SOLAR ROTATION DURING CYCLES 23 AND 24

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Rotation rate in the solar interior

- Data from GONG (1995–2014) and MDI (1996–2011) The splitting coefficients are defined by

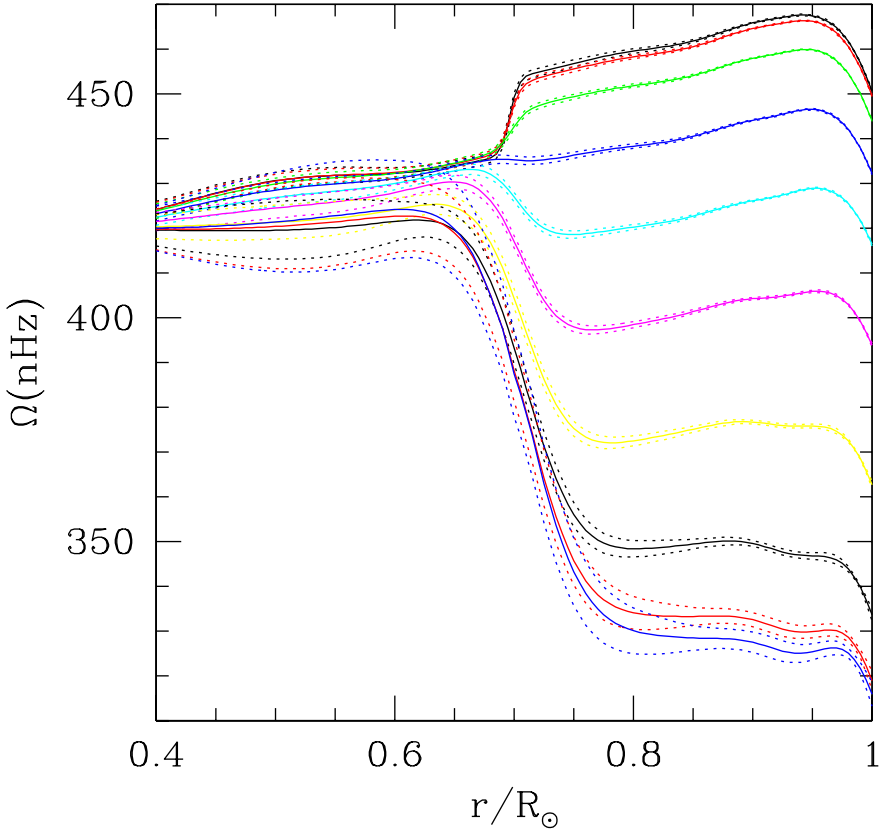
$$\nu_{\ell,m,n} = \nu_{\ell,n} + \sum_j c_j^{\ell,n} P_j^\ell(m)$$

  Only odd order splitting coefficients are required for rotation inversion.

- Rotational splittings are related by

$$c_j^{\ell,n} = \int_0^1 \int_0^1 dr \; d\cos\theta \; K_{n\ell j}(r,\theta)\Omega(r,\theta)$$

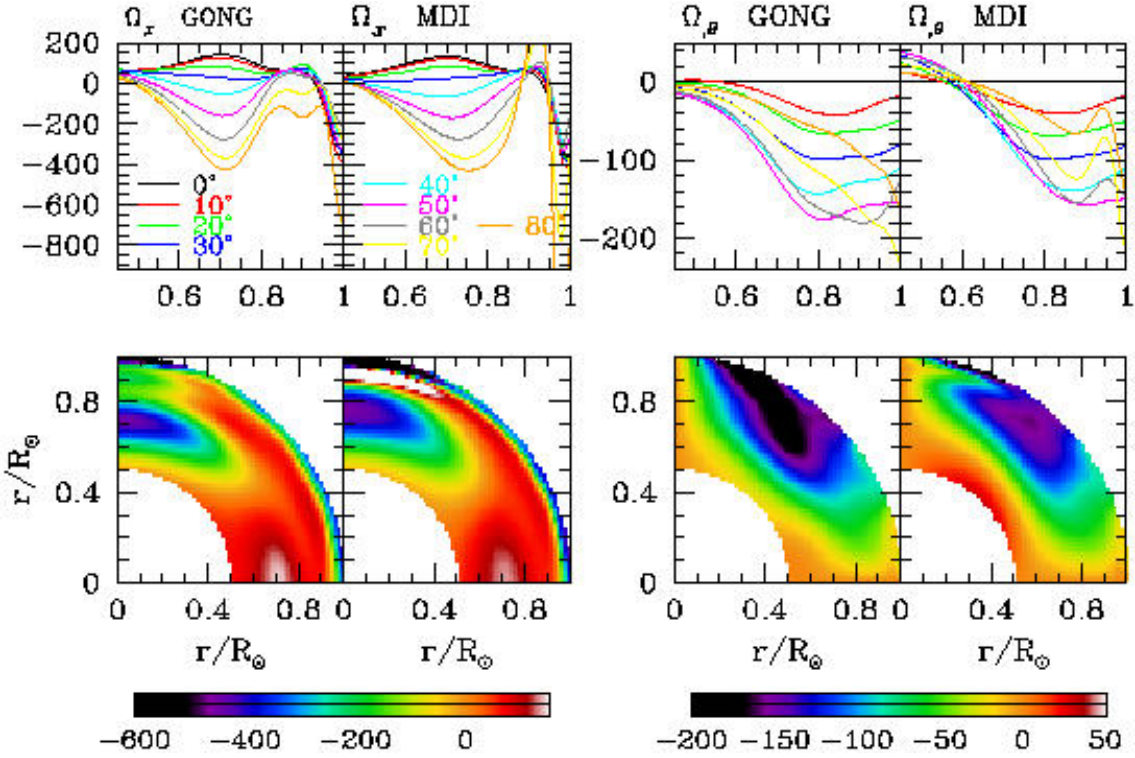
- Rotational splittings are used to calculate the rotation rate $\Omega(r,\theta)$ using 2D RLS.


