

A Theoretical Explanation for the Solar Torsional Oscillations Preceding the Sunspot Cycle

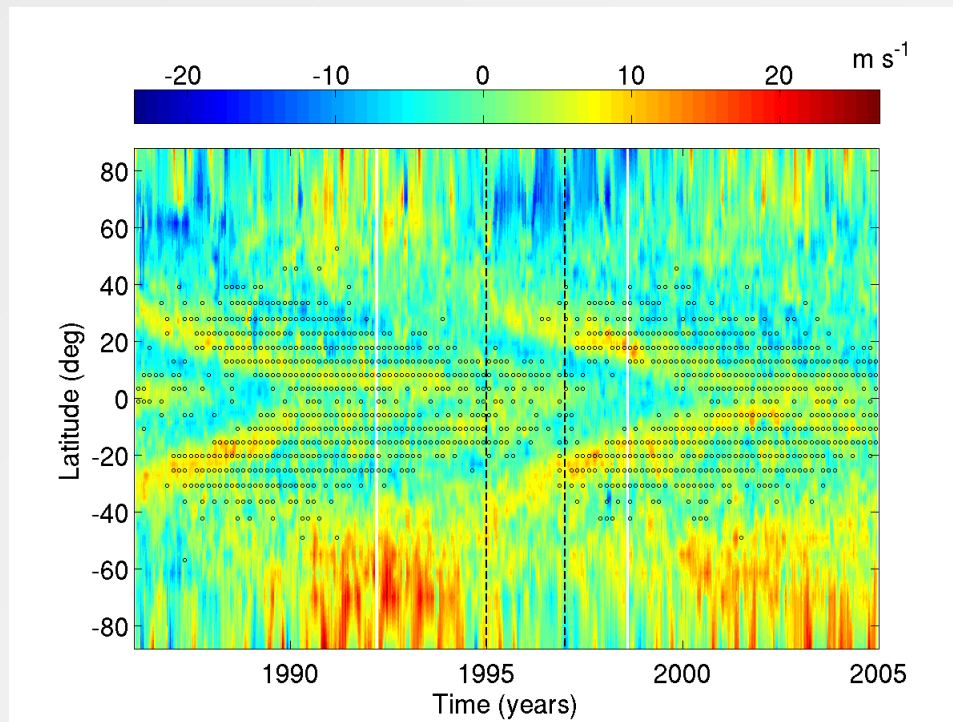
Piyali Chatterjee (Department of Astronomy and Astrophysics, TIFR, Colaba, Mumbai-400005)

Sagar Chakraborty (Department of Theoretical Sciences, S. N. Bose Centre for Basic Sciences, Kolkata -700098)

Arnab Rai Choudhuri (Department of Physics, IISc, Bangalore-560012)

Torsional Oscillations: Salient Features -I

- Bands of faster and slower rotation migrate in latitude on the solar surface with a period of 11 years.



