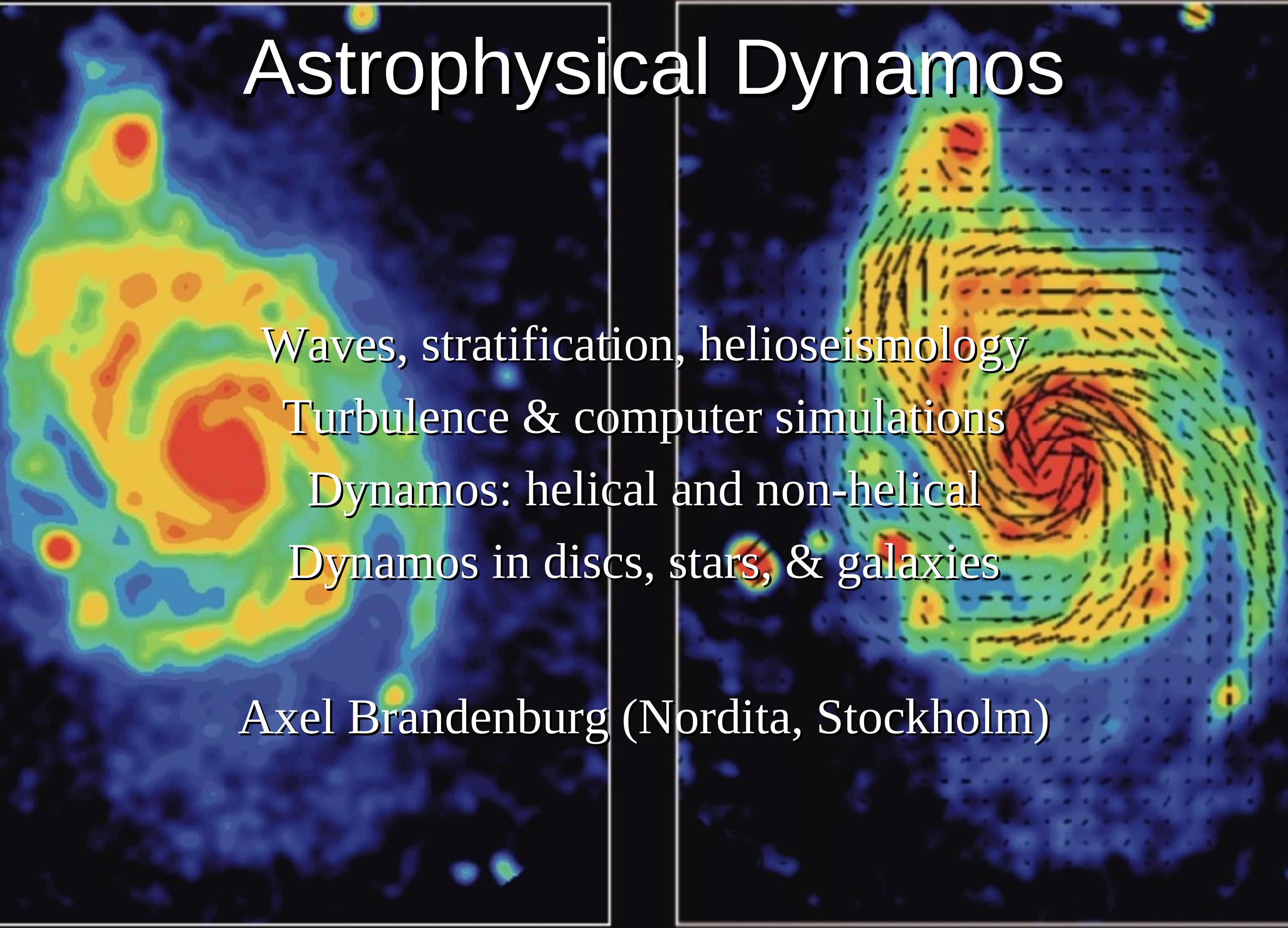
Astrophysical Dynamos



Waves, stratification, helioseismology

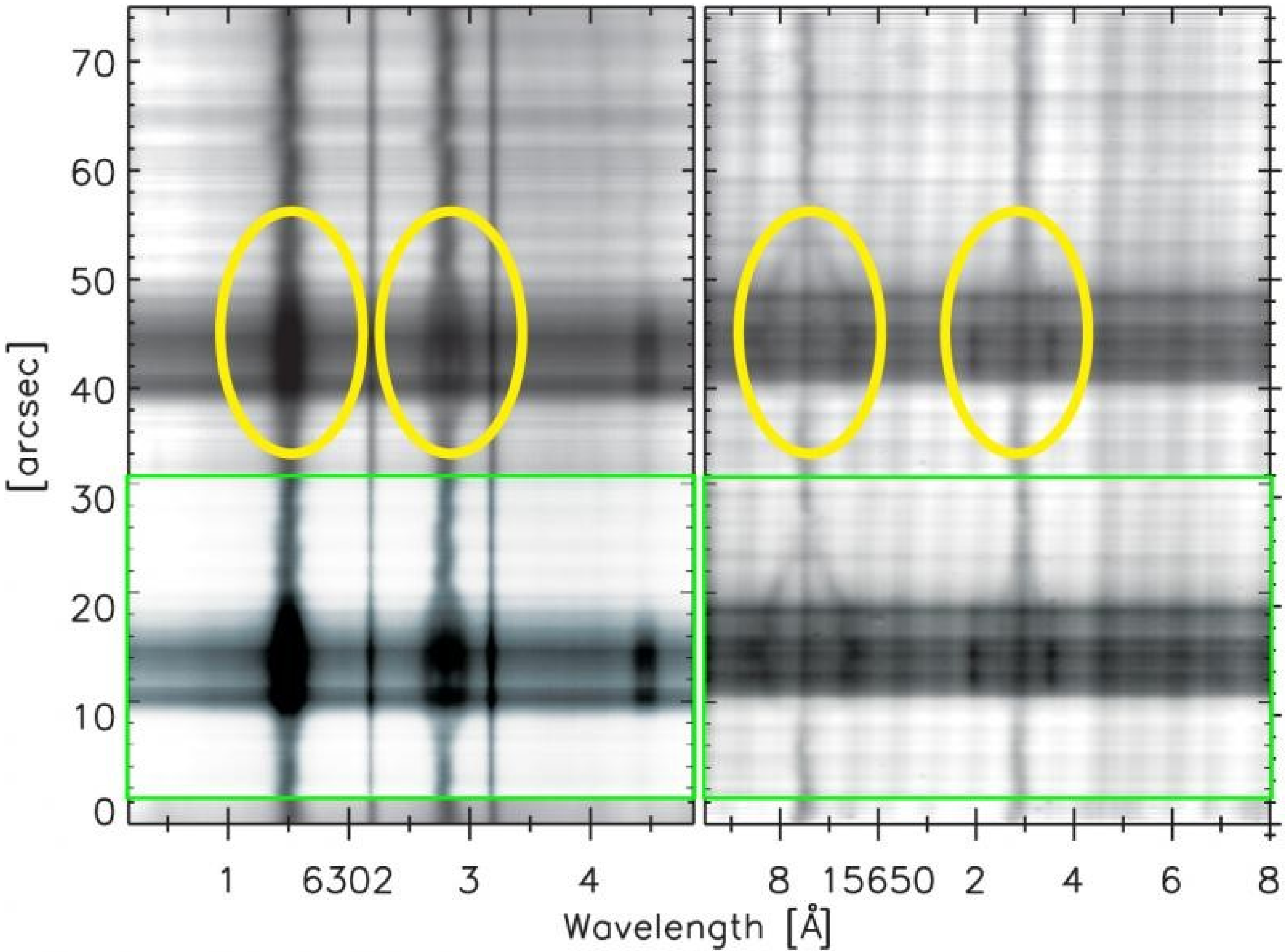
Turbulence & computer simulations

Dynamos: helical and non-helical

Dynamos in discs, stars, & galaxies

Axel Brandenburg (Nordita, Stockholm)

Line splitting (since Hale 1908)



THE MAGNETIC FIELD OF SUNSPOTS.

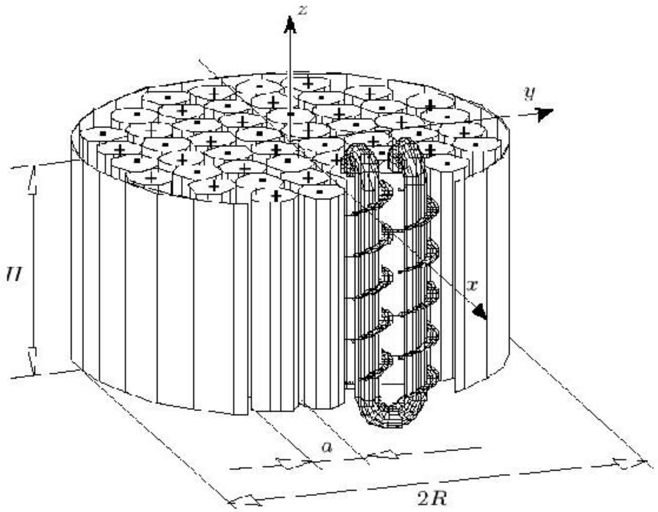
Sir Joseph Larmor, F.R.S.

In *M.N.* for 1933 November (pp. 39–48) there is a paper by Dr. T. G. Cowling on "The Magnetic Field of Sunspots." The Summary appended to it is brief and reads as follows :—

"The theory proposed by Sir Joseph Larmor, that the magnetic field of a sunspot is maintained by the currents it induces in moving matter, is examined and shown to be faulty : the same result also applies for the similar theory of the maintenance of the general field of Earth and Sun. The possibility that the sunspot field may arise as a disturbance in the general field is examined, and it is shown that several of the properties of the spot field are explicable on this hypothesis. Observation, however, must ultimately decide on its validity."

The view that I advanced briefly and tentatively long ago,* which has come to be referred to as, perhaps too precisely, the self-exciting dynamo analogy, is still, so far as I know, the only foundation on which a gaseous body such as the Sun could possess a magnetic field : so that if it is demolished there could be no explanation of the Sun's magnetism even remotely in sight. I am, however, not ready to accept the present adverse decision : and a restatement, not so condensed, perhaps with rather different emphasis, may be permitted.†

Now confirmed even by experiments

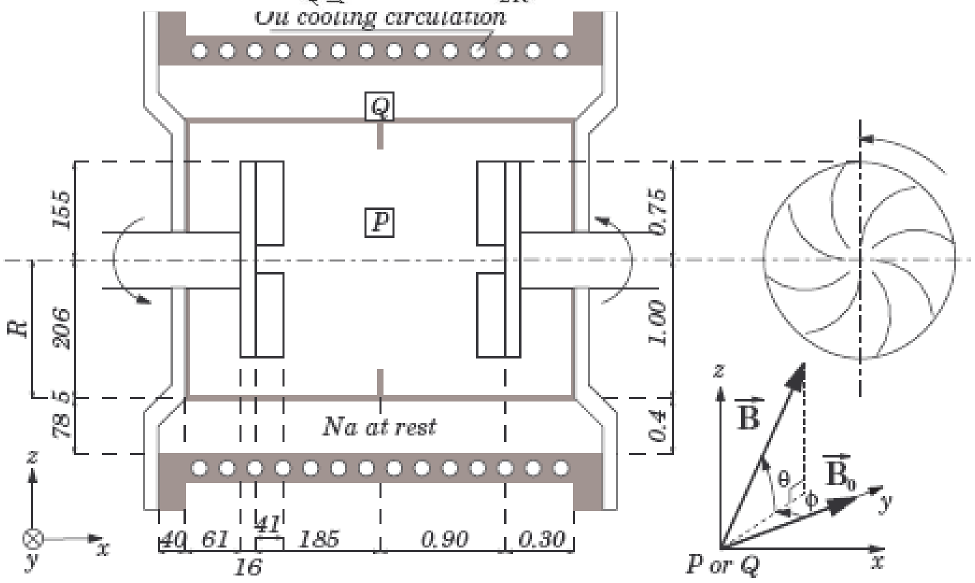


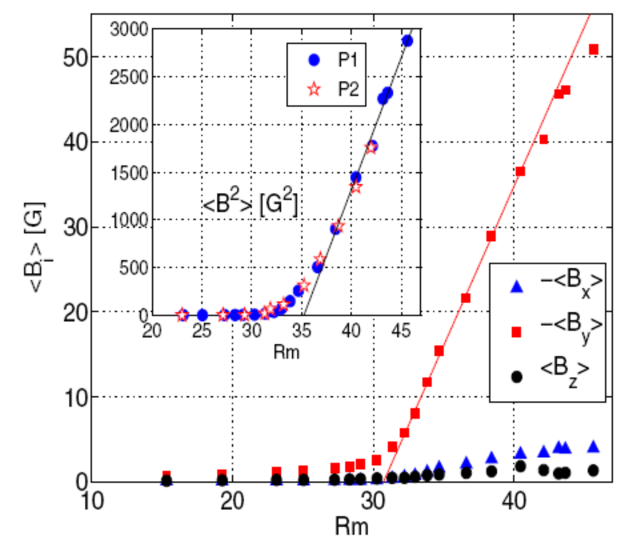
Karlsruhe and Riga: laminar

$$\overline{\mathbf{U}} \times \overline{\mathbf{B}}$$

Cadarache: turbulent

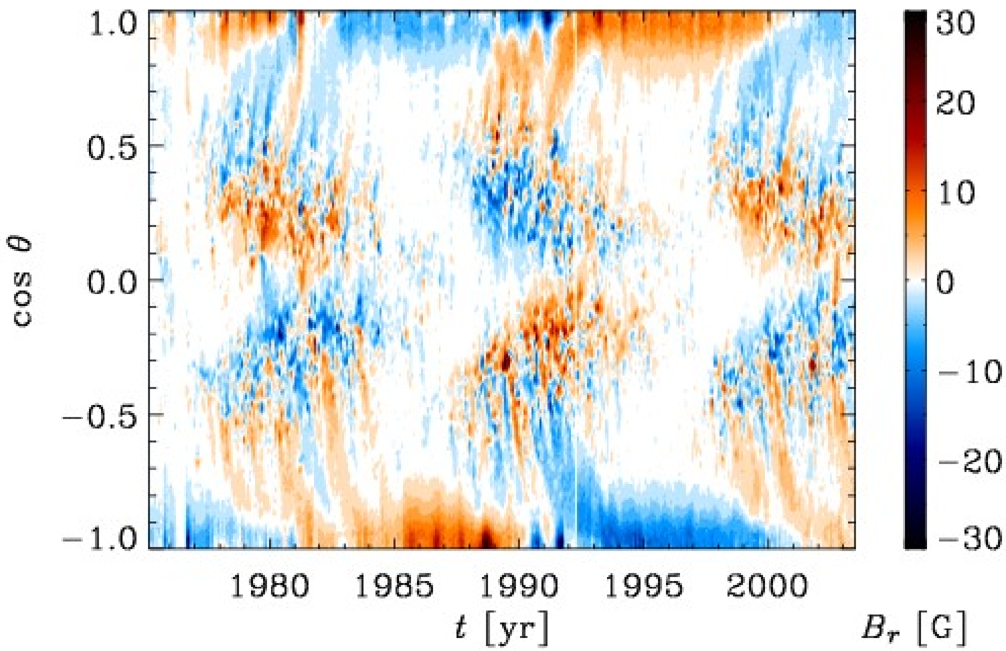
$$\overline{\mathbf{u} \times \mathbf{b}}$$

