“Magnetically Mediated” Deep Meridional Circulation Dynamics

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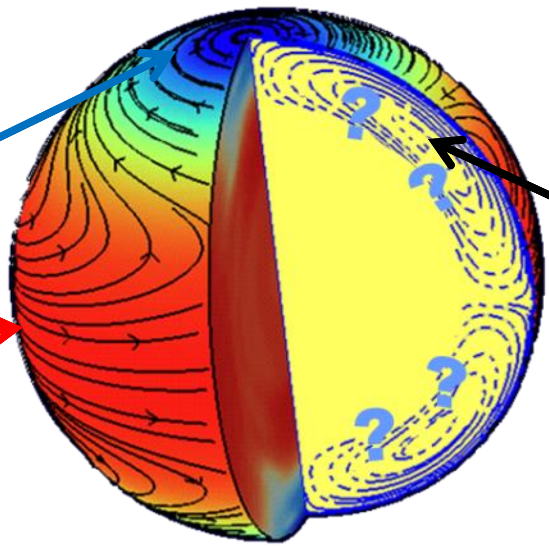
Observable large scale flows

Differential rotation

$u_\phi \hat{\mathbf{e}}_\phi$

slower poles (blue)
and
faster equator (red)

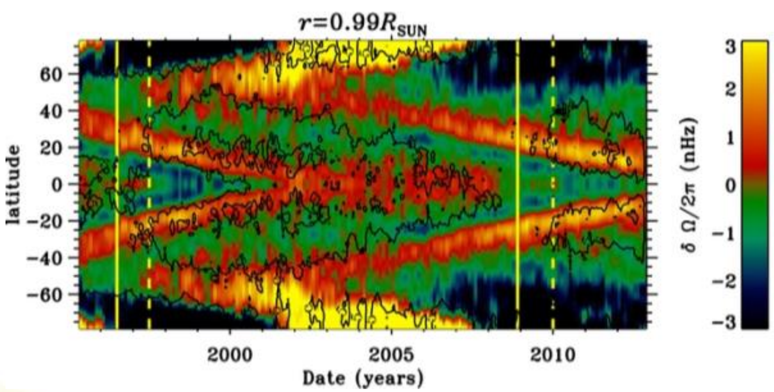


Meridional circulation

$$\mathbf{u}_m = u_r \hat{\mathbf{e}}_r + u_\theta \hat{\mathbf{e}}_\theta$$

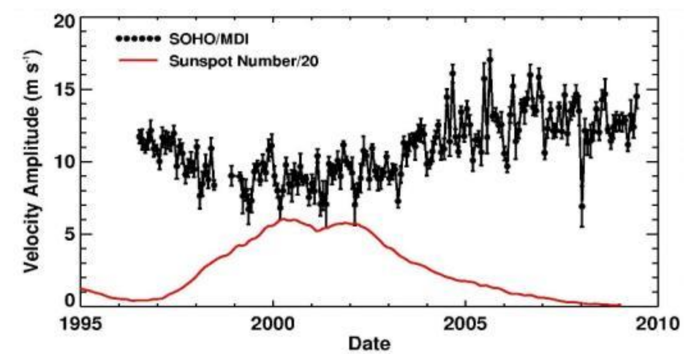
Poleward at the surface and "complex" inside the convection zone.

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)

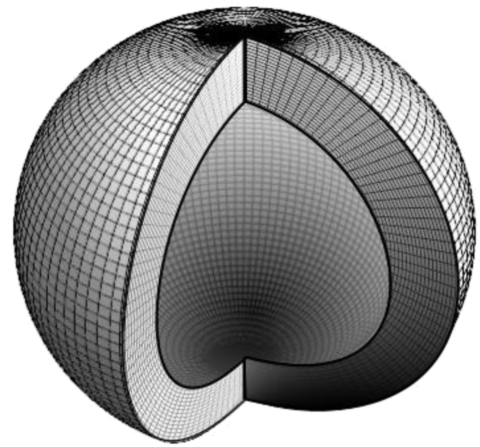
Anelastic form of the ideal MHD equations:

$$\frac{D\boldsymbol{u}}{Dt} = -\nabla\pi' - \mathbf{g}\frac{\Theta'}{\Theta_o} + 2\boldsymbol{u}\times\boldsymbol{\Omega} + \frac{1}{\mu\rho_o}(\boldsymbol{B}\cdot\nabla)\boldsymbol{B},$$

$$\frac{D\Theta'}{Dt} = -\boldsymbol{u}\cdot\nabla\Theta_e + \mathcal{H} - \alpha\Theta',$$

$$\frac{D\boldsymbol{B}}{Dt} = (\boldsymbol{B}\cdot\nabla)\boldsymbol{u} - \boldsymbol{B}(\nabla\cdot\boldsymbol{u}).$$

$$\nabla\cdot(\rho_o\boldsymbol{u}) = 0, \quad \nabla\cdot\boldsymbol{B} = 0$$



Resolution

$$r = 47$$
$$\theta = 66$$
$$\phi = 128$$

$$0.62 \leqslant r/R_\odot \leqslant 0.96$$

Ghizaru et al 2010, Racinne et al 2011, Smolarkiewicz &Charbonneau 2013

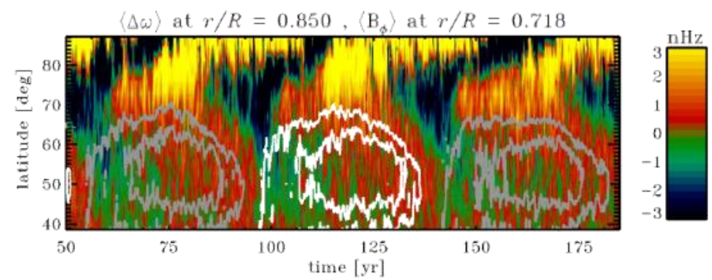
Why this model?