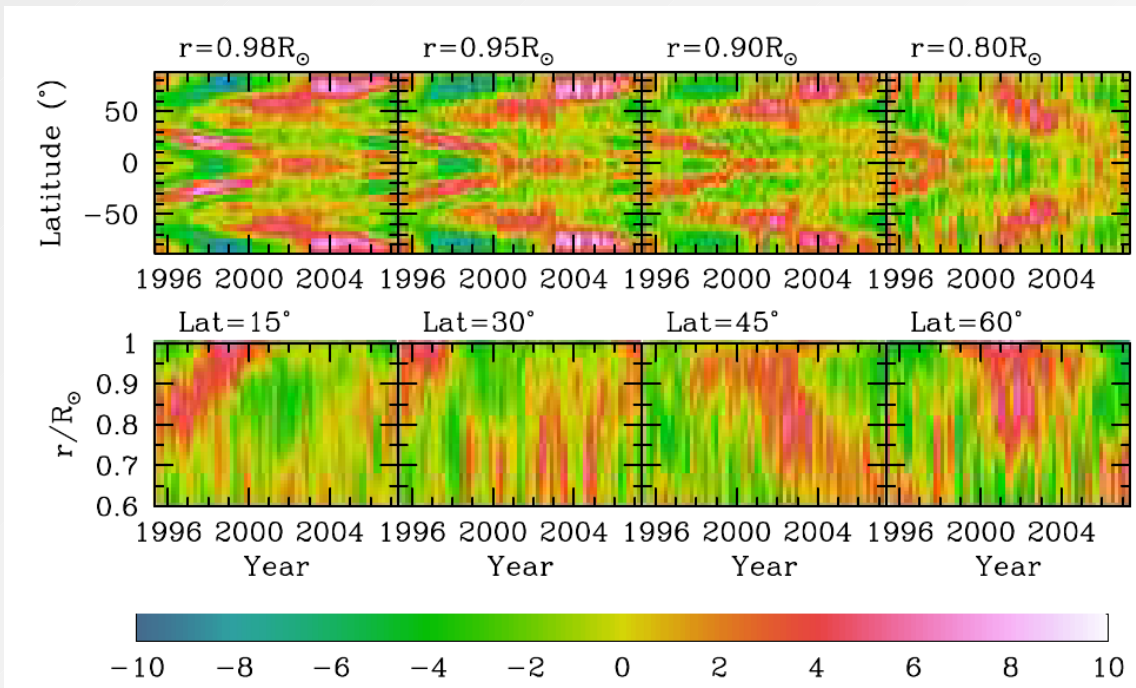
MWO Data courtesy R. Ulrich

Apparent Violation of Causality!

- Two branches: Poleward propagating, equatorward propagating moves with sunspot latitudes.
- Equatorward propagating branch originates 2-3 years prior to first sunspot eruptions of a new cycle.
- The amplitude of oscillation being $\sim 5\text{ms}^{-1}$ near the surface $\sim 1\%$ of $\Omega(r, \theta)$
- The back reaction due to Lorentz force is believed to be the cause.
- How does torsional oscillation 'reach' the surface before start of magnetic activity?

Torsional Oscillations: Salient Features -II

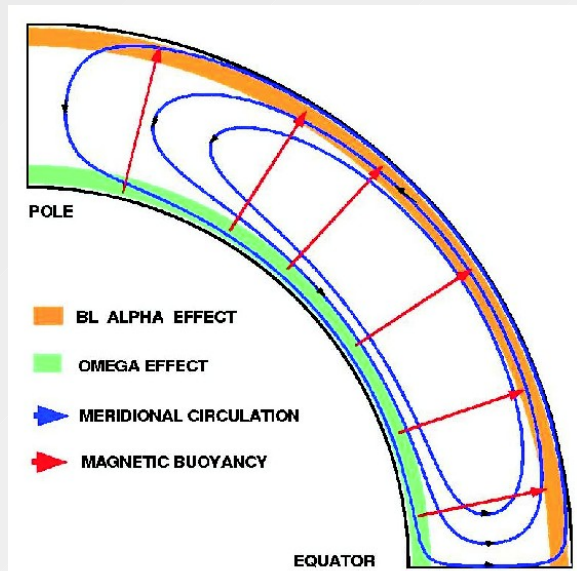
- Equatorward propagating branch at low latitudes seem to have a phase lag of 2-3 years at the surface compared to the oscillations at the $0.7 R_s$
- Torsional oscillations: encompasses the entire convection zone.



GONG data, Figure courtesy Antia et. al. 2008

Flux Transport Dynamos

Flux Transport Dynamo with tachocline shear and Babcock Leighton α



- *Sunspots decay produce poloidal field by $BL \alpha$ effect*
- *Poloidal field carried by meridional circulation to the poles and then sinks to tachocline*
- *Strong rotational shear at the tachocline produces toroidal field which rises to the surface due to magnetic buoyancy.*

$$\mathbf{B} = B(r, \theta)\mathbf{e}_\phi + \nabla \times [A(r, \theta)\mathbf{e}_\phi],$$

$$\frac{\partial A}{\partial t} + \frac{1}{s}(\mathbf{v} \cdot \nabla)(sA) = \eta_p \left(\nabla^2 - \frac{1}{s^2} \right) A + \alpha B,$$

$$\begin{aligned} & \frac{\partial B}{\partial t} + \frac{1}{r} \left[\frac{\partial}{\partial r}(rv_r B) + \frac{\partial}{\partial \theta}(v_\theta B) \right] \\ &= \eta_t \left(\nabla^2 - \frac{1}{s^2} \right) B + s(\mathbf{B}_p \cdot \nabla)\Omega + \frac{1}{r} \frac{d\eta_t}{dr} \frac{\partial}{\partial r}(rB) \end{aligned}$$

