Meridional Circulation on the Sun: Helioseismic Measurements and Implications for Interior Dynamics

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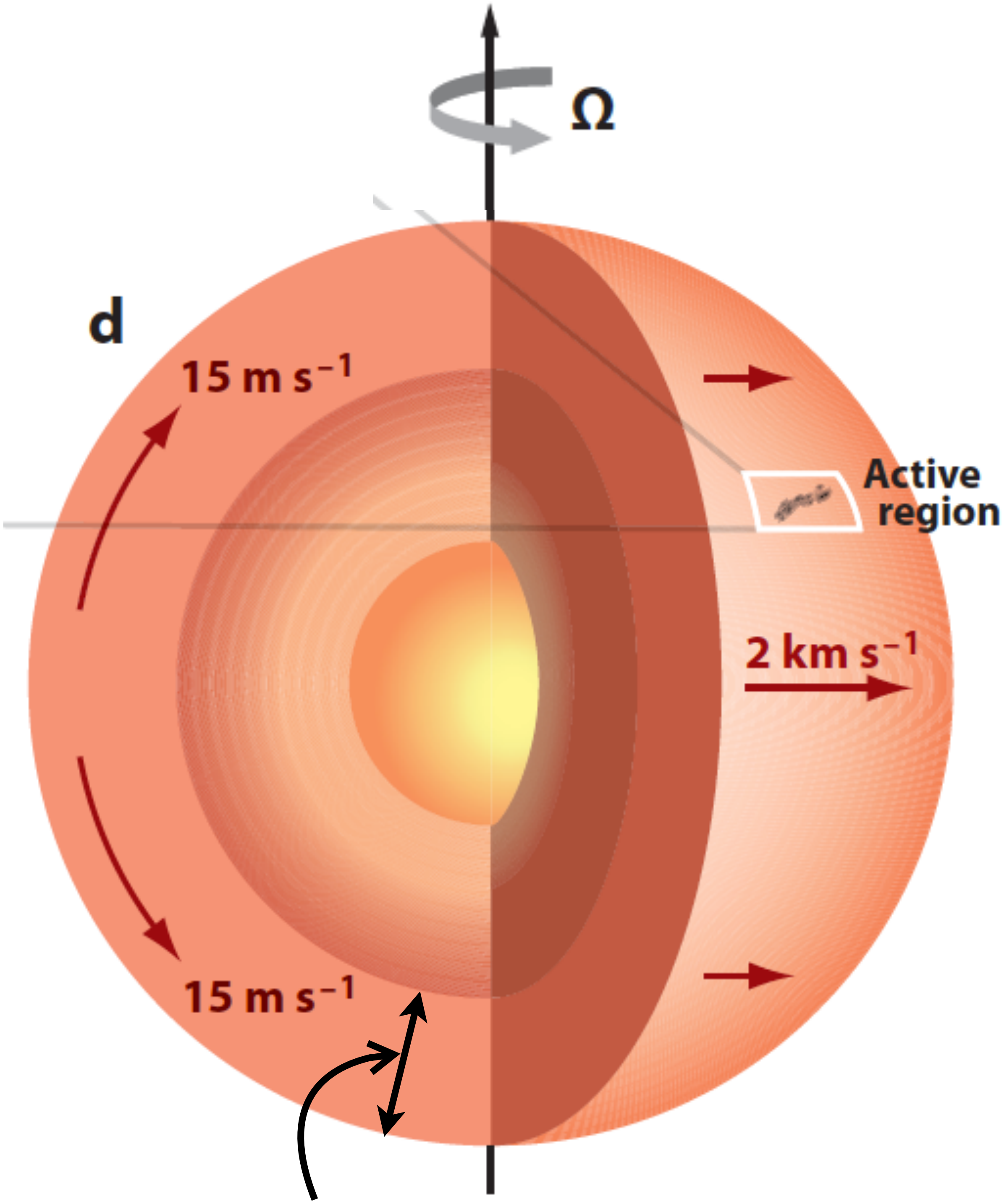
Kolloquium, KIS Freiburg
23 May, 2016

Rotation and Meridional circulation



Convection zone, ~ outer 30%

Eddington (1920) reasoned that a rotating star in radiative equilibrium should develop circulating currents along the meridians. He also suggested that such currents would lead to differential rotation, as observed on the solar surface.

Cartoon Figure by Gizon et al. 2010, ARAA

Surface meridional flow has been observed using several different techniques, and is well established:

(i) from direct Doppler observations
-- **Duvall 1979, Hathaway 1996, Ulrich 2010**

(ii) feature tracking, e.g. magnetic elements
-- **Komm et al. 1993, Hathaway and Rightmire 2010**

(iii) local helioseismology
-- **e.g., Basu and Antia 2010**

An early observation from direct Doppler observations:

LARGE-SCALE SOLAR VELOCITY FIELDS

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Institute for Plasma Research, Stanford University, Stanford, Calif. 94305, U.S.A.

(Received 17 July, 1978; in final form 8 March, 1979)

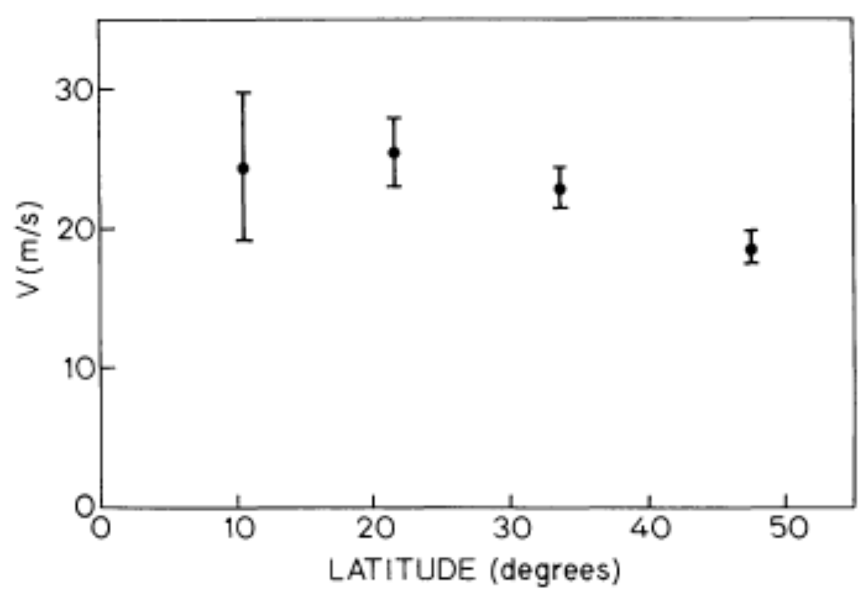
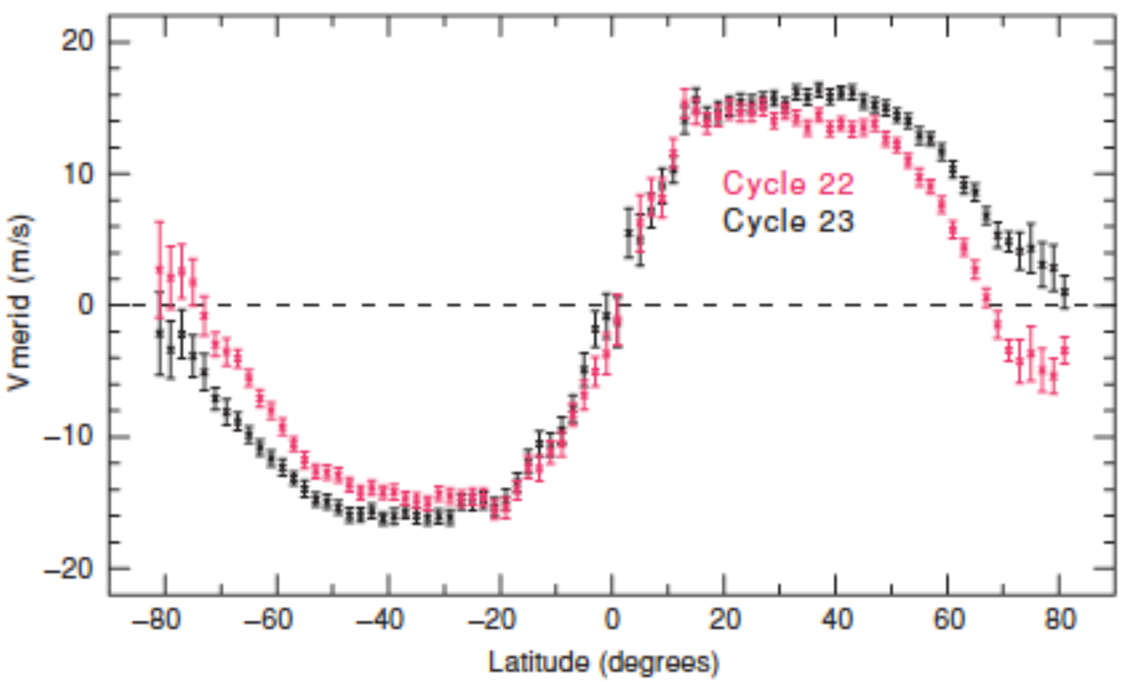
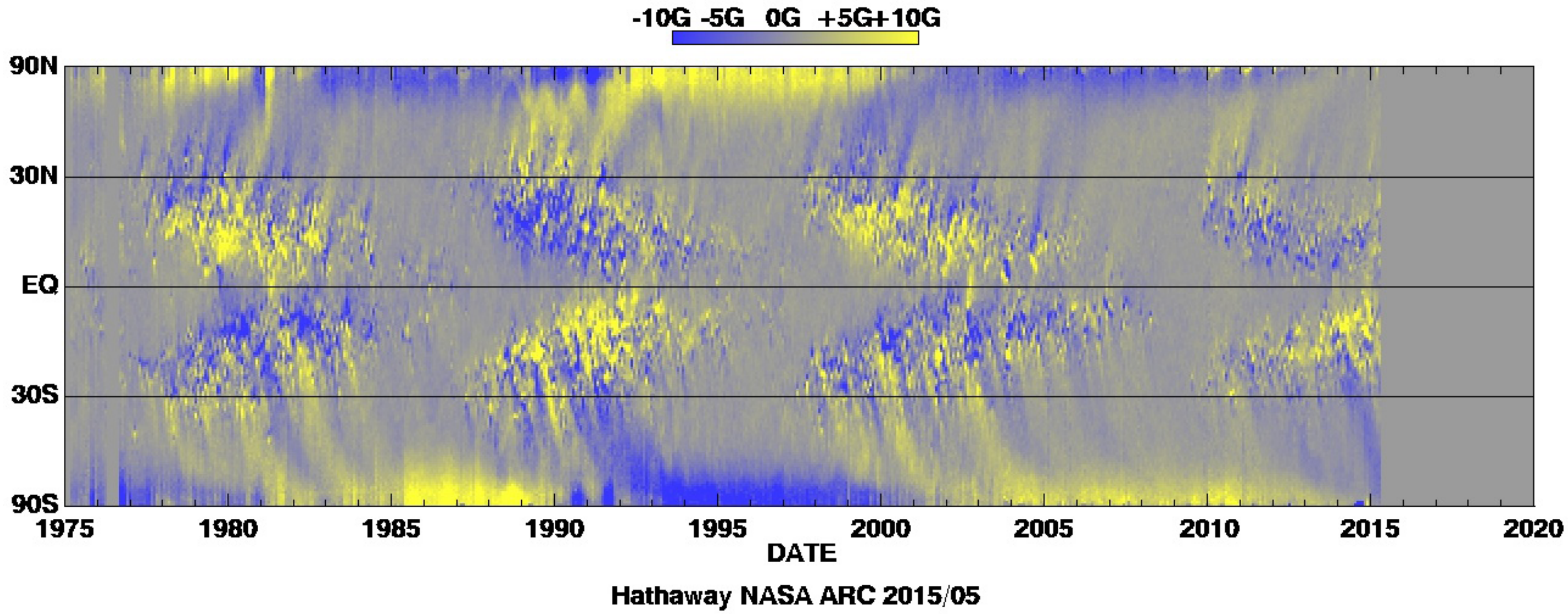


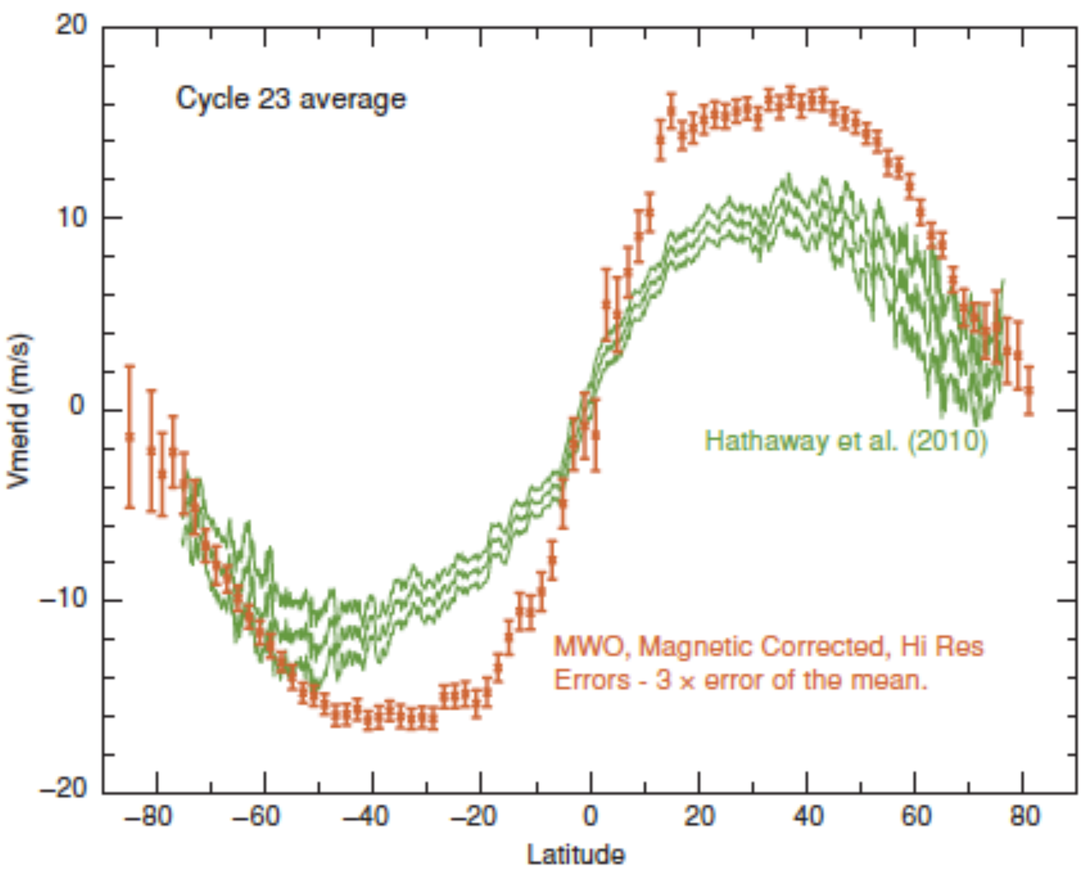
Fig. 11. Assuming the meridional flow is horizontal at the photosphere, the average symmetric component of the meridional circulation has been corrected for the projection of the velocity vector.

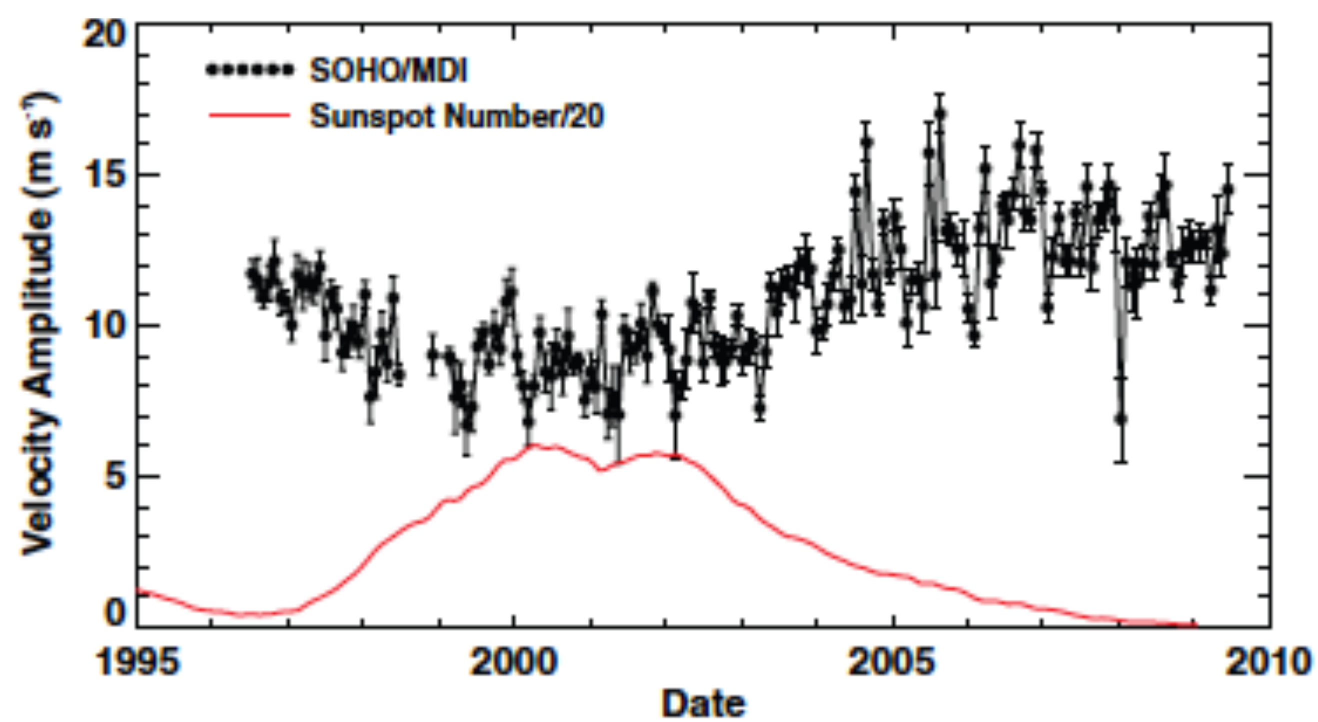
From Dopplergrams, MWO.
Ulrich, R.K. 2010 ApJ



Meridional flow from magnetic feature tracking, e.g. Hathaway et al. (2010, Science)