-Solution with cyclic large scale magnetic field

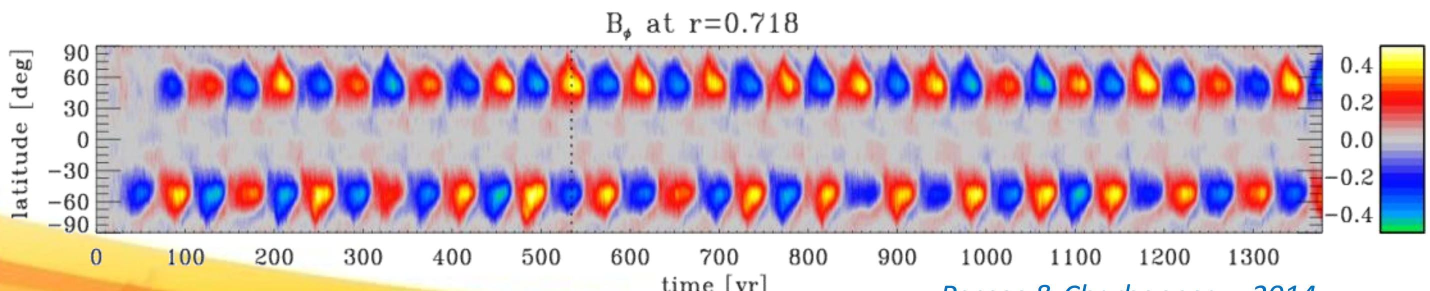
-Large scale flows cyclic variation patterns!