Model Outline

→ Nandy & Choudhuri (2002); Chatterjee et al., (2004)

+
Navier-Stokes Equation with Lorentz Forcing

$$\rho \left\{ \frac{\partial v_\phi}{\partial t} + \frac{v_r}{r} \frac{\partial}{\partial r} (r v_\phi) + \frac{v_\theta}{r \sin \theta} \frac{\partial}{\partial \theta} (\sin \theta v_\phi) \right\} =$$

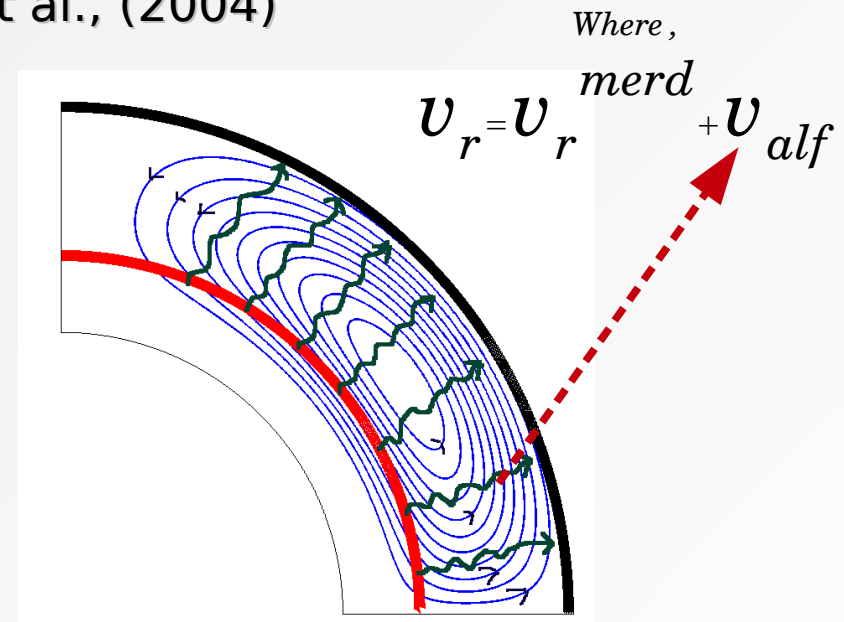
$$(\mathbf{F}_L)_\phi + \frac{1}{r^3} \frac{\partial}{\partial r} \left[\nu \rho r^4 \frac{\partial}{\partial r} \left(\frac{v_\phi}{r} \right) \right] +$$

$$\frac{1}{r^2 \sin^2 \theta} \frac{\partial}{\partial \theta} \left[\nu \rho \sin^3 \theta \frac{\partial}{\partial \theta} \left(\frac{v_\phi}{\sin \theta} \right) \right],$$



