“Magnetically Mediated” Deep Meridional Circulation Dynamics

Dário Passos

Co-authors: Mark Miesch (HAO, USA), Gustavo Guerrero (UFMG, Brazil), Paul Charbonneau (UdM, Canada)
**Observable large scale flows**

Differential rotation

\[ u_\phi \hat{e}_\phi \]

slower poles (blue) and faster equator (red)

Meridional circulation

\[ u_m = u_r \hat{e}_r + u_\theta \hat{e}_\theta \]

Poleward at the surface and “complex” inside the convection zone.

**Cyclic variation patterns**

**DF - Torsional Oscillations**

Courtesy of Rachel Howe

**MC - Variations in the “strength” of the surface component**

Hathaway & Rightmire, 2010
The model: EULAG (ILES, 3D MHD, spherical shell)

Anelastic form of the ideal MHD equations:

\[
\frac{Du}{Dt} = -\nabla \pi' - g \frac{\Theta'}{\Theta_o} + 2u \times \Omega + \frac{1}{\mu \rho_o} (B \cdot \nabla) B,
\]

\[
\frac{D\Theta'}{Dt} = -u \cdot \nabla \Theta_o + \mathcal{H} - \alpha \Theta',
\]

\[
\frac{DB}{Dt} = (B \cdot \nabla) u - B(\nabla \cdot u).
\]

\[\nabla \cdot (\rho_o u) = 0, \quad \nabla \cdot B = 0\]

Resolution

\[r = 47, \quad \theta = 66, \quad \phi = 128\]

\[0.62 \leq r/R_\odot \leq 0.96\]

Why this model?

- Solution with cyclic large scale magnetic field
- Large scale flows cyclic variation patterns!
- Able to access all quantities...

EULAG Torsional oscillations


Passos & Charbonneau, 2014
Differential rotation and Meridional circulation inside TC

Mean toroidal field

Meridional Circulation stream function
MC horizontal component ($u_\theta$)

**EULAG-MHD $u_\theta$ profile**

*Passos et al 2015*

**Helioseismic derived $u_\theta$ profile (2013)**

*Zhao et al 2013*
What is the origin of the meridional flows (1)?

\[ \mathbf{u}_m = u_r \hat{\mathbf{r}} + u_\theta \hat{\mathbf{\theta}} \]

Angular momentum redistribution \( \mathcal{L} \)

Definition

\[ \mathcal{L} = \lambda^2 \Omega, \] where \( \lambda = r \cos(\theta) \) is the momentum arm and \( \Omega = \frac{\langle u_\phi \rangle}{\lambda} + \Omega_0 \) is the rotation profile \( (\Omega_0 = 2.42405 \times 10^{-6} \text{ s}^{-1}) \)

\( \mathcal{L} \) evolution eq.

\[ \rho_0 \frac{\partial \mathcal{L}}{\partial t} + \langle \rho_0 \mathbf{u}_m \rangle \cdot \nabla \mathcal{L} = -\nabla \cdot \left( \mathbf{F}^{\text{RS}} + \mathbf{F}^{\text{MS}} + \mathbf{F}^{\text{MT}} \right) \equiv \mathbf{F} \]

\( \mathbf{F}^{\text{RS}} \equiv \lambda \left( \langle \rho_0 u'_r u'_\phi \rangle \hat{\mathbf{r}} + \langle \rho_0 u'_\theta u'_\phi \rangle \hat{\mathbf{\theta}} \right), \) Reynolds stress

\( \mathbf{F}^{\text{MS}} \equiv -\frac{\lambda}{\mu_0} \left( \langle b'_r b'_\phi \rangle \hat{\mathbf{r}} + \langle b'_\theta b'_\phi \rangle \hat{\mathbf{\theta}} \right), \) Maxwell stress

\( \mathbf{F}^{\text{MT}} \equiv -\frac{\lambda}{\mu_0} \left( \langle b_\phi b_r \rangle \hat{\mathbf{r}} + \langle b_\phi b_\theta \rangle \hat{\mathbf{\theta}} \right). \) Magnetic torque
When $\mathcal{F} > 0$ (red lines and shades) the net torque is prograde inducing a meridional flow away from the rotation axis.

While $\mathcal{F} < 0$ (blue lines and shades), the net torque is retrograde and induces a flow toward the rotation axis.

**Gyroscopic pumping**

Miesch & Hindman 2011
Individual contributions for the Ang. Mom. Balance (MHD)

\[-\nabla \cdot (F^{RS})\]

\[-\nabla \cdot (F^{MS})\]

\[-\nabla \cdot (F^{MT})\]

Passos et al 2017
Cyclic evolution of the Ang. Mom. Balance (MHD)

Passos et al 2017
MC morphological changes along the magnetic cycle

MHD

Passos et al 2017
What is the origin of the meridional flows (2) ?

**Thermal wind balance:** radial and latitudinal gradients in pressure and temperature, generate plasma motions on the meridional plane (classical definition!).

\[
\frac{\partial \omega}{\partial t} = (\omega_a \cdot \nabla) u - (u \cdot \nabla) \omega_a - \omega_a (\nabla \cdot u) - \nabla \times g \frac{\Theta'}{\Theta_0} + \frac{1}{\mu_0} \left( \nabla \frac{1}{\rho_0} \right) \times (B \cdot \nabla) B + \frac{1}{\mu_0 \rho_0} (\nabla \times (B \cdot \nabla) B)
\]

where \( \omega_a = (\nabla \times u) + 2\Omega_0 \) is the absolute vorticity.

