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

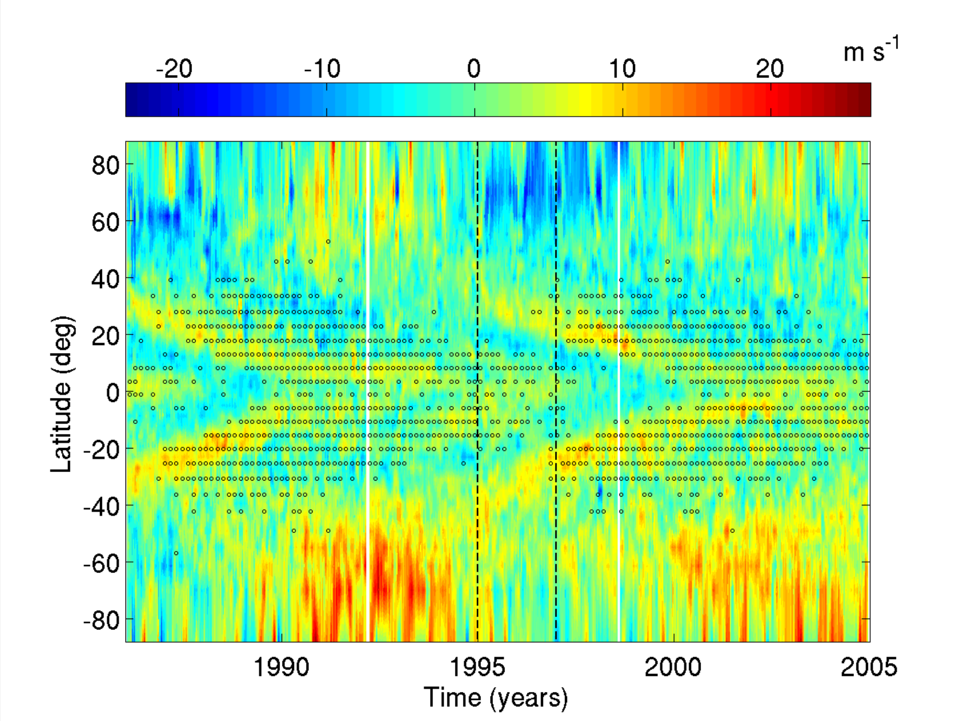
Piyali Chatterjee (Department of Astronomy and Astrophysics, TIFR, Colaba, Mumbai-400005)

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

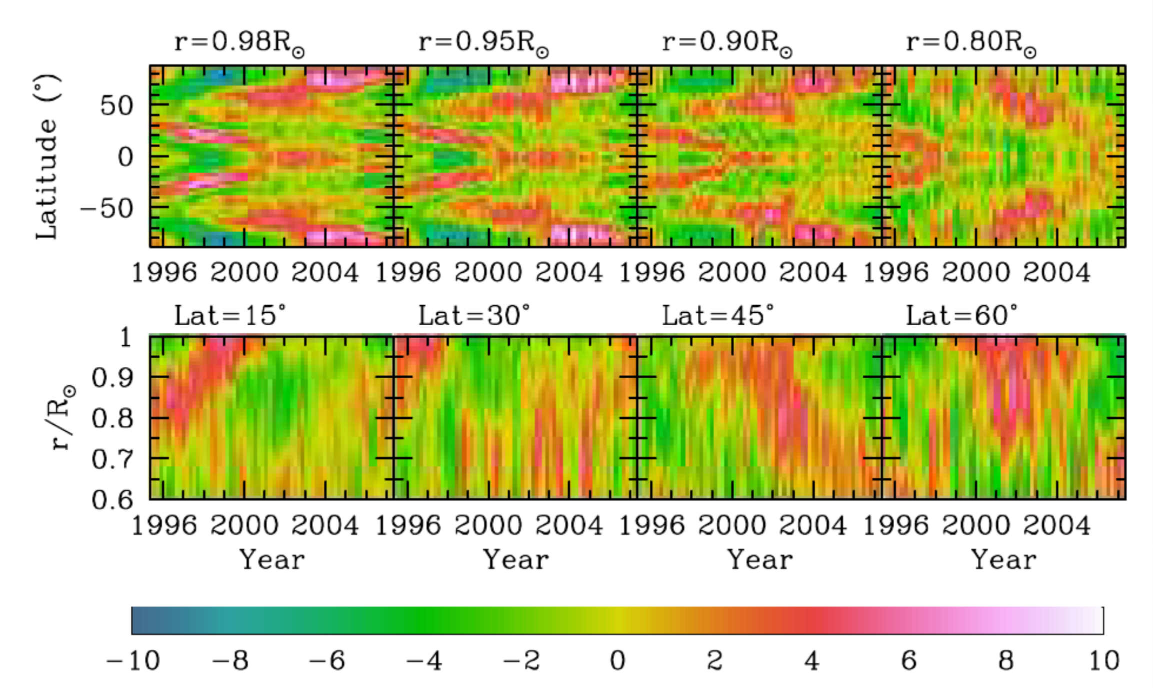
- *Two branches: Poleward propagating, equatorward propagating moves with sunspot latitudes.*
- *Equatorward propagating branch originates 2-3 years prior to first sunspot eruptions of a new cycle.*
- *The amplitude of oscillation being ~ 5ms^{-1} near the surface ~ 1% of $\Omega(r,\theta)$*
- *The back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