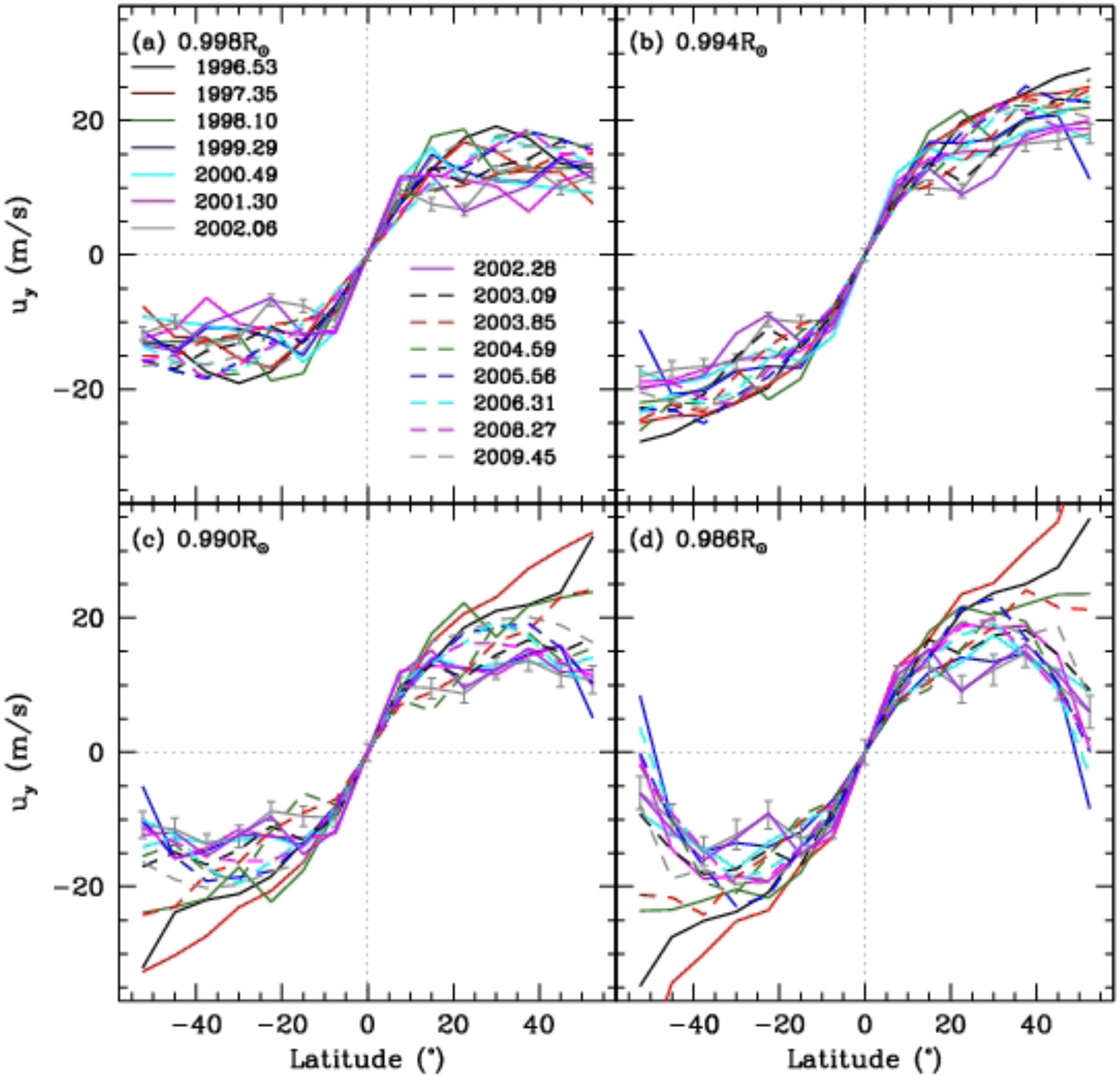




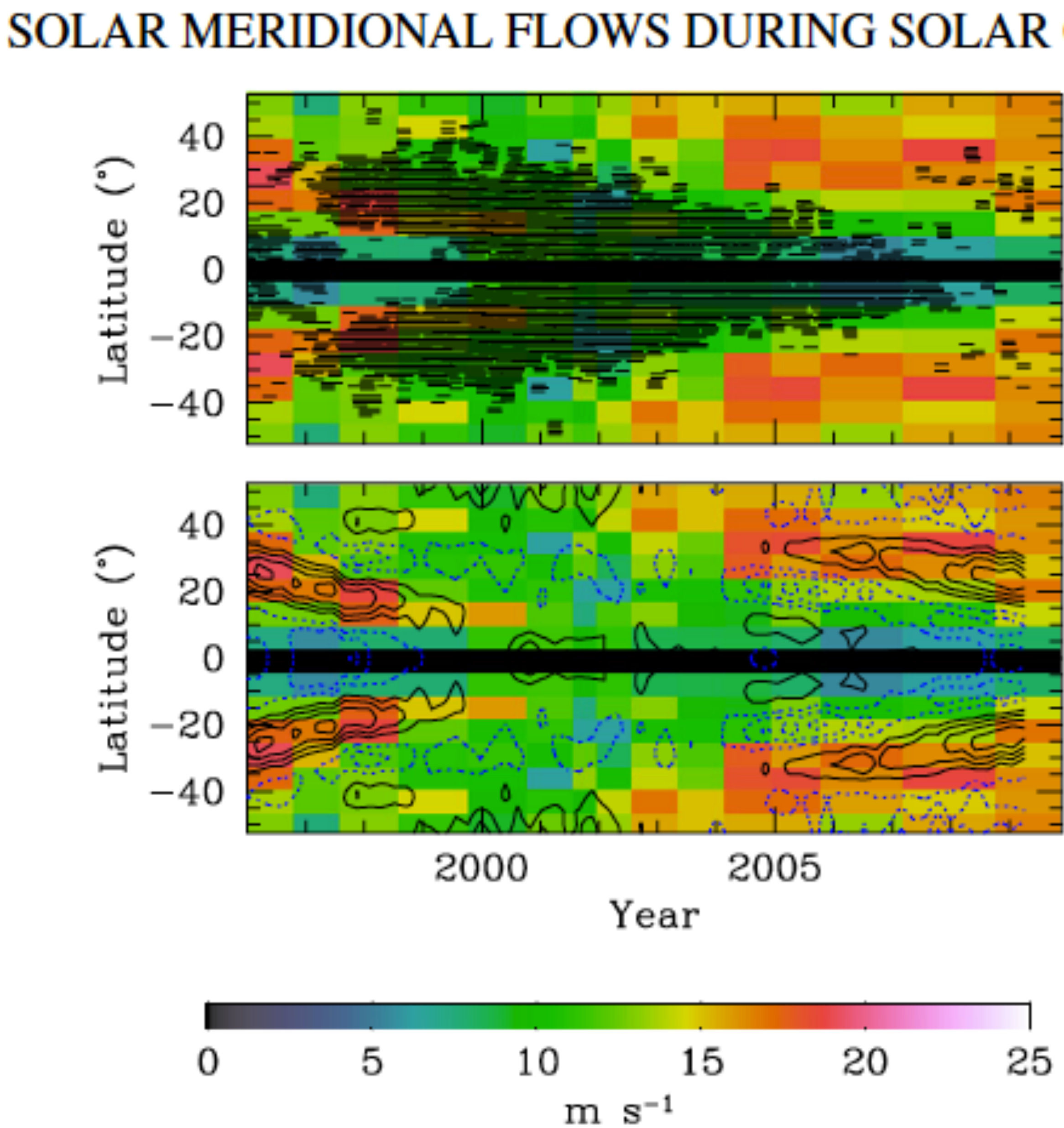


Meridional flow from ring diagram analysis

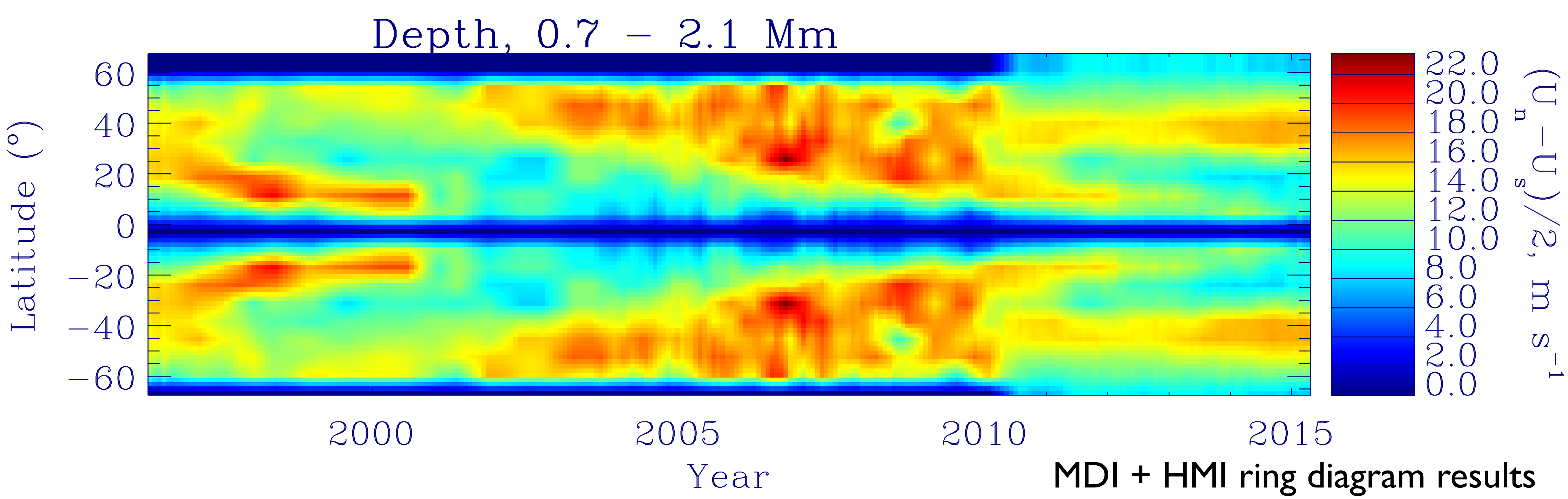
(Basu and Antia 2010)



(Basu and Antia 2010)



Depth, 1.4 Mm

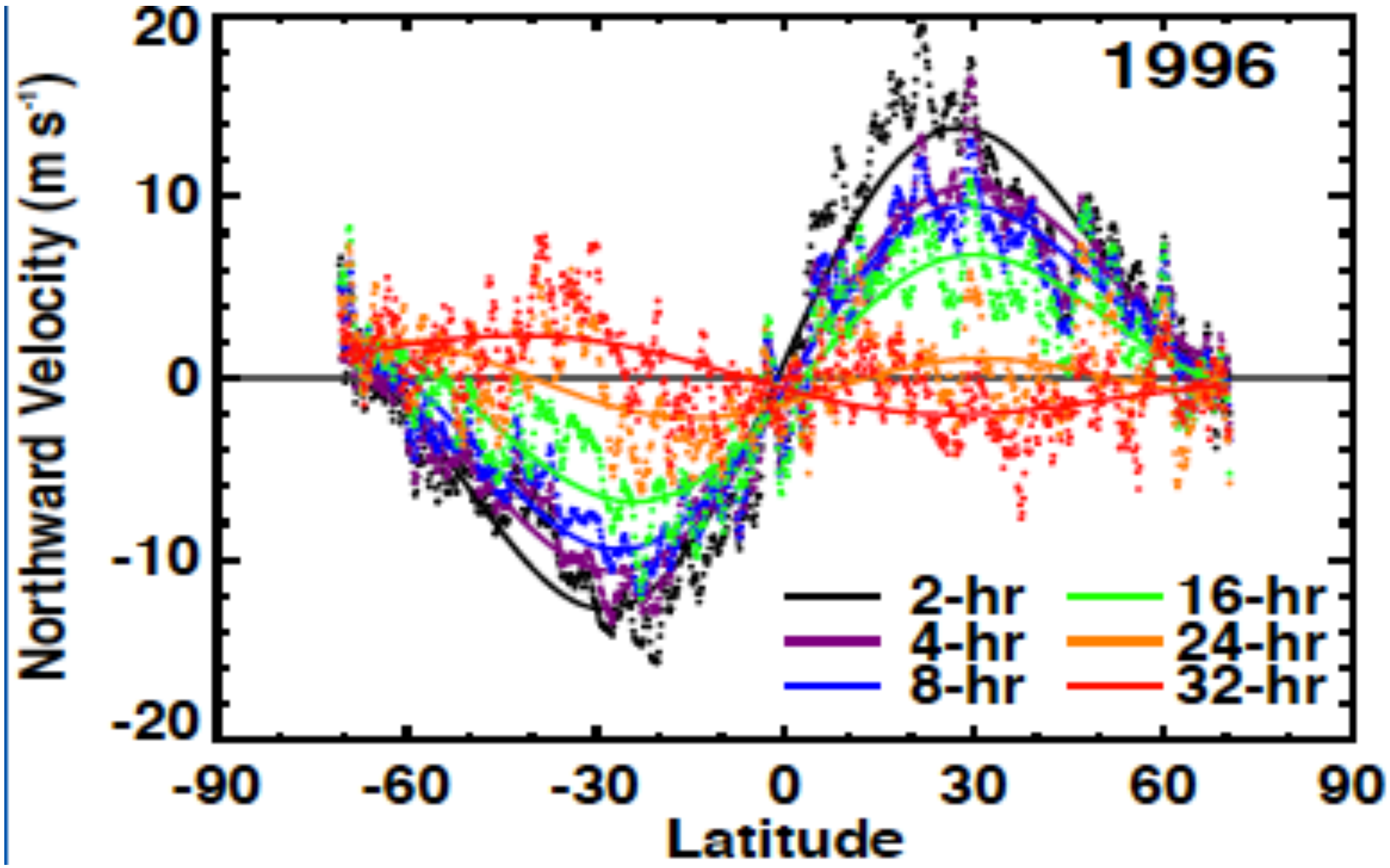


MDI + HMI ring diagram results

(Gilda and Rajaguru, work in progress)

Inferences on meridional circulation from tracking of supergranules

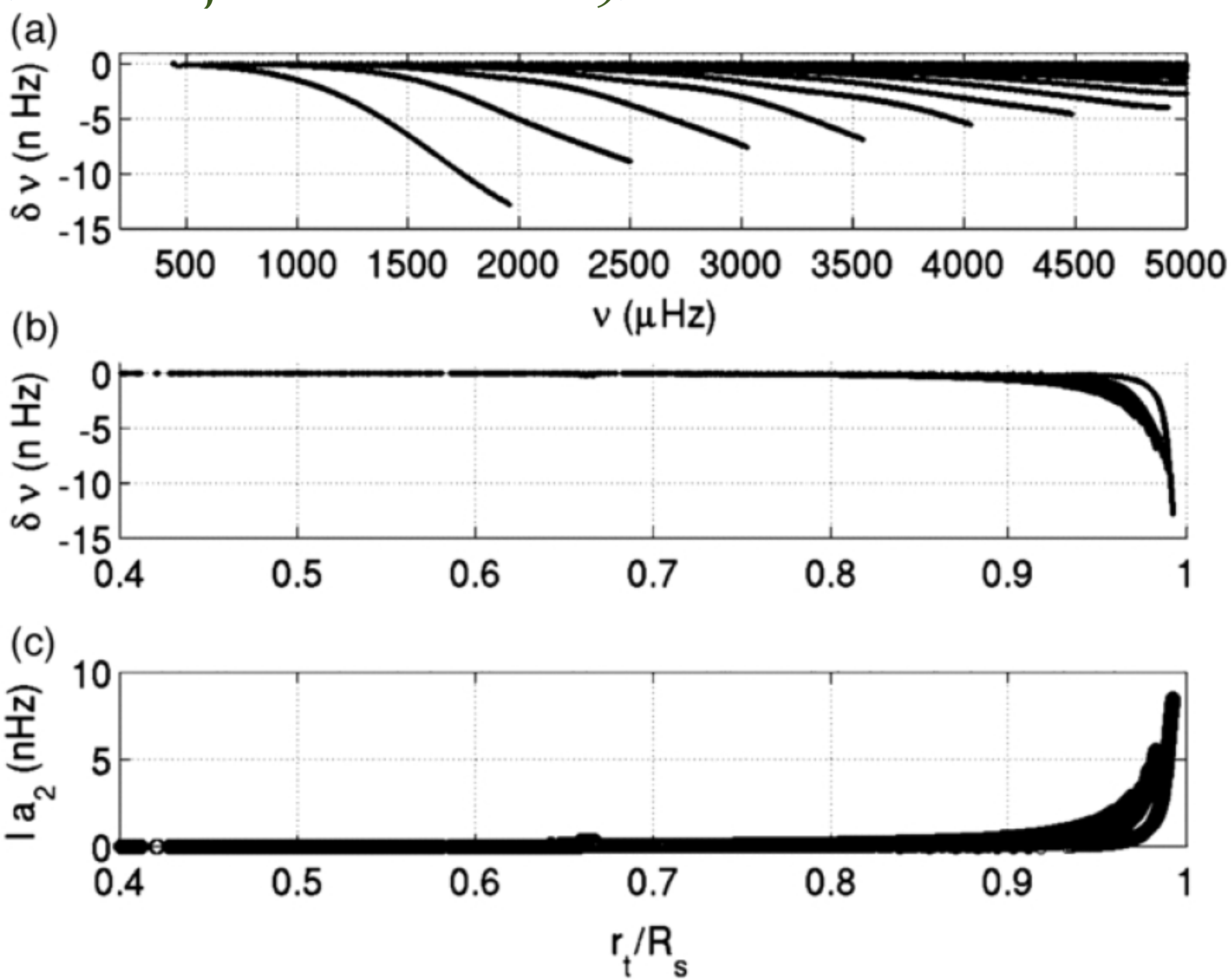
Hathaway 2012



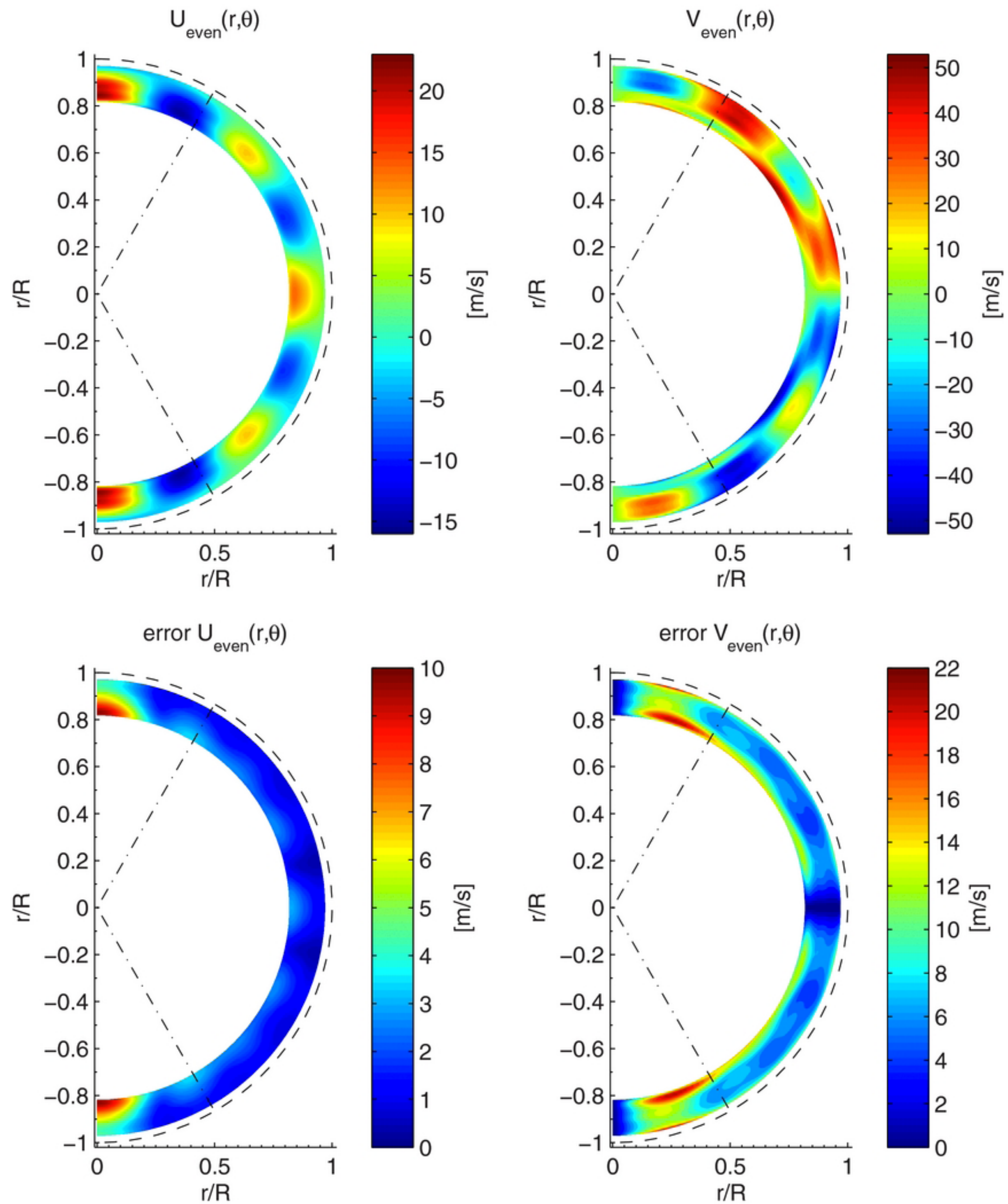
Meridional Flows from Helioseismology

To first order the contribution of meridional flow to frequencies of global modes vanishes and hence these cannot be used to infer meridional flow. Quasi-degenerate perturbation theory can be used to estimate the second order contributions due to mode coupling.