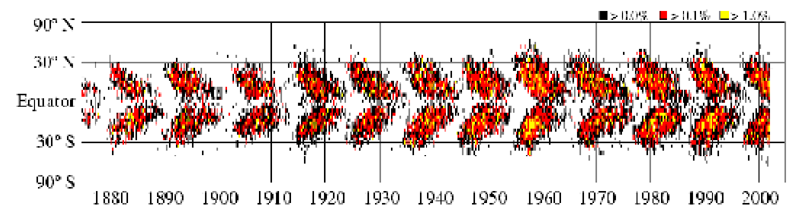




The big challenge: solar cycle

- Longitudinally averaged radial field $\overline{\mathbf{B}} = \int \mathbf{B} \frac{d\phi}{2\pi}$
- Spatio-temporal coherence
  - – 22 yr cycle, equatorward migration

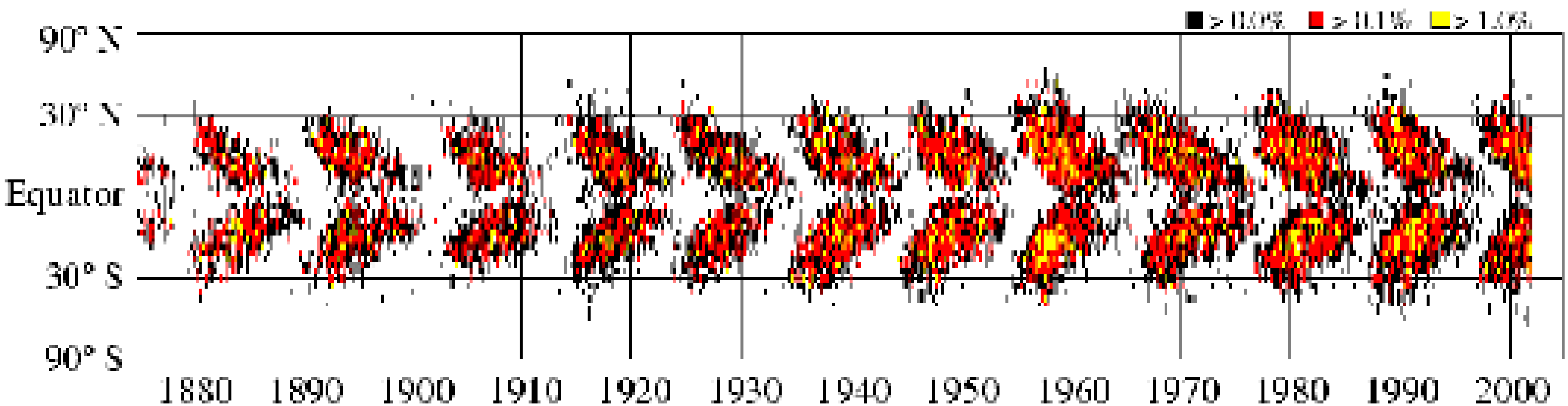




butterfly diagram

Mean field theory
seems sensible

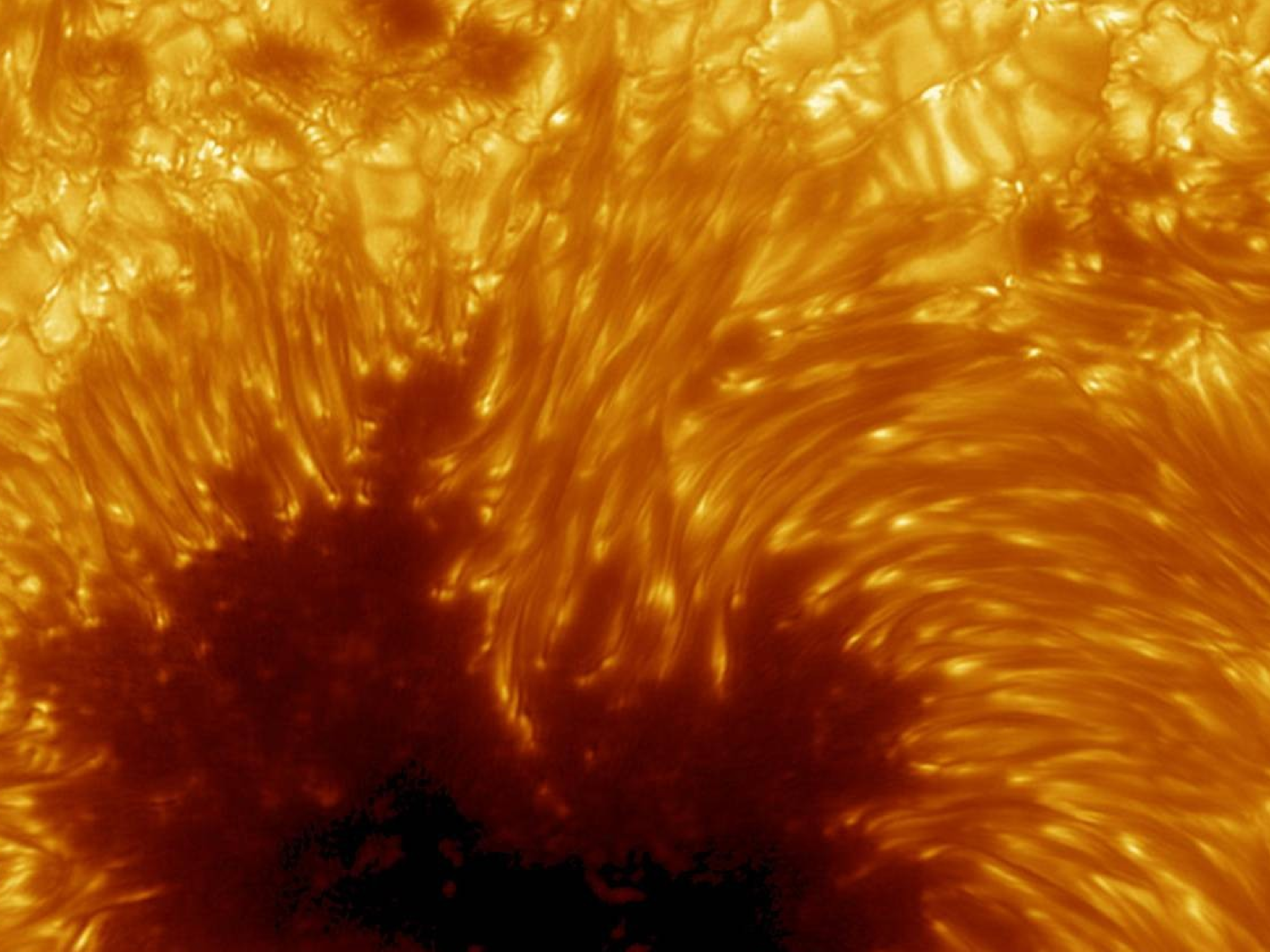
Solar 11 year sunspot cycle



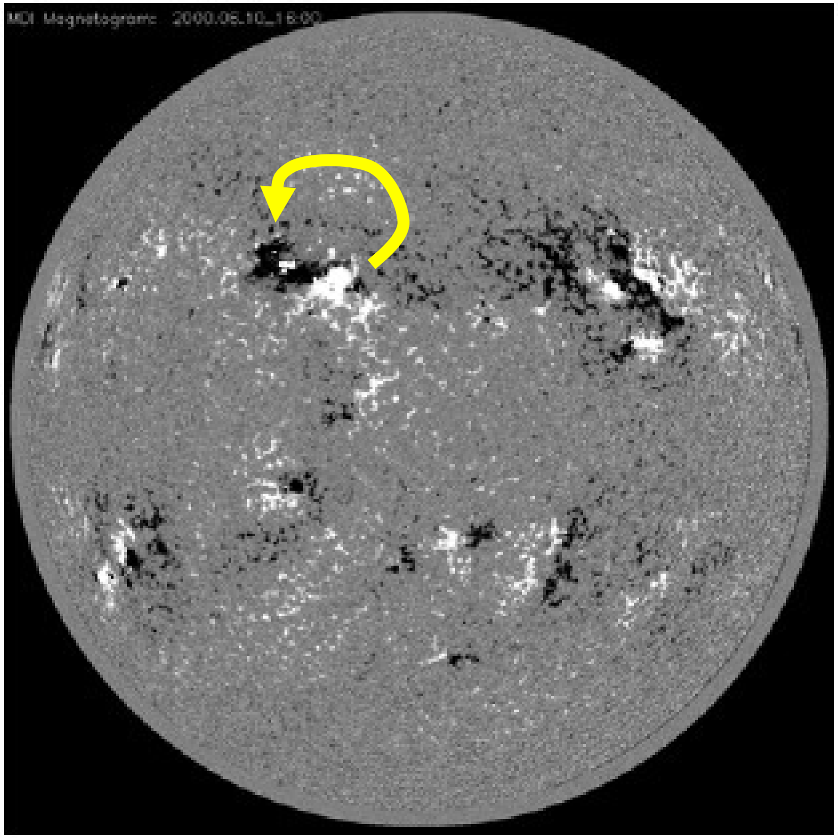
butterfly diagram

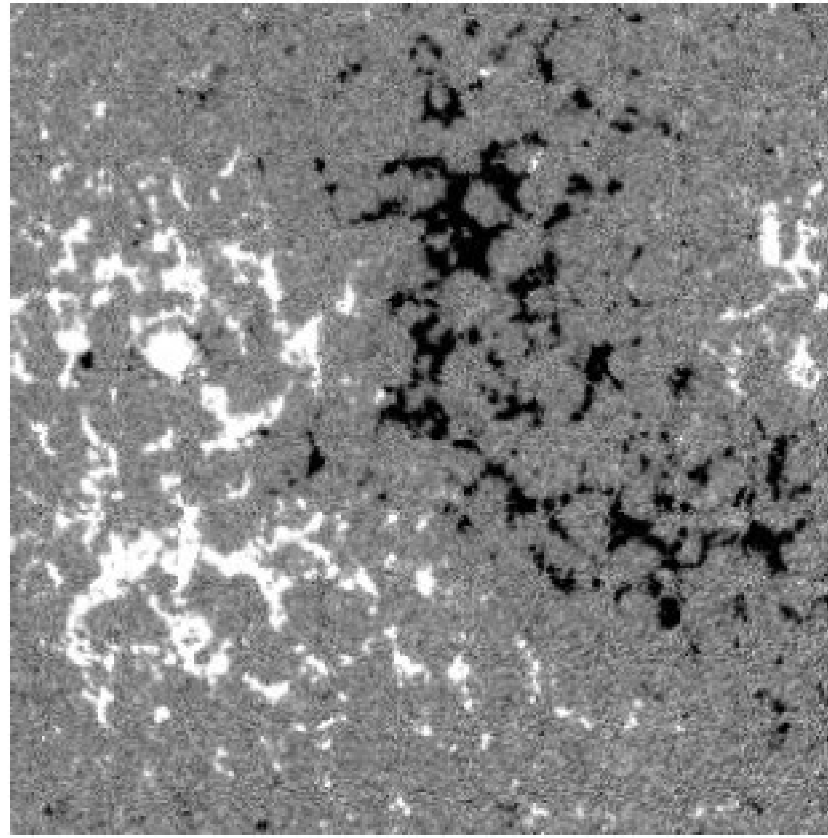
- Sunspots between +/- 30 degrees around equator
- New cycle begins at high latitude
- Ends at low latitudes
  - equatorward migration

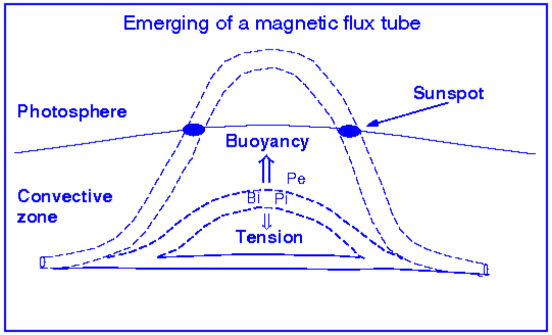
Sunspots



Large scale coherence



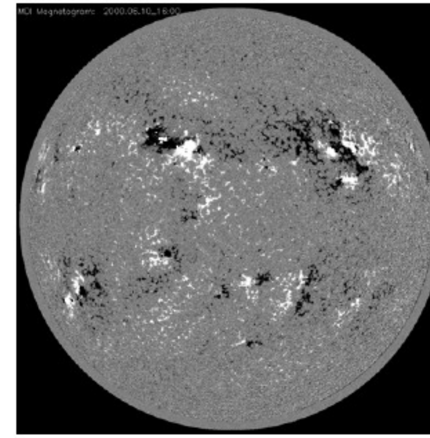


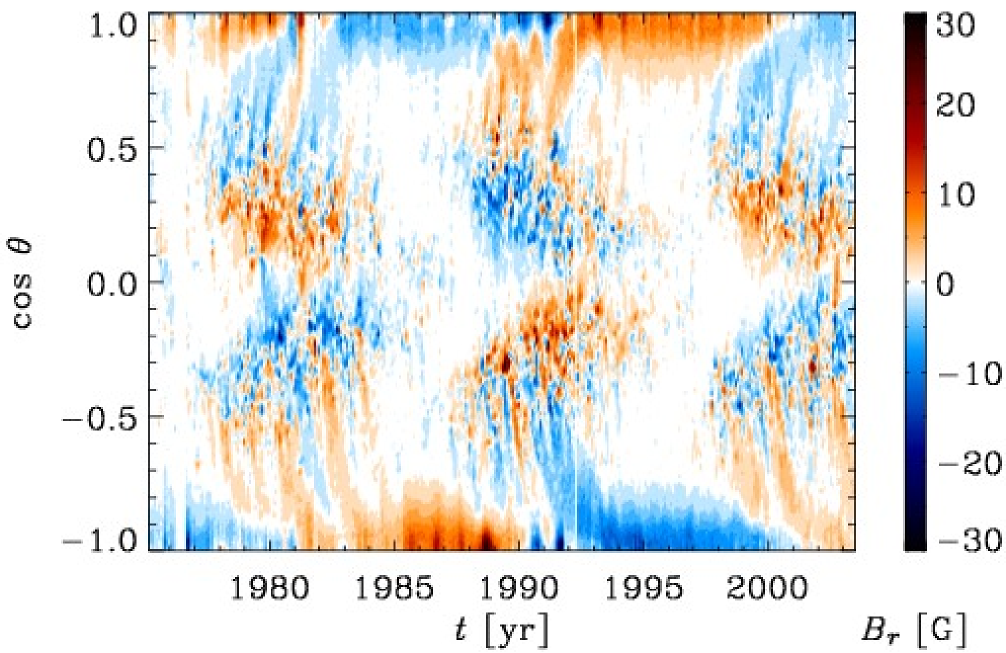


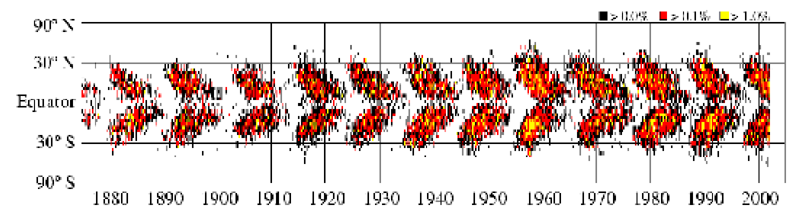
Active regions, bi-polarity
systematic east-west orientation
opposite in the south