450
400
350
Ω(nHz)
0.4
0.6
0.8
1
r/R⊙

- We can also calculate the gradients of rotation rate with radius (r) and latitude (θ)

$$\Omega_r = \frac{\partial \Omega}{\partial r}$$

$$\Omega_\theta = \frac{1}{r} \frac{\partial \Omega}{\partial |\theta|}$$



Antia, Basu & Chitre 2008

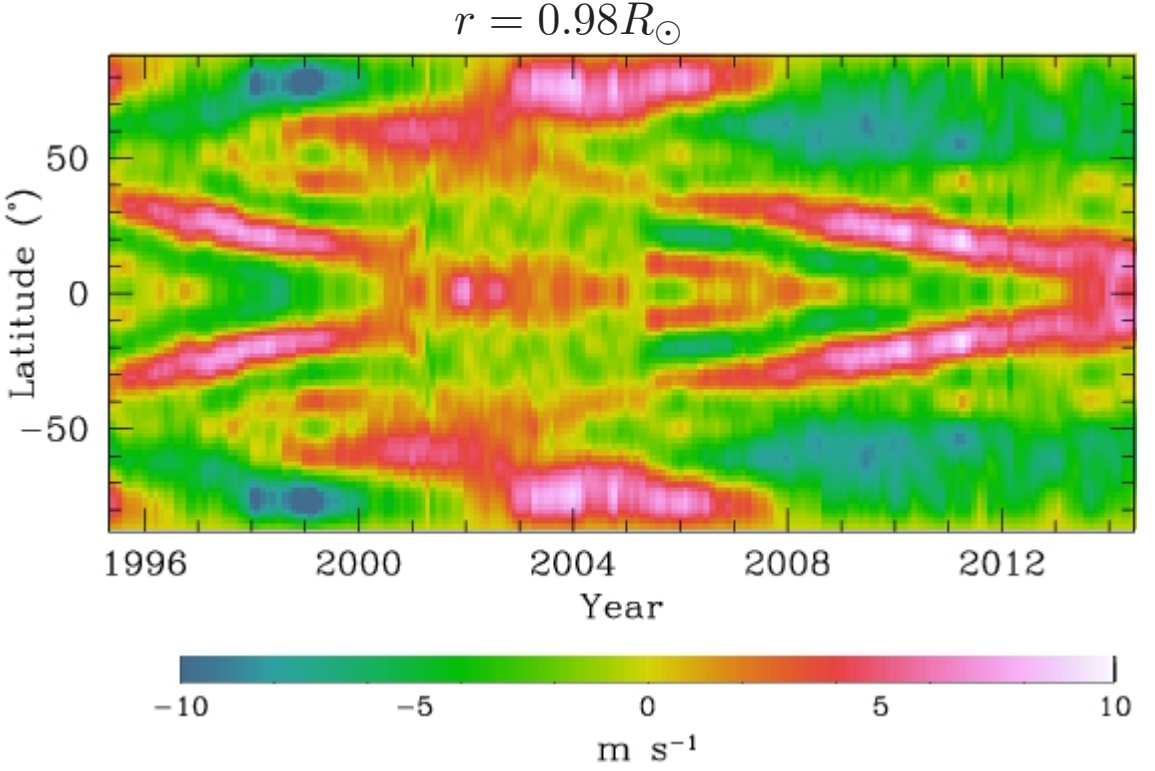
Temporal Variations of the Rotation Rate

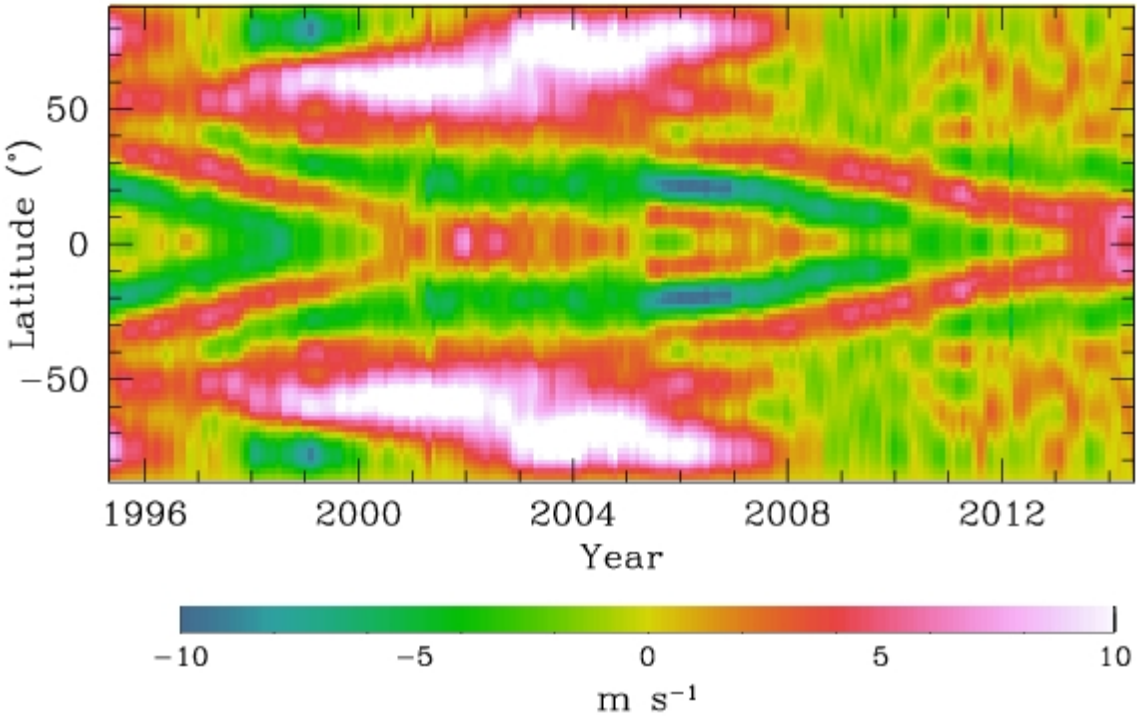
- GONG : 192 data sets covering 108 days each with some overlap
- MDI : 74 data sets covering 72 days each
- Torsional oscillations at the solar surface show that rotation rate is varying with time.
- From seismic inversions: rotation rate residual

