The Meridional flow as derived from Fourier-Legendre decomposition of the first data from the Helioseismic and Magnetic Imager

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GONG 2010/SoHO 24 Conferene

A new era of seismology of the Sun and solar-like stars

Aix en Provence, France
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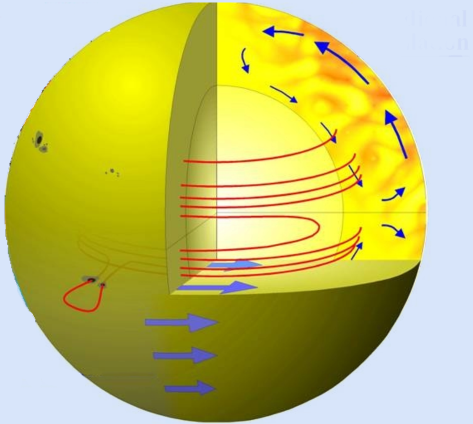
Objectives & Motivation



courtesy R. Arlt, AIP

The Solar Meridional Circulation

- $\approx 20\,\mathrm{m/s}$ on surface (direct measurements)
- $\approx 20\,\mathrm{m/s}$ upper few Mm (helioseismology)
- 2–10 m/s return flow *expected* near bottom of CZ

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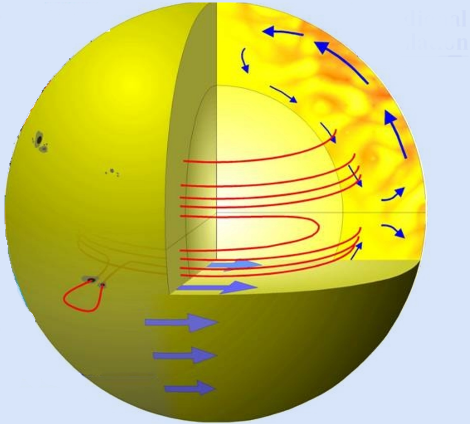

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- Flow pattern changes with solar cycle
- Round-trip time roughly 10 years
- Flow is key ingredient for some dynamo models

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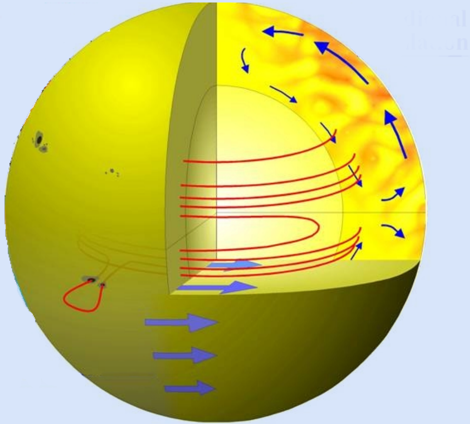

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Motivation

- No significant evidence for return flow found yet
- FLD method potentially able to sense deep flows

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Ring diagram analysis (Hill 1988)

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Fourier-Hankel Decomposition (Braun et al. 1987)

- Wave absorbtion in sunspots; meridional flow (Braun & Fan 1998)
- Sensible to low-degree modes $\Rightarrow$ potential to go deep below surface
- Hankel functions as approximation to Legendre polynomials in plane geometry

Normal Mode Decomposition based on Legendre Polynomials

Expand oscillations as superposition of travelling waves propatating in opposite directions (in-/outward)

$$\Psi(\theta, \varphi, t) = \sum_{l,m,\nu} \left[A_{l,m,\nu} X_l^m(\theta) + B_{l,m,\nu} X_l^{m*}(\theta) \right] e^{i(m\varphi + \nu t)}$$

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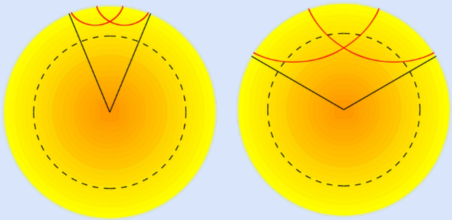
Extract A and B from measured Ψ