22 year magnetic cycle

- Longitudinally averaged radial field
- Spatio-temporal coherence
  - 22 yr cycle, equatorward migration





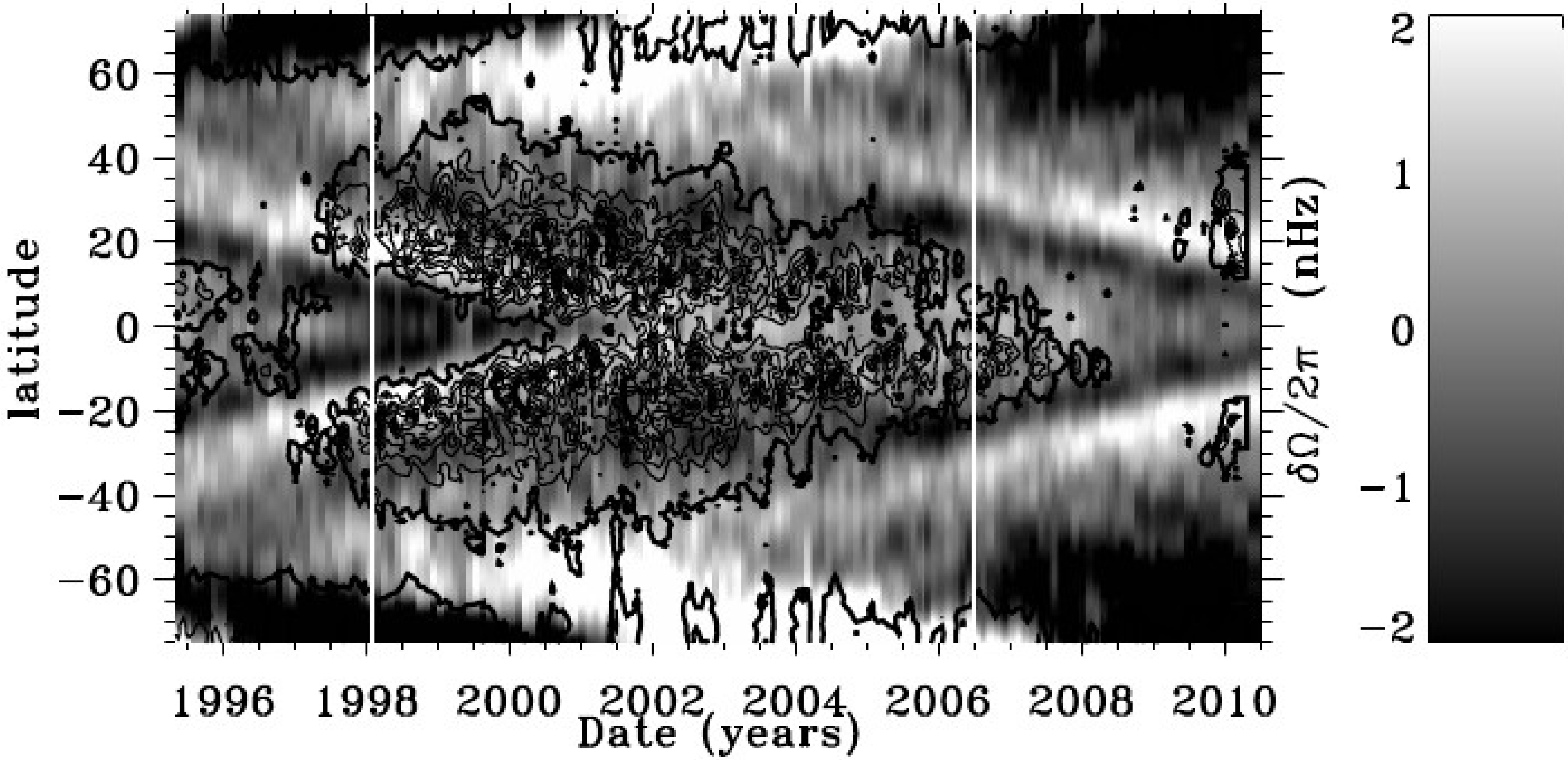


butterfly diagram

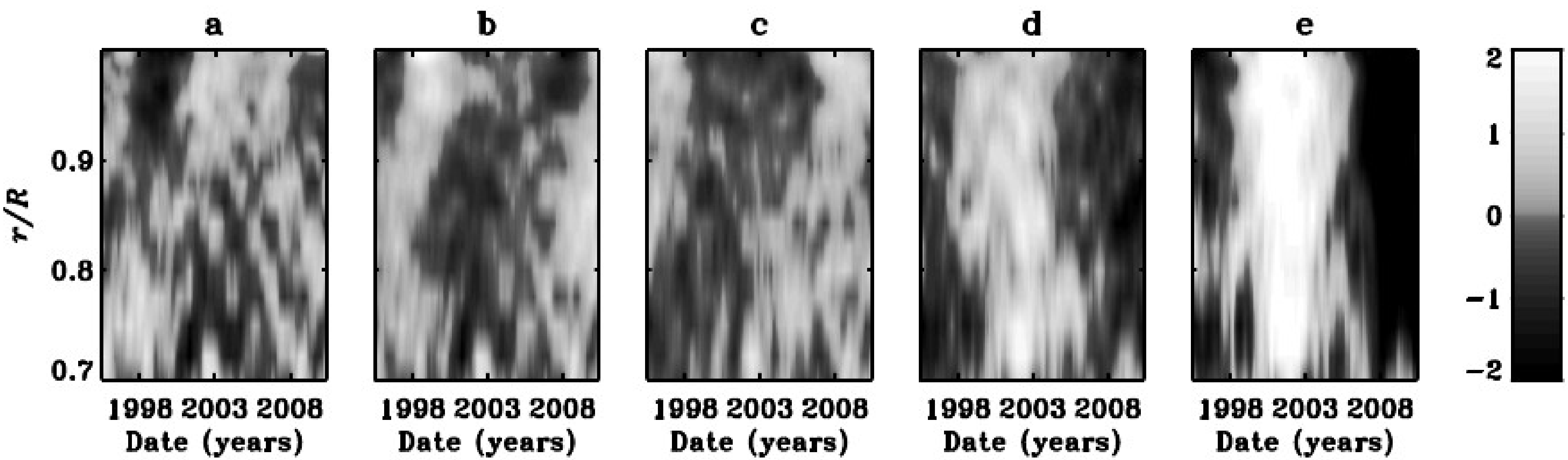
Poleward branch or poleward drift?

”Torsional” oscillation below surface

- At r=0.99R, 7 Mm below surface
- Accessed via helioseismology

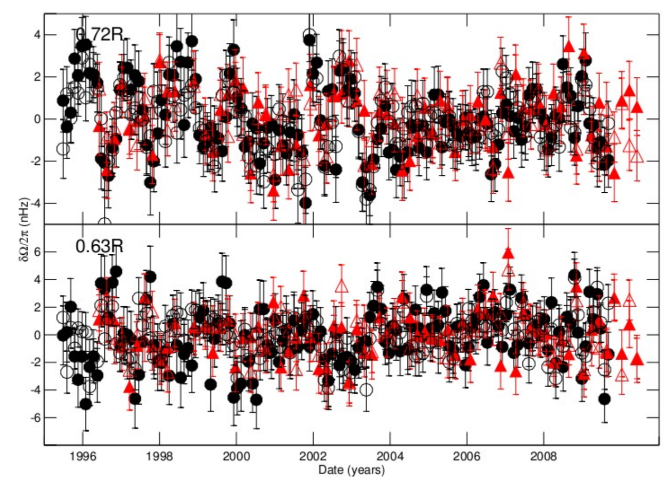


Seismic variations with depth

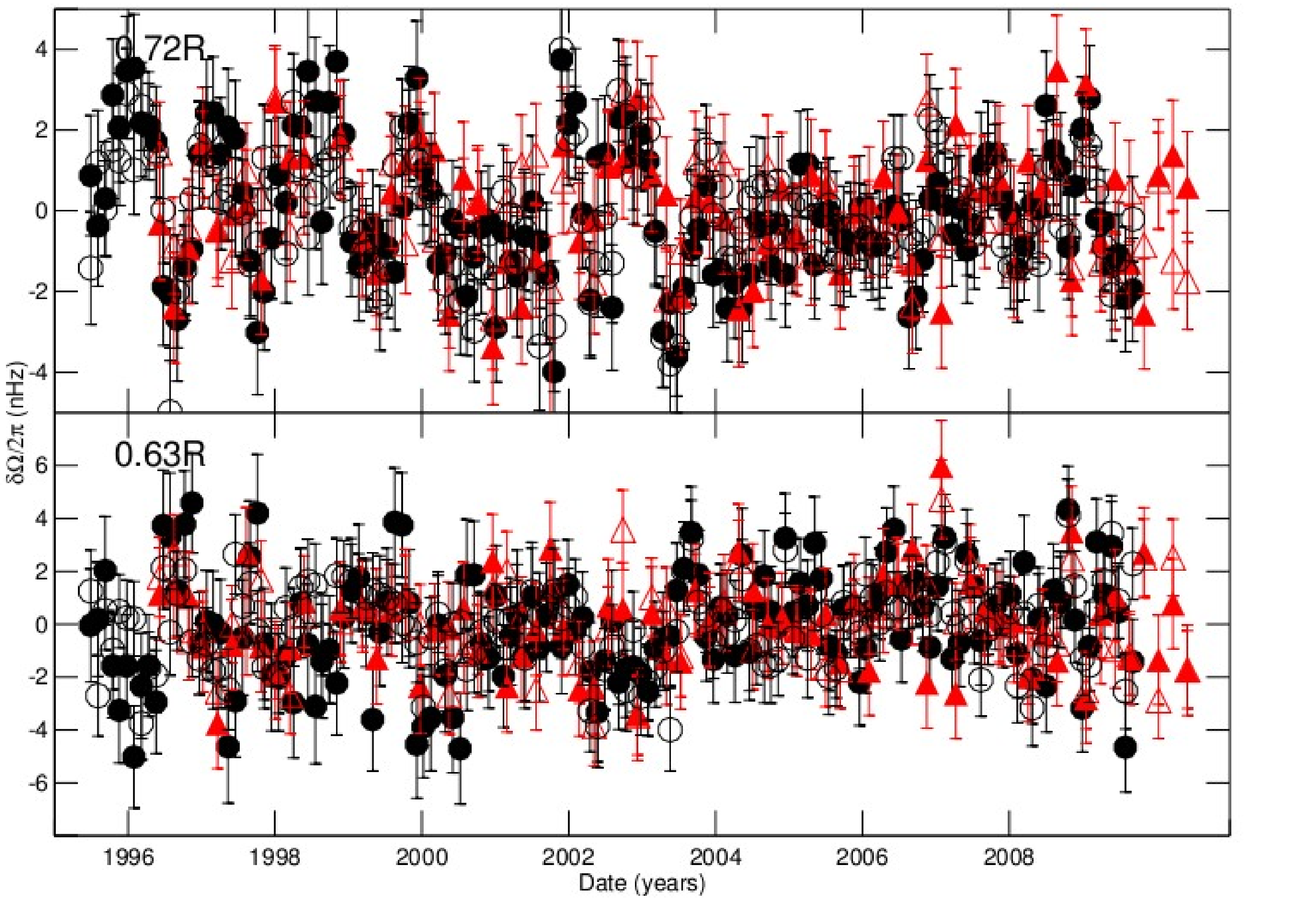


0 degr 15 degr 30 degr 45 degr 60 degr

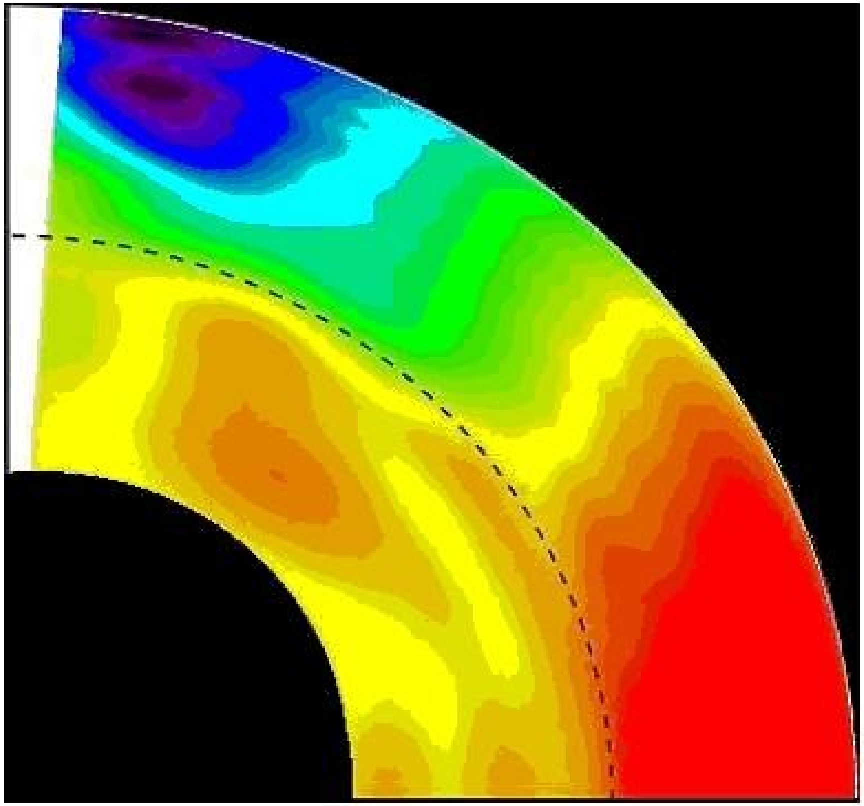
- 11 yr cycle down to r=0.99R
- Radial outward migration
- perhaps 1.3 yr around 0.7R

