Magnetic flux transport: constraints and a nonlinearity

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(M. Schüssler, D. Schmitt, J. Jiang, E. Isik)
The Sun’s open flux

Open flux comes from fields near the equator

Open flux comes from polar fields
Observationally inferred open flux and the strength of the solar cycle

![Graph 1: Correlation between maximum cycle n-1 and minimum aa-derived open flux between cycle n-1 and n. R=0.55]

![Graph 2: Correlation between maximum cycle n and minimum aa-derived open flux between cycle n-1 and n. R=0.86]
Surface flux transport

\[
\frac{\partial B}{\partial t} = -\omega(\lambda, t) \frac{\partial B}{\partial \phi} - \frac{1}{R \cos \lambda} \frac{\partial}{\partial \lambda} \left( v(\lambda, t) B \cos \lambda \right) + \eta_{2d} \left( \frac{1}{R^2 \cos \lambda} \frac{\partial}{\partial \lambda} \left( \cos \lambda \frac{\partial B}{\partial \lambda} \right) + \frac{1}{R^2 \cos^2 \lambda} \frac{\partial^2 B}{\partial \phi^2} \right) + D(B) + S(\lambda, \phi, t)
\]

- Differential Rotation
- Meridional velocity
- Supergranular random walk
- Decay due to 3-D effects ( =0 )
- Source term
With time-independent meridional flow

\[ R = 0.55 \]

\[ R = 0.47 \]

\[ R = 0.86 \]

\[ R = 0.58 \]
Sketch of surface flows explanation given in Dasi-Espuig et al 2010

Meridional flow residuals (surface)

Zonal flow residuals (surface)

Observed surface flows from Gizon and Rempel (2008)
Model for inflow

Longitudinally averaged unsigned flux

Model inflow

Time variability

Hathaway and Rightmire (2010)
Basu and Antia (2010)
Modeled inflow
SFT with inflows

Cameron and Schüssler (in prep.)
With time-dependent meridional flow

- $R=0.37$
- $R=0.55$
- $R=0.82$
- $R=0.86$
Global solar dynamo
Babcock-Leighton model

With M. Schüssler, D. Schmitt, J. Jiang & E. Isik
It’s suprising that the SFT model works!

Cameron, Schmitt, Jiang, Isik 2012 (in press)
The SFT and FTD models without pumping give different answers for the longitudinally averaged Surface field!

FTD vertical BC  
FTD potential BC  
SFT
With vertical BC and pumping agreement is reached.

Black is SFT result

Colors are different amounts of pumping
Fig. 3.— Left: latitude dependences of $u_r$ and $u_\theta$ at $0.9R_\odot$. Right: radial dependences of $u_r$ at $5^\circ$, $u_\theta$ at $36^\circ$, diffusivity $\eta$ and pumping $\gamma$. 

Jiang et al (in prep)
FTD Results

• With constant meridional velocity but cycle dependent inflows
• Poloidal source from sunspot record.
Fig. 7.— Comparison of the magnetic field strength derived from the FTD with observations. Red: 12-month smoothed group sunspot number evolution; Black: simulated averaged toroidal field over all latitudes; Blue: averaged simulated toroidal field at $\pm 15^\circ$ latitudes. The correlation between $B_{bc}^2$ and the sunspot number is 0.9. The correlation between $^{15}B_{bc}^2$ and the sunspot number is 0.93.