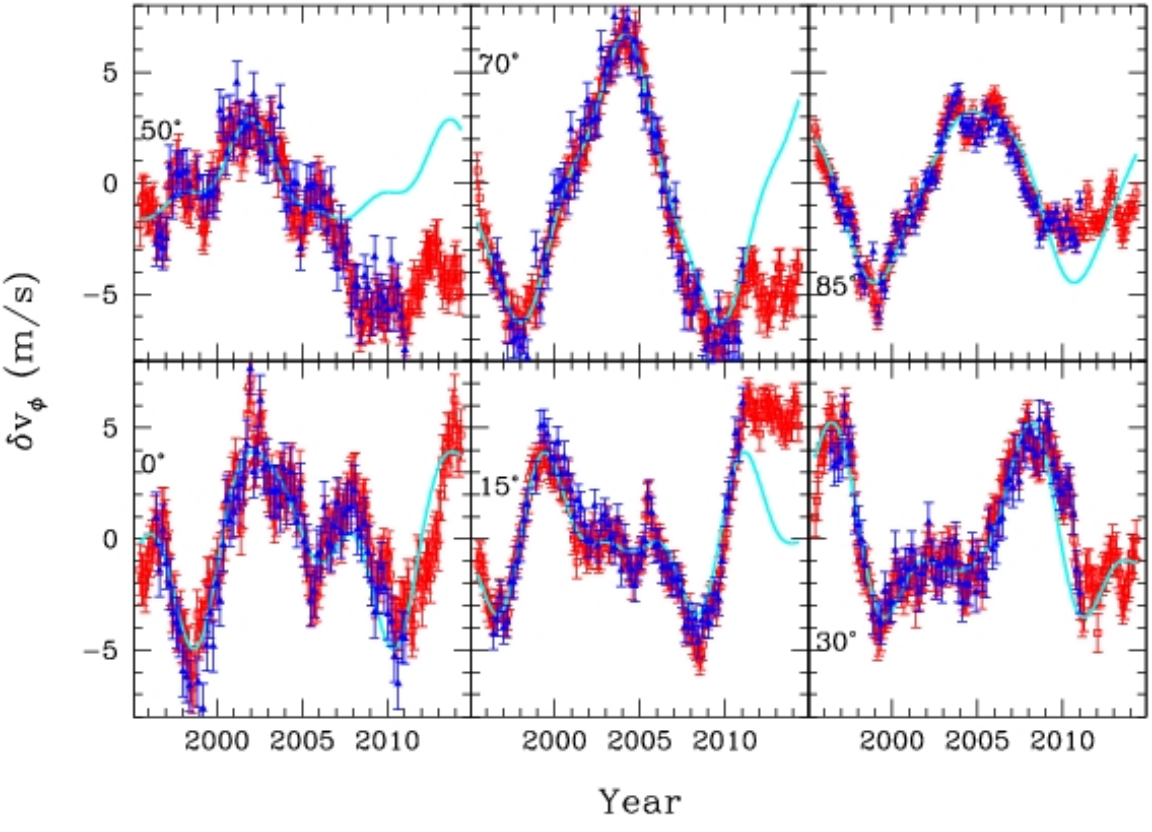
$$\delta\Omega(r,\theta,t) = \Omega(r,\theta,t) - \langle\Omega(r,\theta,t)\rangle$$

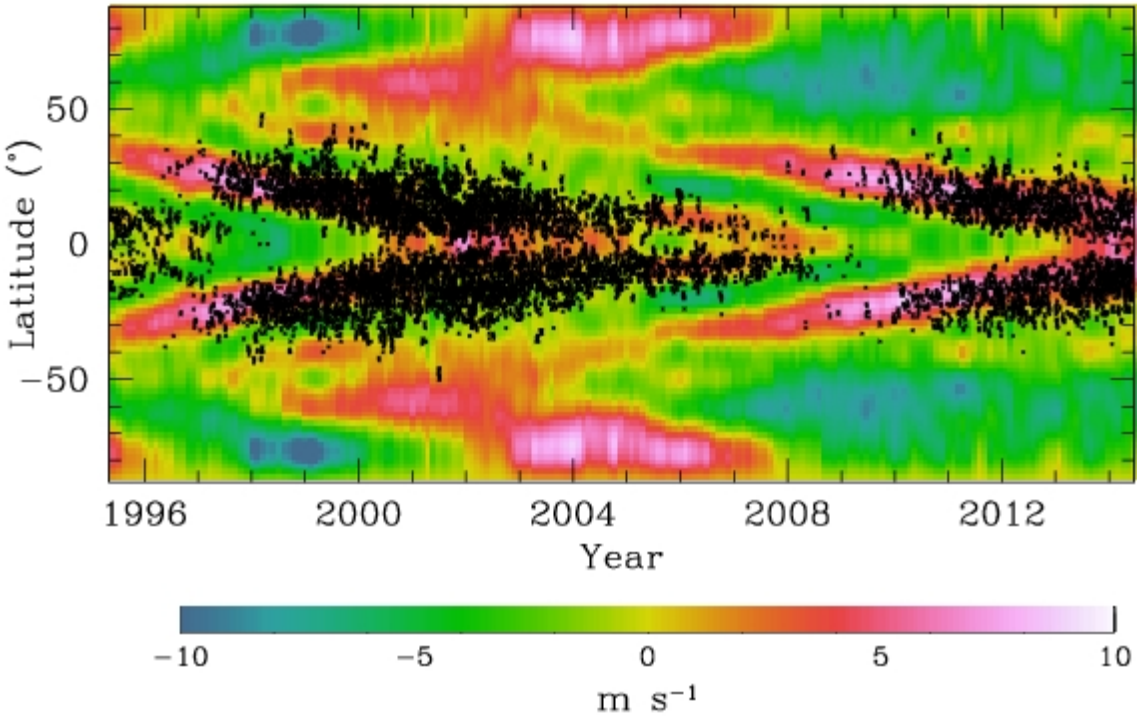
where averaging is over time. Zonal flow velocity