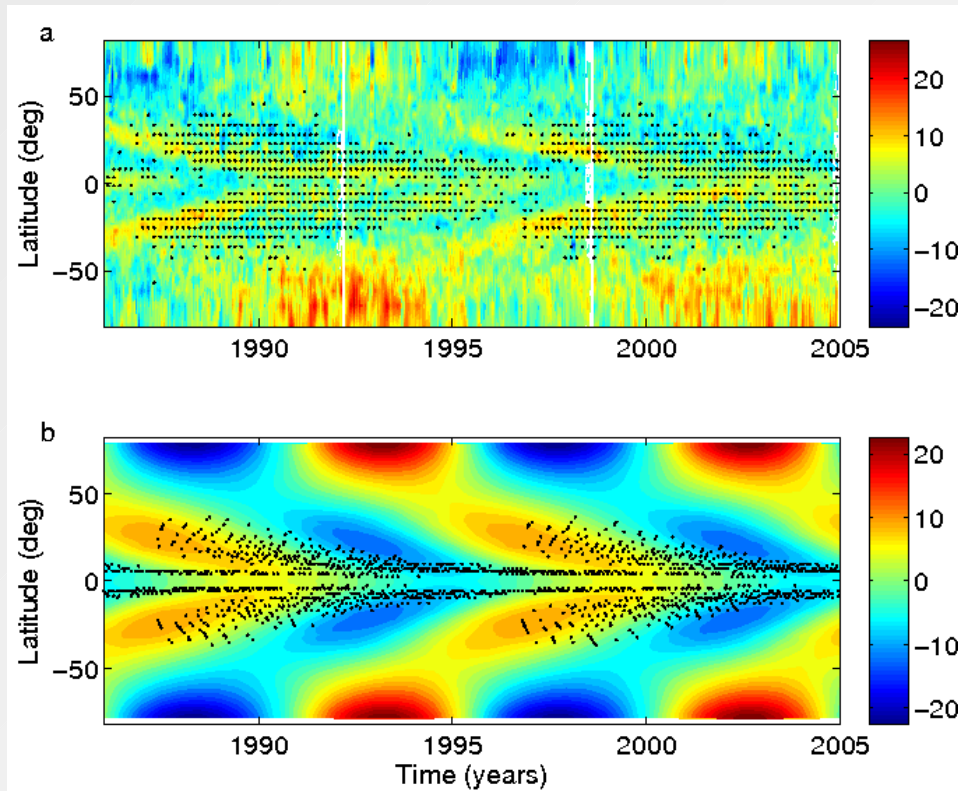
$$(\mathbf{F}_L)_\phi = \frac{J(sB_\phi, sA)}{s^3 f}$$

$$f = \frac{B_\phi}{(B_\phi)_{ft}} = \text{filling factor}$$



NC Hypothesis: Deep penetrating meridional flow allows formation of toroidal field at the high latitude tachocline and carries it downward into stable layers preventing eruptions at high latitudes

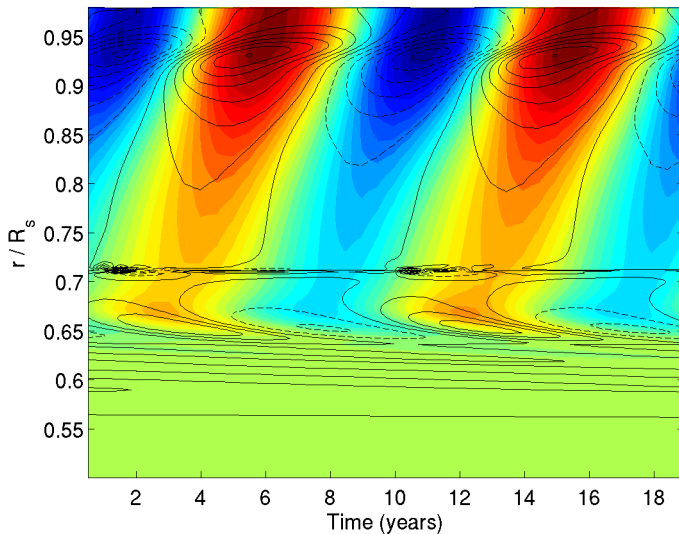
Results-I



- *Deeply penetrating MC.*
- *Alfvén waves in the NS equation carry magnetic stress from tachocline to surface.*
- *Torsional oscillation precedes sunspot eruption.*
- *The high latitude branch also reproduced.*

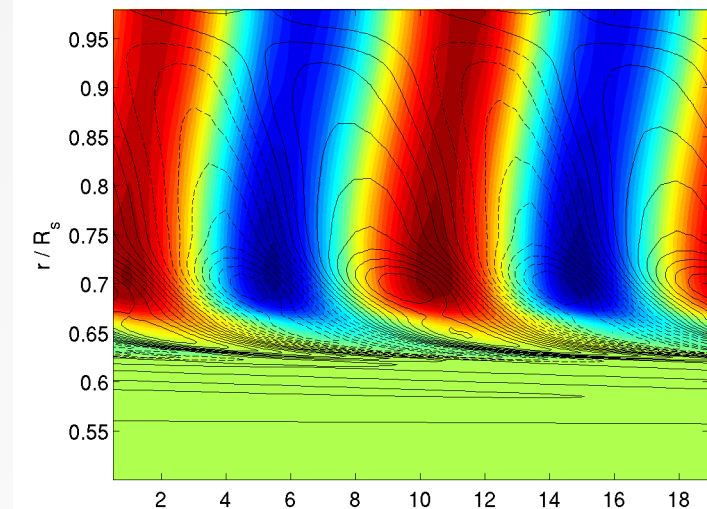
Comparison between theory and observations