Compute azimuthally averaged \( \hat{e}_\phi \) component of the vorticity evolution equation (with \( \omega = \nabla \times u \)) to get a **Meridional force balance** (a.k.a. magneto-thermal wind balance) equation.
\[
\begin{align*}
-\left( 2\Omega_0 \left( \cos \theta \frac{\partial u_\phi}{\partial r} - \frac{\sin \theta}{r} \frac{\partial u_\phi}{\partial \theta} \right) \right) &= \frac{\omega \cdot \nabla u_\phi}{r} + \frac{\omega_\phi u_r}{r} + \frac{\omega_\phi u_\theta \cot \theta}{r} \\
&+ \left\{ -\mathbf{u} \cdot \nabla \omega_\phi - \frac{u_\phi \omega_r}{r} - \frac{u_\phi \omega_\theta \cot \theta}{r} \right\} \\
&+ \left\{ -\omega_\phi \left( \frac{1}{r^2} \frac{\partial (r^2 u_r)}{\partial r} + \frac{1}{r \sin \theta} \frac{\partial (u_\theta \sin \theta)}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial u_\phi}{\partial \phi} \right) \right\} \\
&+ \left\{ \frac{g(r)}{r} \frac{\partial}{\partial \theta} \left( \frac{\Theta'}{\Theta_0} \right) \right\} \\
&+ \left\{ \frac{1}{\mu_0} \frac{\partial}{\partial r} \left( \frac{1}{\rho_0} \right) \right\} \left[ \mathbf{B} \cdot \nabla B_\theta - \frac{B_\phi^2}{r} \cot \theta + \frac{B_\theta B_r}{r} \right] \\
&+ \left\{ \frac{1}{\mu_0 \rho_0} \frac{1}{r} \left[ \frac{\partial}{\partial r} \left( r \mathbf{B} \cdot \nabla B_\theta - B_\phi^2 \cot \theta + B_\theta B_r \right) \right] \\
&- \frac{\partial}{\partial \theta} \left( \mathbf{B} \cdot \nabla B_\theta - \frac{B_\phi^2}{r} - \frac{B_\phi}{r} \right) \right\} \\
\end{align*}
\]
Cyclic evolution of MFB (main terms)

Cossette et al 2013 (and Passos et 2017 soon...)
Can we make any “predictions” about the MC behavior?

Passos et al 2017
Conclusions

• The main mechanism of variations behind MC variations inside the convection zone is Gyroscopic Pumping.

• This mechanism is non local: GP influences the MC in the whole convection zone. Thermal wind balance ensures the way MC achieves equilibrium.

• The large scale component of the magnetic field modulates GP and the MTWB terms. The kinematic approximation should be reconsidered in 2D modelling.

• Model based predictions:
  - Variations in temperatures between poles and equator along the cycle (hotter poles at cycle min)
  - Appearance of an equatorward flow at the surface layers that peaks at cycle minimum at high latitudes (observed ?)
  - Modulation of convective energy transport in the CZ (browse for Cossette et al papers...)

...more at Passos et al 2017 (soon!)
More information at:

http://centra.ist.utl.pt/~dario
http://www.astro.umontreal.ca/~paulchar/grps

dariopassos@ist.utl.pt or dmpassos@ualg.pt
EXTRA SLIDES
A small note on notation

\[ u(r, \theta, \phi, t) = \langle u \rangle (r, \theta, t) + u'(r, \theta, \phi, t) \]

Quantities averaged over the \( \phi \) direction (a.k.a. zonal or azimuthal)

Represent large scale, coherent structures at a global level

(e.g. differential rotation, meridional circulation, magnetic cycle (toroidal field))

Fluctuations in quantities

Represent small scales, related to turbulence
EULAG Radiative Diffusion

$$\mathcal{H}(\Theta') \equiv \frac{\Theta_o}{\rho_o T_o} \nabla \cdot \left( \kappa_r \frac{\rho_o T_o}{\Theta_o} \nabla \Theta' \right)$$

EULAG Ambient Potential Temperature

$$\Theta_e \equiv T_e \left( \frac{\rho_b T_b}{\rho_e T_e} \right)^{1-1/\gamma}$$
Differential rotation and torsional oscillations in 3D simulations

Simulated Differential Rotation
Solar like-differential rotation (slower poles and faster equator) but 3 times less intense than in the Sun. Columnar structures at low latitudes, not radial.

Simulated torsional oscillations
(Beaudoin et al 2013, Sol.Phys. 828)
Appear at higher latitudes but with correct phase and amplitude in respect to the magnetic cycle.

Observed TO pattern
Howe et al (2014)
Building Proxies of solar activity

Toroidal field

Radial field
Toroidal field radial profile

B_\phi at 58 degrees

radius \text{ [R}_\odot\text{]}

400 450 500 550 600 650 700
time \text{ [yr]}

T

-0.4 -0.2 0.0 0.2 0.4
Fig. 17.— Zonal poloidal field $\langle B_\theta \rangle$ averaged over the 4 phases of magnetic cycle 1.
Radial field at 4 cycle phases

A) MHD

B) 

C) 

D) 

\( B_r \) (T)

-0.2
-0.1
0.0
0.1
0.2
Radial velocity component (HD and MHD)
Latitudinal ($\theta$) velocity component (HD and MHD)
Meridional Circulation Stream function (HD and MHD)