Mm

# Time-distance helioseismology
## Sub sunspot dynamics and structure

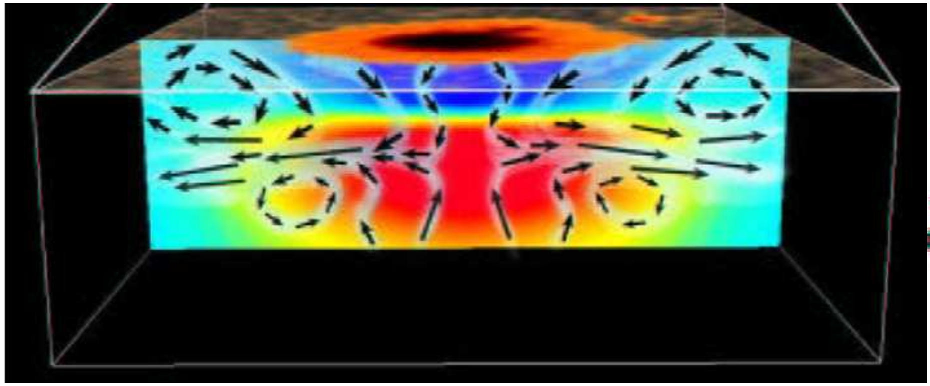
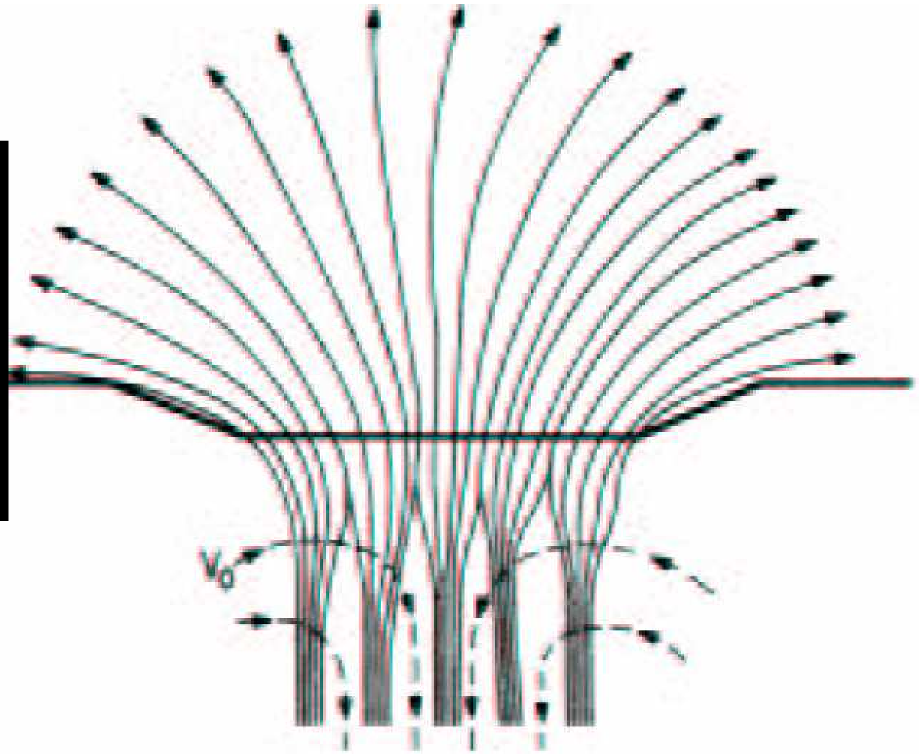


Illustration of sound speed variations and subsurface flow patterns of a sunspot

*Courtesy SoHO/MDI*




The cluster Model of Sunspot

*Parker 1979*