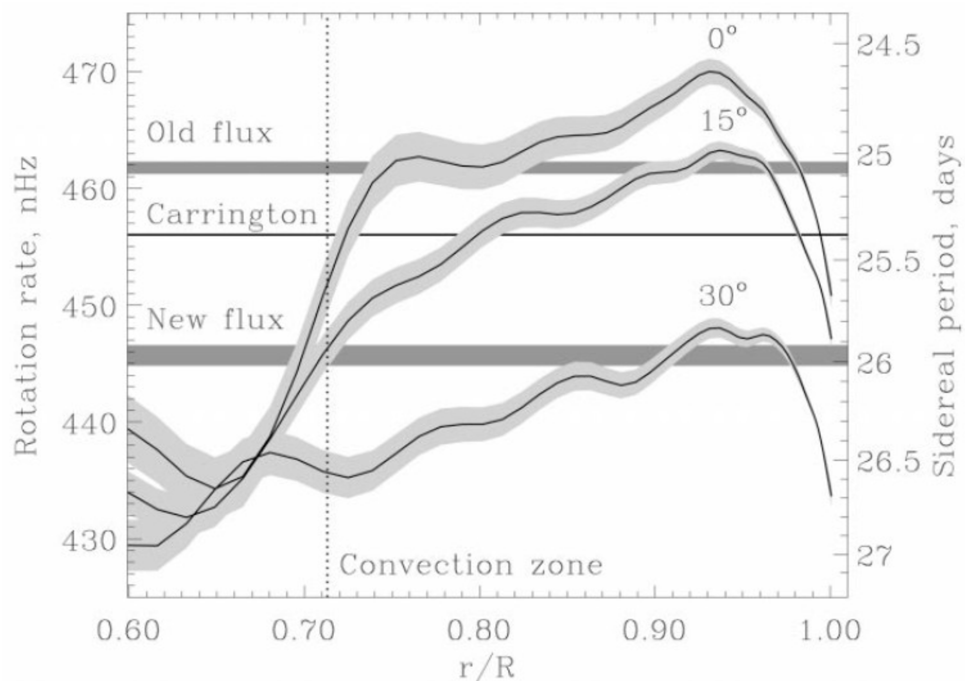


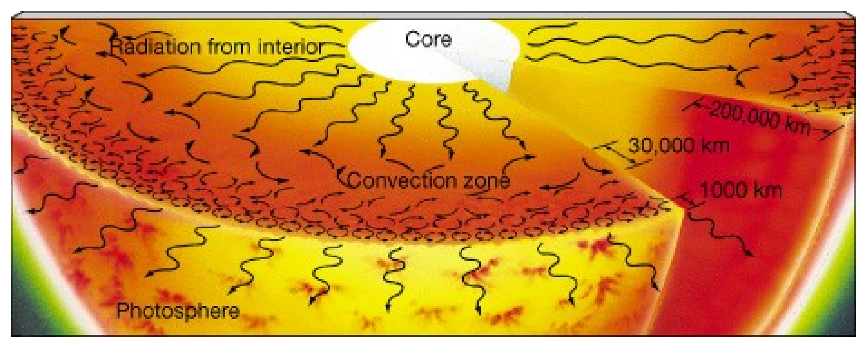
1.3 yr oscillation in tachocline



Spoke-like + radial shear layers

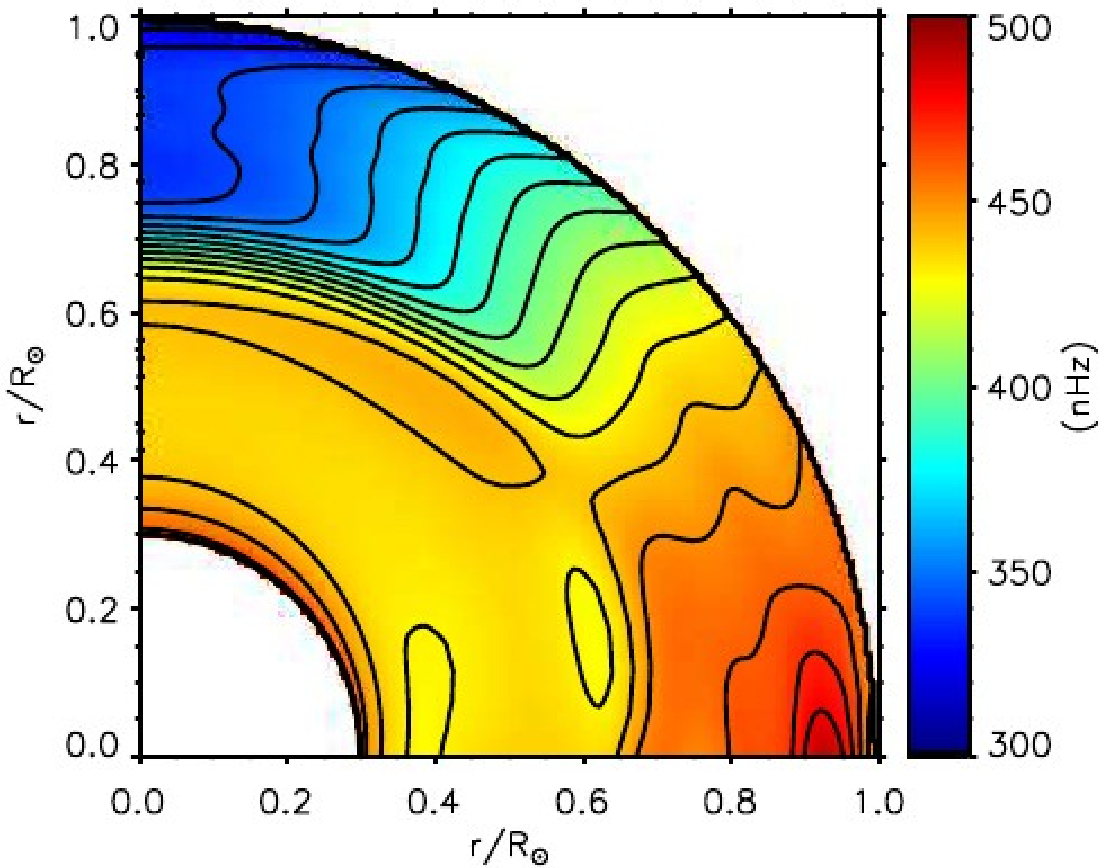


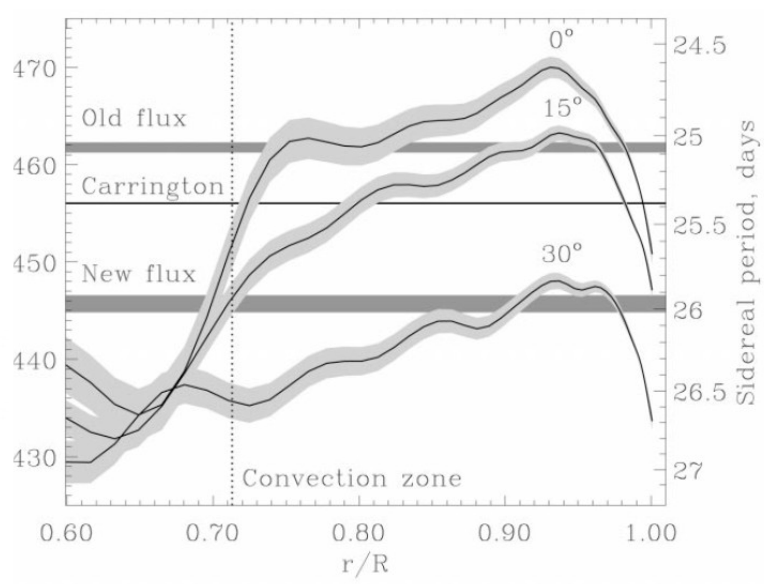




- Tachocline around *r/R*=0.65…0.75
- Near-surface shear layer at *r/R*=0.95…1

Results from PICARD

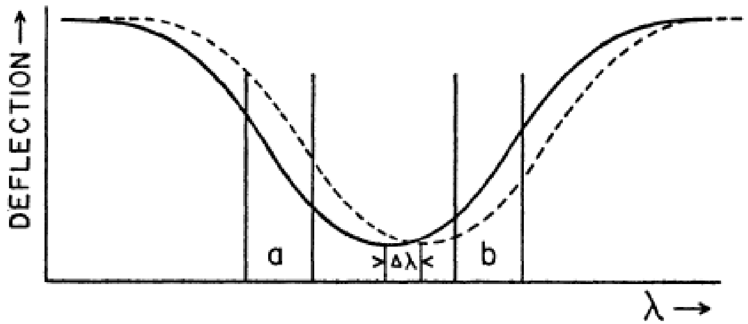


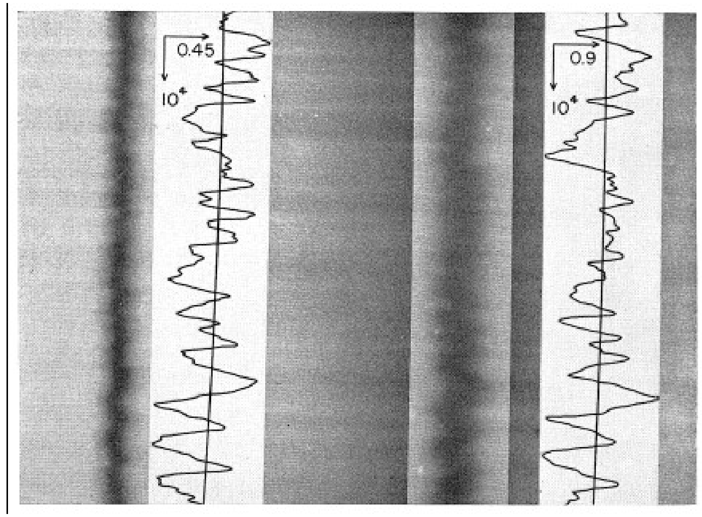


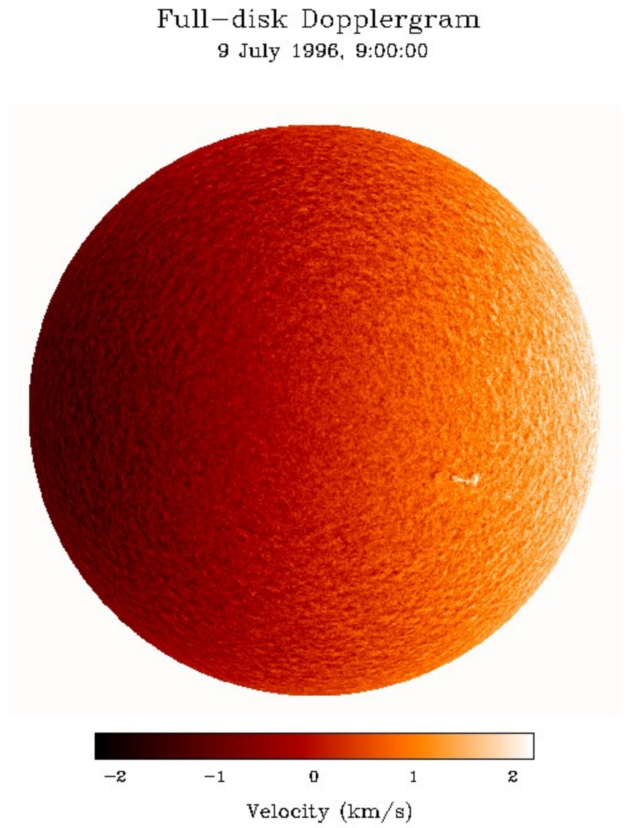
- Cyclindrical contours at high latitudes
- Negative radial shear near equator

5 min oscillations → helioseismology

Discovered in 1960 (Leighton et al. 1962)







Was thought to be response of upper atmosphere to convection

Waves in stratified atmosphere

$$\rho \frac{D\boldsymbol{v}}{Dt} + \nabla p - \rho \boldsymbol{g} = 0$$

$$\frac{Ds}{Dt} = 0$$

$$\frac{D\rho}{Dt} + \rho \nabla . \boldsymbol{v} = 0$$

$$\frac{\partial \boldsymbol{v}^{(1)}}{\partial t} - \boldsymbol{e}_z g \left(\frac{s^{(1)}}{c_p} - \frac{p^{(1)}}{\gamma p^{(0)}} \right) + \frac{1}{\rho^{(0)}} \nabla p^{(1)} = 0$$

$$\frac{\partial s^{(1)}}{\partial t} + v_z^{(1)} \frac{ds^{(0)}}{dz} = 0$$

$$\frac{\partial p^{(1)}}{\partial t} + v_z^{(1)} \frac{dp^{(0)}}{dz} + \gamma p^{(0)} \nabla . \boldsymbol{v}^{(1)} = 0$$

$$\boldsymbol{x}' = \boldsymbol{x}/H_0 \quad \text{with} \qquad H_0 = \gamma H_p/(1 - \gamma/2)$$

$$t' = t/T_0 \quad \text{with} \qquad T_0 = H_0/c$$

$$\boldsymbol{v}' = \boldsymbol{v}^{(1)} \exp(-z/2H_p)/(ic)$$

$$s' = s^{(1)} \exp(-z/2H_p)/[ic_p \sqrt{\gamma - 1}\,]$$

$$p' = p^{(1)} \exp(+z/2H_p)/[i\gamma p^{(0)}(0)]$$

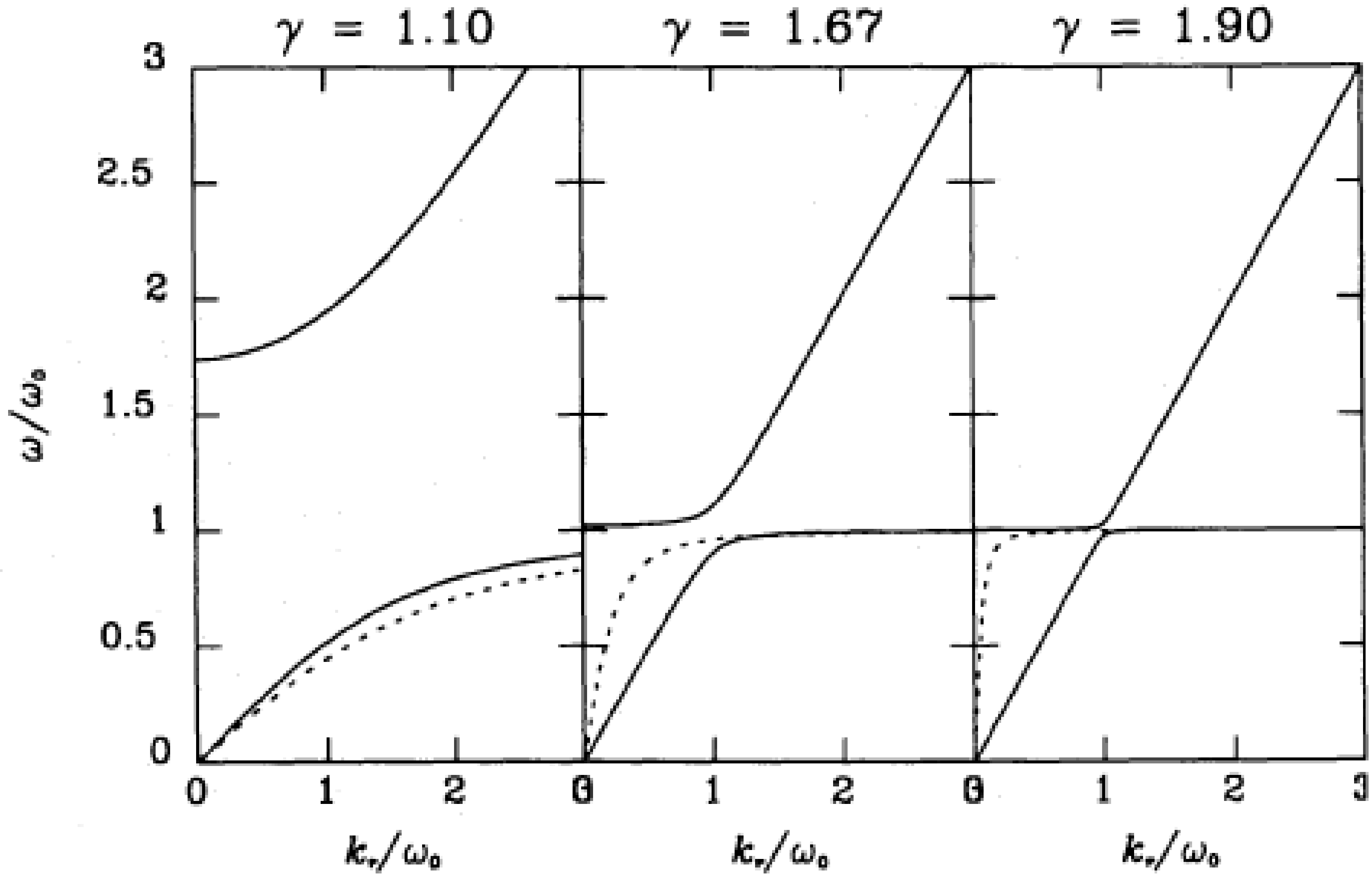
Waves in stratified atmosphere

$$\begin{pmatrix} i\partial_t & 0 & 0 & 0 & i\partial_x \\ 0 & i\partial_t & 0 & 0 & i\partial_y \\ 0 & 0 & i\partial_t & -i\omega_0 & i+i\partial_z \\ 0 & 0 & i\omega_0 & i\partial_t & 0 \\ i\partial_x & i\partial_y & -i+i\partial_z & 0 & i\partial_t \end{pmatrix} \begin{pmatrix} v'_x \\ v'_y \\ v'_z \\ s' \\ p' \end{pmatrix} = 0$$