Quasi-degenerate perturbation theory is used to calculate the effect of meridional flow (Chatterjee & Antia 2009)



In general the effect of meridional flow on frequencies is small but for some pair of modes with close frequencies and neighbouring l values the effect could be large because of mode coupling, which also distorts the eigenfunction. Schad et al. (2013) have used this distortion in eigenfunction to infer meridional flows.



Schad et al. (2013)

Why is meridional circulation important?

Astron. Astrophys. 303, L29–L32 (1995)

The solar dynamo with meridional circulation

A.R. Choudhuri[1,2], M. Schüssler[1], and M. Dikpati[2,3]

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[2] Department of Physics, Indian Institute of Science, Bangalore - 560012, India
[3] Indian Institute of Astrophysics, Bangalore - 560034, India

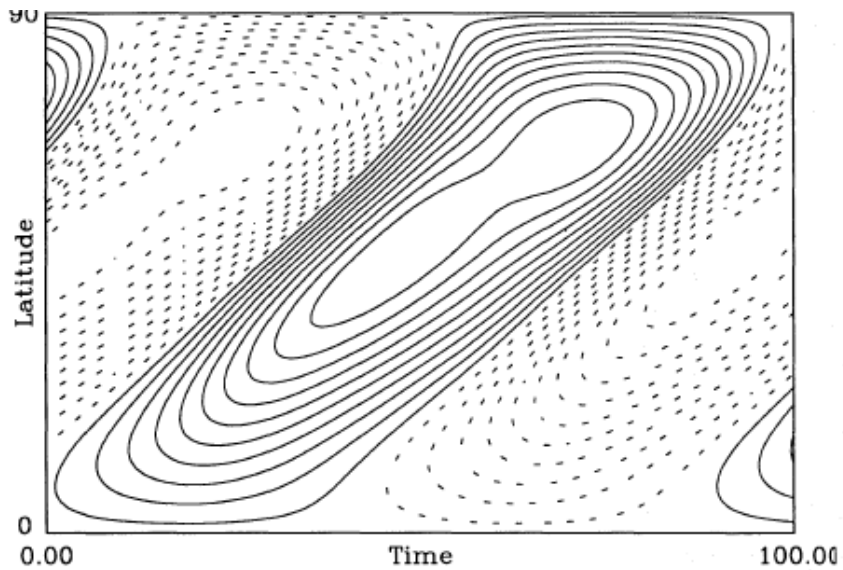


Fig. 1. Butterfly diagram for the toroidal field, taken near the bottom of the convection zone. Meridional circulation is switched off. Time is given in units of $t_0 \simeq 3.5$ years.

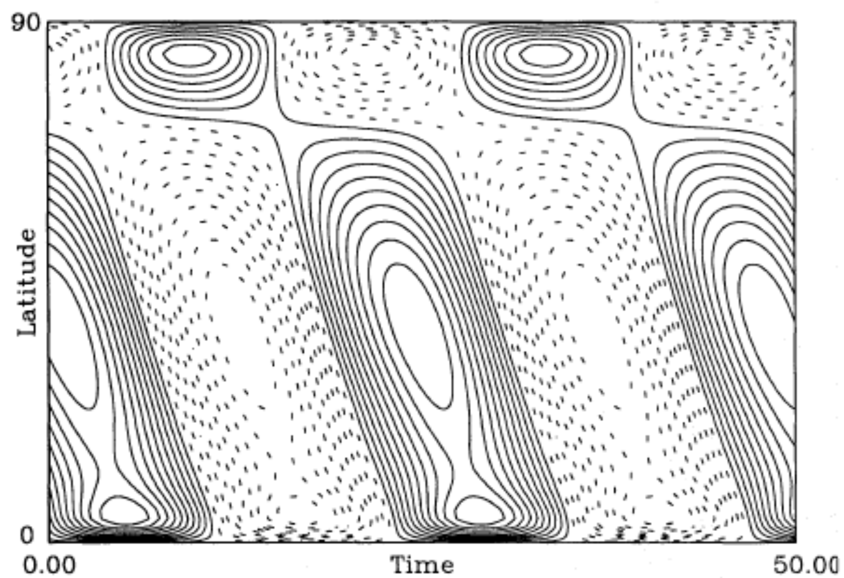
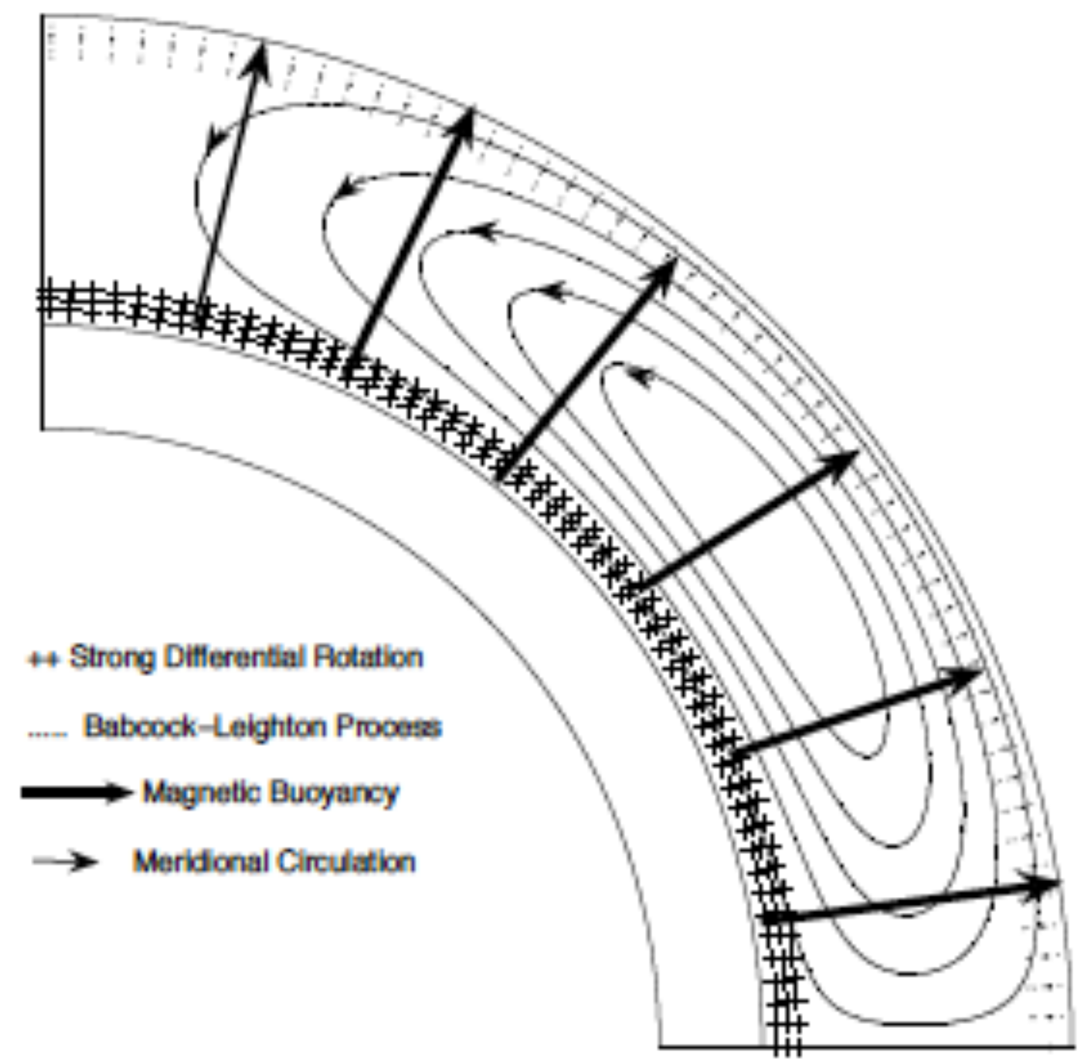


Fig. 2. Same as Fig. 1, but for the case with meridional circulation ($v_0 = 7\ \mathrm{m \cdot s^{-1}}$). The dynamo waves now propagate equatorward and the period has decreased (note the different time interval).

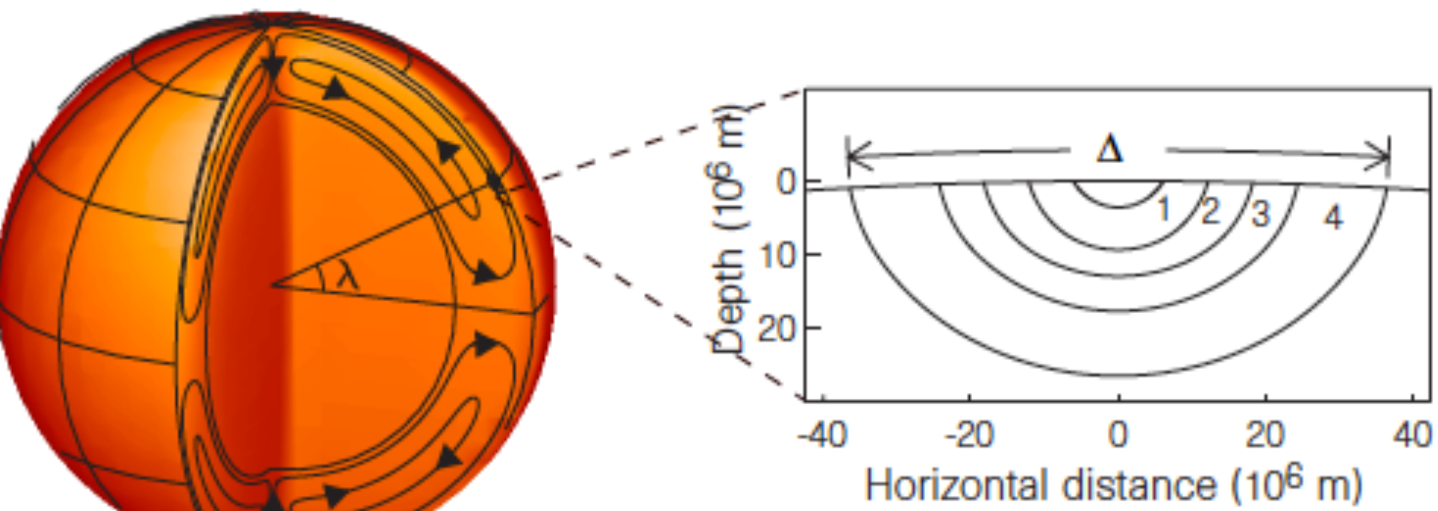
Flux Transport Dynamos

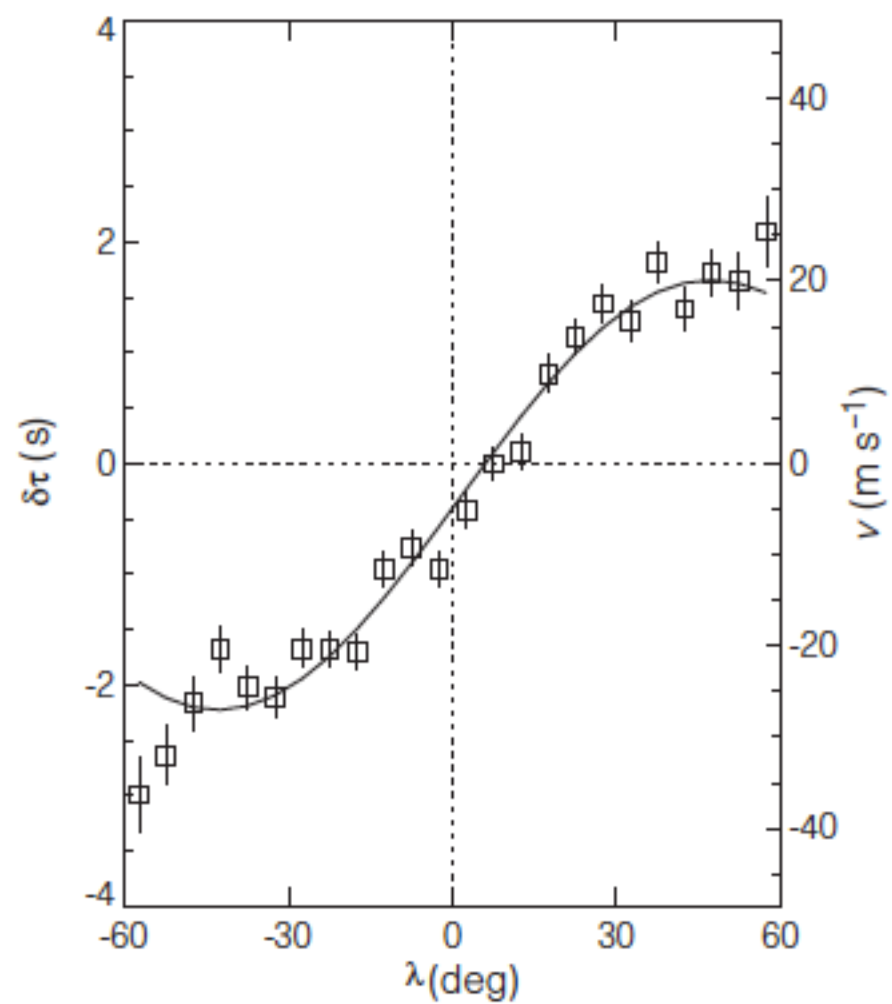


Cartoon by A.R. Choudhuri (2014)

