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

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Torsional Oscillations: Salient Features -I

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

- 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?

MWO Data courtesy R. Ulrich

Apparent Violation of Causality!
Equatorward propagating branch at low latitudes seem to have a phase lag of 2-3 years at the surface compared to the oscillations at 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 $\alpha$

- 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.
Model Outline

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

Navier-Stokes Equation with Lorentz Forcing

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

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

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

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.
- Alfven waves in the NS equation carry magnetic stress from tachocline to surface.
- Torsional oscillation preceeds 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 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.
Results-III

Meridional snapshots showing distribution of $v_{\phi}$ 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