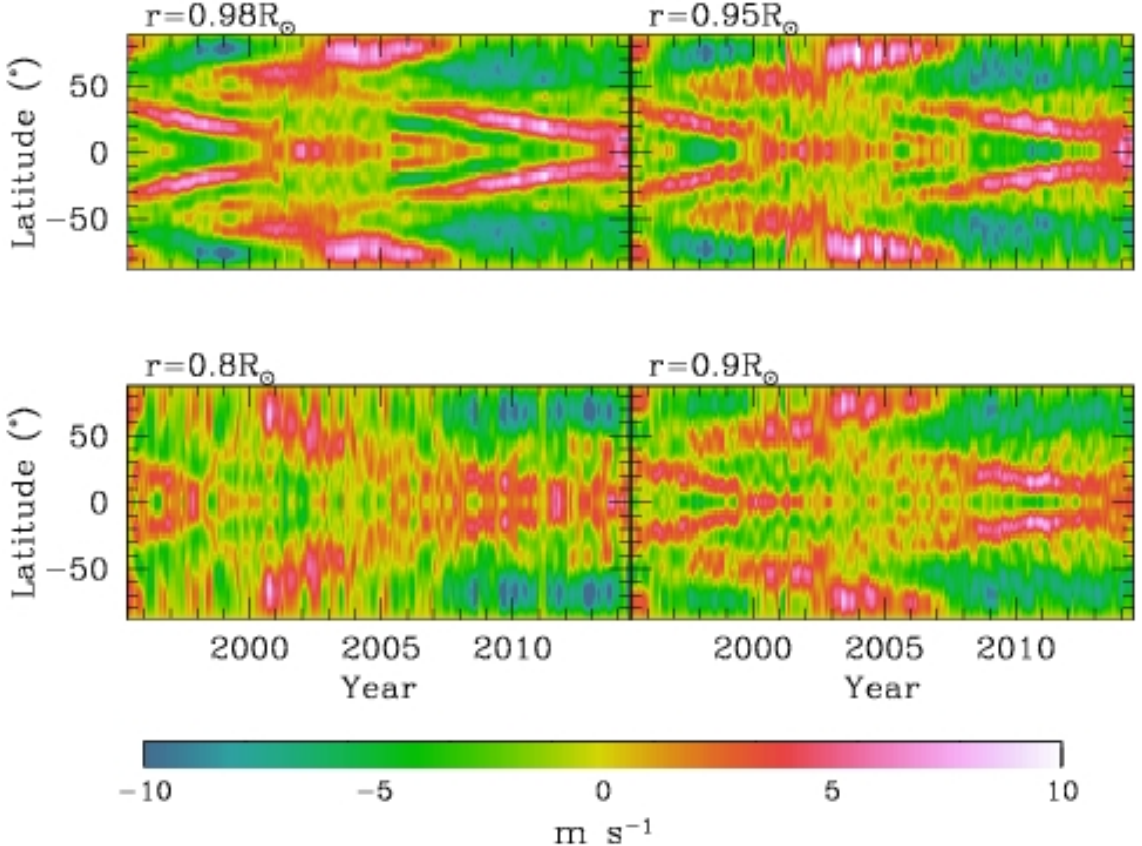
$$\delta v_\phi = \delta\Omega r\cos\theta$$

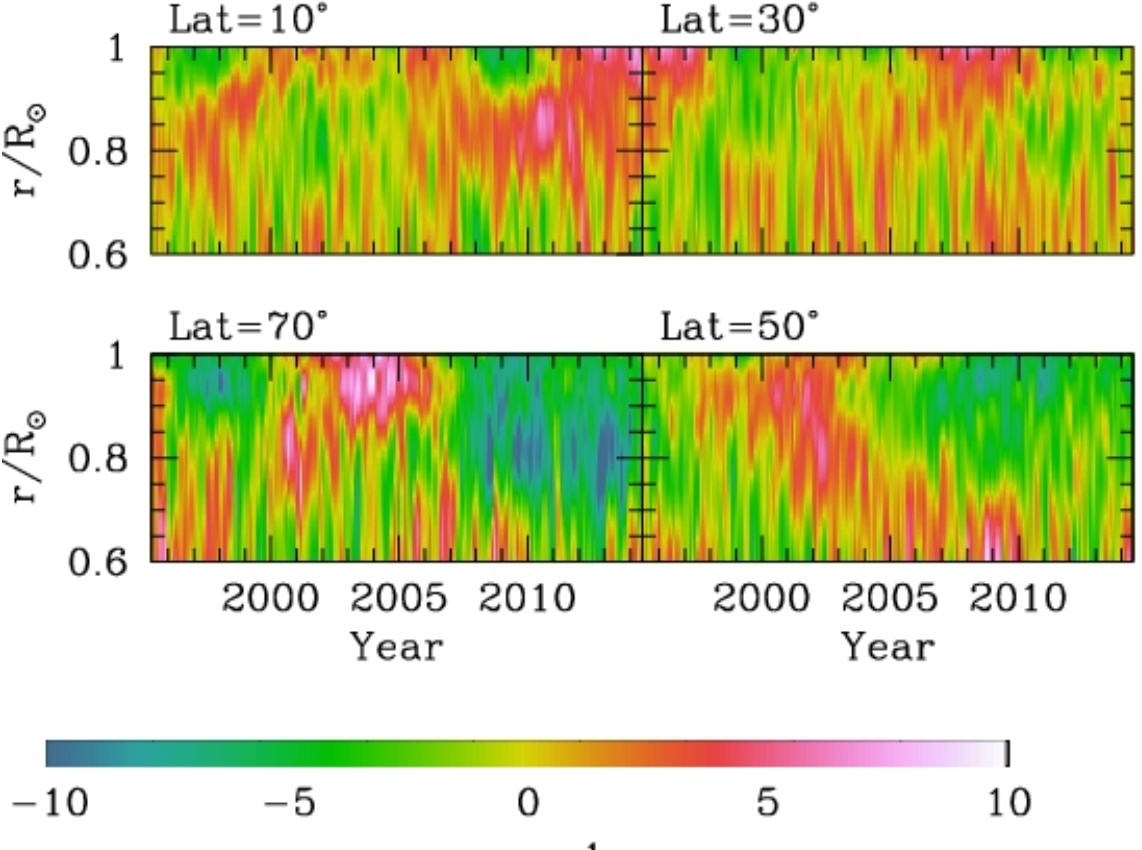

$r = 0.98R_\odot$
50
0
−50
Latitude (°)
1996
2000
2004
2008
2012
Year
−10
−5
0
5
10
m s⁻¹