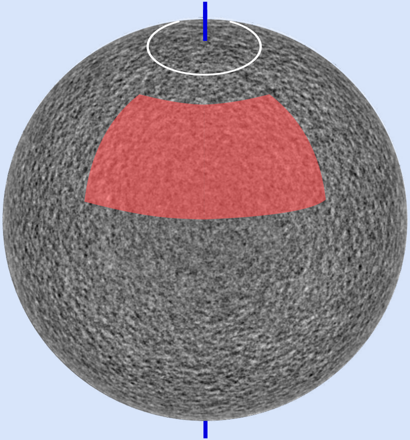
$$A_{lm}(t) = C \int_0^{2\pi} \int_{\theta_{\min}}^{\theta_{\max}} \Psi(\theta,\,\phi,\,t)\, X_l^m(\theta)^* e^{-im\phi}\, \theta \,\mathrm{d}\theta \,\mathrm{d}\phi$$

Power-spectra of $A(t)$ and $B(t)$ show frequency shift in presence of flows

FLD Applied to Meridional Flow Measurements

- Center of annular region at north/south pole
- In-/outwards $\Rightarrow$ pole-/equatorward
- Small patches for spatially resolved near-surface flow
- Very large patches for average deep flow





Inversion for the Vertical Flow Profile

Frequency shift

$$\delta\nu_{nl} = C \int_0^R \bar{U}_\theta(r)\, K_{nl}(r)\, \mathrm{d}r$$

$\bar{U}_\theta$ ... horizontal flow velocity, K_{nl} ... mode kinetic energy density

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- Invert for $\bar{U}_\theta$ by means of SOLA method (Pijpers & Thompson 1992)
- Kernels computed from solar model "S" (Christensen-Dalsgaard et al. 1996)
- Special care to be taken at low l (Gaugh & Hindman 2010)

Status of our Ongoing Work

New FLD Pipeline

- Decomposition code handles data from MDI, GONG and HMI
- Fast enough to process available and upcoming data
- Flexible (eg. p-mode absorbtion in sunspots; TBD)
- Easy to use (TBD)

will be made publically available when ready

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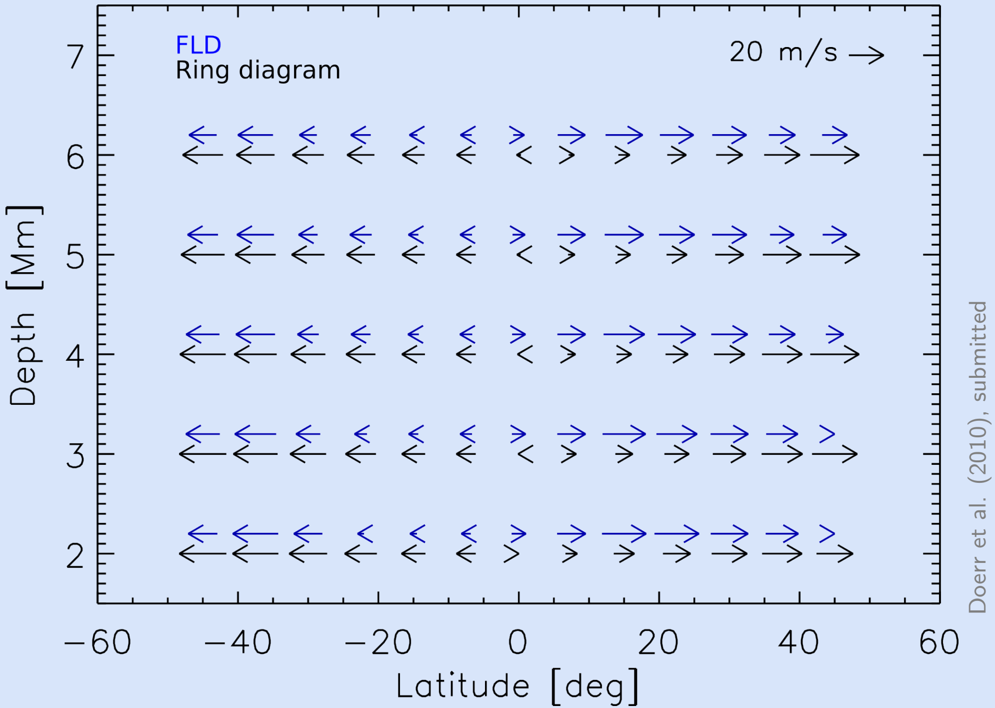
Current Work

- Handling of leakage
- Interpretation of observed doppler shift as discussed by Gaugh & Hindmann (2010)
- Apply FLD to long time series
- Forward modelling