Time-distance helioseismic measurements of meridional flow

Early measurements by Giles, Duvall et al. 1997, Nature, using MDI/SOHO data





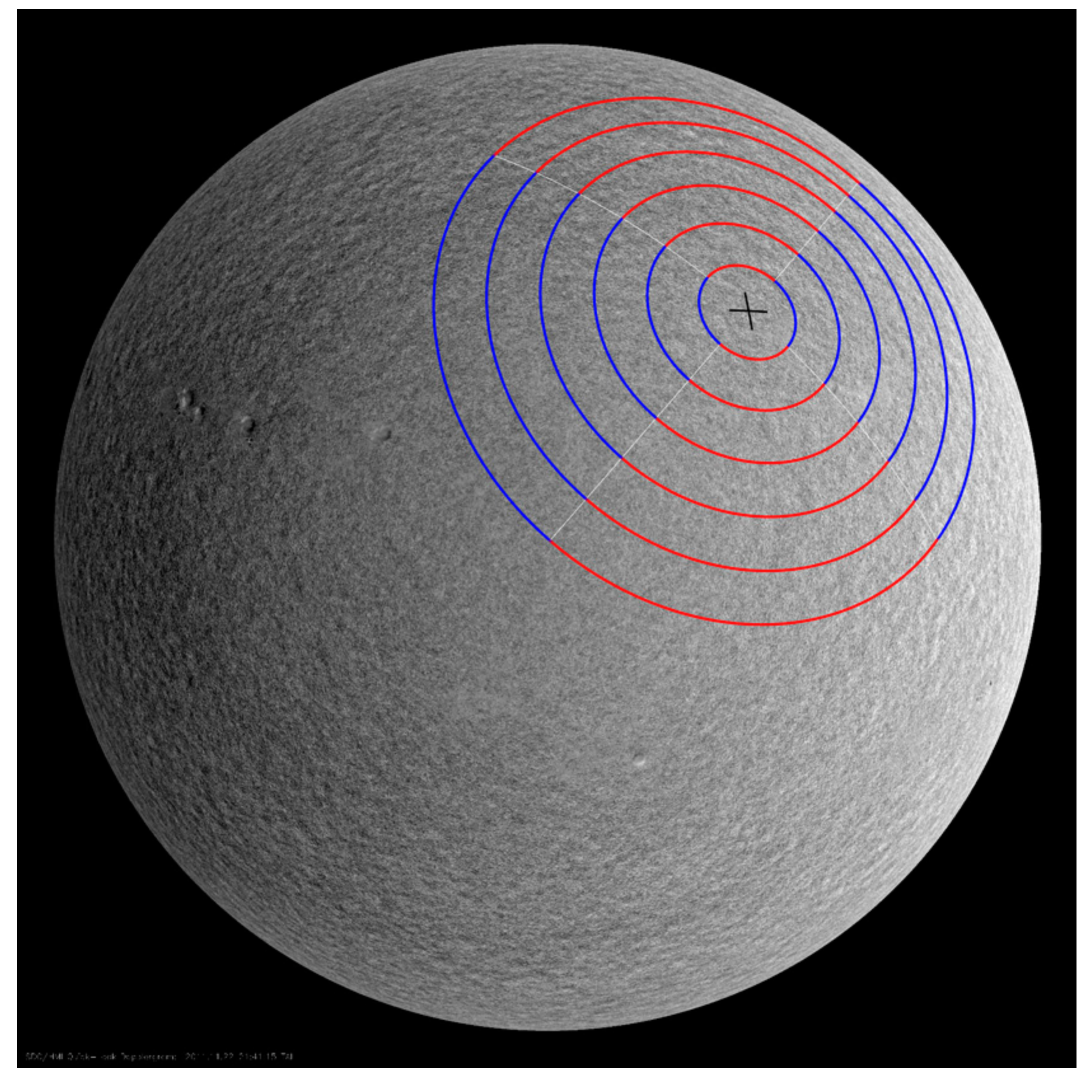


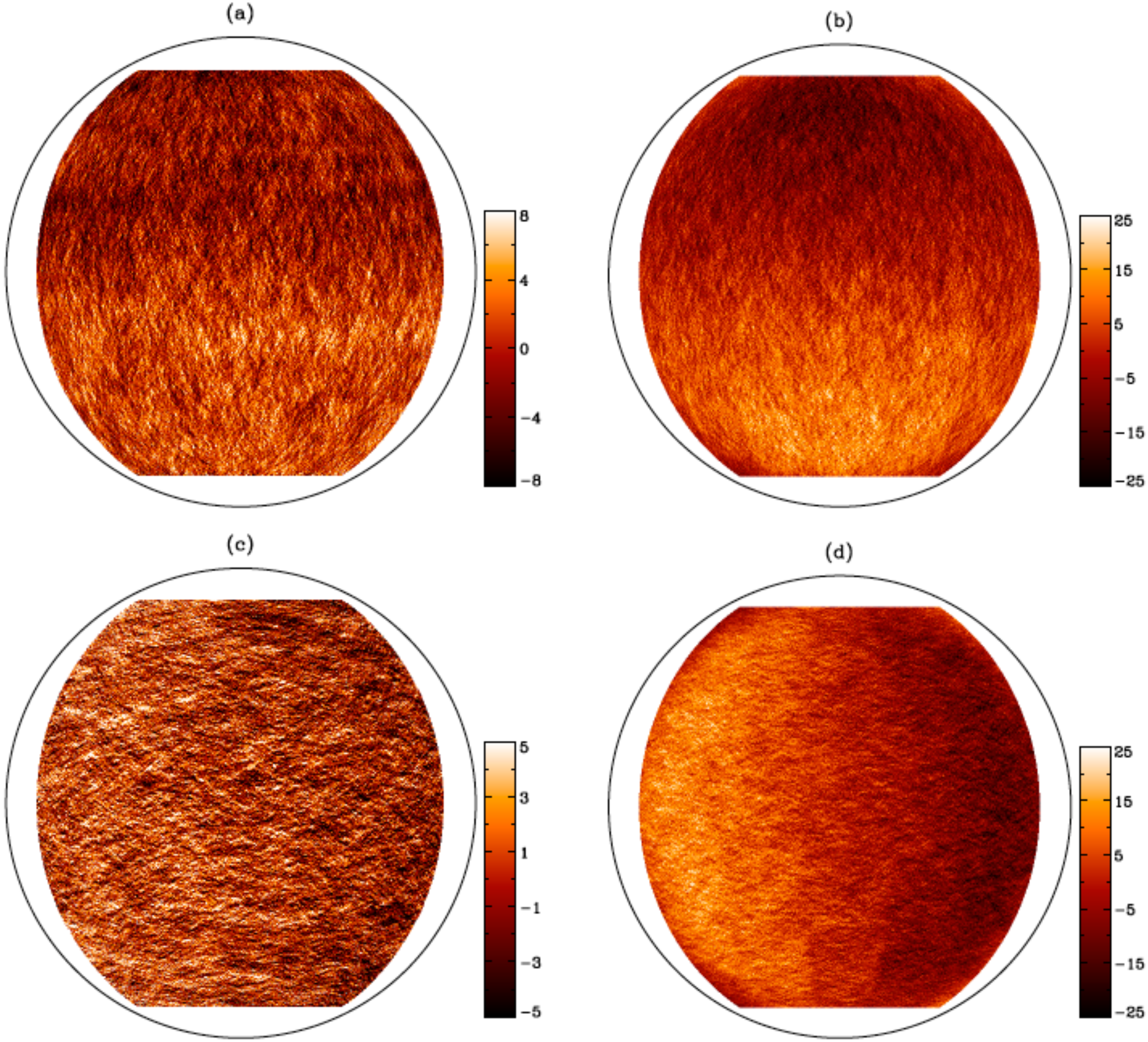
Figure Credit: Hanasoge et al. 2011

Center-to-limb Systematics in Helioseismic Travel Times

-- Zhao et al. 2012, ApJ

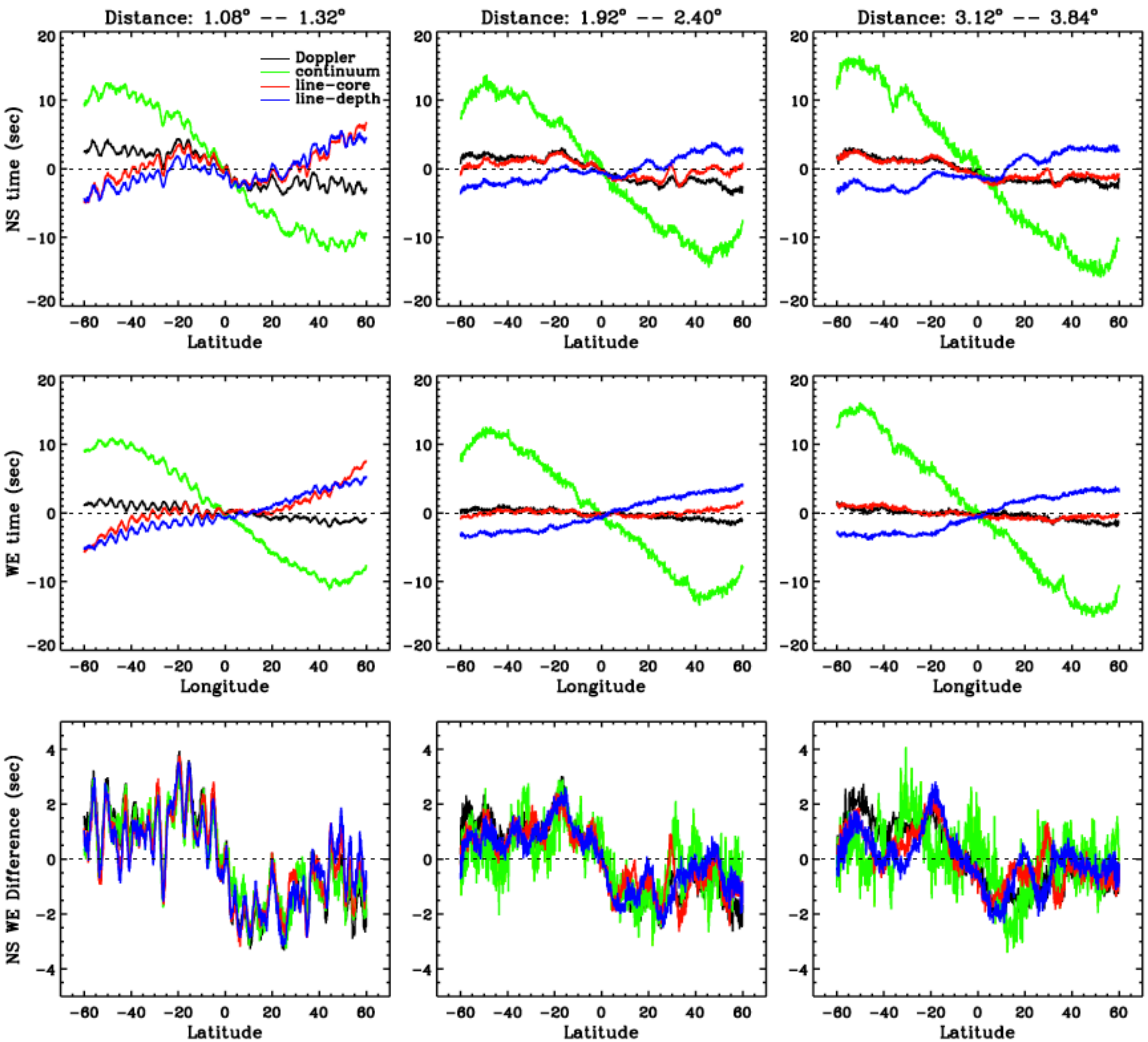
from HMI Doppler Velocities

from HMI continuum intensities



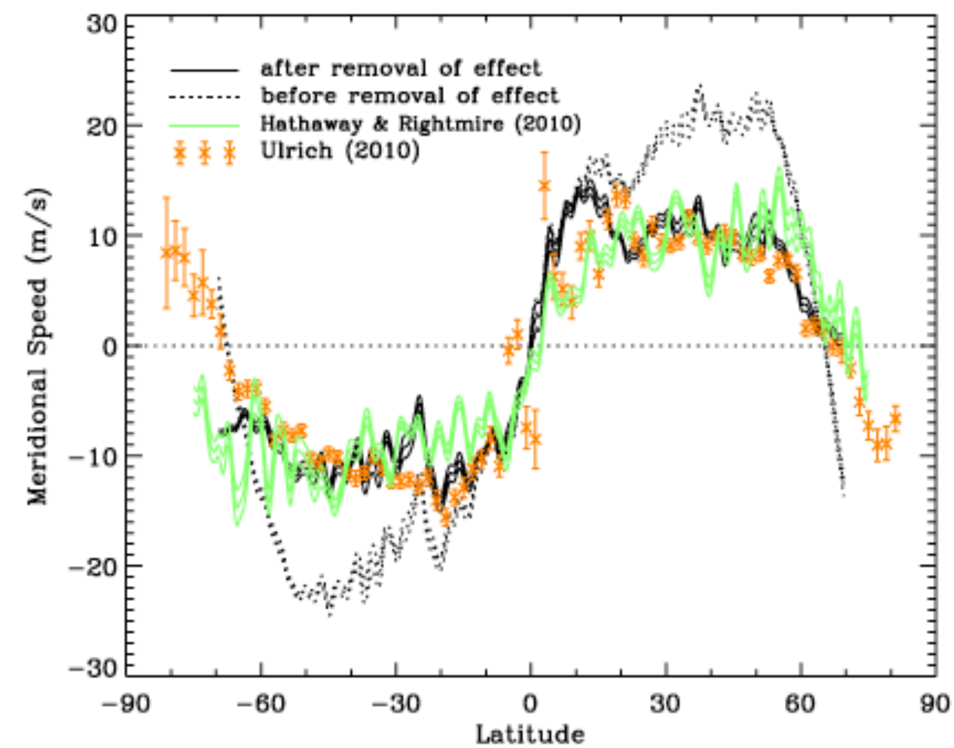
Center-to-limb Systematics in Helioseismic Travel Times

-- Zhao et al. 2012, ApJ

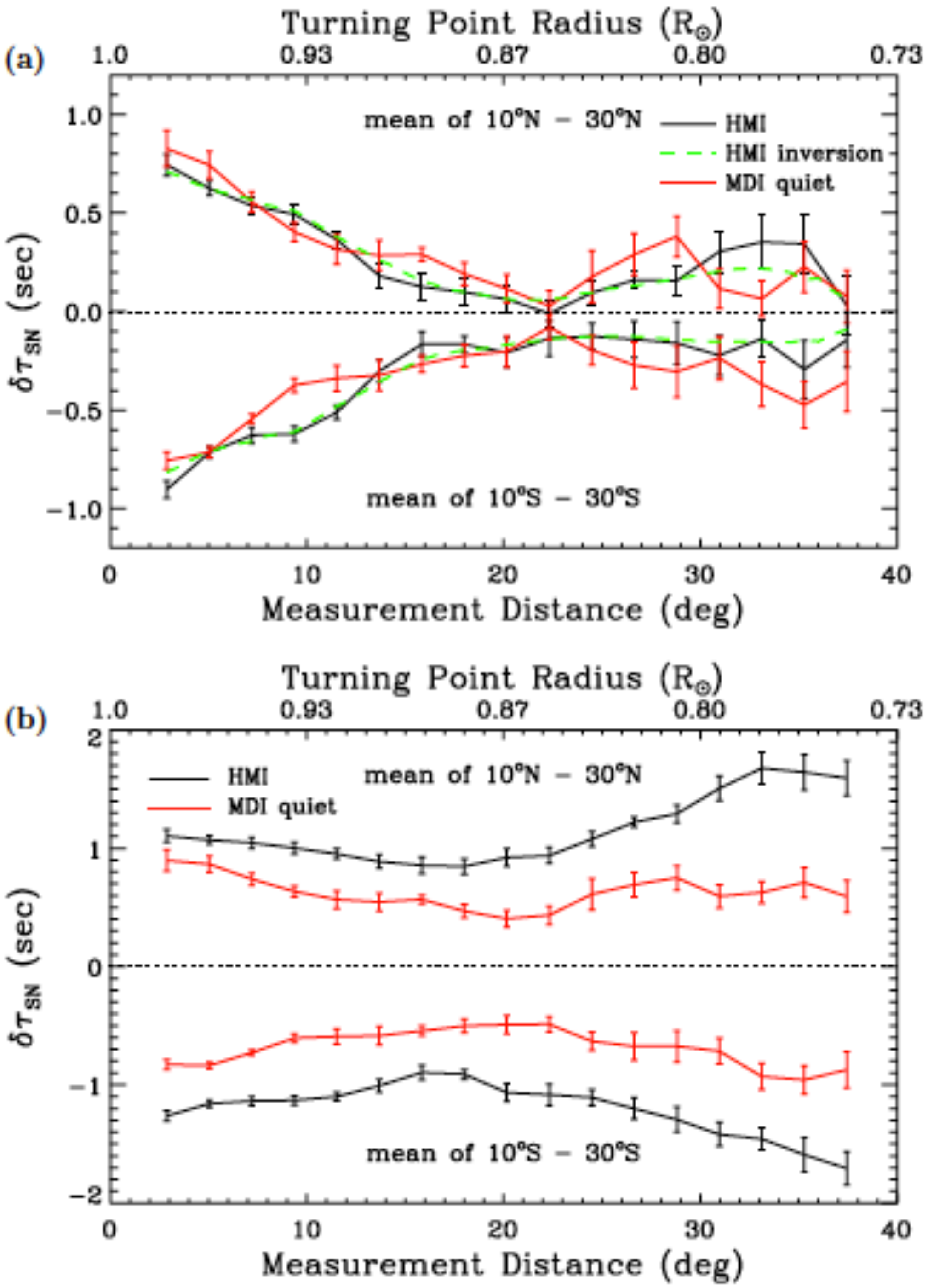


igure 2. Top: averaged curves of latitude-dependent τ_{ns}, obtained from different HMI observables and for different measurement distances. Middle: averaged curves f longitude-dependent τ_{we}, obtained from different observables and for different measurement distances. Bottom: differences of τ_{ns} and τ_{we}. Note that the vertical cales for the upper two rows are different from those for the bottom row.

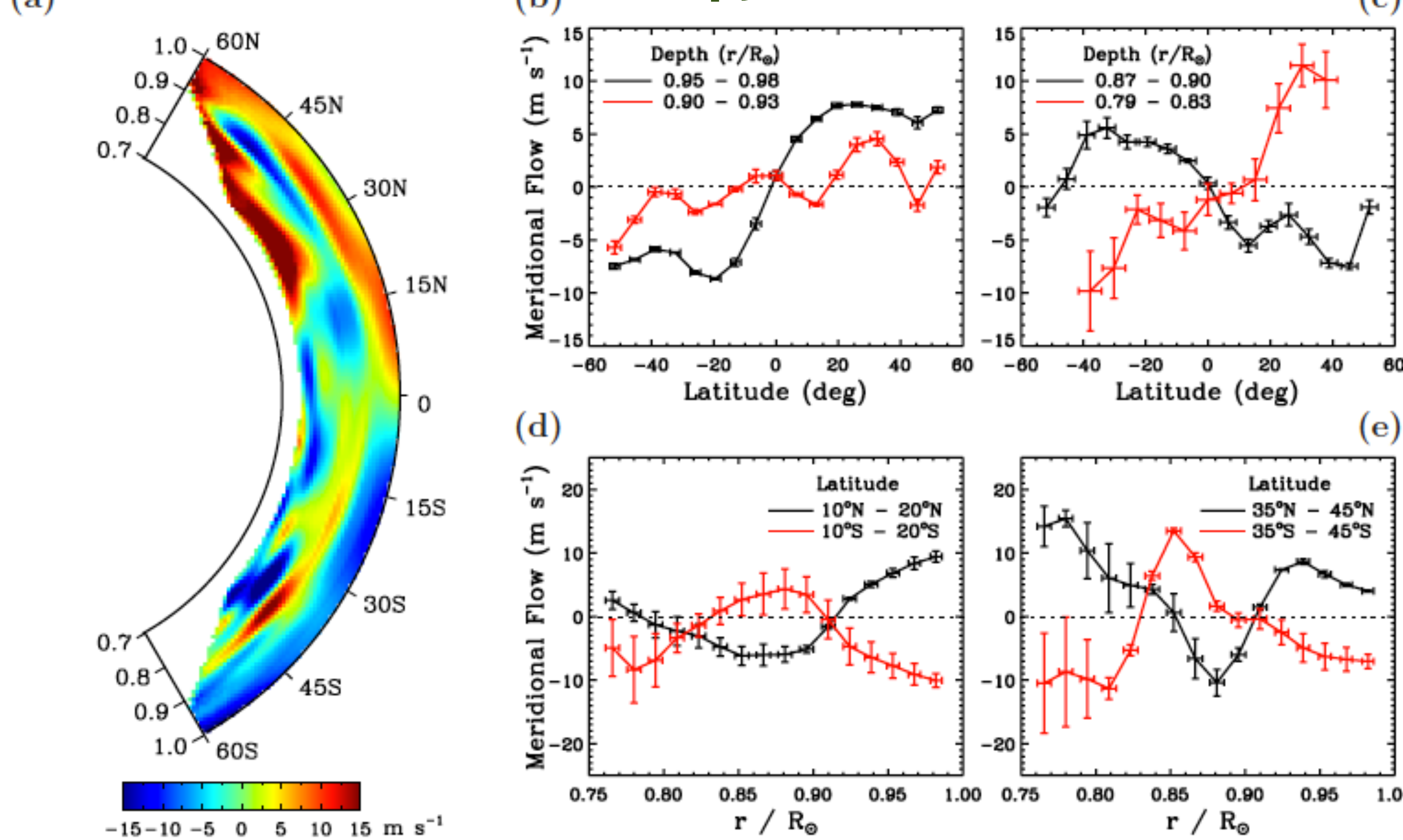
A color version of this figure is available in the online journal.)

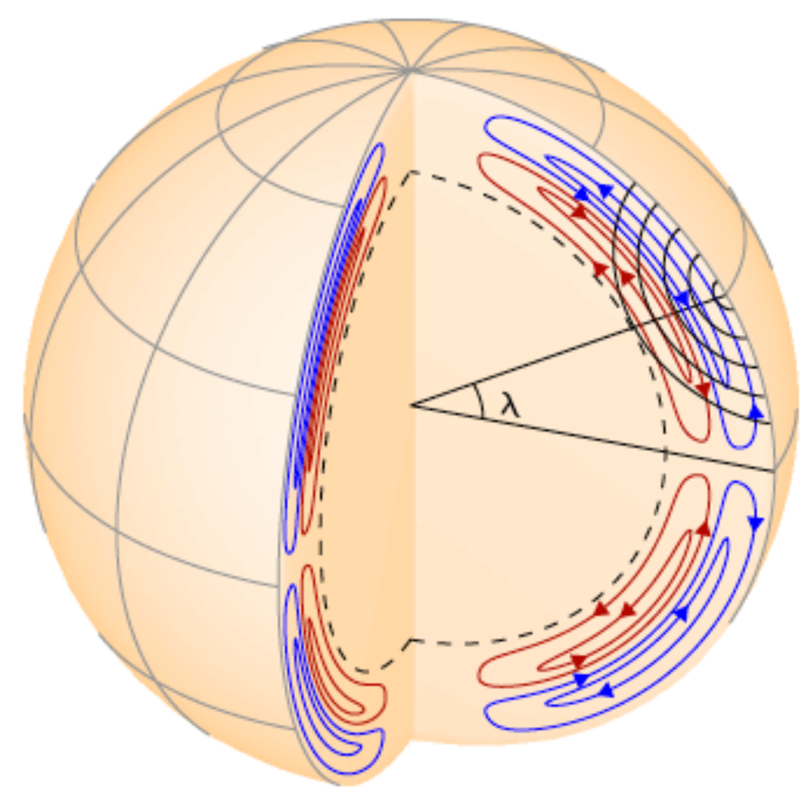


Shallow return-flow and double-cell signature after removing CTL systematics.

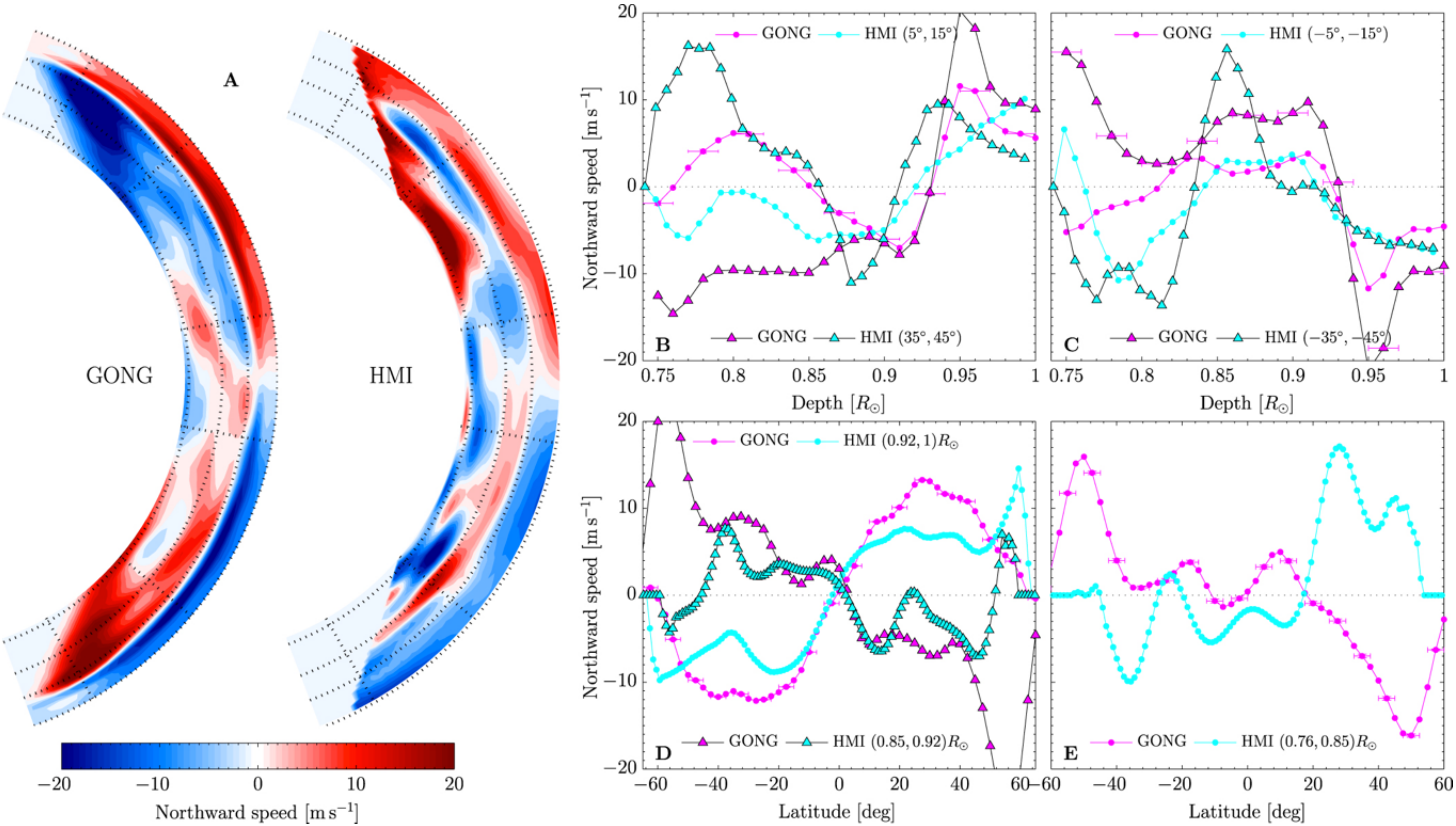


Zhao et al. 2013, ApJL.