Results-II

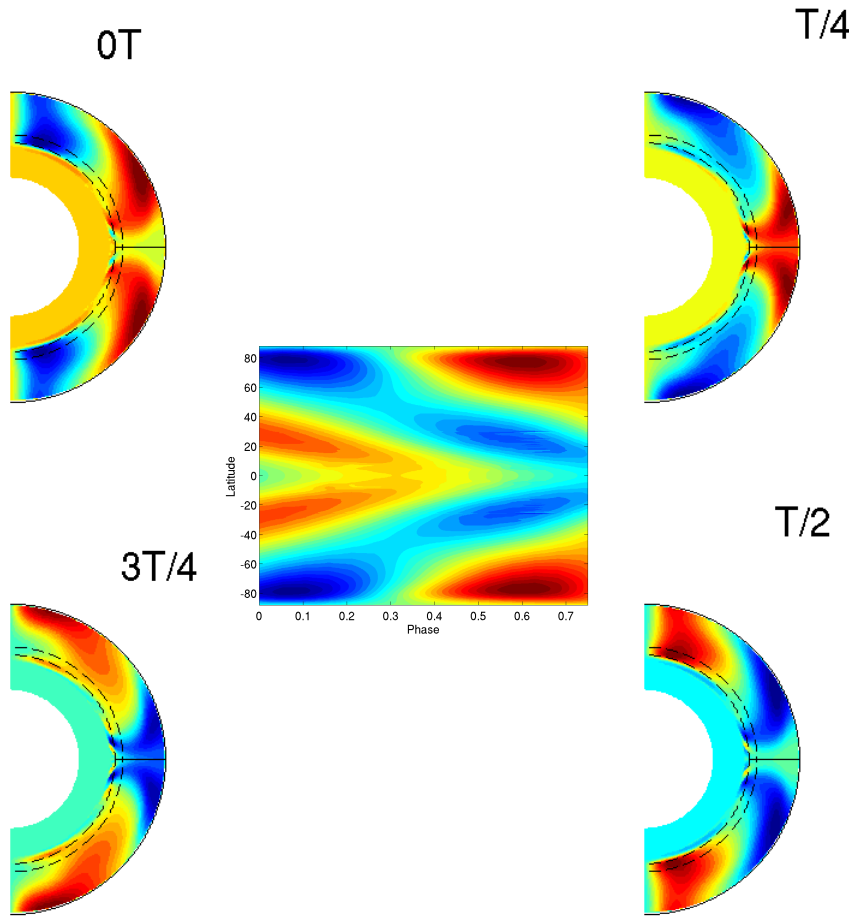


- **Low latitudes:** Lorentz stress concentrated near the tachocline. Tor Osc. launched at the base propagate upwards due to Alfvén waves, rising MC and diffusion. Time-radius plot agrees with observations (Vorontsov et al. 2002).

- **High latitudes:** Sinking MC carries poloidal field downward; Latitudinal shear acts on poloidal field to produce toroidal component thereby Lorentz stress. MC moves region of Lorentz stress downward.



Results-III



→ Meridional snapshots showing distribution of v_ϕ inside the convection zone

Conclusions

- *The novel features of our model are,*
 - 1) *NC Hypothesis : Allows formation of strong toroidal fields at high latitude tachocline without erupting at the surface at high latitudes.*
 - 2) *Alfven waves: Transmit the magnetic stresses to the surface.*
- *Our model reproduces*
 - 1) *2-3 year delay between appearance of faster rotating belt at low latitude before eruption of active regions of the new cycle.*
 - 2) *Phase lag between torsional oscillation pattern at the base and at the surface.*
 - 3) *Strong tor. osc. signal near the surface at low latitudes.*

Thank You