Apparent Violation of Causality!

Piyali Chatterjee, Dept of Astronomy & Astrophysics, TIFR, Mumbai, India.
piyalic@tifr.res.in

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.

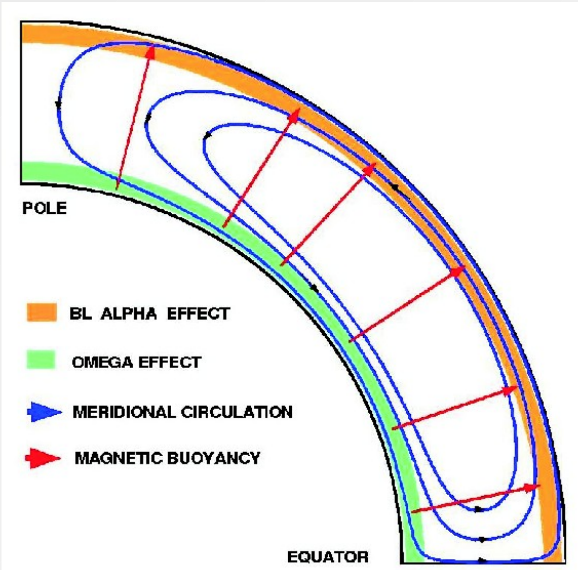


GONG data, Figure courtesy Antia et. al. 2008

Piyali Chatterjee, Dept of Astronomy & Astrophysics, TIFR, Mumbai, India.
piyalic@tifr.res.in

Flux Transport Dynamos

Flux Transport Dynamo with tachocline shear and Babcock Leighton α



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

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

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

- *Sunspots decay produce poloidal field by BL α 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.*

Piyali Chatterjee, Dept of Astronomy & Astrophysics, TIFR, Mumbai, India.
piyalic@tifr.res.in

Model Outline

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

+

Navier-Stokes Equation with Lorentz Forcing

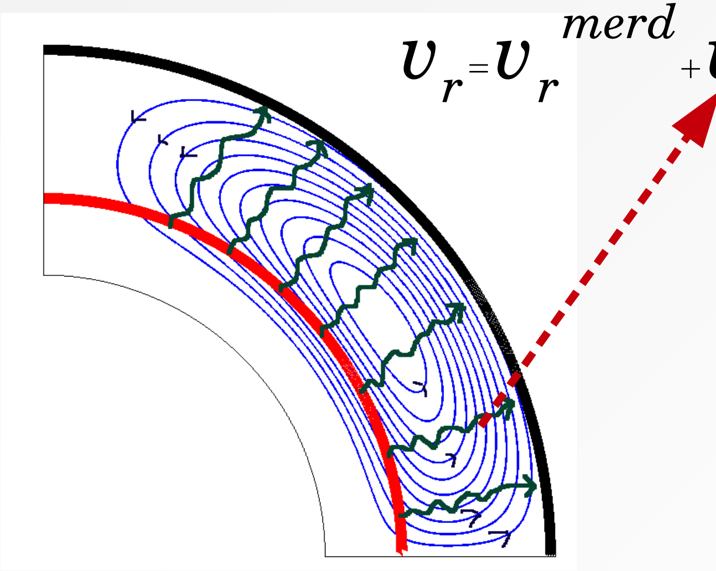
$$\rho\left\{\frac{\partial v_\phi}{\partial t} + \frac{v_r}{r}\frac{\partial}{\partial r}(r v_\phi) + \frac{v_\theta}{r\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta\, v_\phi)\right\} = (\mathbf{F}_L)_\phi + \frac{1}{r^3}\frac{\partial}{\partial r}\left[\nu\rho r^4\frac{\partial}{\partial r}\left(\frac{v_\phi}{r}\right)\right] + \frac{1}{r^2\sin^2\theta}\frac{\partial}{\partial\theta}\left[\nu\rho\sin^3\theta\frac{\partial}{\partial\theta}\left(\frac{v_\phi}{\sin\theta}\right)\right],$$