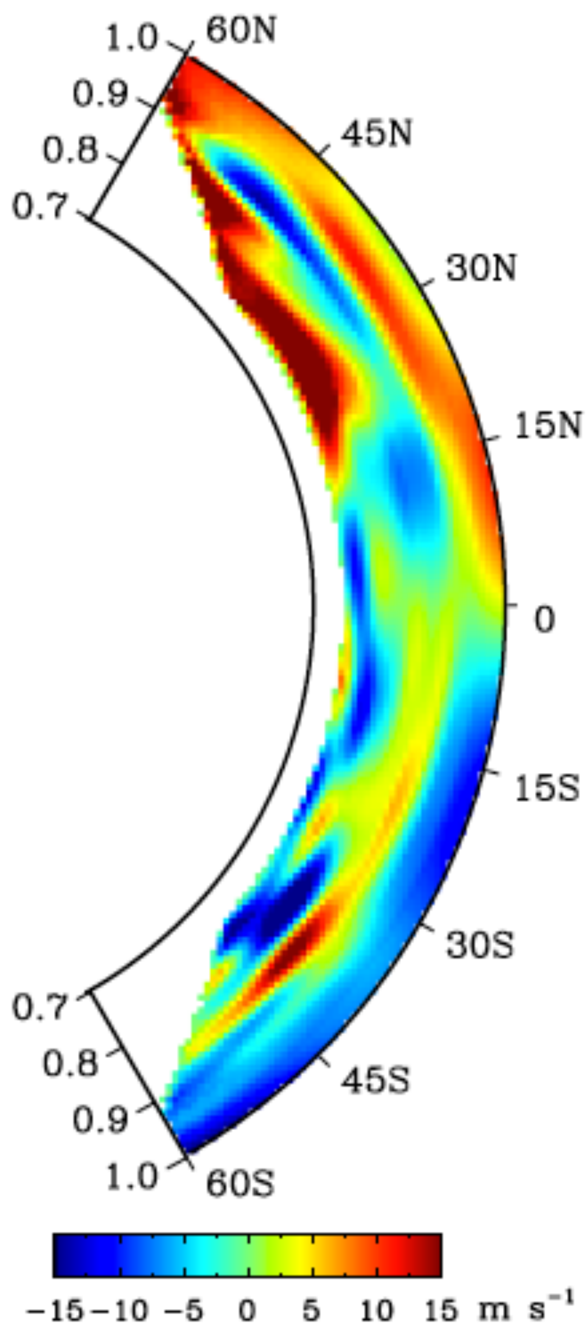


Jackiewicz et al. (2015)

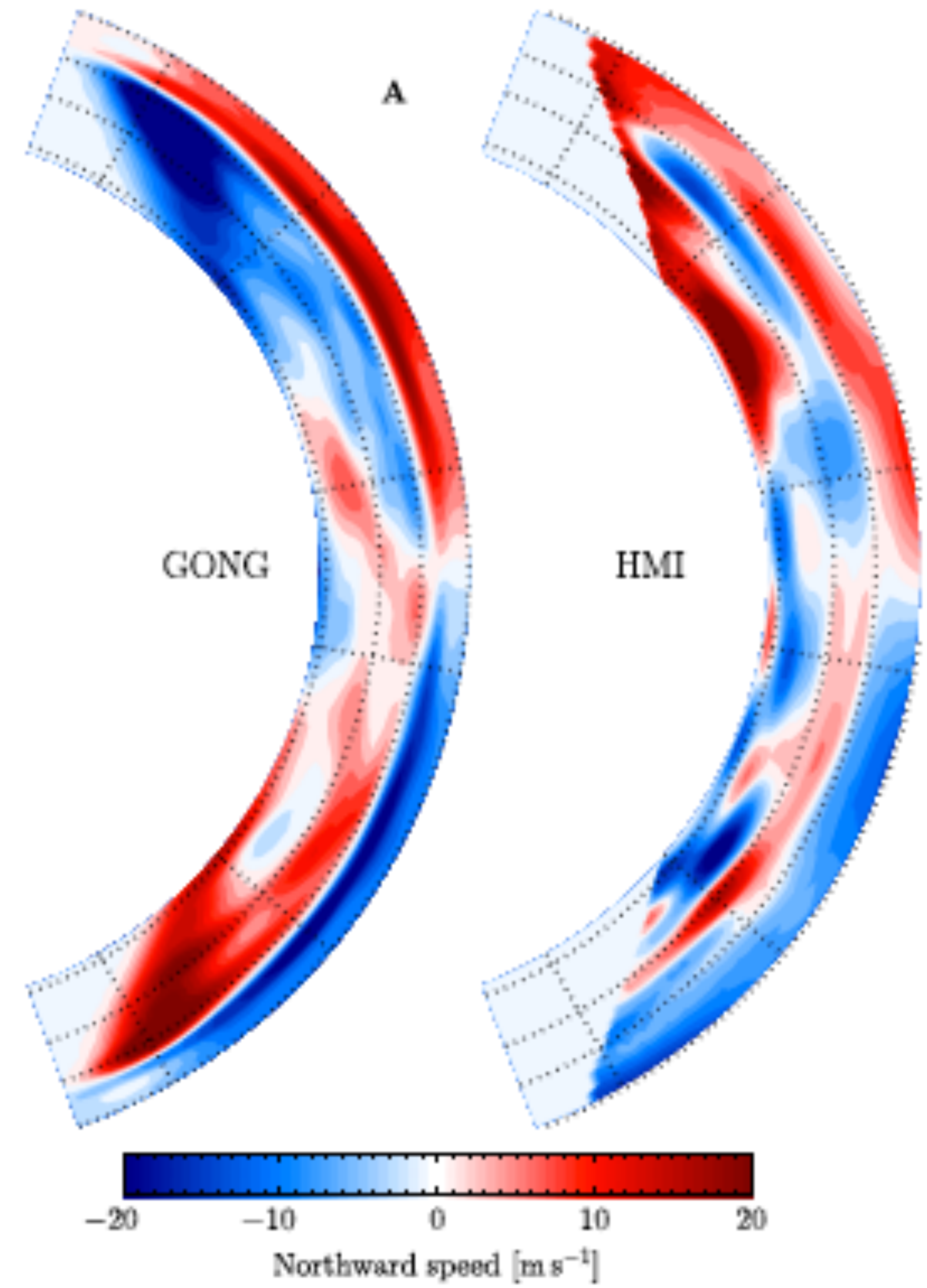


Meridional circulation without mass-conservation constraint in the inversions.

Zhao et al. 2013



Jackiewicz et al. 2015



How do flux transport dynamos work in multi-cellular MC?

The Astrophysical Journal, 782:93 (12pp), 2014 February 20 doi:10.1088/0004-63

IS A DEEP ONE-CELL MERIDIONAL CIRCULATION ESSENTIAL FOR THE FLUX TRANSPORT SOLAR DYNAMO?

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The Astrophysical Journal, 776:36 (9pp), 2013 October 10 doi:10.1088/0004-637X/776/1/36

THE MEAN-FIELD SOLAR DYNAMO WITH A DOUBLE CELL MERIDIONAL CIRCULATION PATTERN

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Received 2013 May 21; accepted 2013 August 10; published 2013 September 24

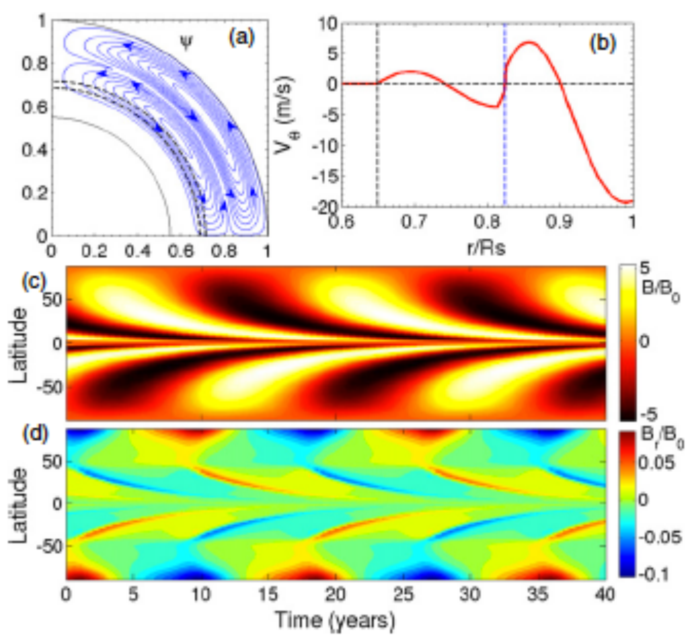


Figure 2. (a) Streamlines for two radially stacked cells of meridional circulation. Arrows show the direction of the flow. (b), (c), and (d) are the same plots as in Figure 1 for this meridional circulation.

(A color version of this figure is available in the online journal.)

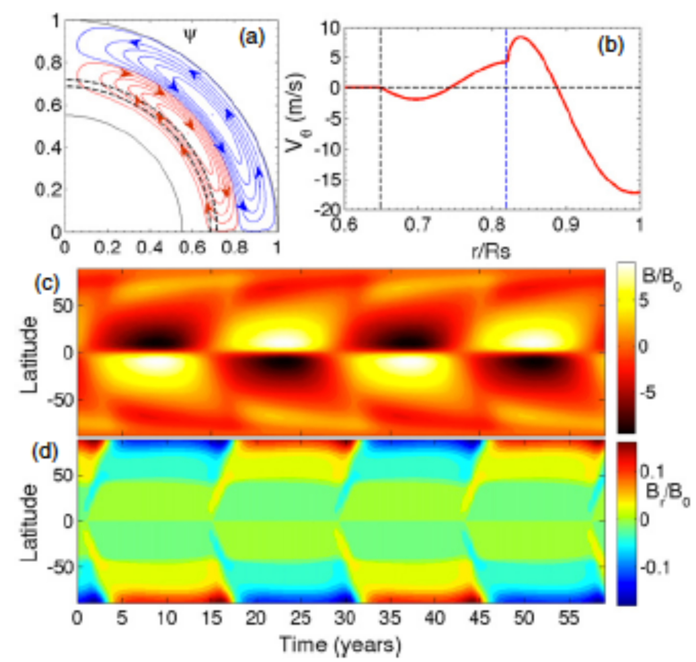


Figure 3. (a) Streamlines for two radially stacked cells of meridional circulation with circulations in the opposite sense. Arrows show the direction of the flow. (b), (c), and (d) are the same plots as in Figure 1 for this meridional circulation.

(A color version of this figure is available in the online journal.)

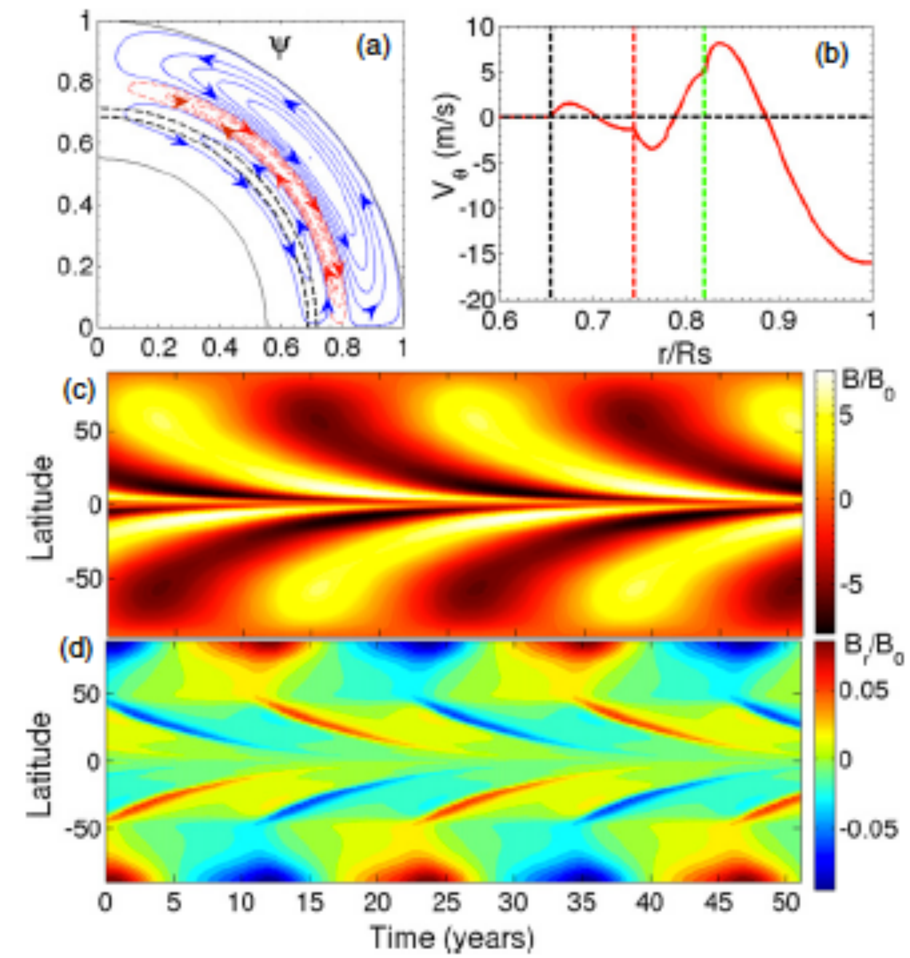
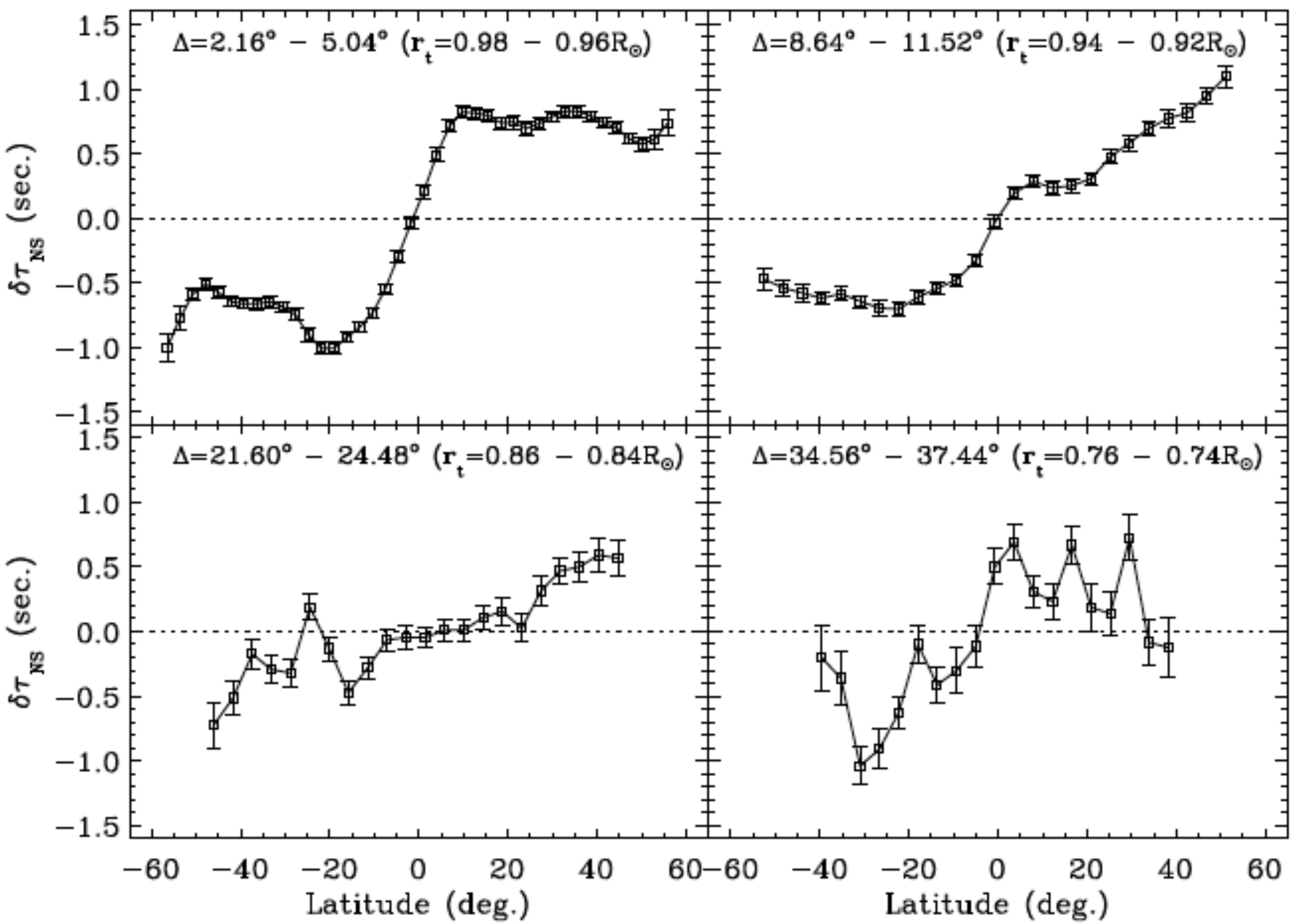
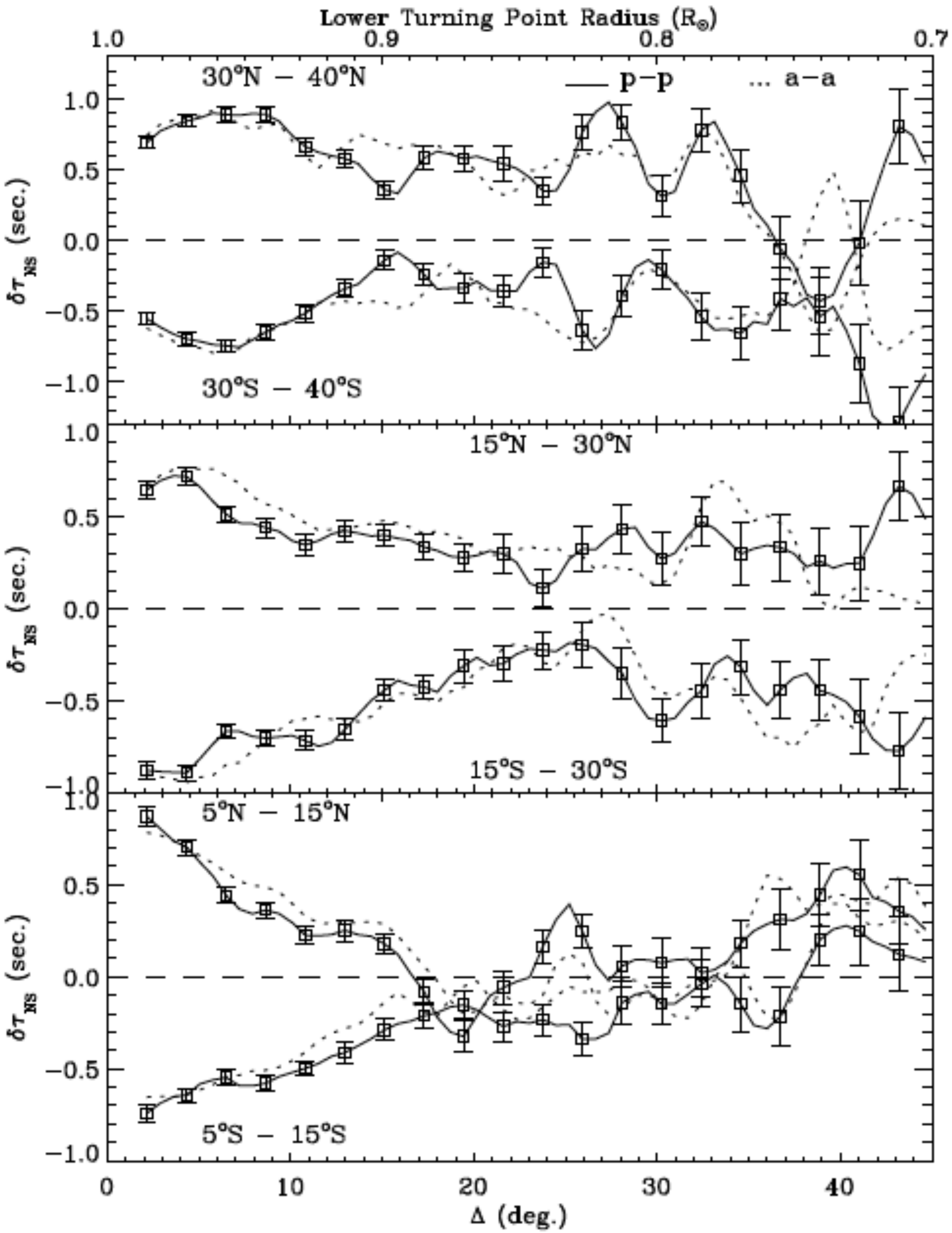


