Effect Of Subsurface Radial Differential Rotation On Flux-transport Solar Dynamos

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Motivation

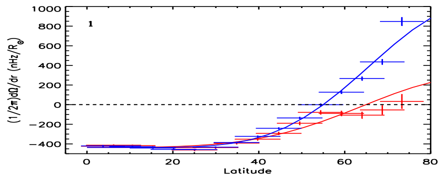
The recent quantitative analysis of strong radial shear at the surface by Corbard & Thompson (2001) immediately raises the questions:

- *Where is the solar dynamo?*
- *Is it operating primarily near the surface?*
- *Do the toroidal fields manifest directly after they are generated there?*
- *Are the poloidal fields also generated there by the decay of active regions?*
- *Is there no longer need for flux-storage in the subadiabatically stratified overshoot layer and radiative zone?*

To answer these questions, we simulate a kinematic flux-transport dynamo incorporating this newly observed solar rotation profile.

Observation of the subsurface shear

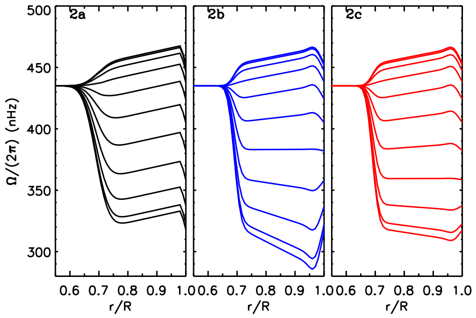
In order to infer the radial gradient of angular velocity close to the surface, Corbard & Thompson (2001) used the small, but significant, radial dependance of the f modes with degrees between l=117 and l=300 observed by MDI between May 1996 and April 2001 (Schou, 1999).



The outward gradient is found negative with a value of $\sim$ 400nHz/$R_\odot$ up to $30°$, and decreases to a small value above $30°$ to reach close to zero at about $50°$ (red curve).

At higher latitudes the gradient may reverse its sign in a thin layer extending only 5 Mm beneath the visible surface as eveidenced by the most superficial modes with degrees $l > 250$ (blue curve).

Analytical models of the rotation rate



Profile of the soar angular velocity between 0.55$R_\odot$ and the surface at different latitudes from equator (top) to pole (bottom), every 10 degrees.
a) The original model of Kosovichev (1996) where the surface shear was not based on observation but on the assumption that the angular momentum is preserved in the supergranulation layer,
b) model with the surface radial gradient from Fig. 1, (blue),
c) model with the surface radial gradient from Fig. 1 (red).

$$\Omega(r,\mu) = A_1(r,\mu) + \phi_{tac}(r)(\Omega_{zc} - \Omega_0 + a_2\mu^2 + a_4\mu^4), \qquad (1)$$

with:

$$\left\{\begin{array}{ll} A_1(r,\mu) & = \Omega_0 + \phi_{zc}\{\alpha(\mu)(r - r_{zc})\} + \phi_s(r)\times \\ & \quad \{\Omega_{eq} - \Omega_{zc} - \beta(\mu)(r-1) - \alpha(\mu)(r - r_{zc})\} \\ \alpha(\mu) & = \{\Omega_{eq} - \Omega_{zc} + \beta(\mu)(1 - r_s)\} \\ \beta(\mu) & = \beta_0 + \beta_3\mu^3 + \beta_6\mu^6 \\ \phi_x(r) & = 0.5(1 + erf(2(r - r_x)/\omega_x)) \quad (x \equiv tac, zc \text{ or } s) \\ \Omega_0 & = \Omega_{zc} + \frac{a_2}{5} + 3\frac{a_4}{35} \text{ (no net torque across the tachocline)} \end{array}\right.$$

This model includes 13 parameters (in blue) which are obtained to fit BBSO observations as in the original model of Kosovichev (1996) except for

- the width of the tachocline which, according to more recent determination (see the review from Corbard et al. (2001)) is taken thinner ($\omega_{tac} = 0.05R_\odot$),
- the coefficients β which are obtained from the observations reported on Fig. 1
- the widths of the transitions between gradients (ω_{zc}&ω_s) which are included in order to avoid discontinuities in the derivatives

The Dynamo model:
Babcock-Leighton type flux-transport dynamo

Why this model?

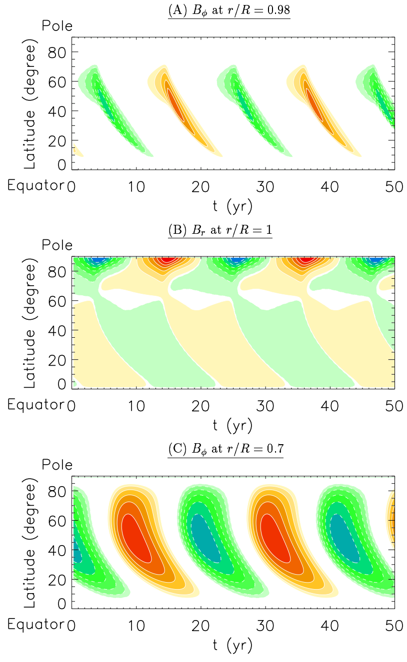
To focus primarily on the question whether the major toroidal fields are generated near the surface or at the tachocline.