-Able to access all quantities…

EULAG Torsional oscillations

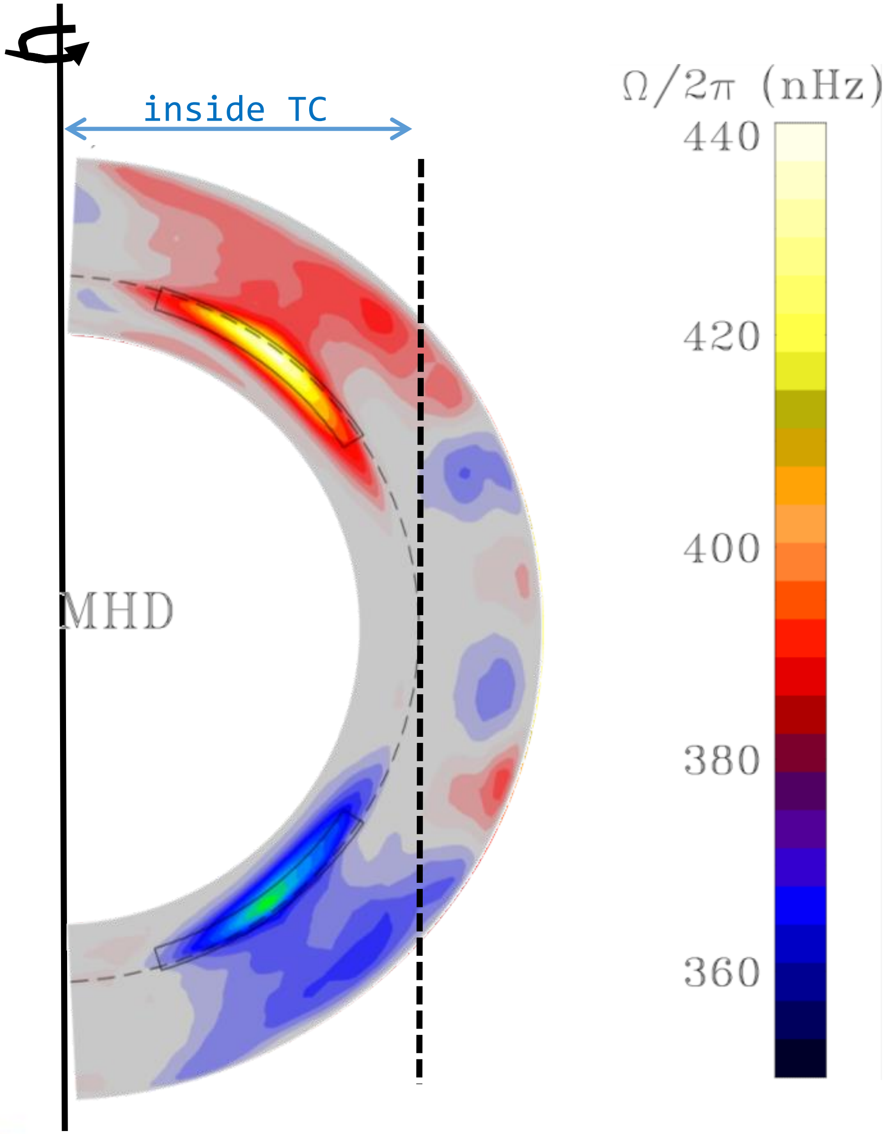


Beaudoin et al 2013, Guerrero et al 2016

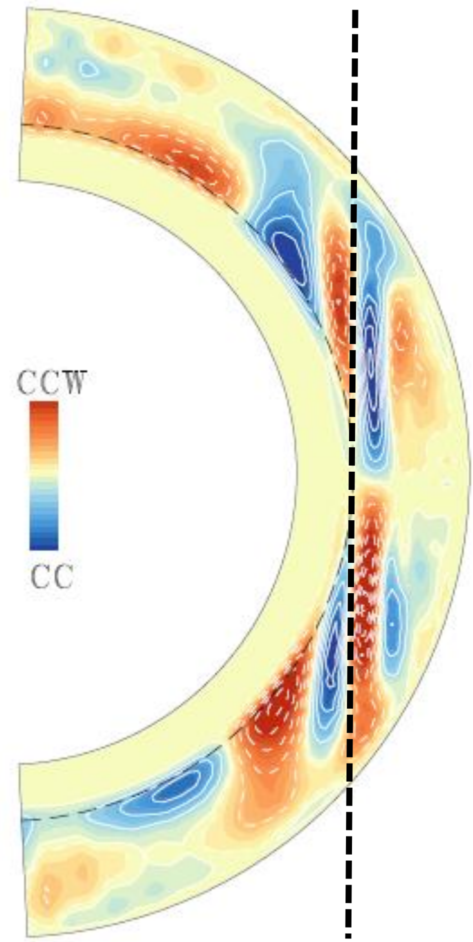


Passos & Charbonneau, 2014

Differential rotation and Meridional circulation

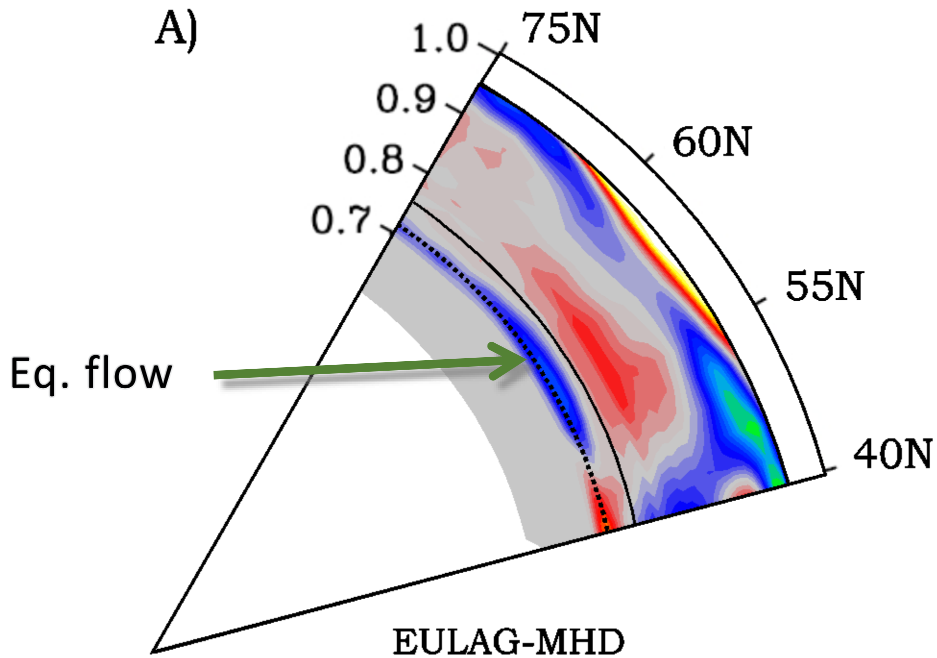


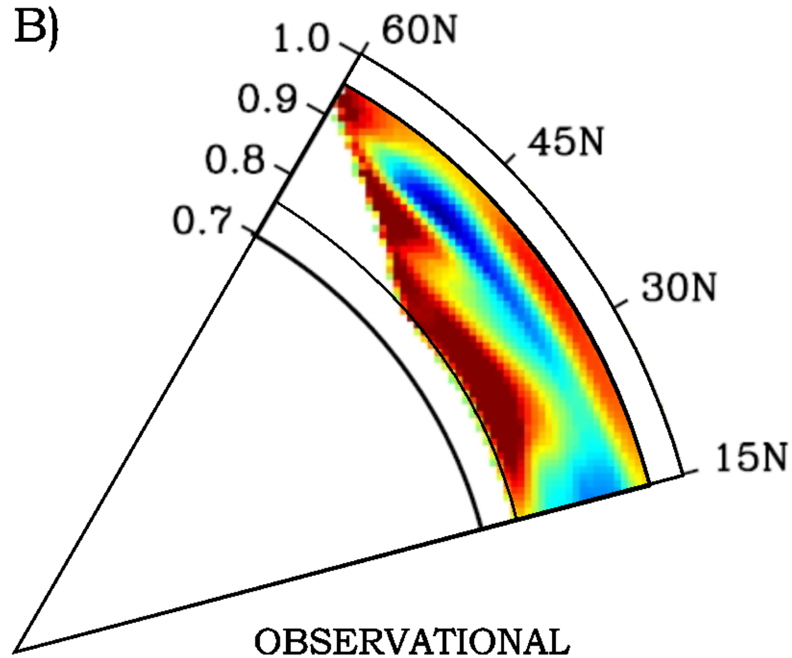
Mean toroidal field



Meridional Circulation stream function

MC horizontal component (u_θ)