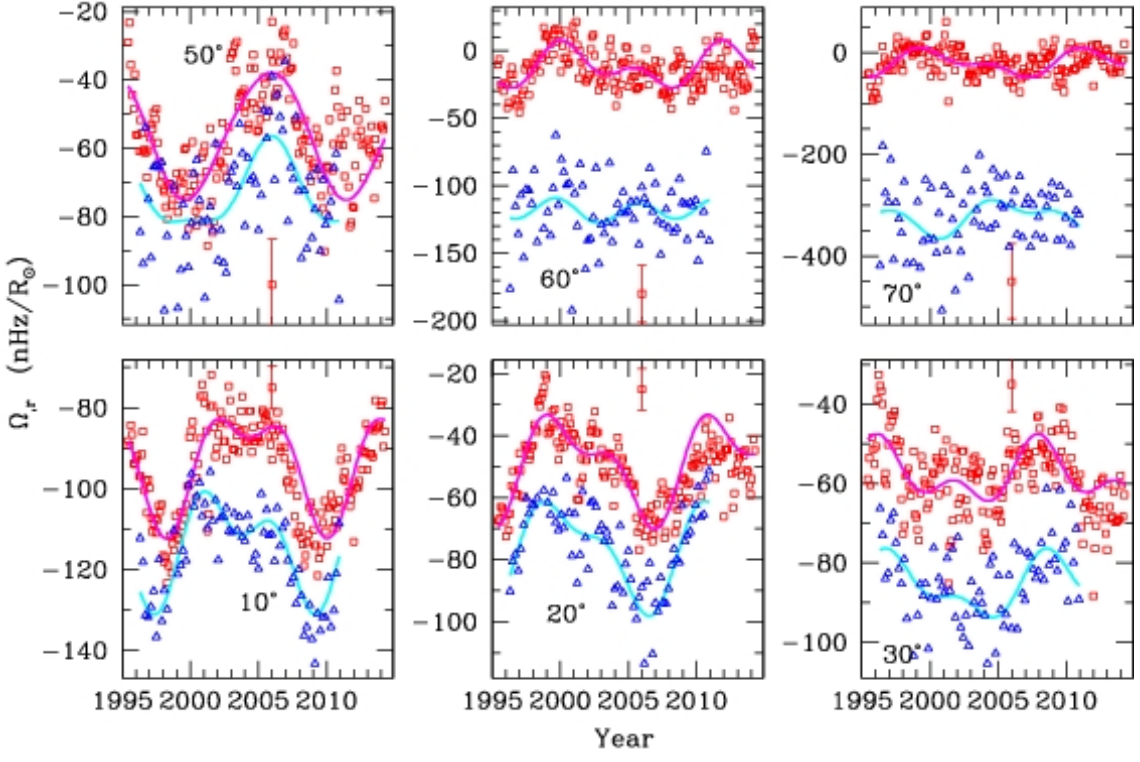

Latitude (°)
50
0
−50
1996
2000
2004
2008
2012
Year
−10
−5
0
5
10
m s−1

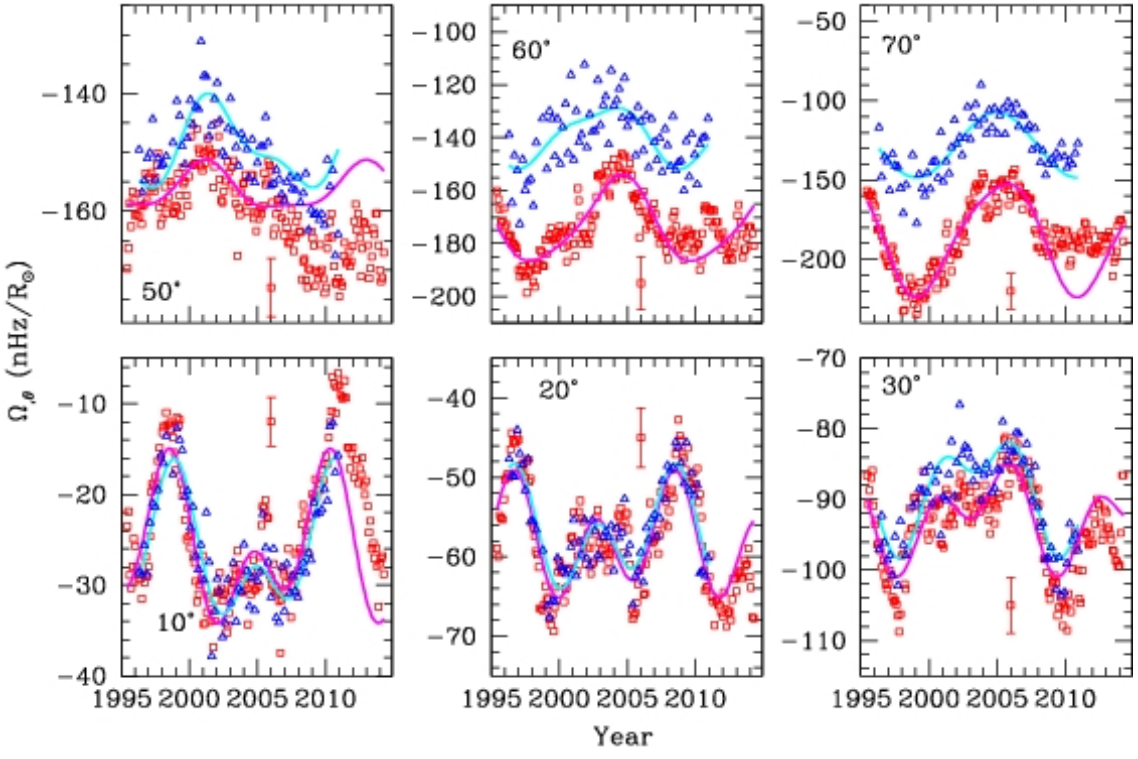

50°
70°
85°
0°
15°
30°
5
0
−5
2000
2005
2010
Year
δv_φ (m/s)