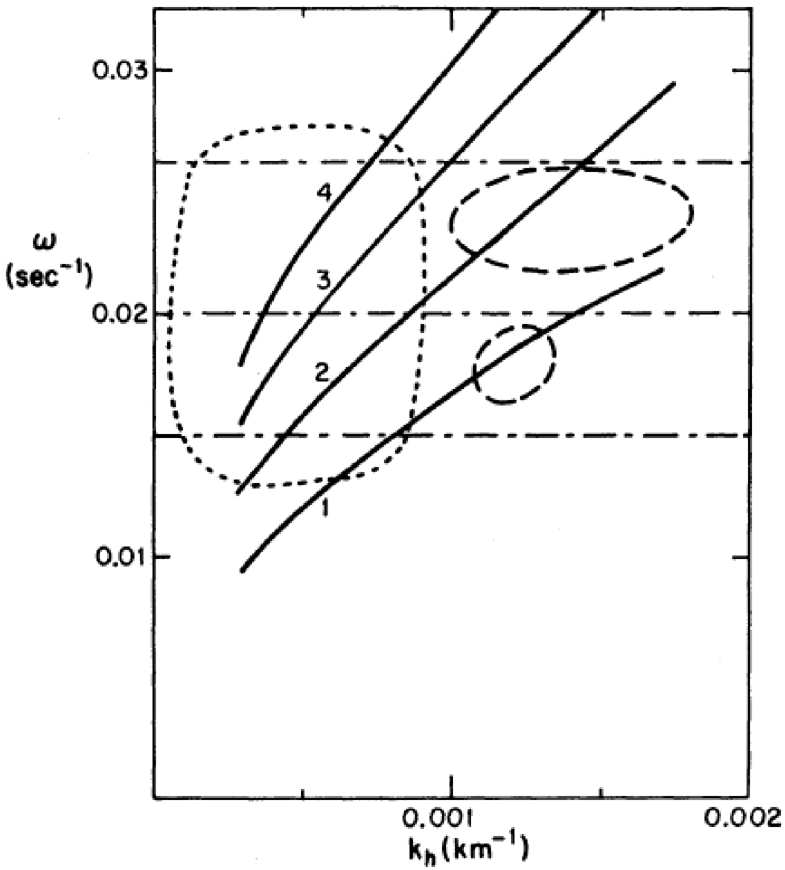
$$\det L = \omega[(\omega^2 - k_r^2)(\omega^2 - \omega_0^2) - \omega^2(k_z^2 + 1)]$$

$$= \omega[\omega^4 - \omega^2(k^2 + \omega_0^2 + 1) + \omega_0^2 k_r^2]$$

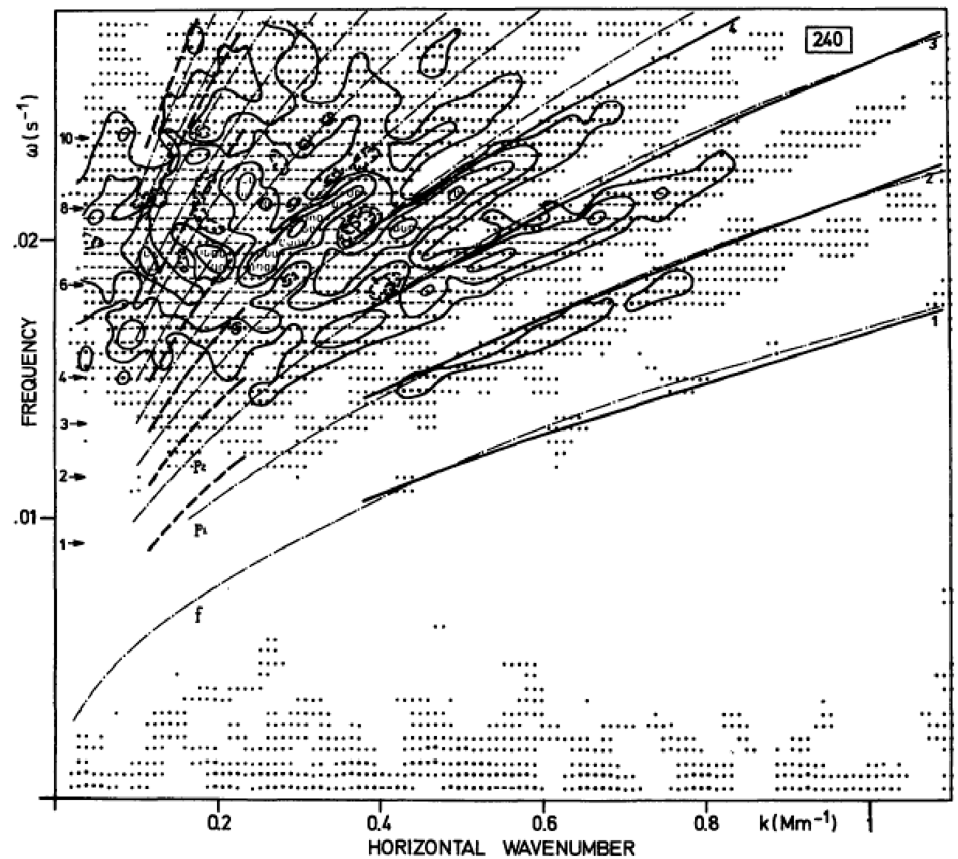
Dispersion relation



5 min osc are global

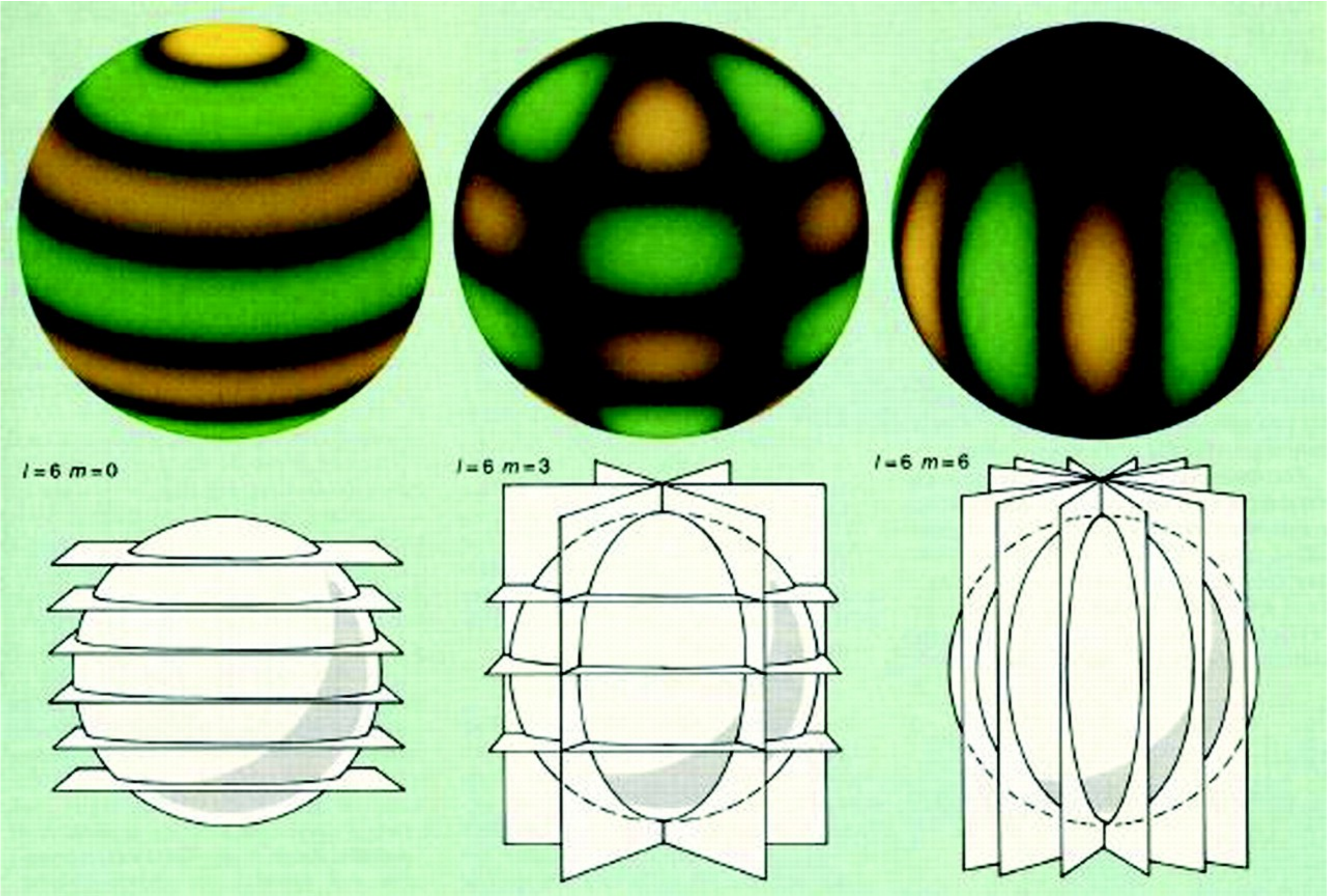


Roger Ulrich
(1970)



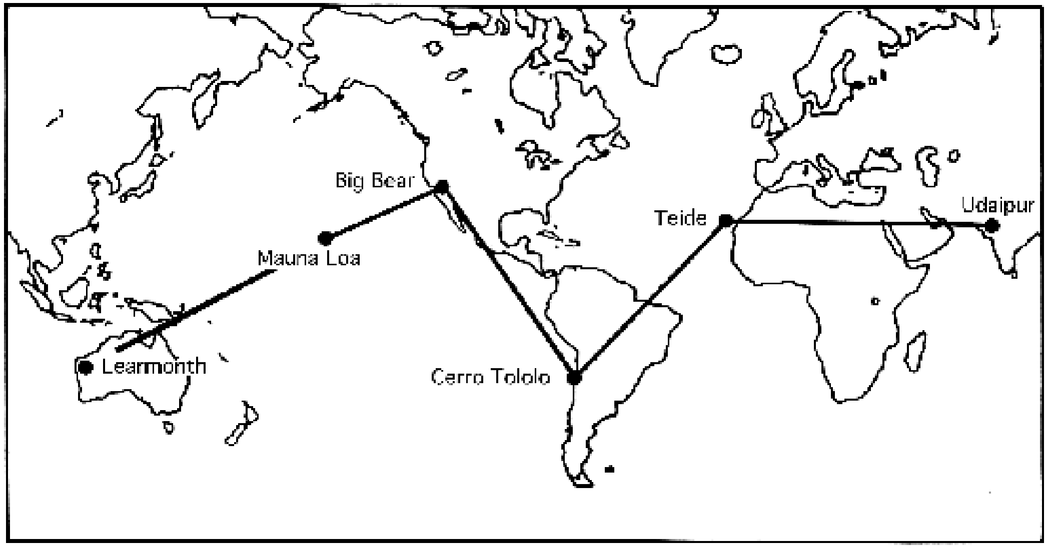
Franz-Ludwig Deubner
(1974)