EULAG-MHD u_θ profile

Passos et al 2015

Helioseismic derived u_θ profile (2013)

Zhao et al 2013

What is the origin of the meridional flows (1)?

$$\mathbf{u}_m = u_r \hat{\mathbf{e}}_r + u_\theta \hat{\mathbf{e}}_\theta$$

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 ($\Omega_0 = 2.42405 \times 10^{-6}\ \mathrm{s}^{-1}$)

$\mathcal{L}$ **evolution eq.**

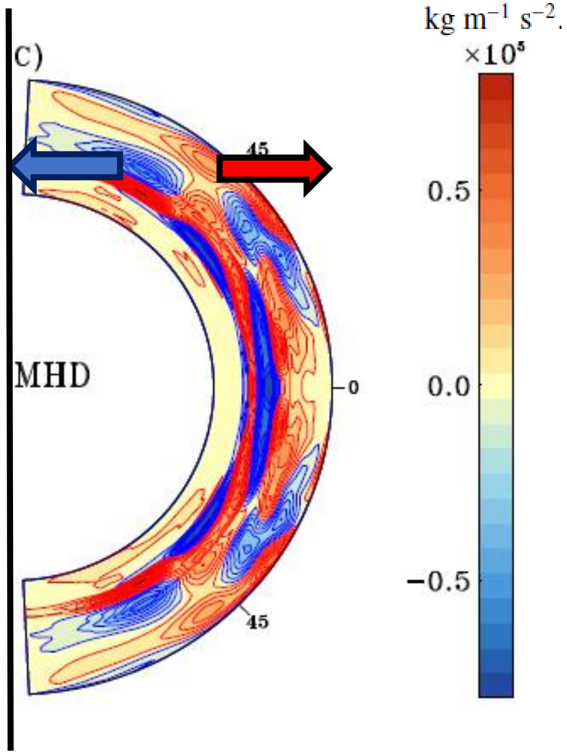
$$\rho_0 \frac{\partial \mathcal{L}}{\partial t} + \langle \rho_0 \mathbf{u}_m \rangle \cdot \nabla \mathcal{L} = -\nabla \cdot \left(\mathbf{F}^{\mathrm{RS}} + \mathbf{F}^{\mathrm{MS}} + \mathbf{F}^{\mathrm{MT}} \right) \equiv \mathcal{F}$$

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

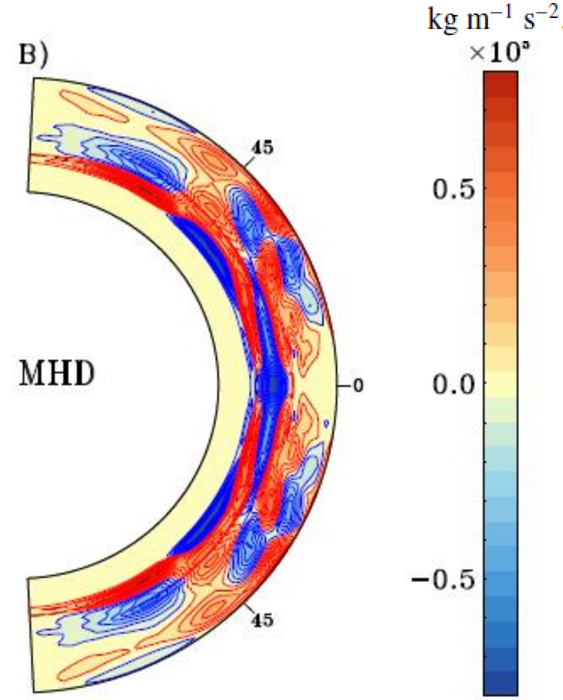
$$\mathbf{F}^{\mathrm{MS}} \equiv -\frac{\lambda}{\mu_0} \left(\langle b'_r b'_\phi \rangle \hat{\mathbf{e}}_\mathbf{r} + \langle b'_\theta b'_\phi \rangle \hat{\mathbf{e}}_\theta \right),$$ Maxwell stress

$$\mathbf{F}^{\mathrm{MT}} \equiv -\frac{\lambda}{\mu_0} \left(\langle b_\phi b_r \rangle \hat{\mathbf{e}}_\mathbf{r} + \langle b_\phi b_\theta \rangle \hat{\mathbf{e}}_\theta \right).$$ Magnetic torque

Ang. Mom. Balance: MHD simulation



$$\langle \rho_0 \mathbf{u}_m \rangle \cdot \nabla \mathcal{L}$$



$$-\nabla \cdot \left(\mathbf{F}^{RS} + \mathbf{F}^{MS} + \mathbf{F}^{MT} \right)$$