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

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

Where,

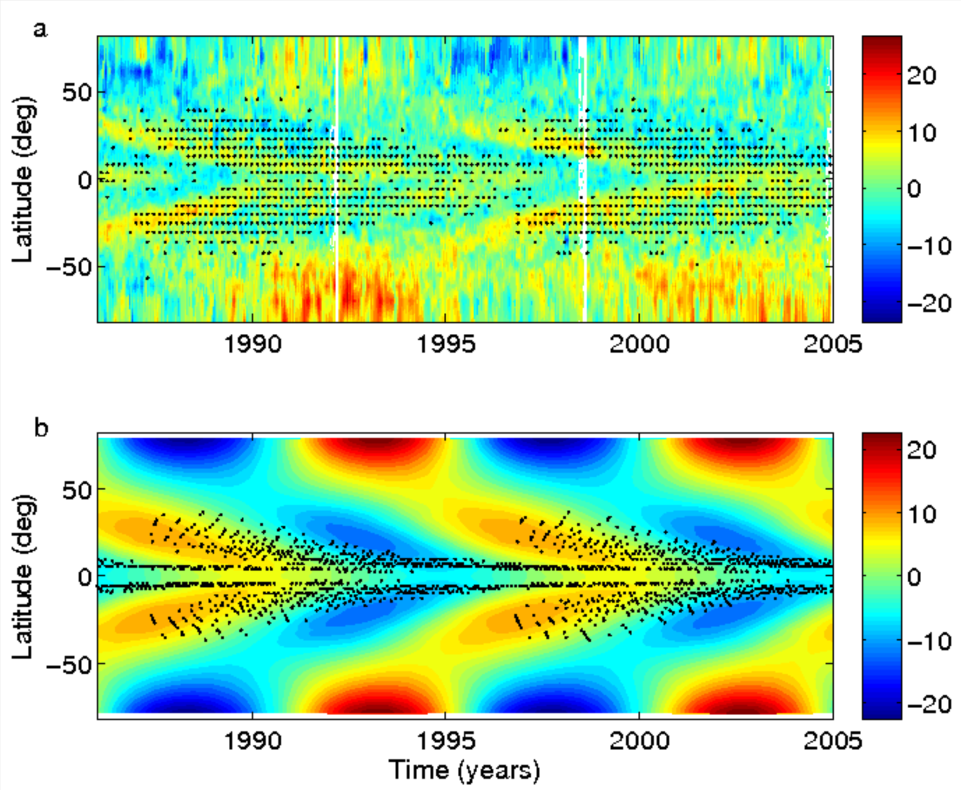
$$v_r = v_r^{merd} + v_{alf}$$



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

Piyali Chatterjee, Dept of Astronomy & Astrophysics, TIFR, Mumbai, India.
piyalic@tifr.res.in

Results-I



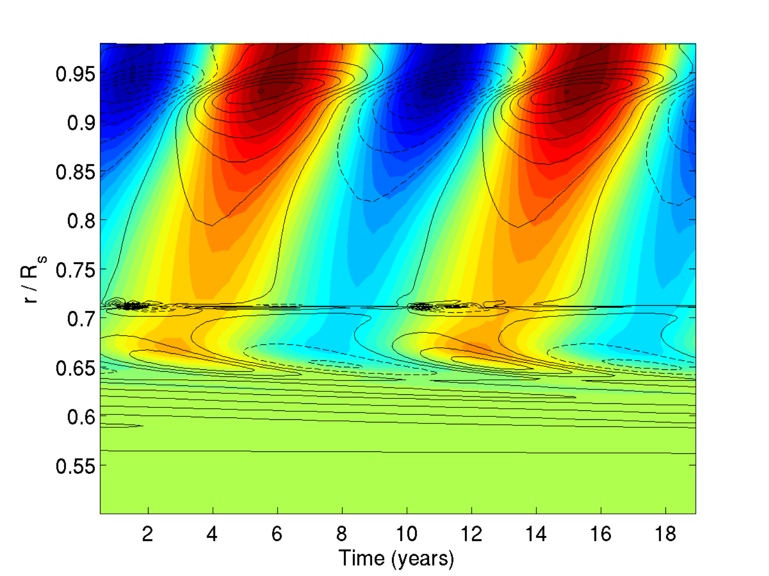
Comparison between theory and observations

- ***Deeply penetrating MC.***
- ***Alfven waves in the NS equation carry magnetic stress from tachocline to surface.***

- ***Torsional oscillation preceeds sunspot eruption.***
- ***The high latitude branch also reproduced.***