Degree *l*, order *m*



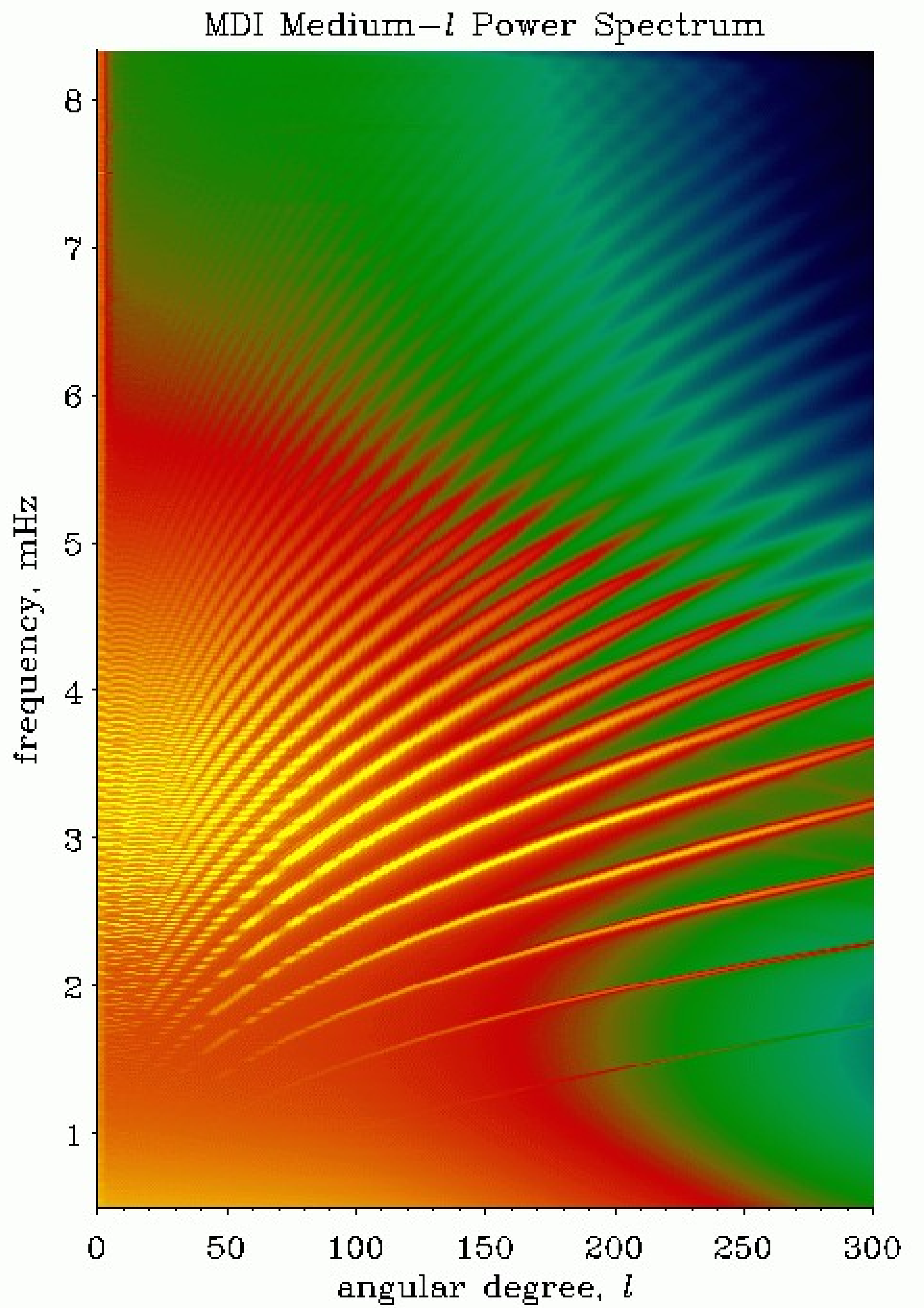
GONG
global oscillation network group

Since late 1980ties

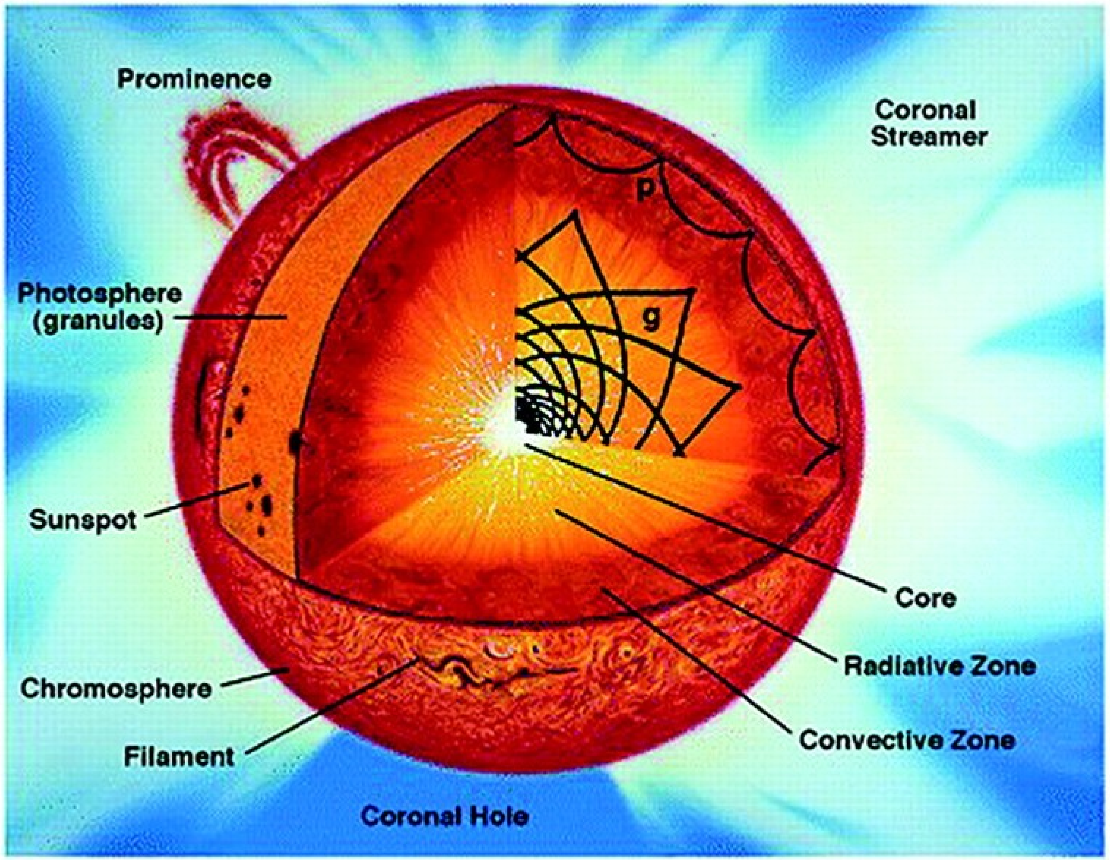


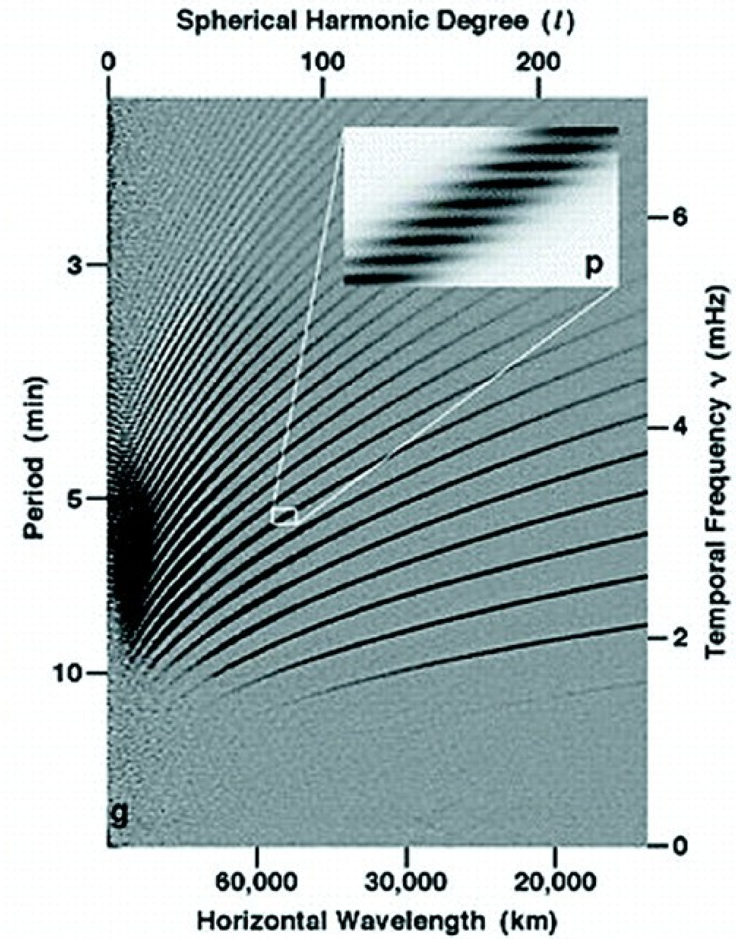
Current state of the art

SOHO
Space craft
1993 – 2014
(lost in 1998)



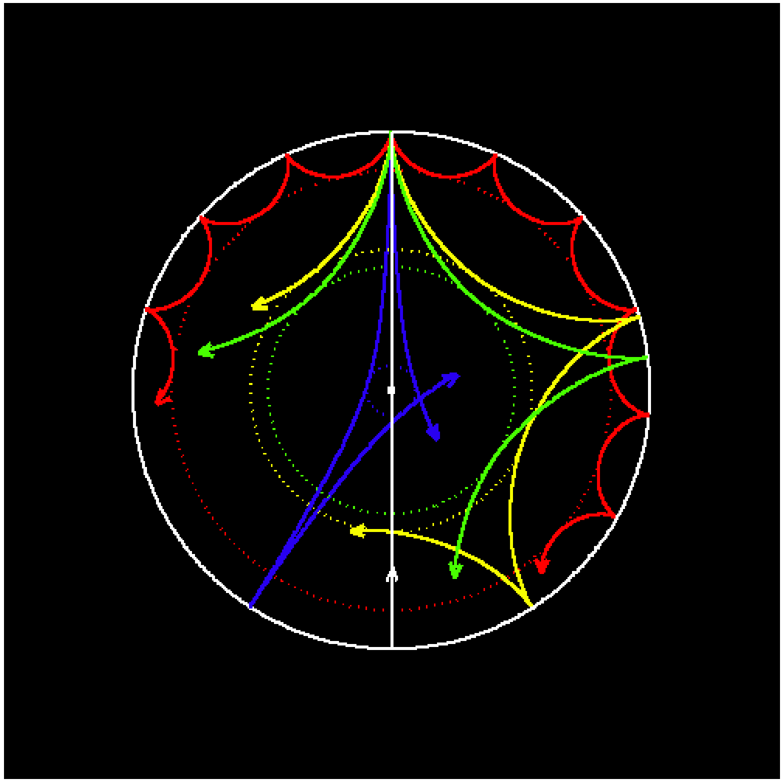
Only p-modes observed



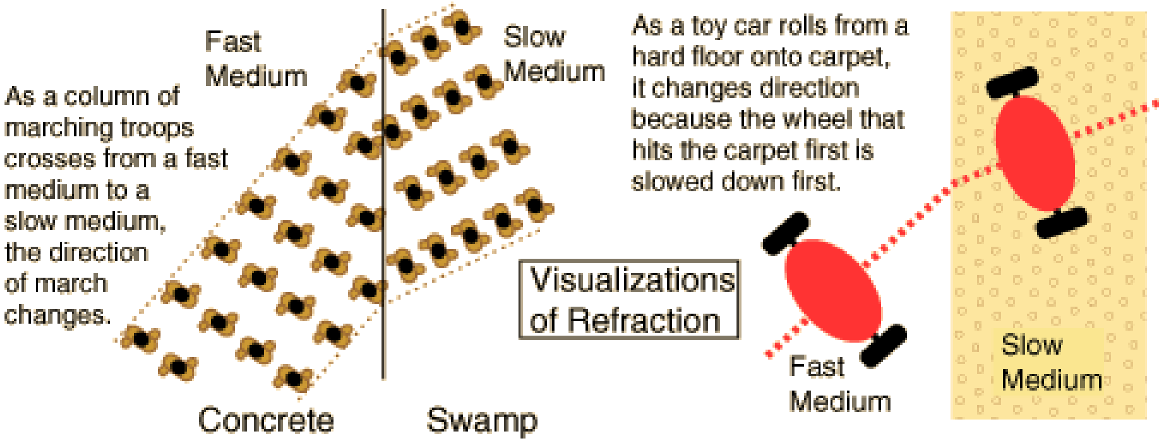


$$\omega^4 + \omega^2(\quad) + ..; = 0$$

Refraction Reflection



Top: reflection
when wavenlength
~ density scale height



Deeper down:
Sound speed large

$$c_s^2 = \frac{RT}{\mu}$$

Inversion: input/output

$$n\pi = \int_{r_0}^{R_0} k_r \, \mathrm{d}r$$

$$k_r = \sqrt{\frac{\omega^2}{c_s^2} - \frac{l(l+1)}{r^2}}$$

$$k_r = \frac{\omega}{r}\sqrt{\frac{r^2}{c_s^2} - \frac{l(l+1)}{\omega^2}}$$

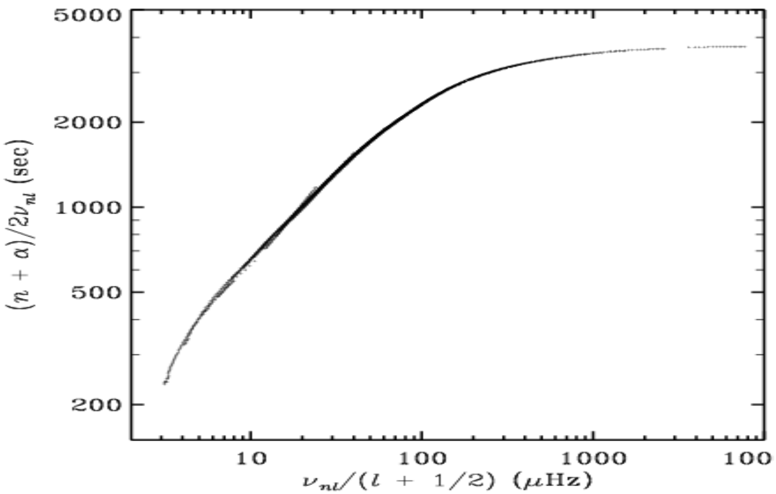
$$F(u) = \int_u^{\xi_0} \sqrt{\xi - u}\, G'(\xi)\, \mathrm{d}\xi$$

$$G(\xi) = \frac{2}{\pi}\int_{\xi}^{\xi_0} \frac{1}{\sqrt{\xi - u}} F'(u)\, \mathrm{d}u$$