Passos et al 2017

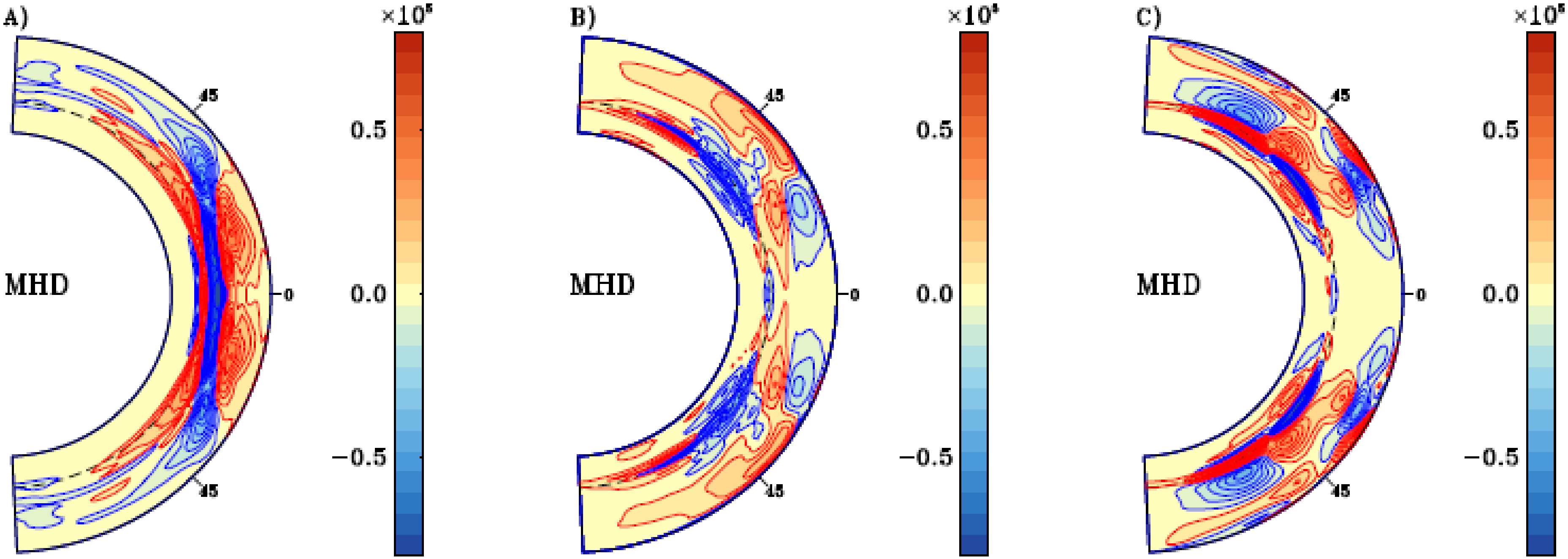
When $\mathcal{F} > 0$ (red lines and shades) the net torque is prograde inducing a meridional flow away from the rotation axis.

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

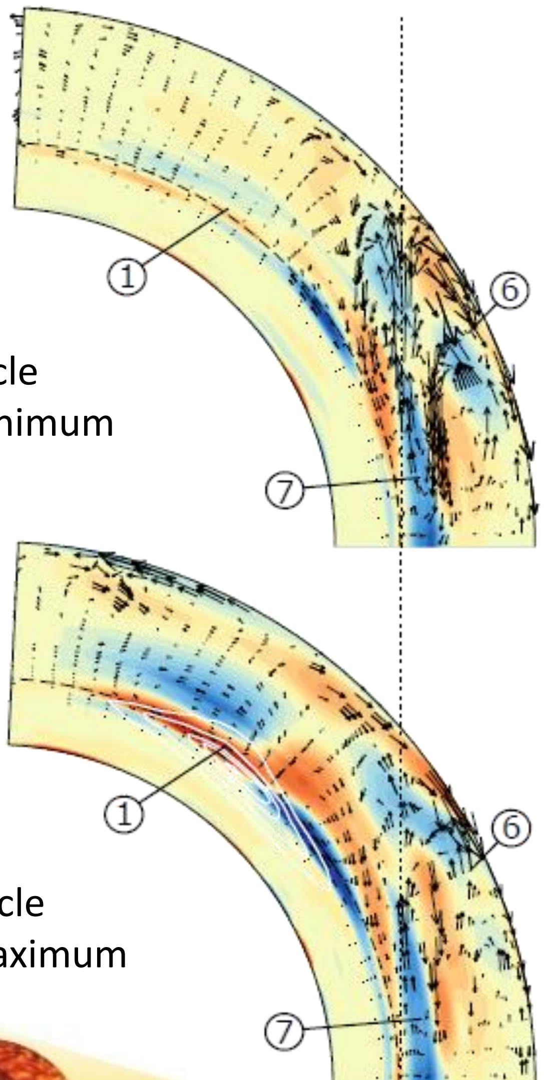
Individual contributions for the Ang. Mom. Balance (MHD)



$-\nabla \cdot \left(\mathbf{F}^{RS}\right)$ $-\nabla \cdot \left(\mathbf{F}^{MS}\right)$ $-\nabla \cdot \left(\mathbf{F}^{MT}\right)$