Comparision with Ring Diagram Analysis

Setup

- Two month of GONG data (Jan–Feb 2006)
- FLD: 13 stripes of 16° extend in latitude along central meridian
- Ring diagram: 16×16°patches covering same area

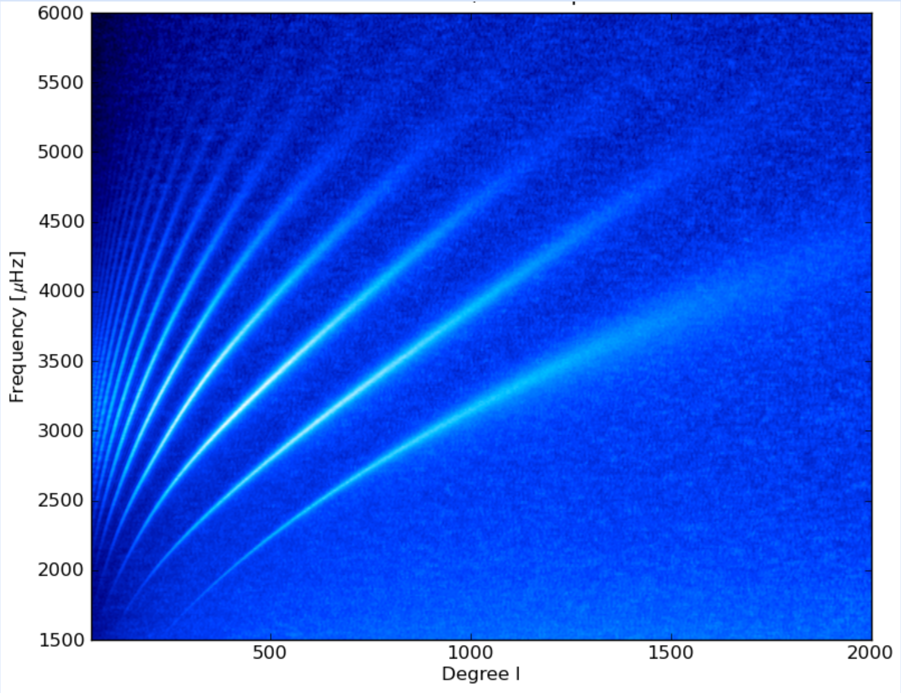


FLD
Ring diagram
20 m/s
Depth [Mm]
Latitude [deg]
7
6
5
4
3
2
−60
−40
−20
0
20
40
60
Doerr et al. (2010), submitted

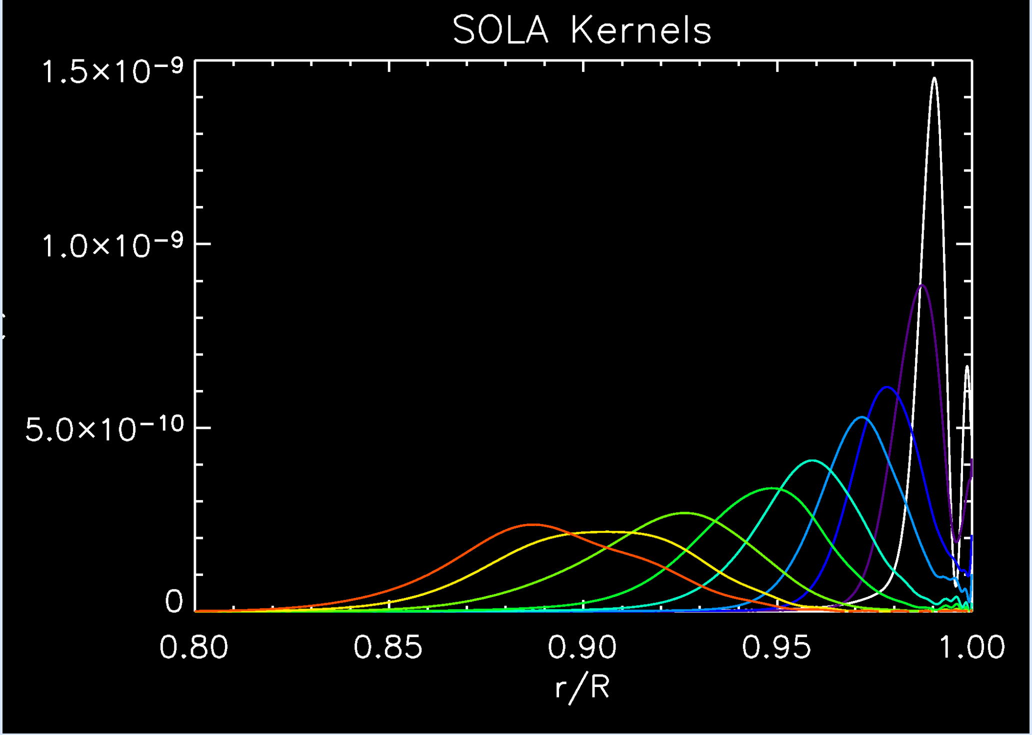
Average Meridional flow on Both Hemispheres (preliminary HMI data)