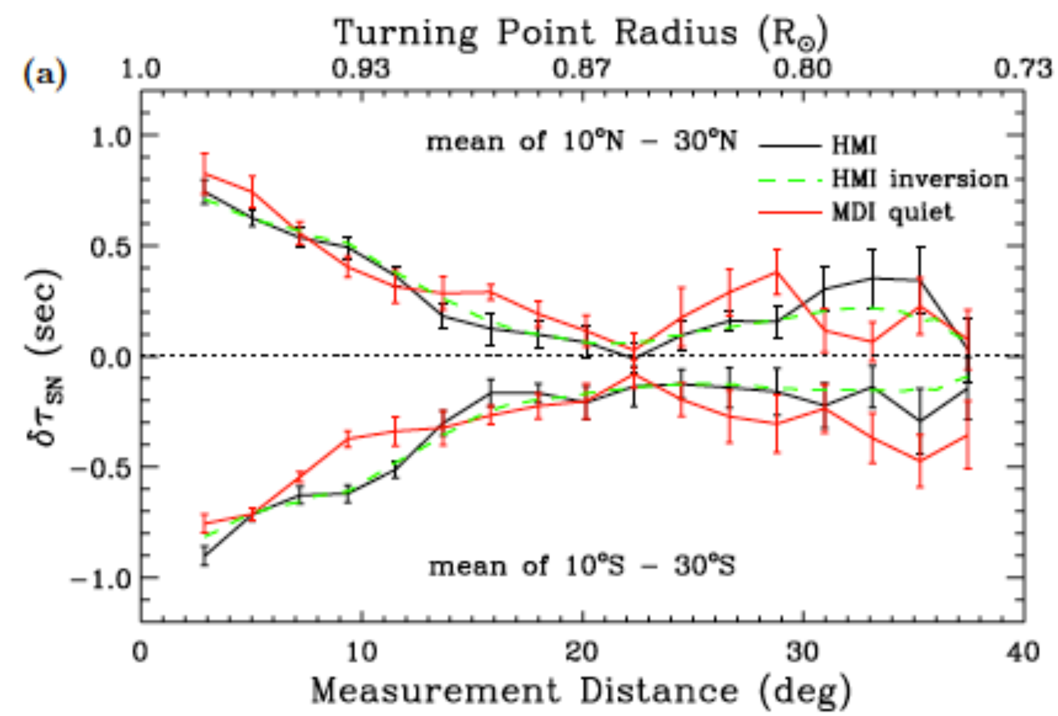
Figure 4. (a) Streamlines for three radially stacked cells of meridional circulation. Directions are shown by arrows. (b), (c), and (d) are the same plots as in Figure 1 for this meridional circulation.

Travel-time differences from 4 years of HMI data

Rajaguru and Antia (2015 ApJ)




Lower Turning Point Radius (R⊙)
1.0
0.9
0.8
0.7
30°N − 40°N
p−p
a−a
30°S − 40°S
15°N − 30°N
15°S − 30°S
5°N − 15°N
5°S − 15°S
δτNS (sec.)
Δ (deg.)


(a)
Turning Point Radius (R⊙)
1.0
0.93
0.87
0.80
0.73
mean of 10°N − 30°N
HMI
HMI inversion
MDI quiet
mean of 10°S − 30°S
δτSN (sec)
Measurement Distance (deg)

Meridional flows with mass-conservation constraints in the inversions of travel times

$$\delta\tau = -2\int_{\Gamma_0} \frac{\mathbf{u}\cdot\hat{\mathbf{n}}}{c^2}\, ds, \qquad (1)$$

The solutions here are obtained by fitting stream functions satisfying mass conservation while inverting the travel times.

$$\rho u_r = \frac{1}{r}\frac{\partial\psi}{\partial\theta} + \frac{\cos\theta}{r\sin\theta}\psi,$$
$$\rho u_\theta = -\frac{\partial\psi}{\partial r} - \frac{\psi}{r},$$

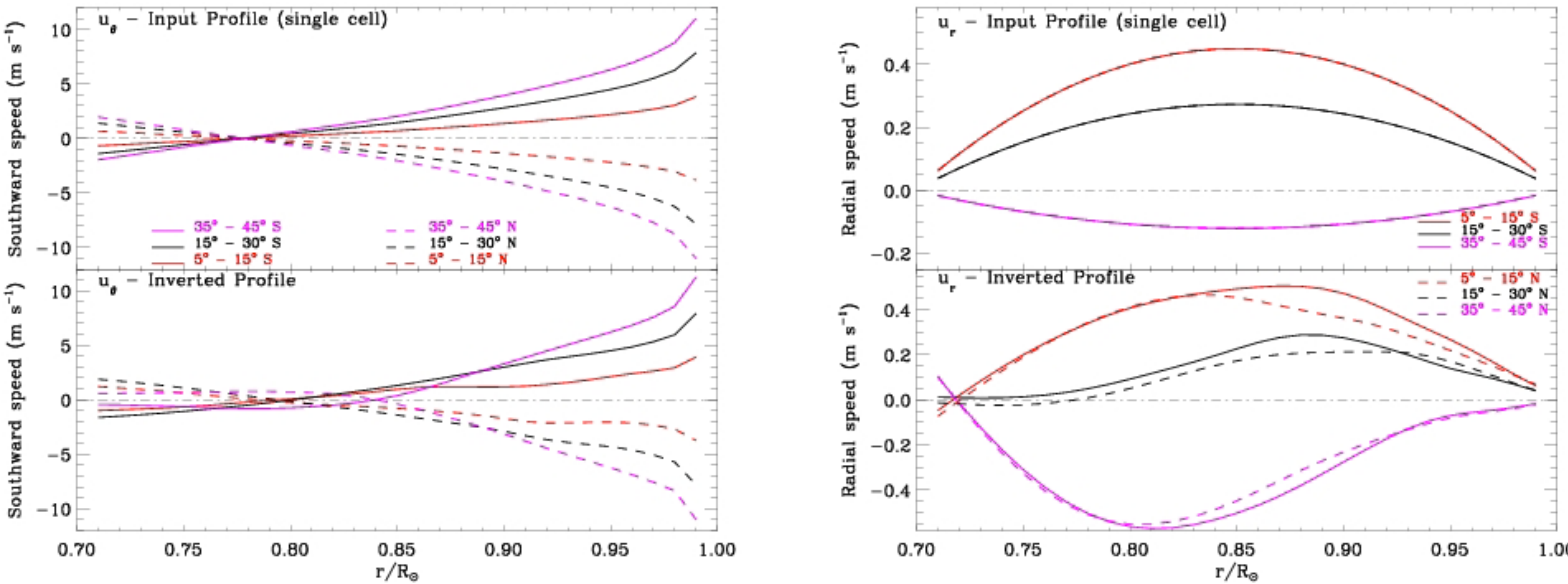
$$\psi'(r,\theta) = \sum_i \sum_j a_{ij}\Phi_i^r(r)\Phi_j^\theta(\theta), \qquad \psi' = \psi/\rho$$

where $\Phi_i^r(r)$ are the cubic B-spline basis covering $0.7R_\odot \le r \le R_\odot$ and $\Phi_j^\theta(\theta)$ are the cubic B-spline basis covering $|\theta - \pi/2| \le 1.055$. We use 38 knots in r which are uniformly spaced in acoustic depth and 31 knots in θ which are uniformly spaced in θ to define the B-spline

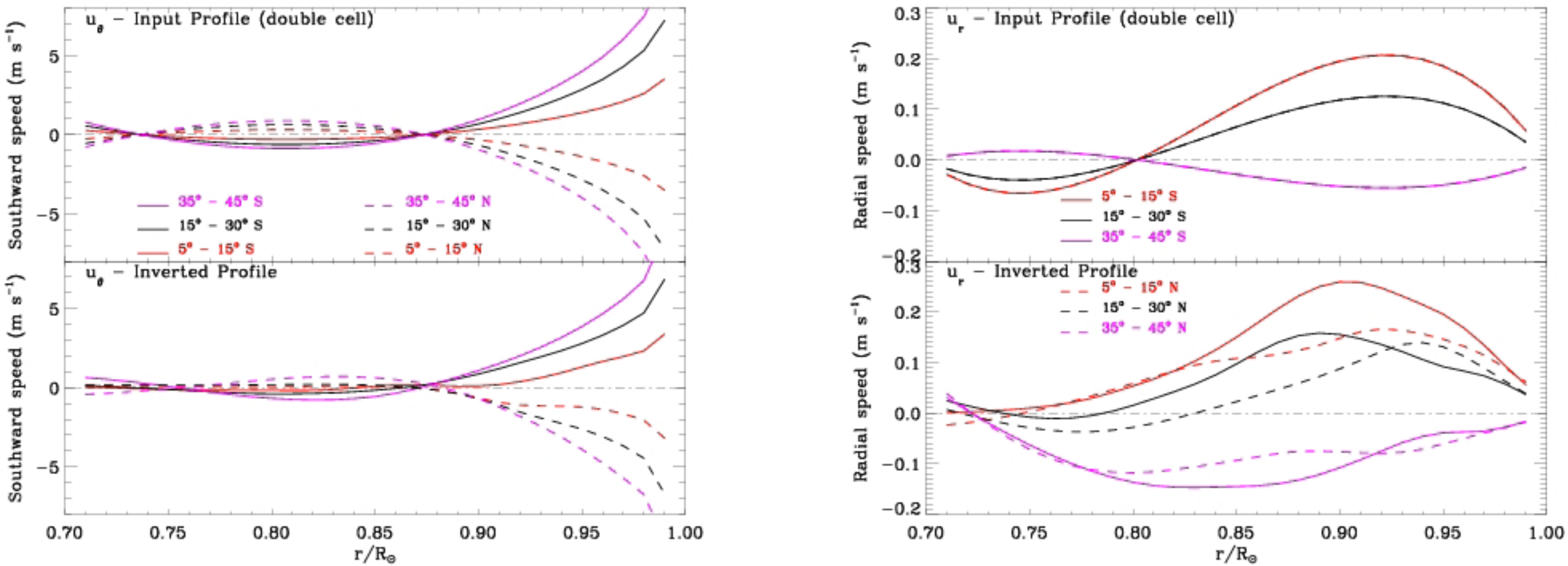
The coefficients a_{ij} determined using RLS with second derivative smoothing in both r and θ by minimizing

$$\sum_i \left(\frac{d_i}{\sigma_i}\right)^2 + \lambda_r^2 \sum \left(\frac{\partial^2\psi'}{\partial r^2}\right)^2 + \lambda_\theta^2 \sum \left(\frac{\partial^2\psi'}{\partial\theta^2}\right)^2$$

d_i are the residuals in the fit to eqn.(1) and σ_i are the corresponding errors in the travel-time differences. λ_r and λ_θ are the two smoothing parameters.

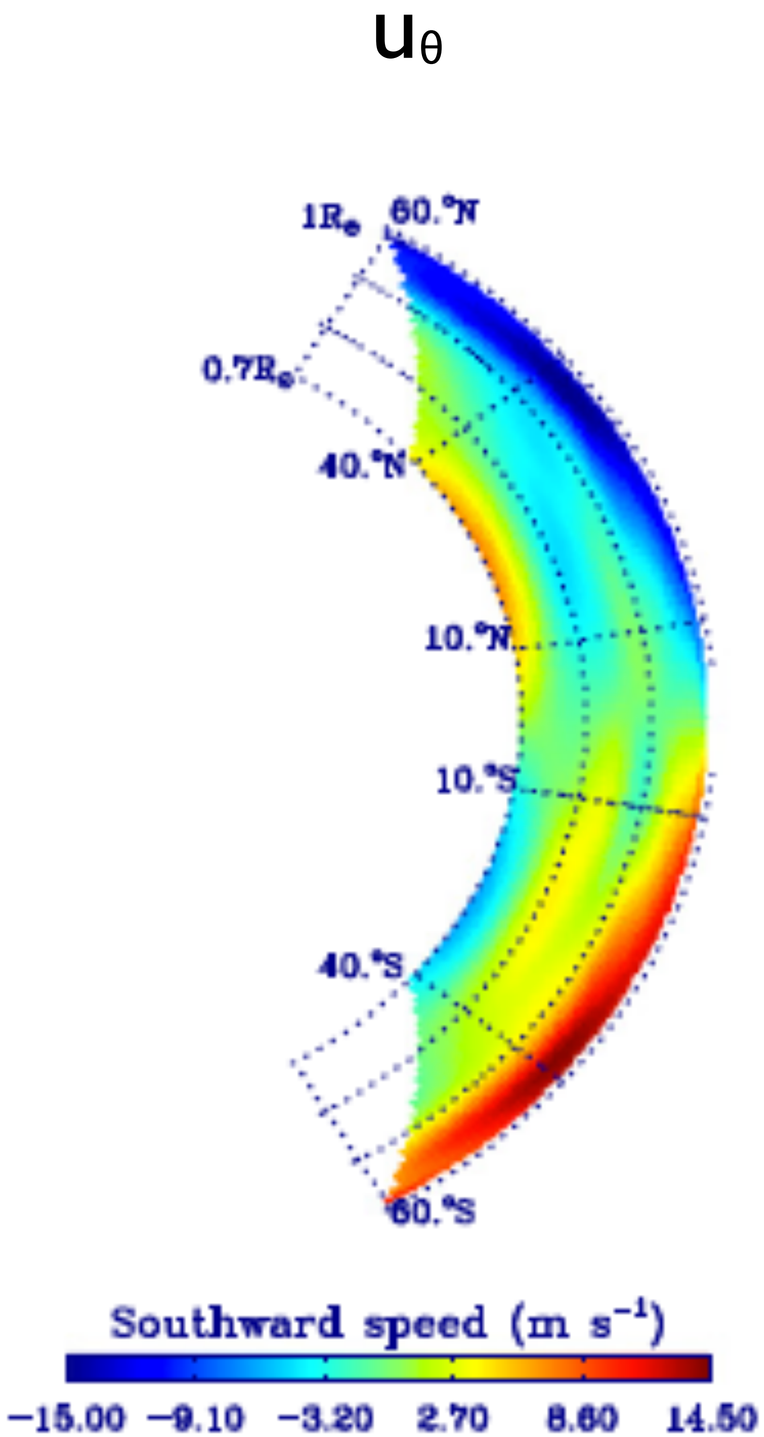


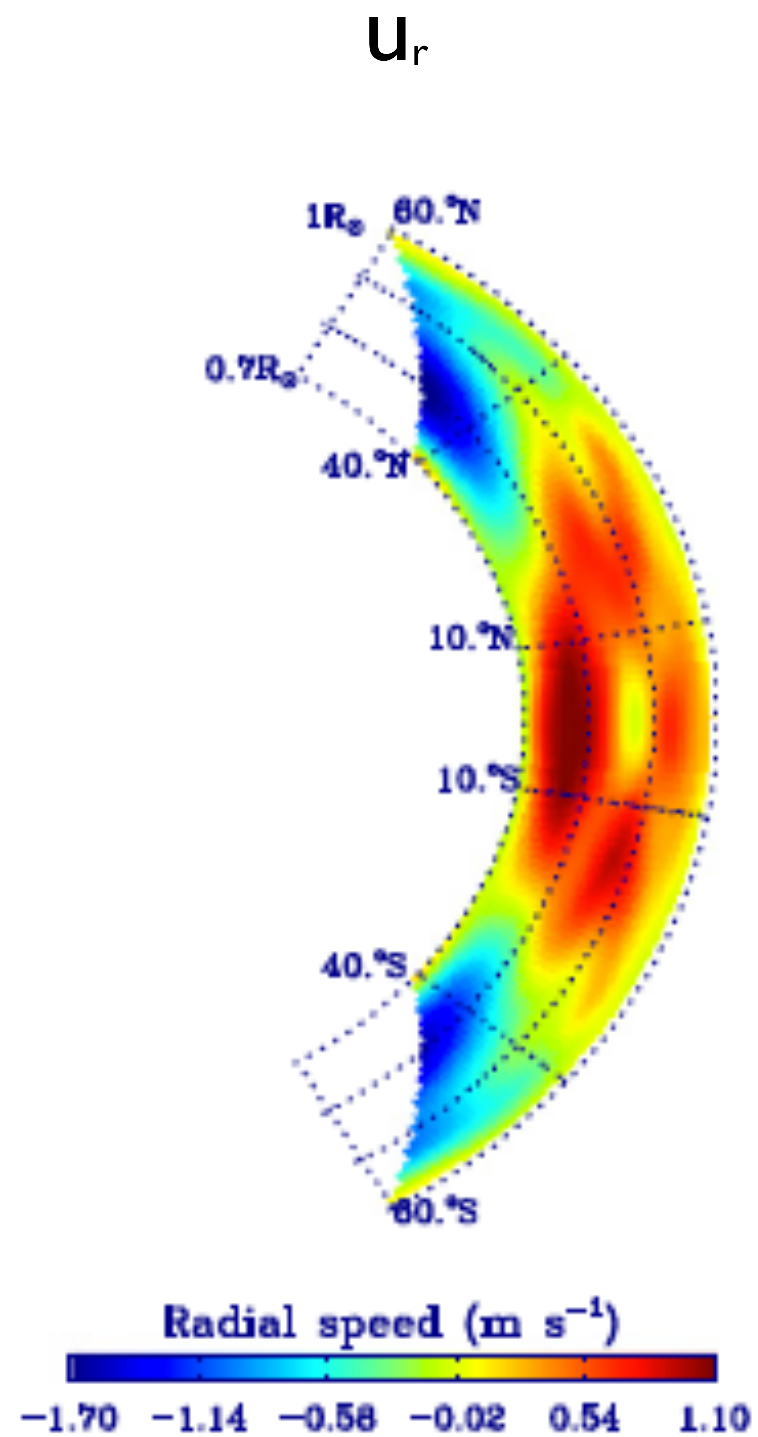
Single cell test profile (Rajaguru & Antia 2015)