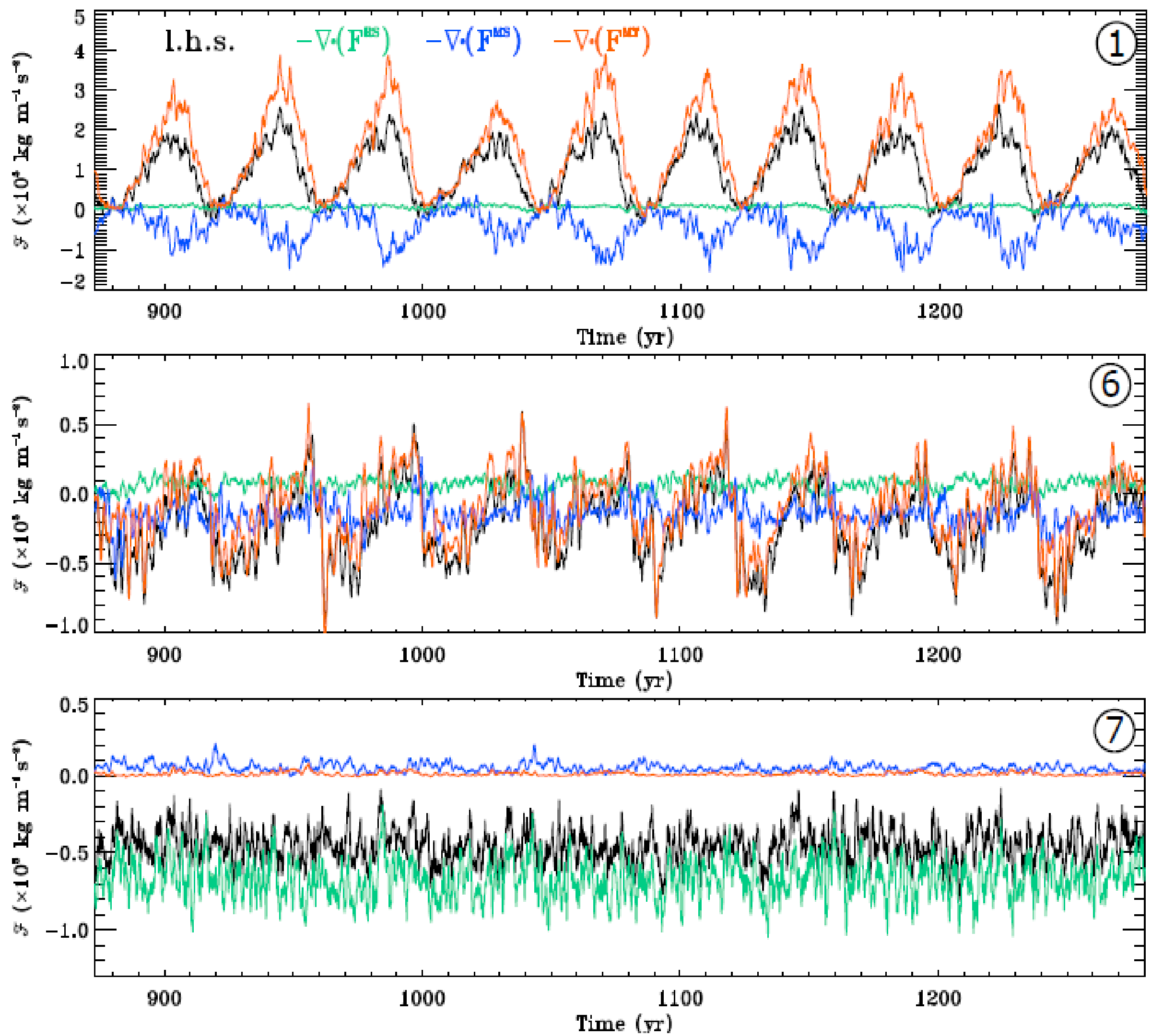
Passos et al 2017

Cyclic evolution of the Ang. Mom. Balance (MHD)