The poloidal fields in Babcock-Leighton models are also generated near the surface, and therefore they can be available immediately after they are born for further generation of toroidal fields by the action of strong, surface radial shear.

The model:

- We prescribe a solar rotation profile (see Fig 2b) with strong positive gradients at high latitudes. The other case (Fig 2c), has been tested and do not change our main conclusions.
- We keep the other ingredients same as used by Dikpati & Charbonneau (1999) i.e. :
  - The meridional flow pattern.
  - A Babcock-Leighton type poloidal source term that depends on latitude and magnetic field strength.
  - A depth-dependent diffusivity profile.
- Applying the similar boundary conditions and employing the same numerical technique, we solve the dynamo equations 3a and 3b of Dikpati & Charbonneau (1999).

Results



We extract the solutions for the evolution of toroidal and poloidal fields at the required depth, and plot in the respective time-latitude diagrams. **Figure 3 (above)** shows the evolutionary pattern of dynamo generated magnetic field components:

- **Top frame:** Toroidal fields close to the surface (at $0.98R$) (the toroidal field at the top boundary is zero)
- **Middle frame:** Surface radial fields.
- **Bottom frame:** The toroidal fields at the convection zone base.

The field strength (68 kG) generated at the convection zone base is 40 times the field (1.7 kG) generated at $0.98R$. To make all the time-latitude diagrams visible, the contour shadings have been constructed in such a way that the same dark red shade implies 1.7 kG field in the top frame, but 68 kG in the bottom frame. Lowest field strength plotted in bottom frame is 16 kG.

Discussion

In Figure 3A, equatorward migration of toroidal fields near the surface appears intriguing at first sight.
To find a definite answer for the cause of this equatorward migration, we need to perform further studies which will help determine the parameter values for which the equatorward classical dynamo wave speed near the surface would take over the advective poleward transport there.

Table 1. Field Strengths at Different Depths

η_T(cm^{2}s^{-1})	$\frac{\eta_T}{\eta_{\rm core}}$	$\frac{\partial\Omega}{\partial r}\|_{r=0.98R}$	$B_\phi\|_{r=0.98R}$	$B_\phi\|_{r=0.7R}$
3 10^{11}	1000	present	1.7 kG	68 kG
3 10^{11}	1000	absent	1.2 kG	68 kG
10^{11}	1	present	5.7 kG	28 kG

η_T → turbulent diffusion coefficient in the convection zone
$\eta_{\rm core}$ → diffusion coefficient in the radiative tachocline

The Table above reveals that the presence of surface radial shear at $0.98R_\odot$ only increases the strength by 0.5 kG.
The toroidal fields generated in the shear layer located at or below the subadiabatically stratified convection zone base undergo much less decay than those generated near the surface, therefore $B_\phi|_{r=0.7R}$ is stronger than $B_\phi|_{r=0.98R}$.
If we take a constant diffusivity throughout our computation domain, then $B_\phi|_{r=0.7R}$ and $B_\phi|_{r=0.98R}$ are generated in comparable strength (see the **third row in the Table**).

We find from Figure 3 that B_r is in approximately $90°$ phase lead with respect to the $B_\phi|_{r=0.98R}$ rather than a $90°$ phase lag.
A toroidal field of strength of 1.7 kG can produce spots of 3 kG field strength if convective collapse works to concentrate the flux. But the polarities of the leader and follower spots produced from these near-surface toridal fields would appear with a phase, completely opposite to that observed, with respect to the large-scale, poleward drifting, radial fields.

Conclusion

- Simulation of a kinematic flux-transport dynamo operating in presence of this surface radial shear indicates that the strongest toroidal fields in the Sun are generated at the convection zone base rather than near the surface.
- Toroidal fields from the convection zone base manifest at the surface as bipolar spots due to their buoyant rise through the convection zone.
- If spots are produced from the near-surface toroidal fields, the polarities of the leader and follower spots will not match with the observed polarity of the polar field.

Prospective

- $B_\phi|_{r=0.98R}$ is not weak because surface poloidal fields are also not weak. The polar fields from this model are $\sim 100 - 200$ Gauss due to polar convergence of meridional flow. Turbulent diffusion of 10^{11-12}cm^{2}s^{-1} is not enough to reduce them. One remedy to this problem could be that a much larger supergranular diffusion ($\sim 10^{13-14}$cm^{2}s^{-1}) very near the surface destroys much of the poloidal flux before polar concentration takes place. In future, we shall further explore this possibility for creating a solar-like polar fields through Babcock-Leighton type source.
- A flux-transport dynamo driven by a tachocline α-effect produces much weaker polar fields. A forthcoming paper will address issues regarding how the diffusivity contrast across the core-envelope interface affects the strength of the field generated in the tachocline with respect to the surface.

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