Double cell test profile (Rajaguru & Antia 2015)

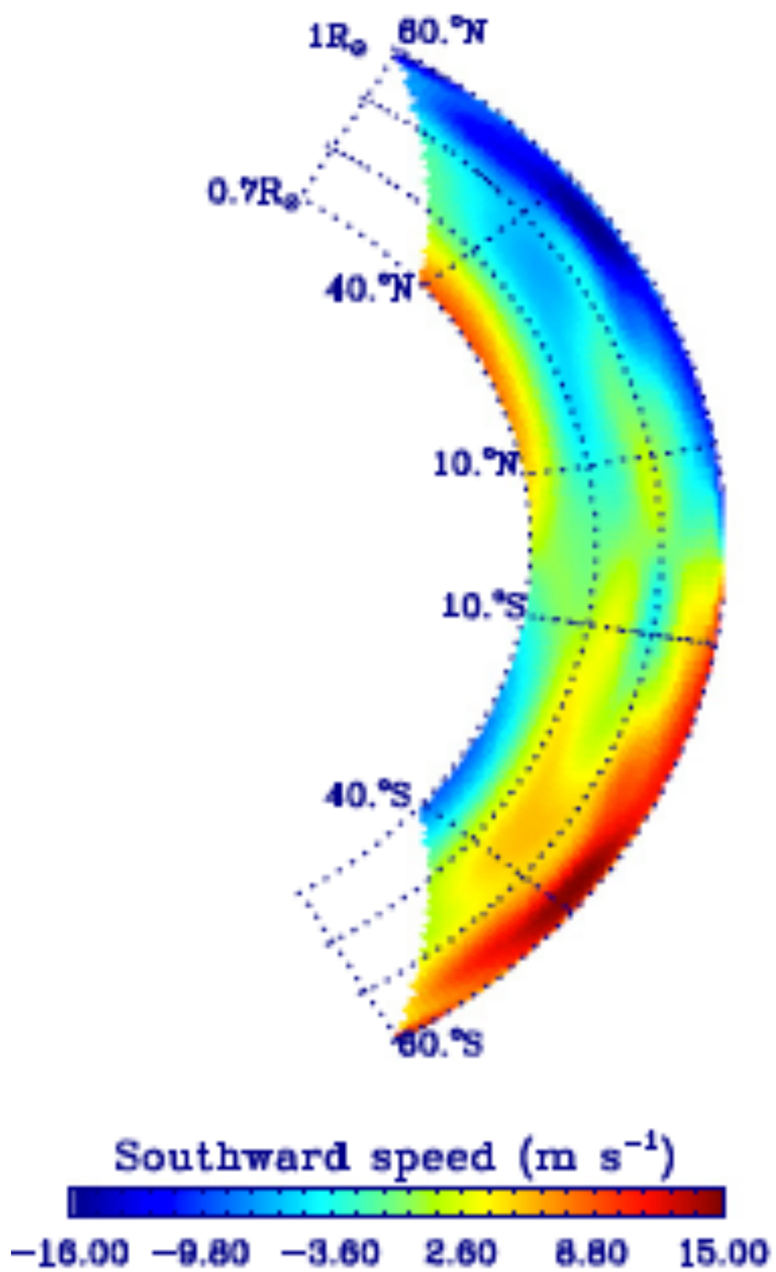
A solution with higher smoothing and lower errors.



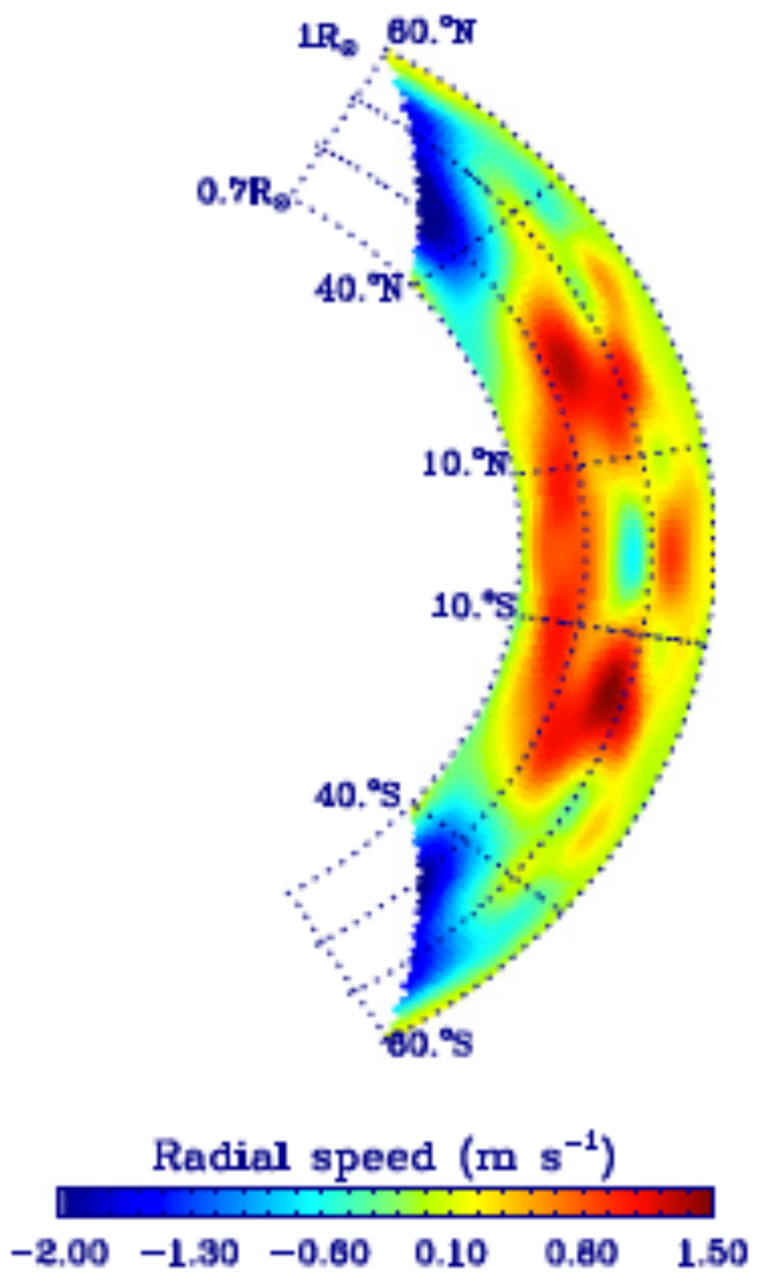


A solution with lower smoothing and slightly larger errors.

u_θ



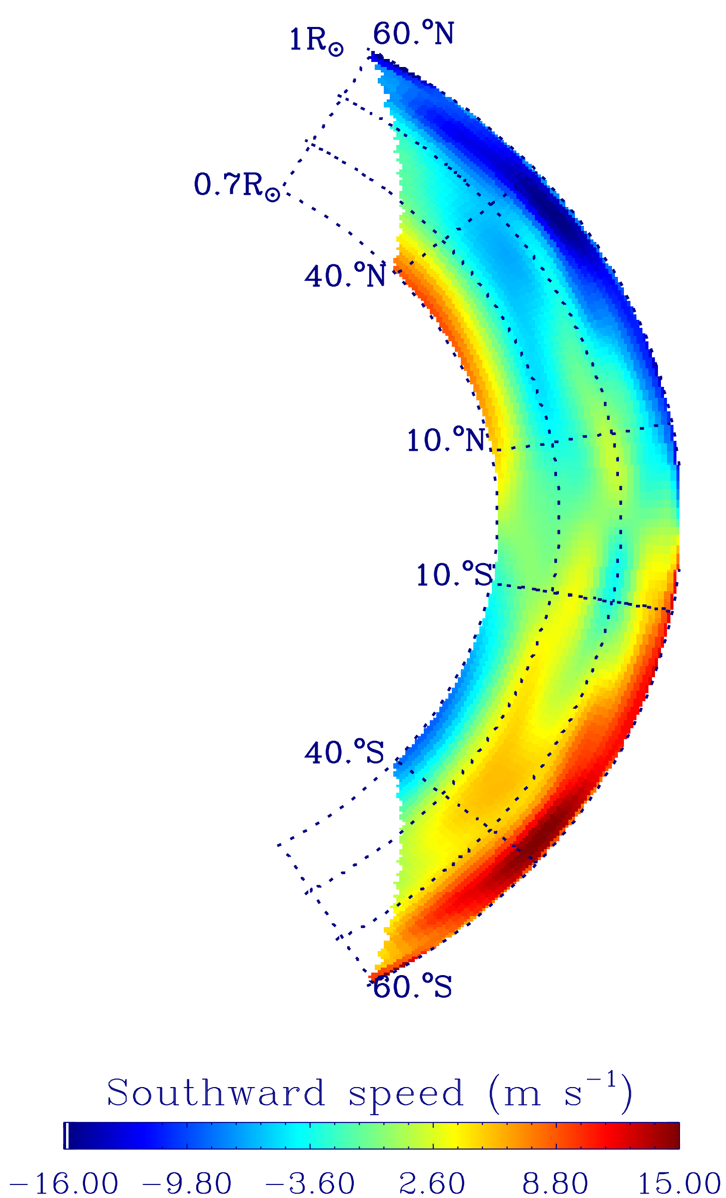
u_r



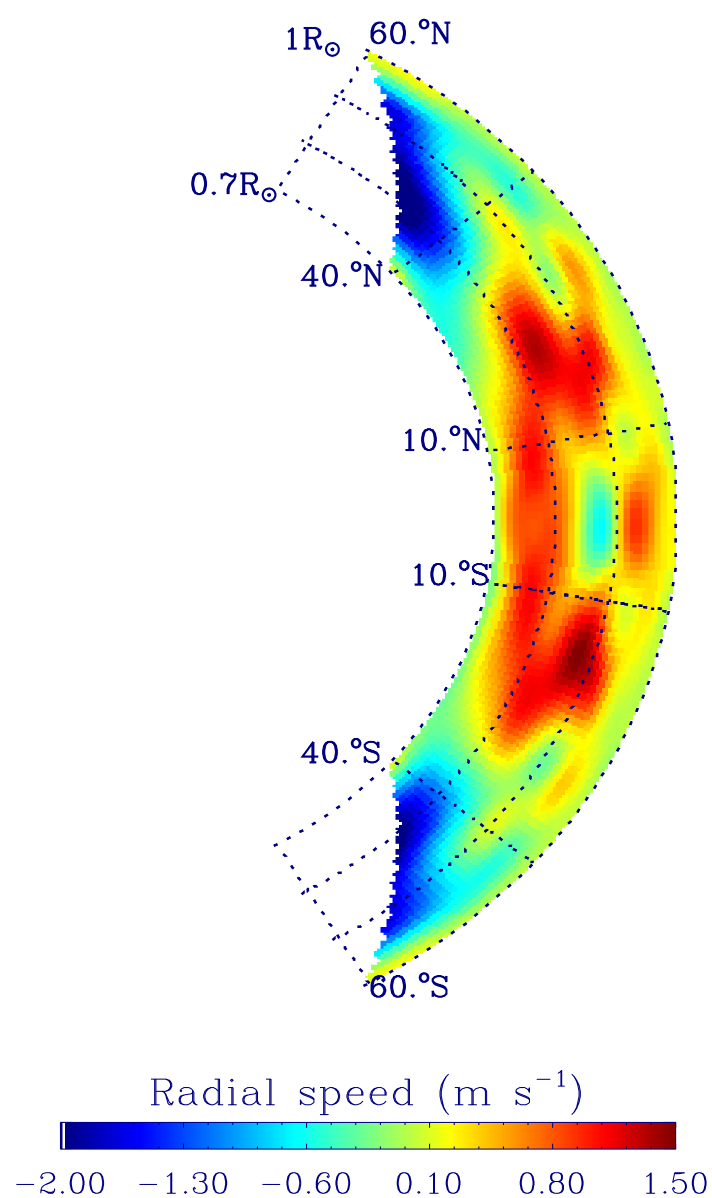
Inverted Meridional Circulation

Rajaguru and Antia (2015)

u_θ



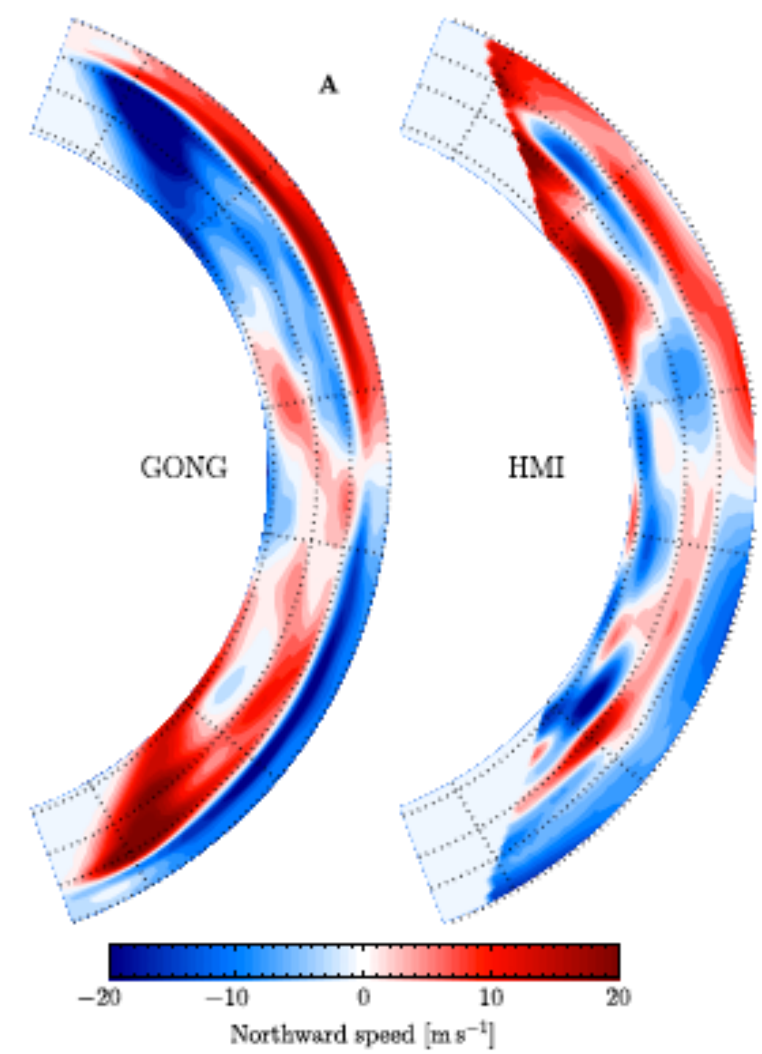
u_r



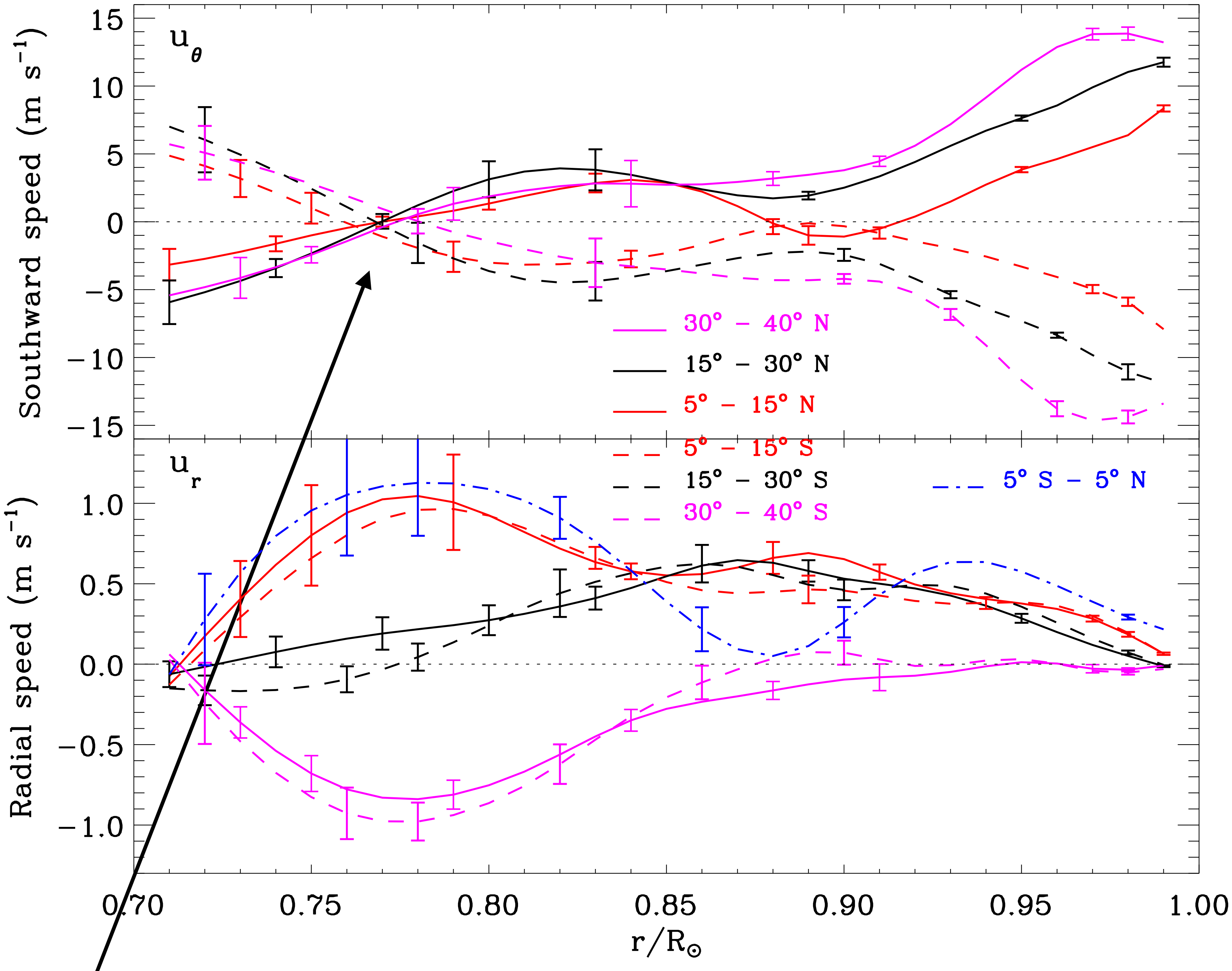
with mass-conservation constraints in the inversions

Jackiewicz et al. (2015)

u_θ



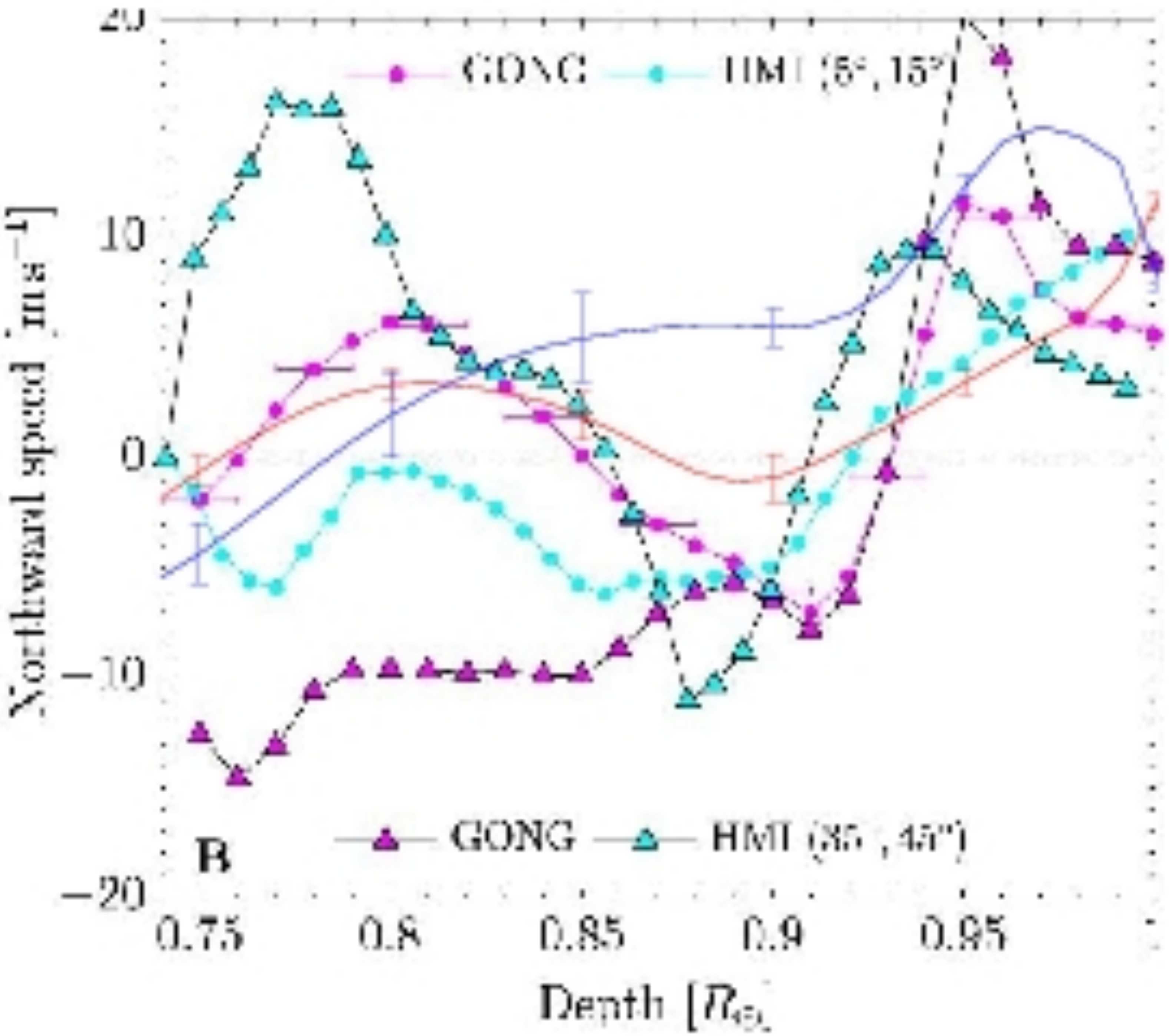
without mass-conservation constraint in the inversions



Likely reversal of flow at about 0.77 R_{sun} .