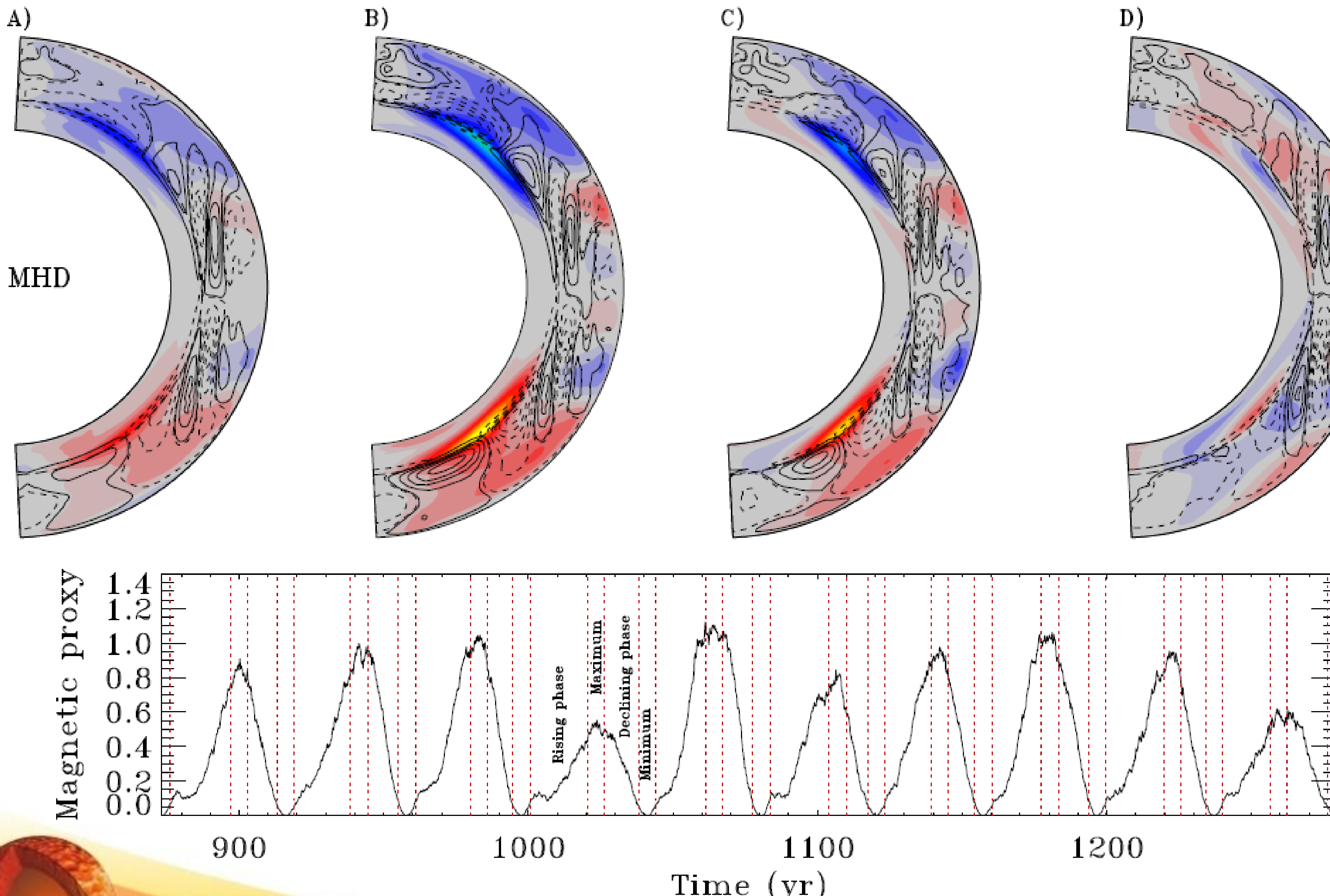
Cycle minimum

Cycle maximum



Passos et al 2017

MC morphological changes along the magnetic cycle



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!*).

$$\frac{\partial \omega}{\partial t} = (\omega_{\mathbf{a}} \cdot \nabla)\mathbf{u} - (\mathbf{u} \cdot \nabla)\omega_{\mathbf{a}} - \omega_{\mathbf{a}}(\nabla \cdot \mathbf{u}) - \nabla \times \mathbf{g}\frac{\Theta'}{\Theta_0} + \frac{1}{\mu_0}\left(\nabla \frac{1}{\rho_0}\right) \times (\mathbf{B} \cdot \nabla)\mathbf{B} + \frac{1}{\mu_0 \rho_0}(\nabla \times (\mathbf{B} \cdot \nabla)\mathbf{B})$$

where $\omega_{\mathbf{a}} = (\nabla \times \mathbf{u}) + 2\mathbf{\Omega_0}$ is the absolute vorticity.

Compute azimuthally averaged $\hat{\mathbf{e}}_\phi$ component of the vorticity evolution equation (with $\omega = \nabla \times \mathbf{u}$)

to get a ***Meridional force balance*** (a.k.a. magneto-thermal wind balance) equation

$$
-\left\langle 2\Omega_0\left(\cos\theta\frac{\partial u_\phi}{\partial r}-\frac{\sin\theta}{r}\frac{\partial u_\phi}{\partial\theta}\right)\right\rangle = \underbrace{\left\langle \omega\cdot\nabla u_\phi+\frac{\omega_\phi u_r}{r}+\frac{\omega_\phi u_\theta\cot\theta}{r}\right\rangle}_{Stretching}
$$

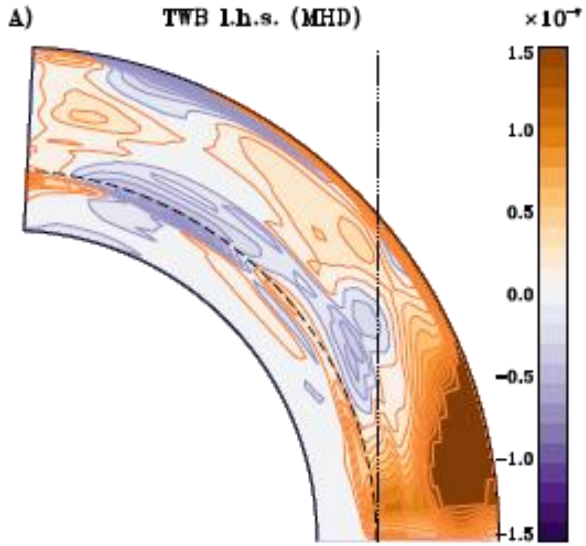
$$
+\underbrace{\left\langle -\mathbf{u}\cdot\nabla\omega_\phi-\frac{u_\phi\omega_r}{r}-\frac{u_\phi\omega_\theta\cot\theta}{r}\right\rangle}_{Advection}
$$

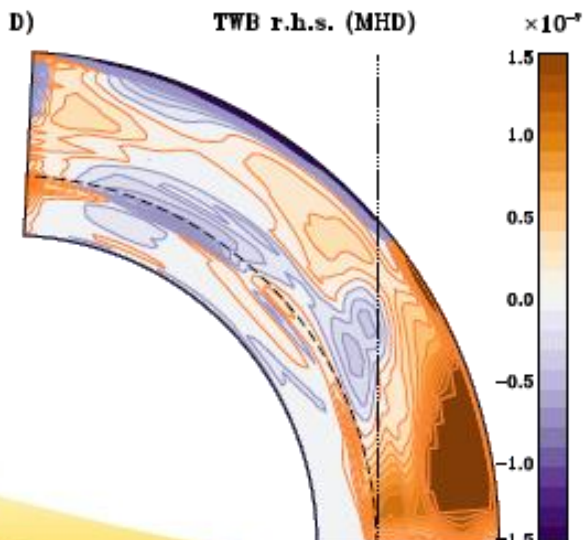
$$
+\underbrace{\left\langle -\omega_\phi\left(\frac{1}{r^2}\frac{\partial(r^2u_r)}{\partial r}+\frac{1}{r\sin\theta}\frac{\partial(u_\theta\sin\theta)}{\partial\theta}+\frac{1}{r\sin\theta}\frac{\partial u_\phi}{\partial\phi}\right)\right\rangle}_{Compressibility}
$$