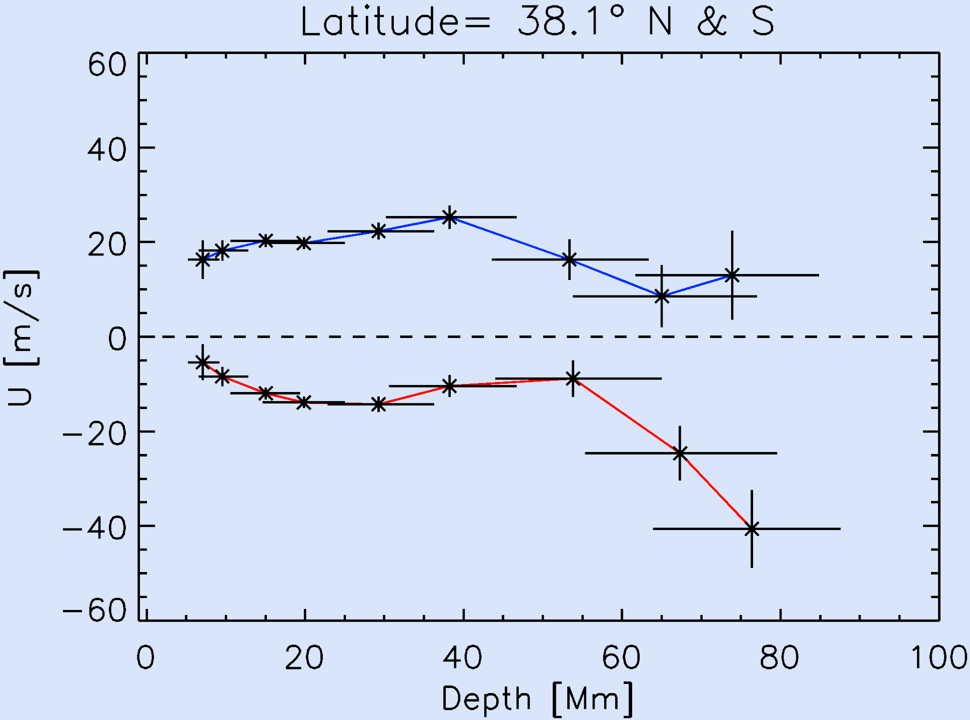
Setup

- Two weeks of data from the `hmi_test.V_45s` series (2010.05.24 22:24 - 2010.06.07 22:24; 26880 dopplergrams)
- patch size: $112.5 \times 56.5°$at $\pm 38.125°$, centered on central meridian



6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
Frequency [μHz]
500
1000
1500
2000
Degree l


SOLA Kernels
1.5×10⁻⁹
1.0×10⁻⁹
5.0×10⁻¹⁰
0
0.80
0.85
0.90
0.95
1.00
r/R


Latitude= 38.1° N & S
U [m/s]
Depth [Mm]
60
40
20
0
−20
−40
−60
0
20
40
60
80
100

Conclusions

- Fourier-Legendre decomposition can be used for meridonal flow measurements
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- New FLD Pipeline developed; ready for science now
- First results comparable to ring diagram analysis
- Preliminary results from HMI data shows potential of FLD to greatly extend range in depth that is currently accessible to other methods
- FLD resolves good averaging kernels throughout upper half of convection zone from only two weeks of observational data
- However, known issues have to be resolved before FLD will give reliable results for large depth

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