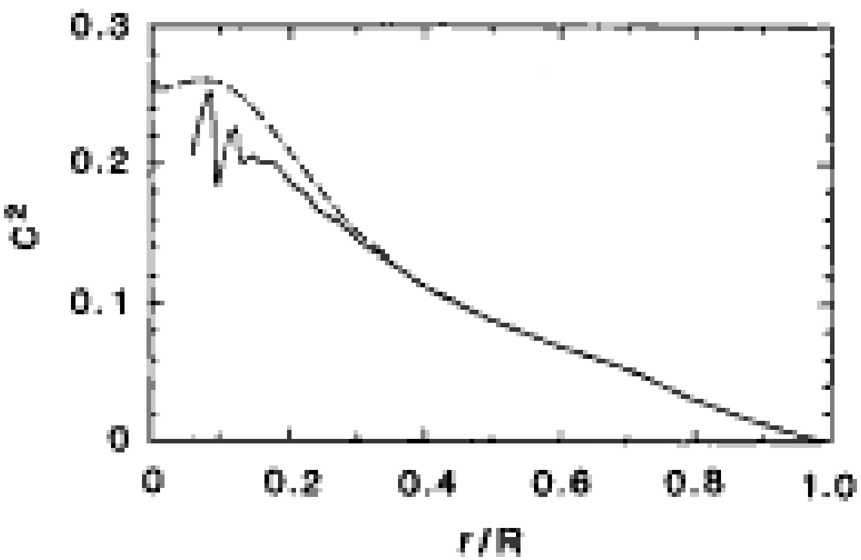
$$\xi \equiv \frac{r^2}{c_s^2}$$

$$u \equiv \frac{l(l+1)}{\omega^2}$$

Abel integral eqn



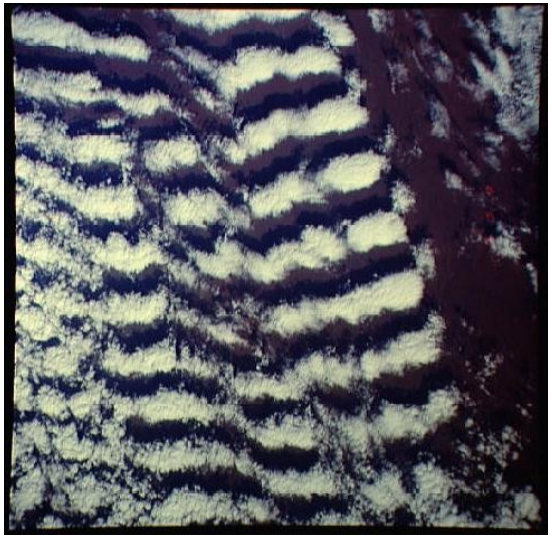
Duval law: collapsed kω-diagram



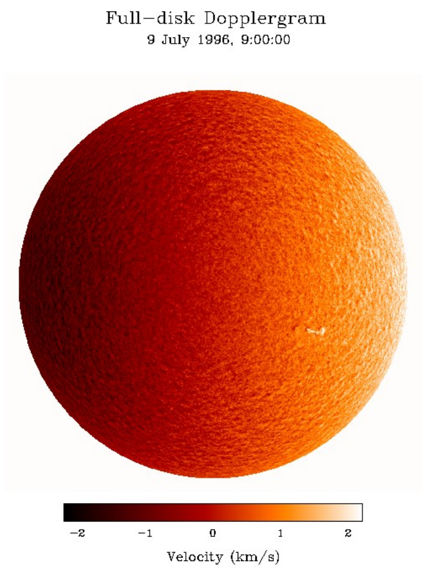
Sound speed

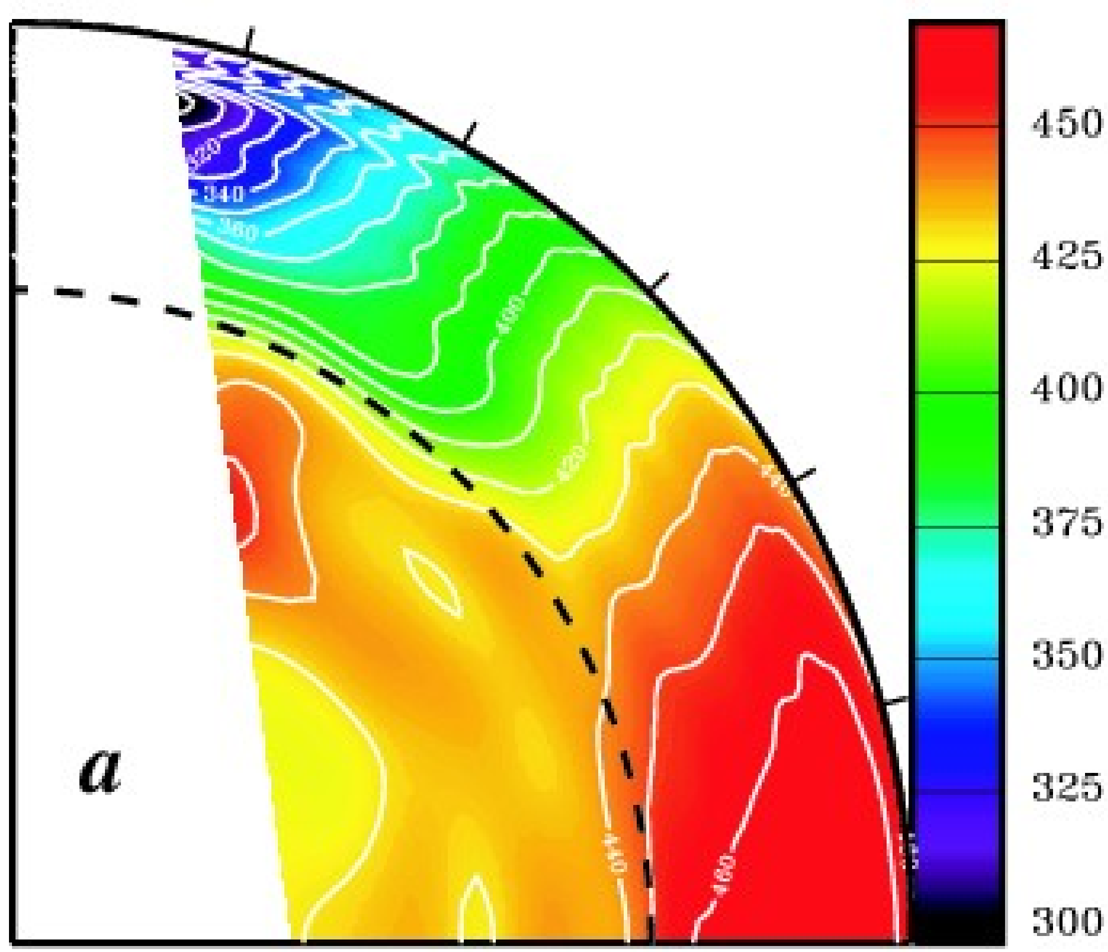
g-modes

- Would probe the center
- Are evanescent in the convection zone



What else from helioseismology?

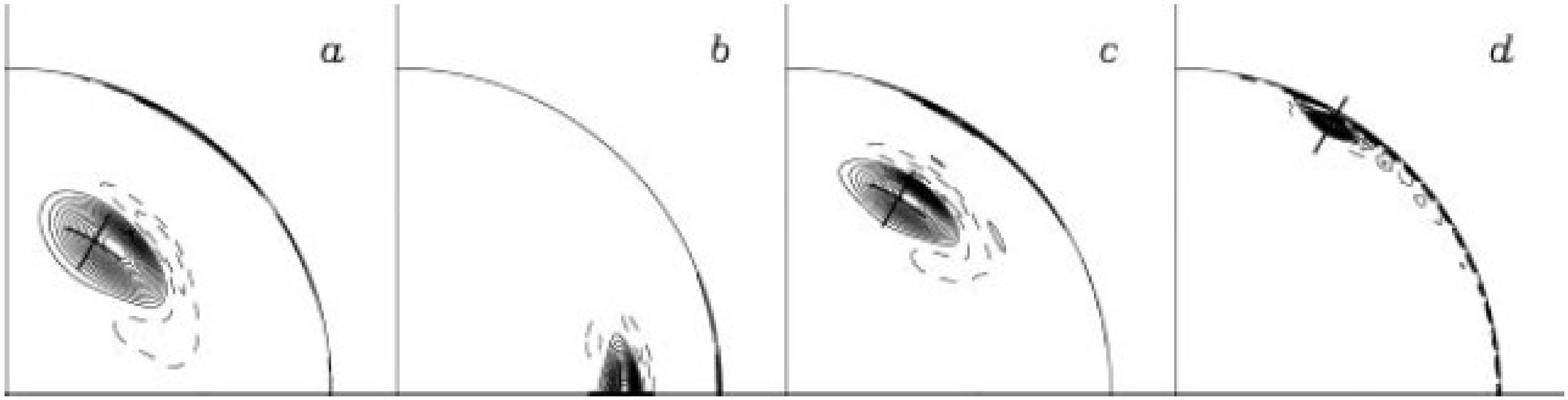




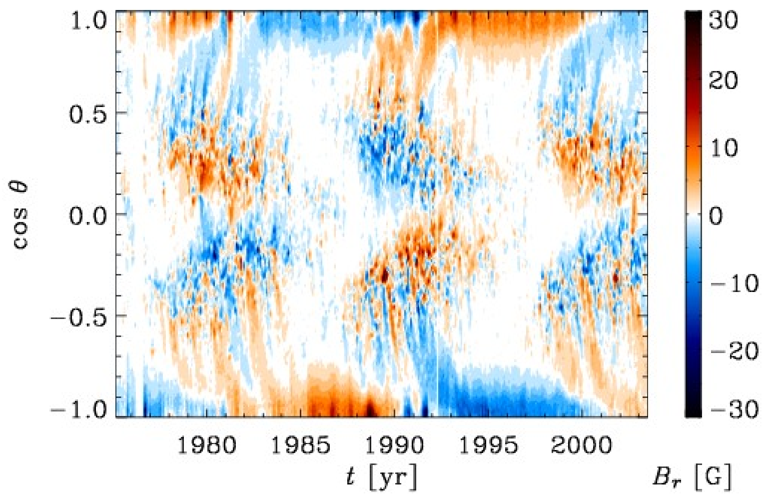
spoke-like at equ.
dΩ/dr>0 at bottom
dΩ/dr<0 at top
Rigid below CZ

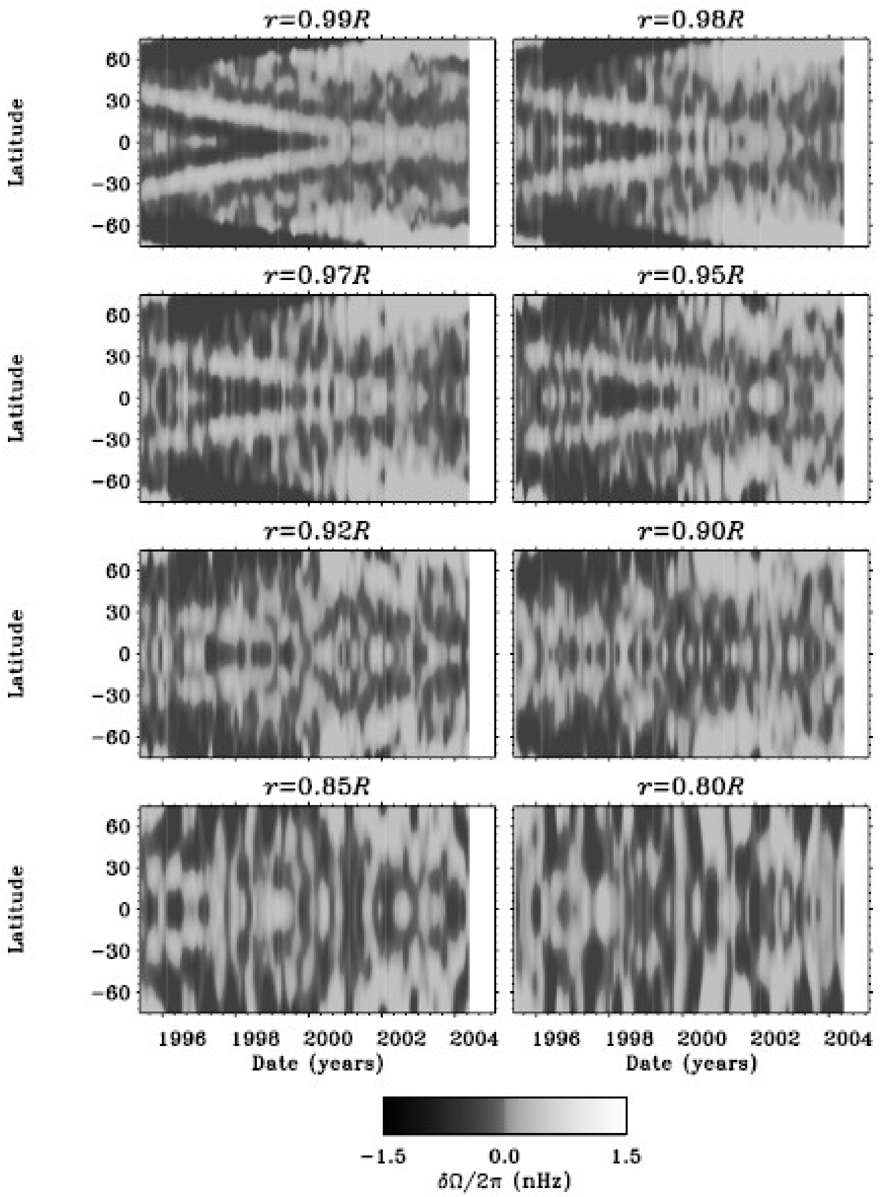
Internal angular velocity

$$\omega_{nlm} - \omega_{nl0} = m \int_0^{\pi} \int_0^{R} K(r,\theta)\, \Omega(r,\theta)\, r\mathrm{d}r\, \mathrm{d}\theta$$

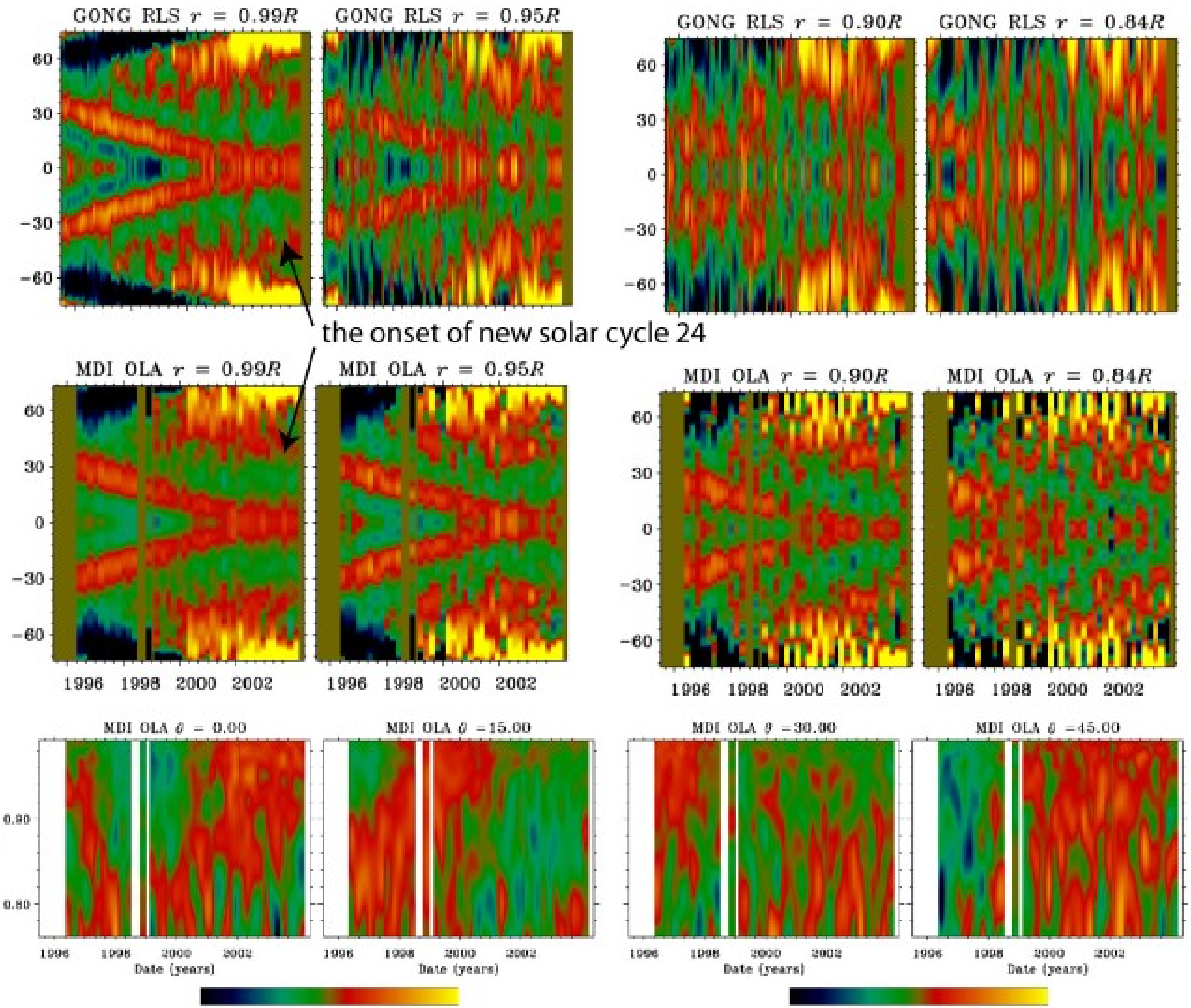


Cycle dependence of Ω(r,θ)