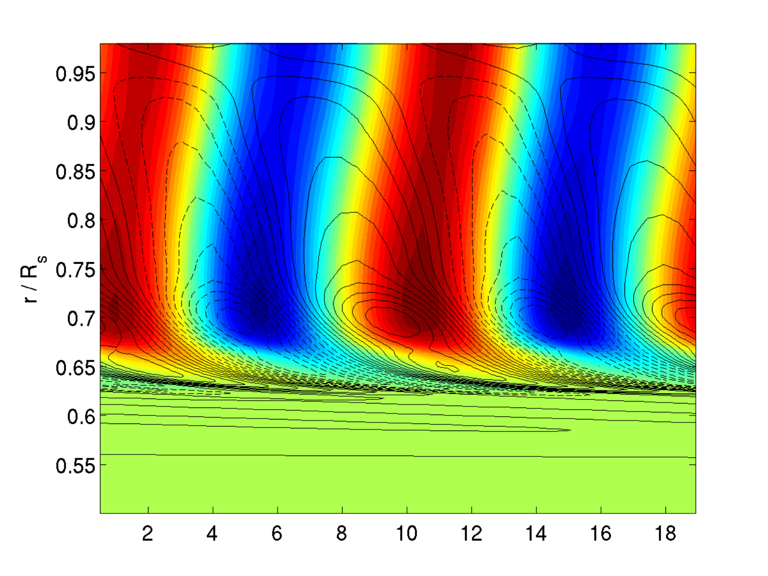
Piyali Chatterjee, Dept of Astronomy & Astrophysics, TIFR, Mumbai, India.
piyalic@tifr.res.in

Results-II



- **Low latitudes:** Lorentz stress concentrated near the tachocline. Tor Osc. lauched at the base propagate upwards due to Alfven 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.



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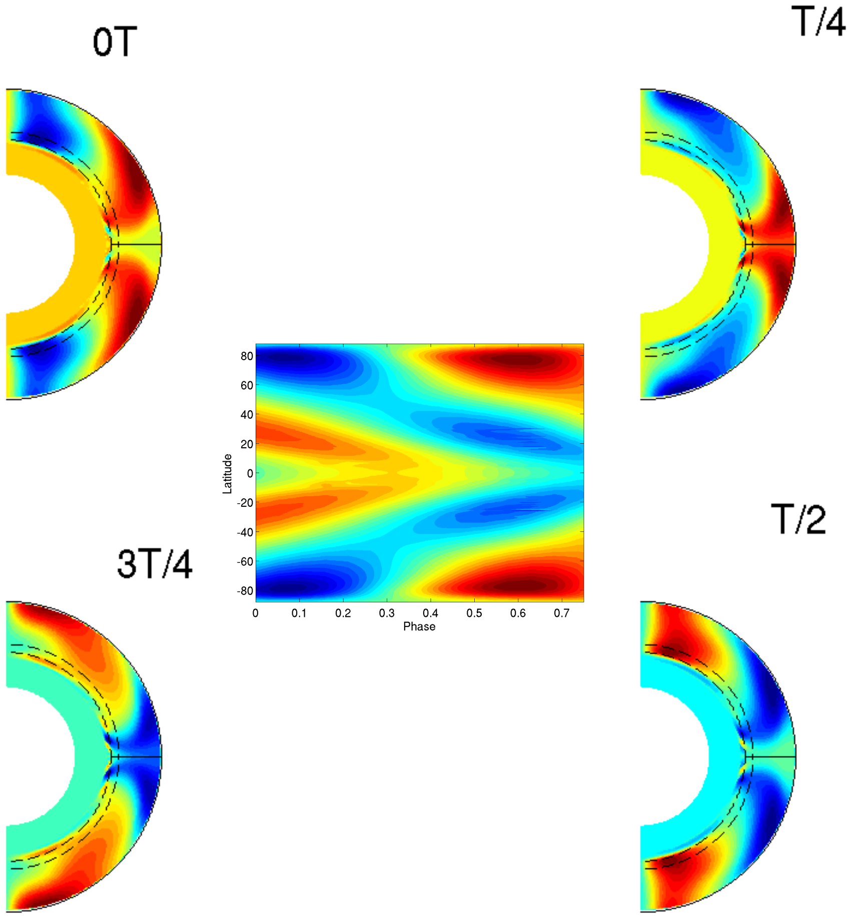
piyalic@tifr.res.in

Results-III



- Meridional snapshots showing distribution of v_{ϕ} inside the convection zone

Piyali Chatterjee, Dept of Astronomy & Astrophysics, TIFR, Mumbai, India.
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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.*

Piyali Chatterjee, Dept of Astronomy & Astrophysics, TIFR, Mumbai, India.
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Thank You

Piyali Chatterjee, Dept of Astronomy & Astrophysics, TIFR, Mumbai, India.
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