50
0
−50
Latitude (°)
1996
2000
2004
2008
2012
Year
−10
−5
0
5
10
m s^{-1}

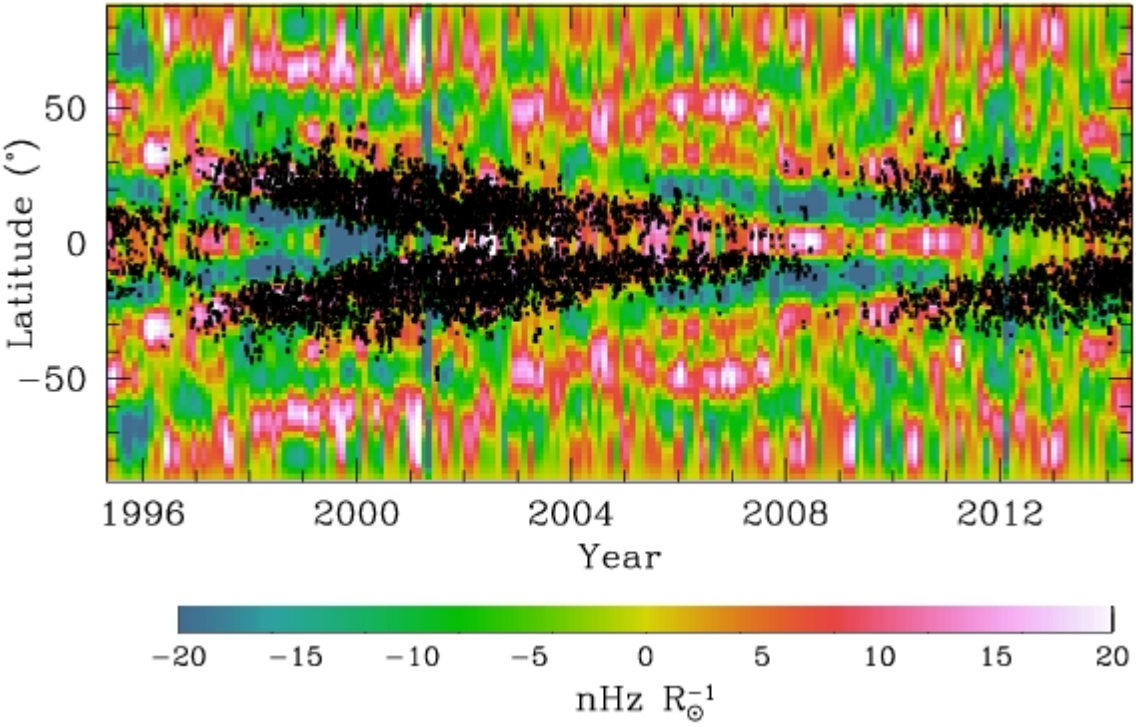

r=0.98R⊙
r=0.95R⊙
r=0.8R⊙
r=0.9R⊙
Latitude (°)
50
0
−50
2000
2005
2010
Year
−10
−5
0
5
10
m s−1

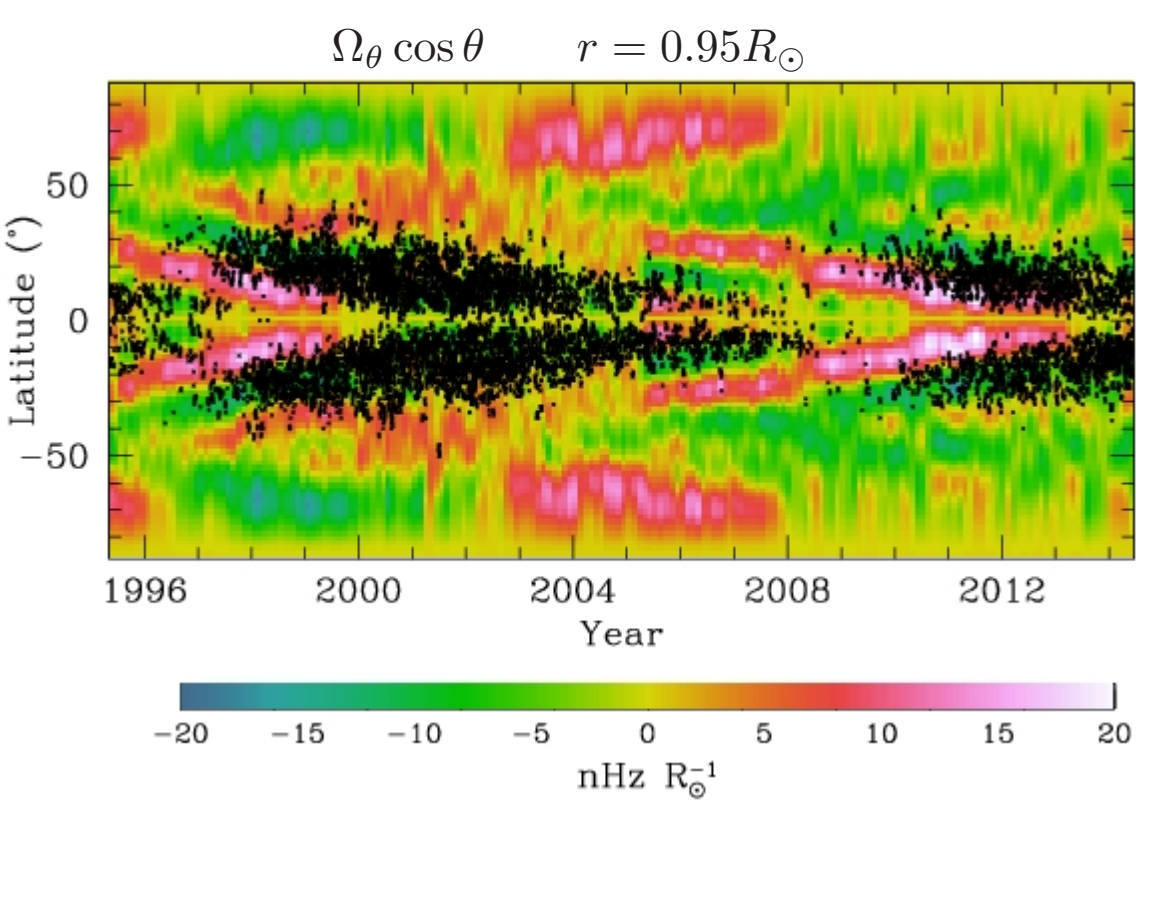

Lat=10°
Lat=30°
Lat=70°
Lat=50°
1
0.8
0.6
r/R⊙
2000
2005
2010
Year
−10
−5
0
5
10
m s⁻¹