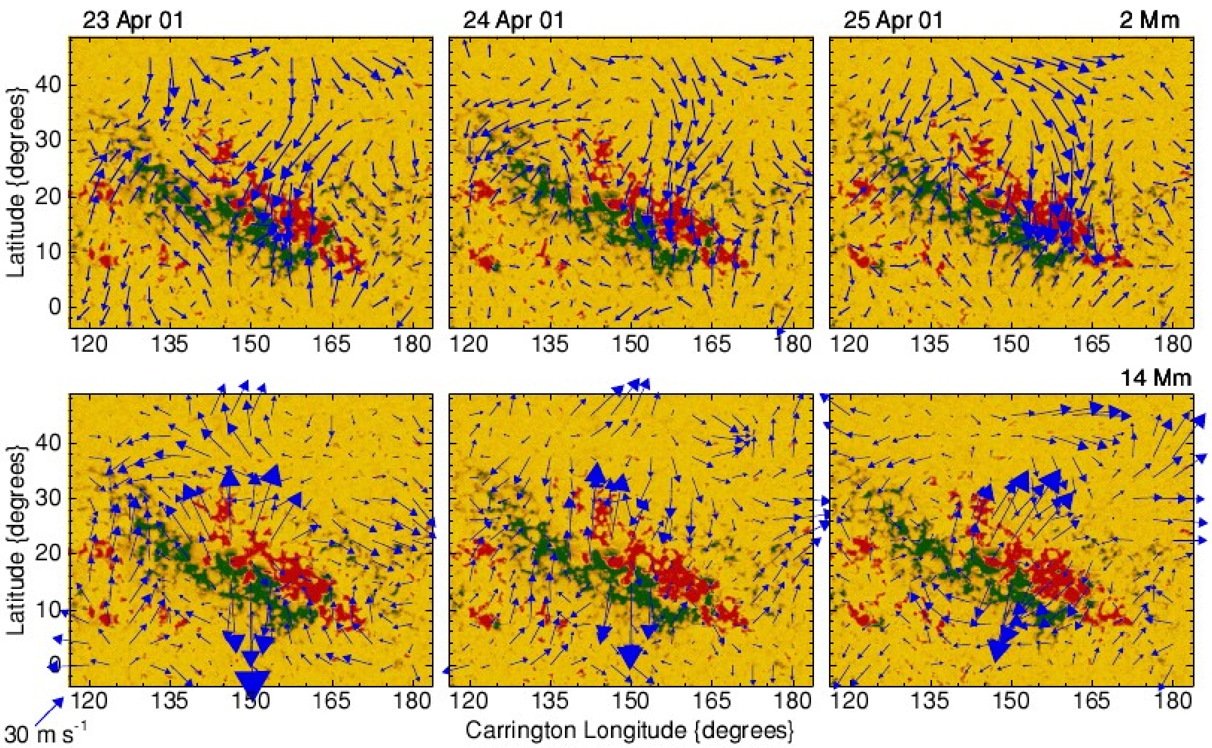


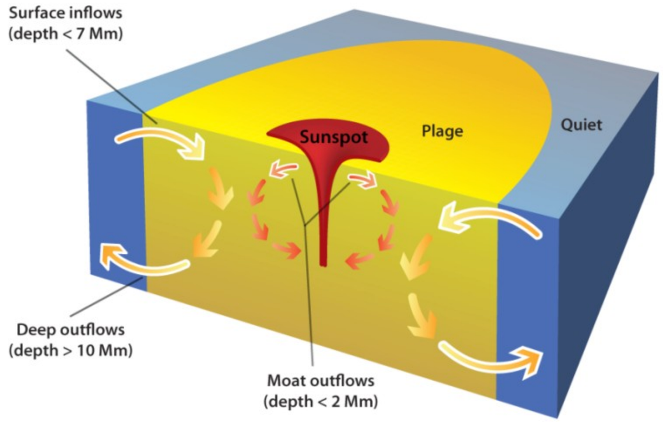
GONG vs SOHO



GONG RLS $r = 0.99R$
GONG RLS $r = 0.95R$
GONG RLS $r = 0.90R$
GONG RLS $r = 0.84R$
60
30
0
−30
−60
the onset of new solar cycle 24
MDI OLA $r = 0.99R$
MDI OLA $r = 0.95R$
MDI OLA $r = 0.90R$
MDI OLA $r = 0.84R$
1996
1998
2000
2002
MDI OLA $\theta = 0.00$
MDI OLA $\theta = 15.00$
MDI OLA $\theta = 30.00$
MDI OLA $\theta = 45.00$
r/R
0.90
0.80
Date (years)

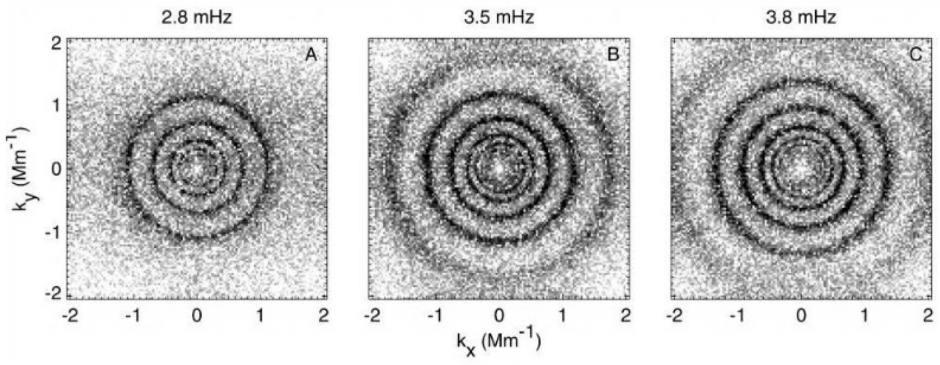
Active region subsurface flows





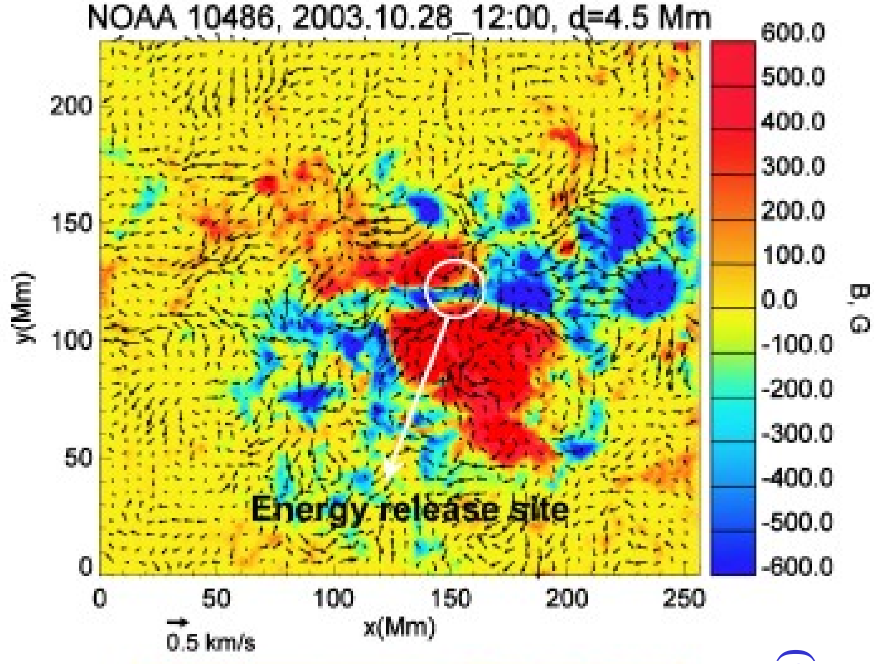
Hindman et al. (2009, ApJ)

Ring diagram analysis

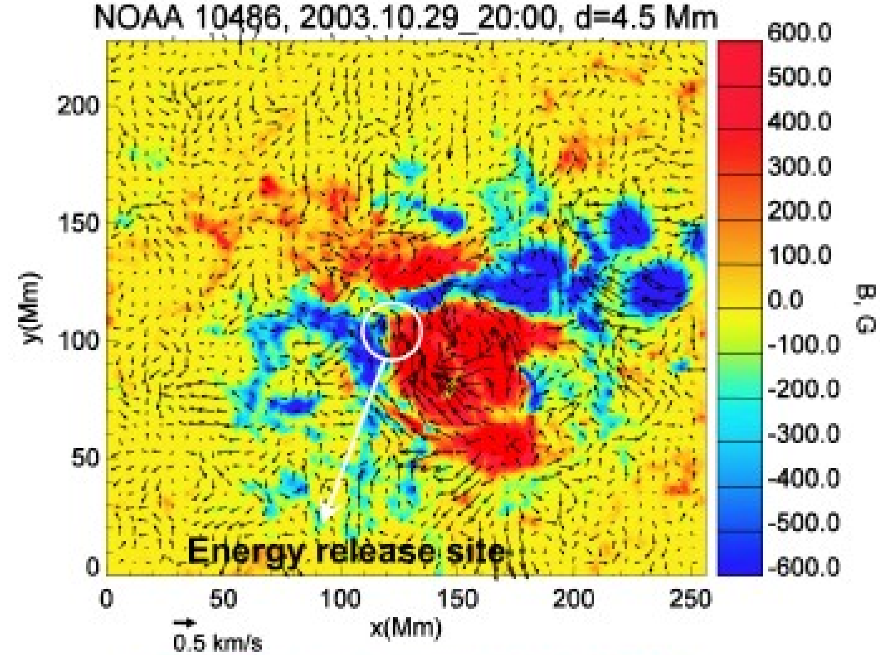


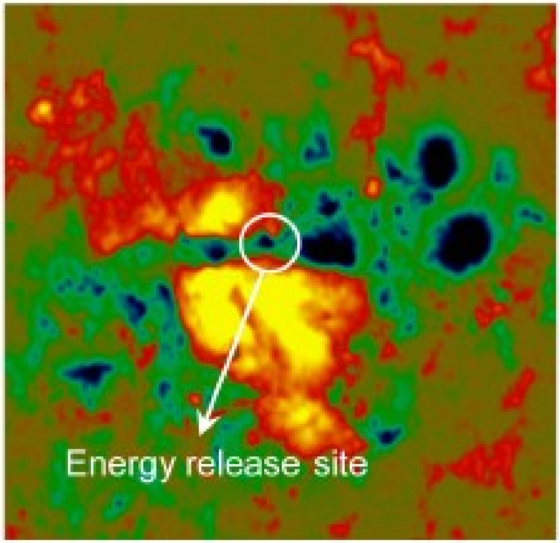
Sunquakes

X17 flare

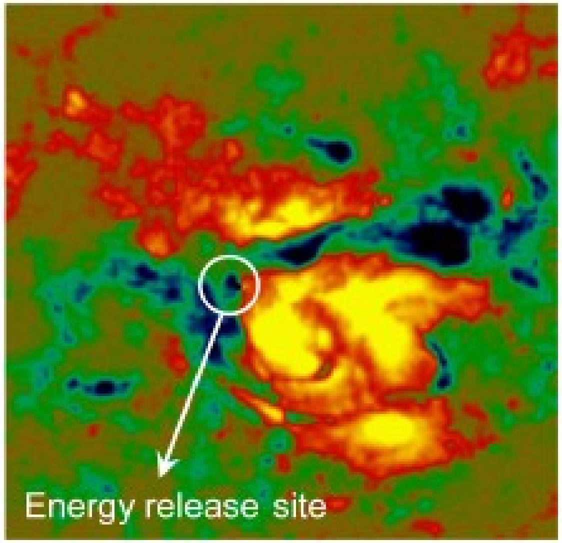


X10 flare

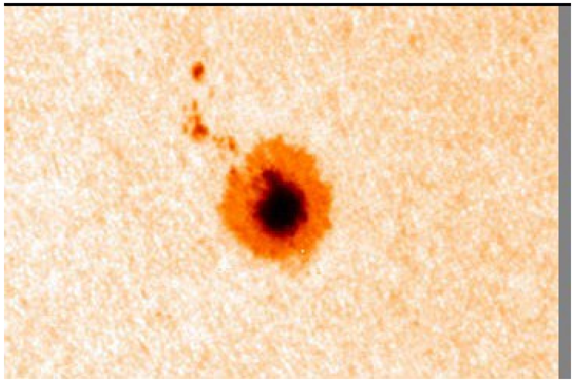


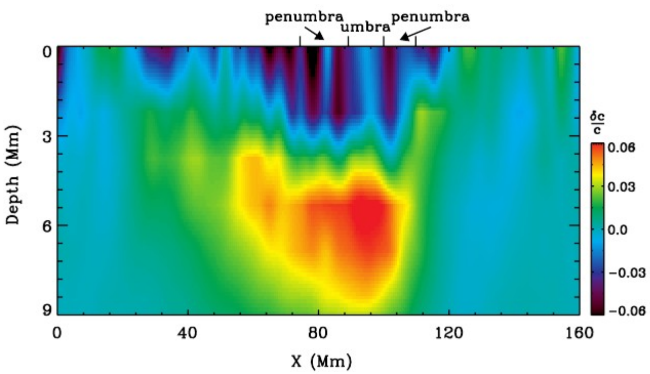


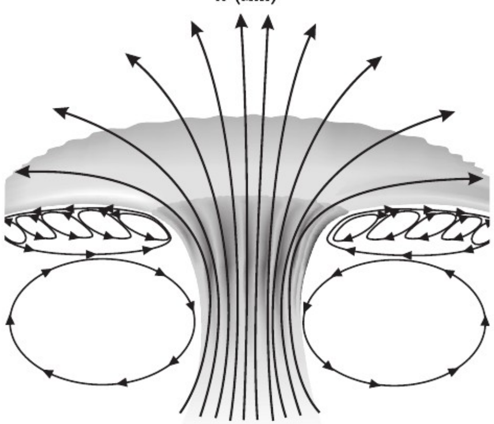
Kosovichev & Zharkova (1998)



Helioseismology vs current thinking







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Theories of the Solar Cycle and Its Effect on Climate

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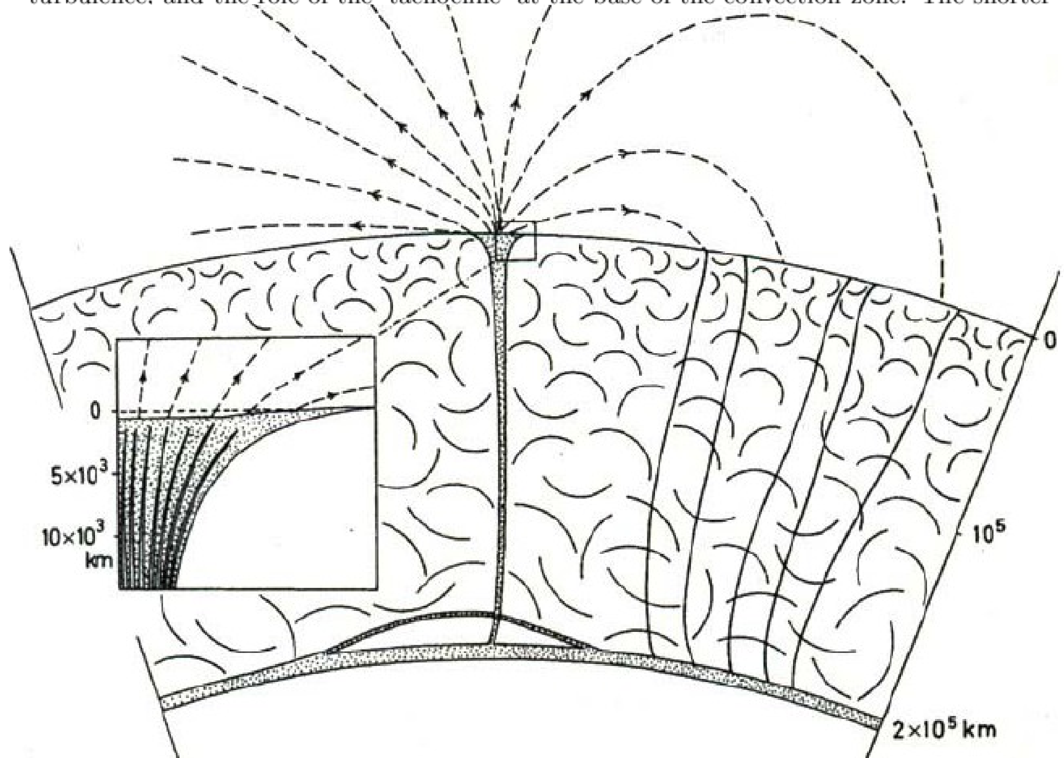
In the first part, some views of the solar magnetic cycle are discussed and confronted with observations, with focus on two aspects at the core of most models: the role of convective turbulence, and the role of the 'tachocline' at the base of the convection zone. The shorter



Tomorrow

- MHD on the computer
- Numerical aspects
- Simple wave experiments