Hints of flow reversals at about 0.89 Rsun are not significant.

A single cell of meridional flow with return flow at about 0.77 R_{sun} is consistent with the above inversions.


GONG
HMI (5°, 15°)
GONG
HMI (35°, 45°)
B
Northward speed [m s^{-1}]
Depth [$R_\odot$]
20
10
0
−10
−20
0.75
0.8
0.85
0.9
0.95

Reasons for the differences between inferences on the deep structure of MC:

(1) mass-conservation constraints

(2) differences in inversion strategy -- sensitivity to errors and systematics in measurements.

→ Significant improvements are needed to address the noise and systematics.

Mon. Not. R. Astron. Soc. **411,** 1059–1066 (2011) doi:10.1111/j.1365-2966.2010.17737.x

Differential rotation of main-sequence dwarfs and its dynamo efficiency

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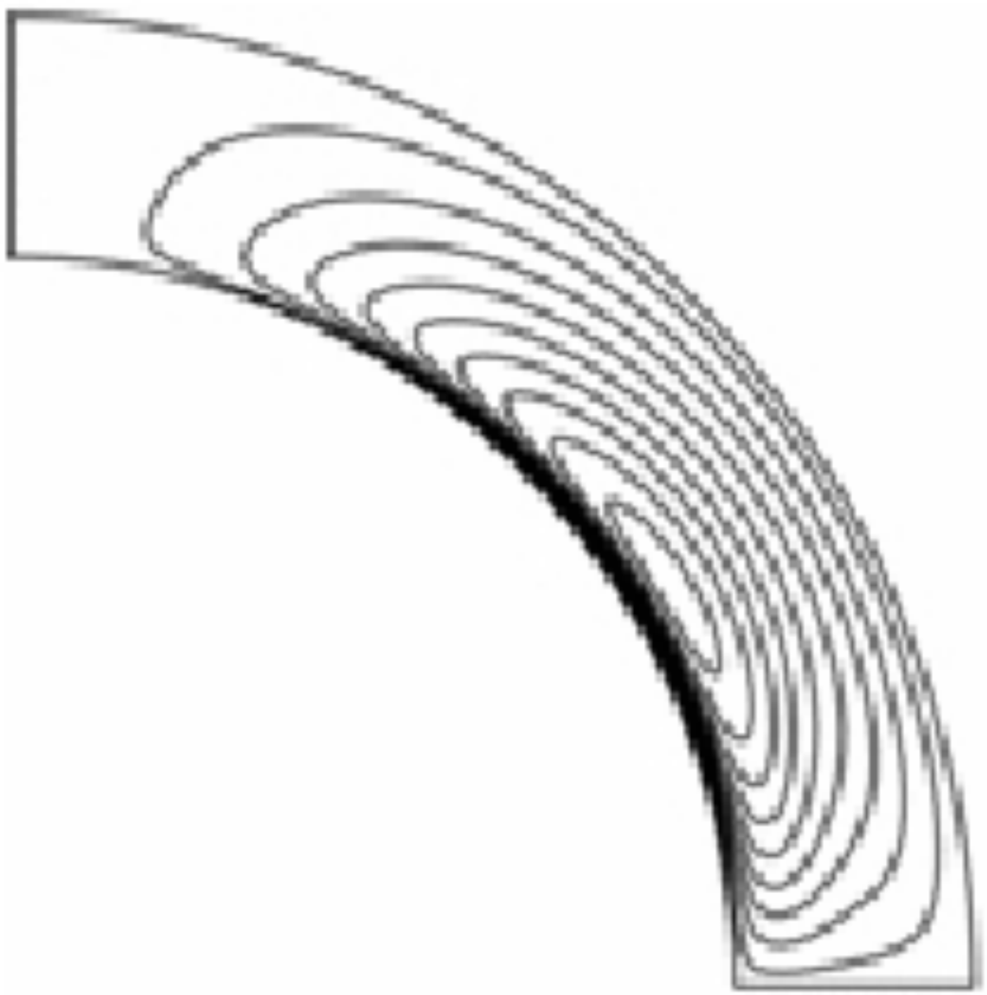
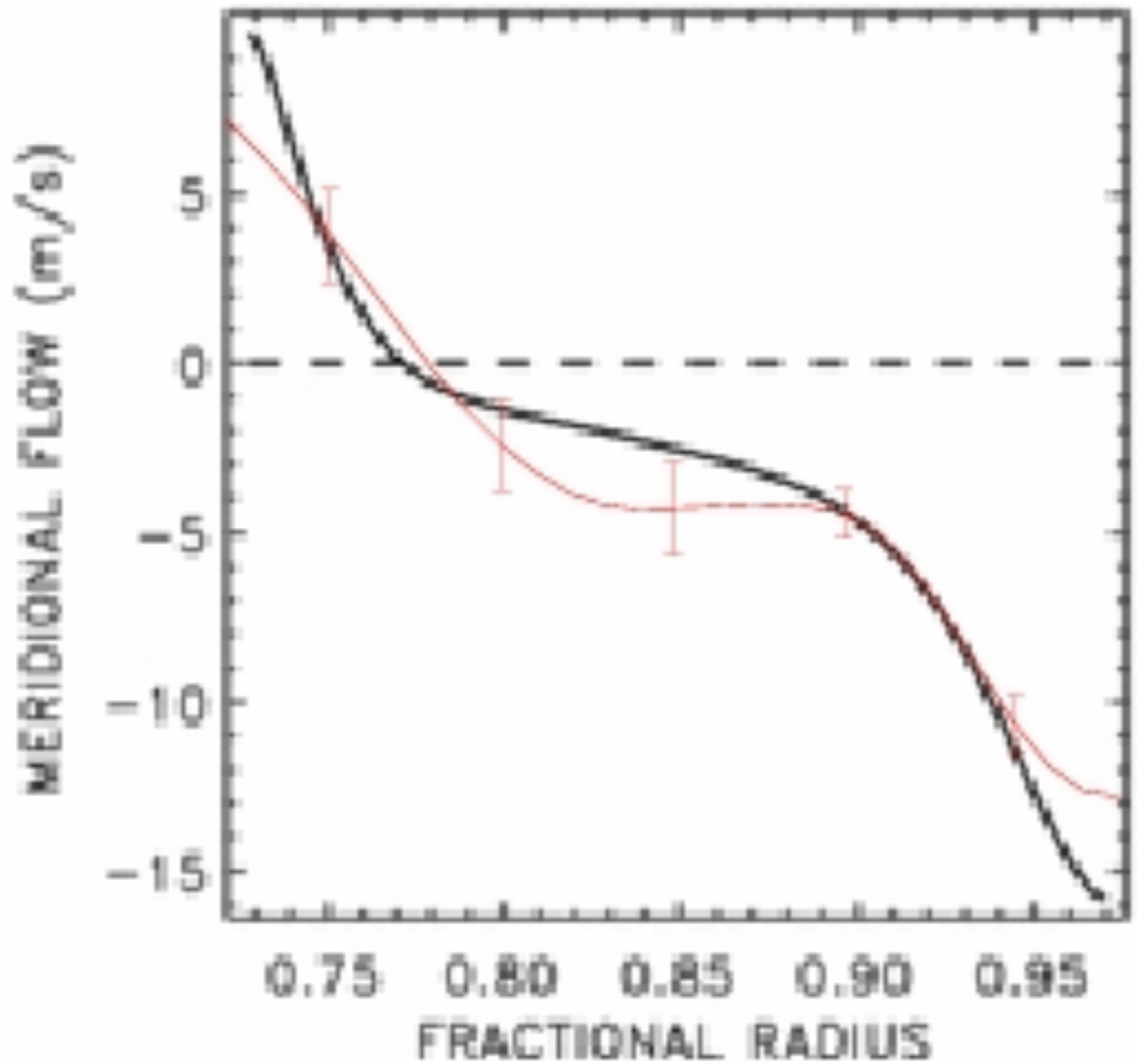
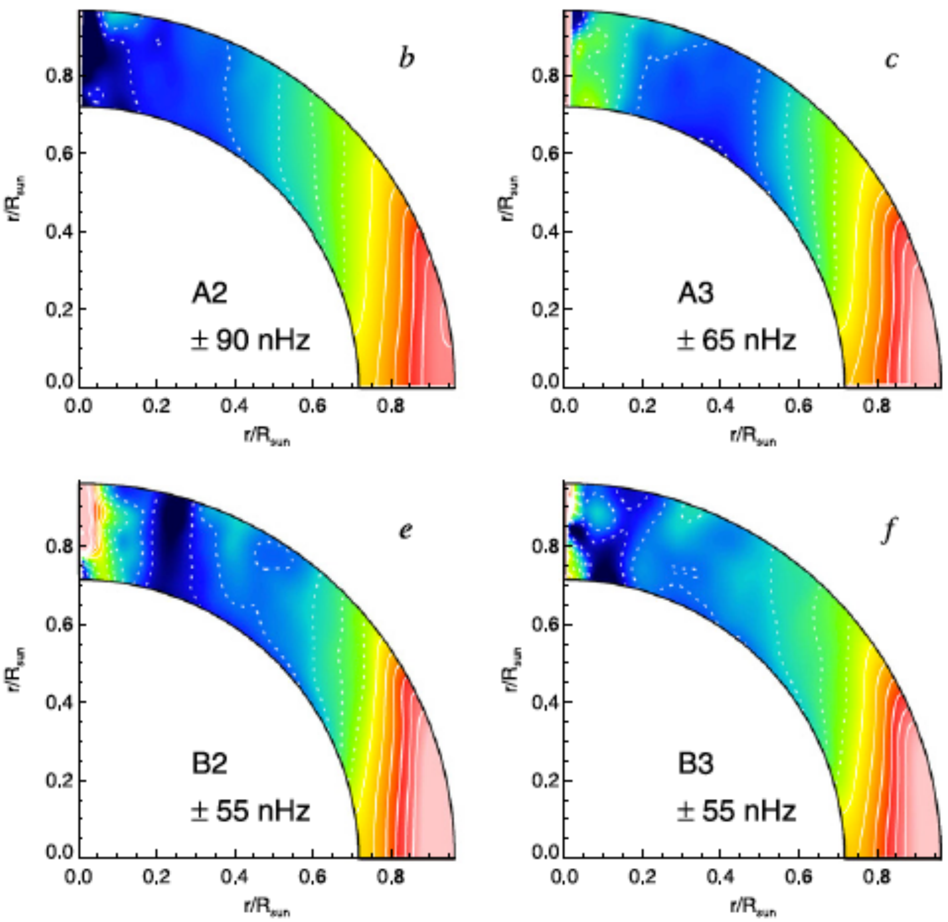
[2] *Pulkovo Astronomical Observatory, St. Petersburg 196140, Russia*

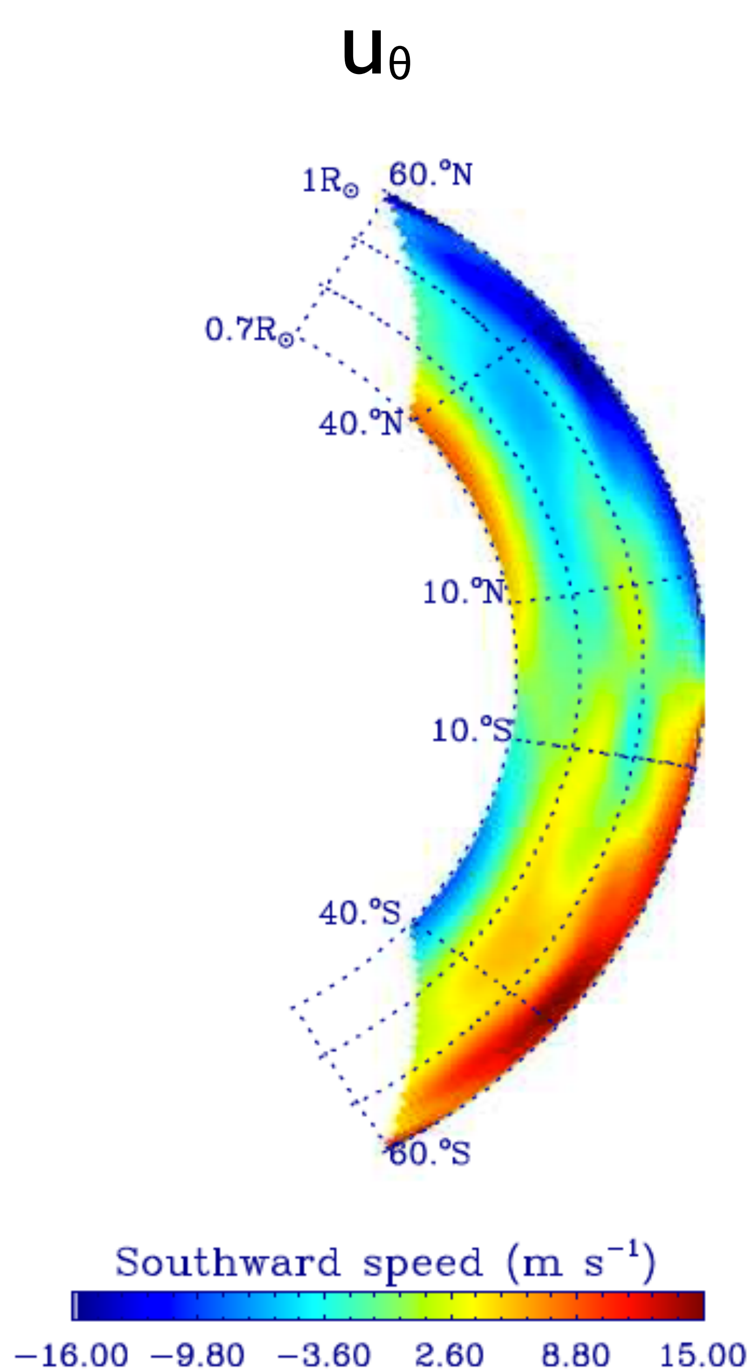


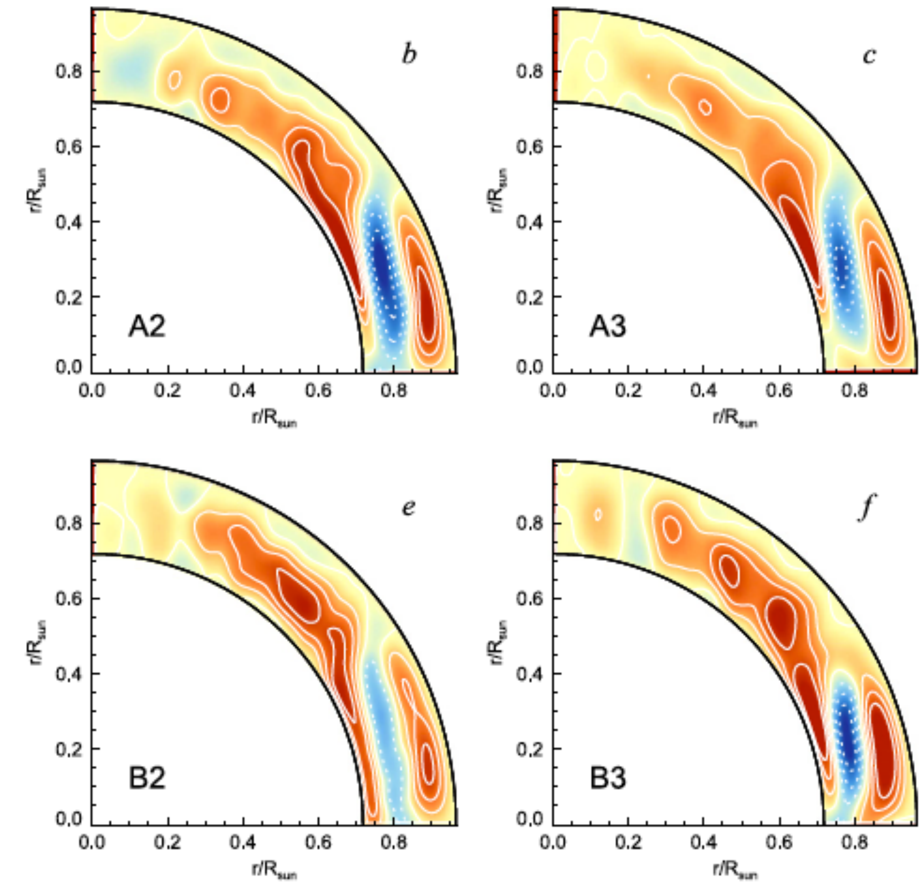


Numerical models of differential rotation and MC

Featherstone & Miesch (2015)







Main inferences:

(1) Within errors, the measurements are consistent with a single deep cell of MC

- return-flow likely below 0.77 R_{sun}

- broad upwellings near the equatorial regions (10°S - 10°N) with radial speeds of ~ 1 m/sec over the depth ranges of 0.7 - 0.8 R_{sun} and 0.9 - 0.97 R_{sun}

(2) There are signatures of multi-cellular structure at low latitudes (< 25 deg.) but the signals are close to error limits.

What next?

1. Understand the Centre-to-Limb Systematics – devise new correction strategies

2. Improve S/N in measurements – use longer data sets

3. Closer exchange between researchers and concerted efforts to understand the differences in methods of analyses and results.

Thank you! .