50°
60°
70°
10°
20°
30°
$\Omega_{,r}$ (nHz/R$_\odot$)
1995 2000 2005 2010
Year


50°
60°
70°
10°
20°
30°
Ω_ϕ (nHz/R$_\odot$)
Year
1995 2000 2005 2010

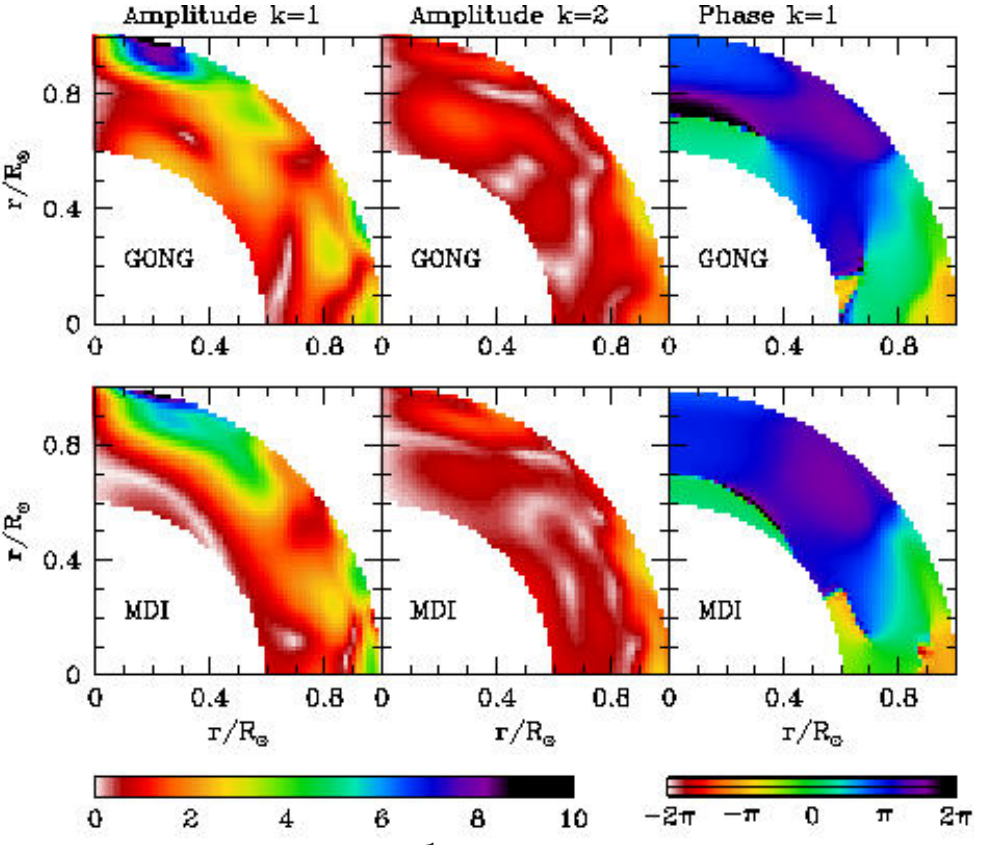
$\Omega_r \cos\theta \qquad r = 0.95 R_\odot$




$\Omega_\theta \cos\theta$
$r = 0.95 R_\odot$
50
0
−50
Latitude (°)
1996
2000
2004
2008
2012
Year
−20
−15
−10
−5
0
5
10
15
20
nHz $R_\odot^{-1}$

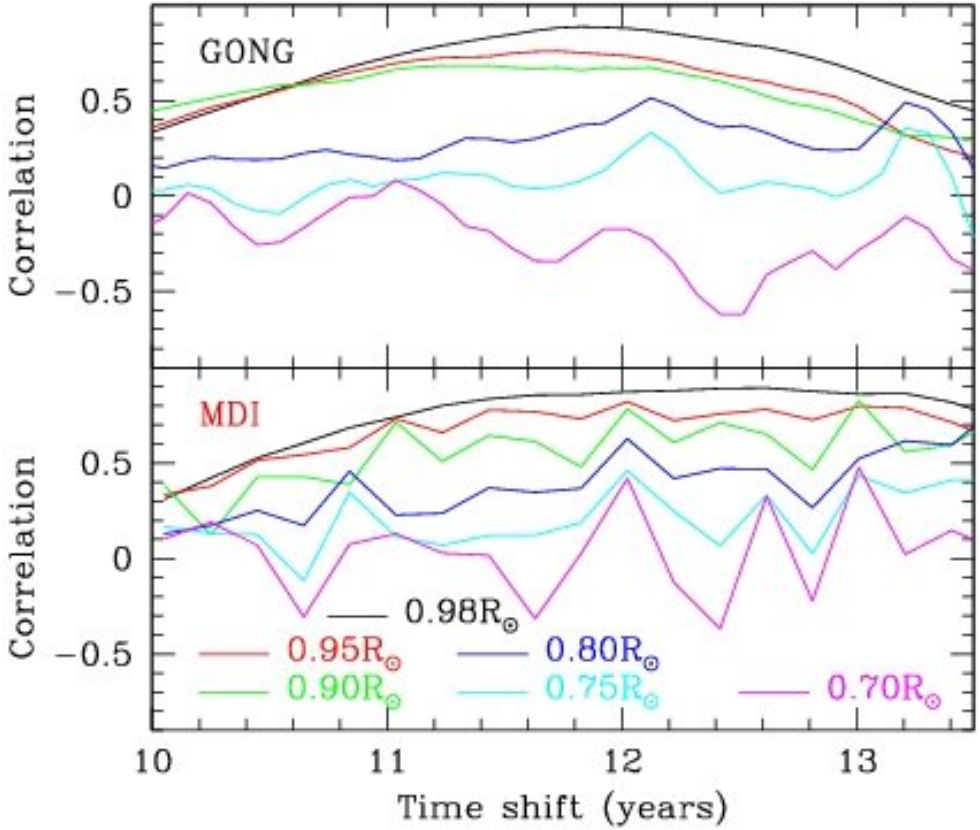
- If we assume that the pattern is periodic with period of 11.7 years, we can fit the pattern at each depth and latitude to a form:

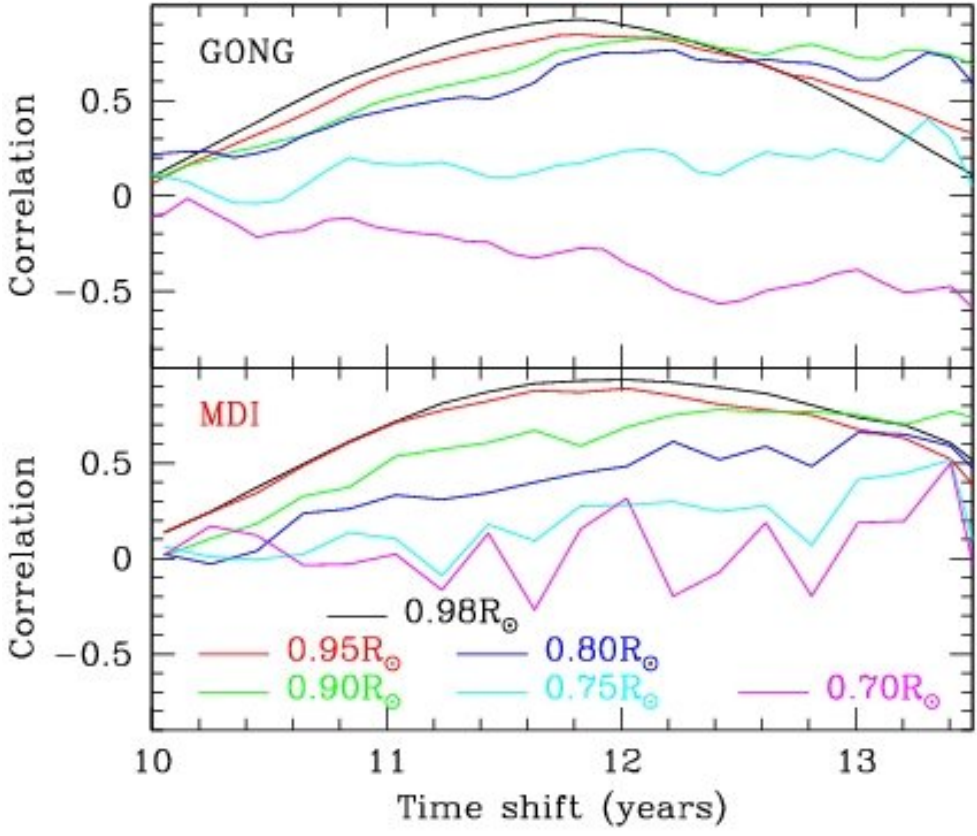
$$\delta v_\phi(r,t,\theta) = \sum_{k=1}^{N} a_k(r,\theta)\sin(k\omega_0 t + \phi_k)$$


Amplitude k=1
Amplitude k=2
Phase k=1
GONG
GONG
GONG
MDI
MDI
MDI
r/R⊙
0
0.4
0.8
0
2
4
6
8
10
−2π
−π
0
π
2π
m s^{-1}

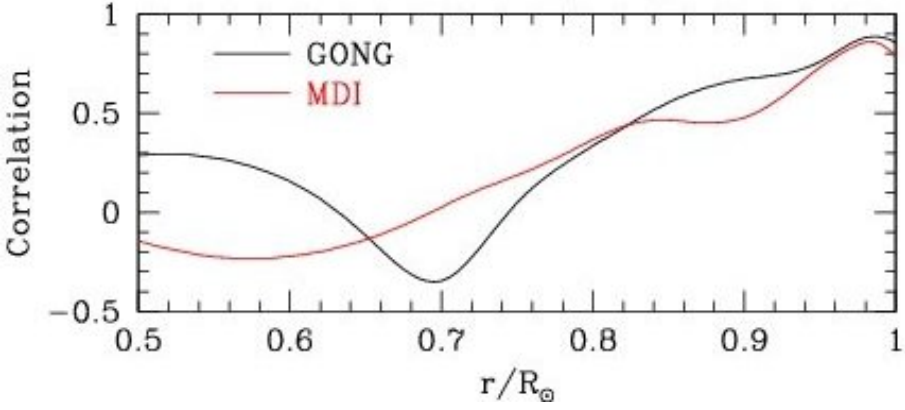
- To estimate the period of solar cycle we find autocorrelation of zonal flow pattern with time-shift (Antia & Basu 2010)

$$C(T,r) = \frac{\sum_{i,j} \delta v_\phi(r,\theta_i,t_j)\, \delta v_\phi(r,\theta_i,t_j+T)}{\sqrt{(\sum_{i,j} \delta v_\phi(r,\theta_i,t_j)^2)(\sum_{i,j} \delta v_\phi(r,\theta_i,t_j+T)^2)}}$$

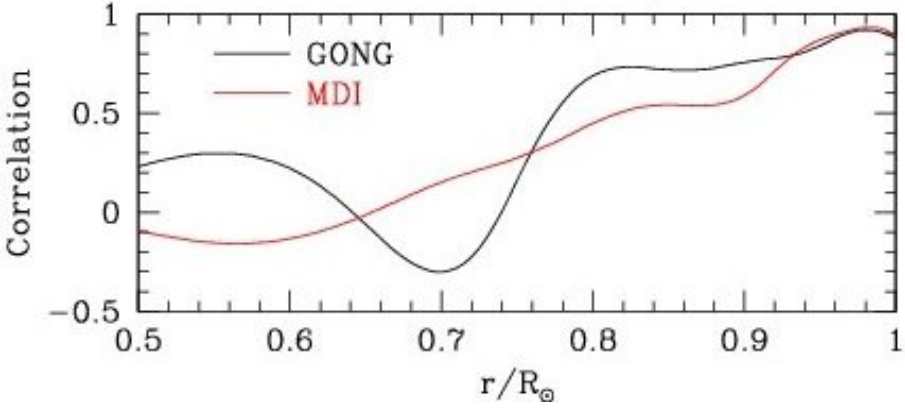

GONG
MDI
Correlation
Correlation
0.5
0
−0.5
0.5
0
−0.5
0.98R⊙
0.95R⊙
0.80R⊙
0.90R⊙
0.75R⊙
0.70R⊙
10
11
12
13
Time shift (years)


GONG
MDI
Correlation
0.5
0
−0.5
0.98R⊙
0.95R⊙
0.90R⊙
0.80R⊙
0.75R⊙
0.70R⊙
10
11
12
13
Time shift (years)

Low lat



all latitudes



low latitudes