$$
+\underbrace{\left\langle -\frac{g(r)}{r}\frac{\partial}{\partial\theta}\left(\frac{\Theta'}{\Theta_0}\right)\right\rangle}_{Baroclinicity}
$$

$$
+\underbrace{\left\langle \frac{1}{\mu_0}\frac{\partial}{\partial r}\left(\frac{1}{\rho_0}\right)\left[\mathbf{B}\cdot\nabla B_\theta-\frac{B_\phi^2}{r}\cot\theta+\frac{B_\theta B_r}{r}\right]\right\rangle}_{Magnetic\ contribution\ 1}
$$

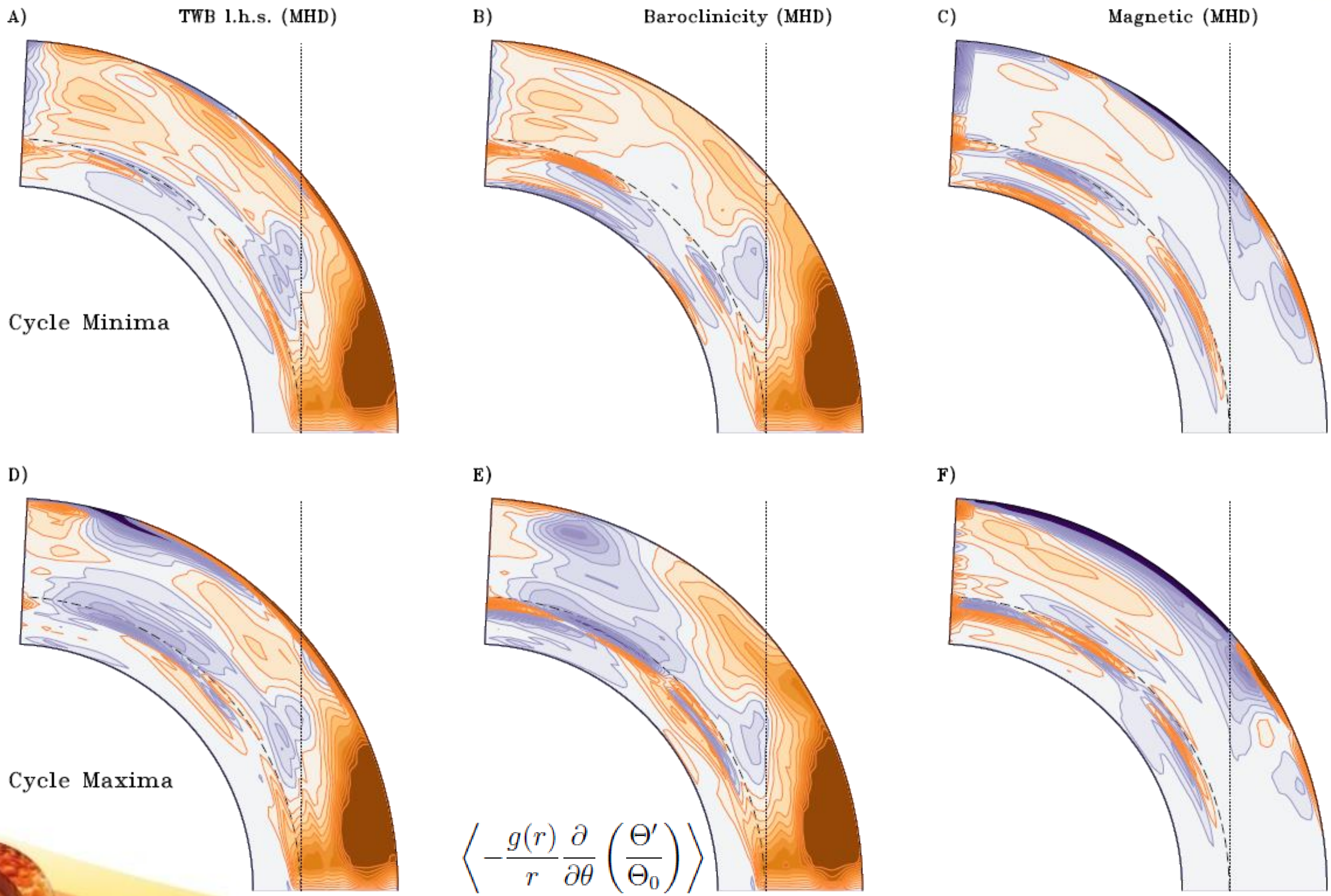
$$
+\underbrace{\left\langle \frac{1}{\mu_0\rho_0}\frac{1}{r}\left[\frac{\partial}{\partial r}\left(r\mathbf{B}\cdot\nabla B_\theta-B_\phi^2\cot\theta+B_\theta B_r\right)-\frac{\partial}{\partial\theta}\left(\mathbf{B}\cdot\nabla B_r-\frac{B_\theta^2}{r}-\frac{B_\phi^2}{r}\right)\right]\right\rangle}_{Magnetic\ contribution\ 2}
$$





Passos et al 2017

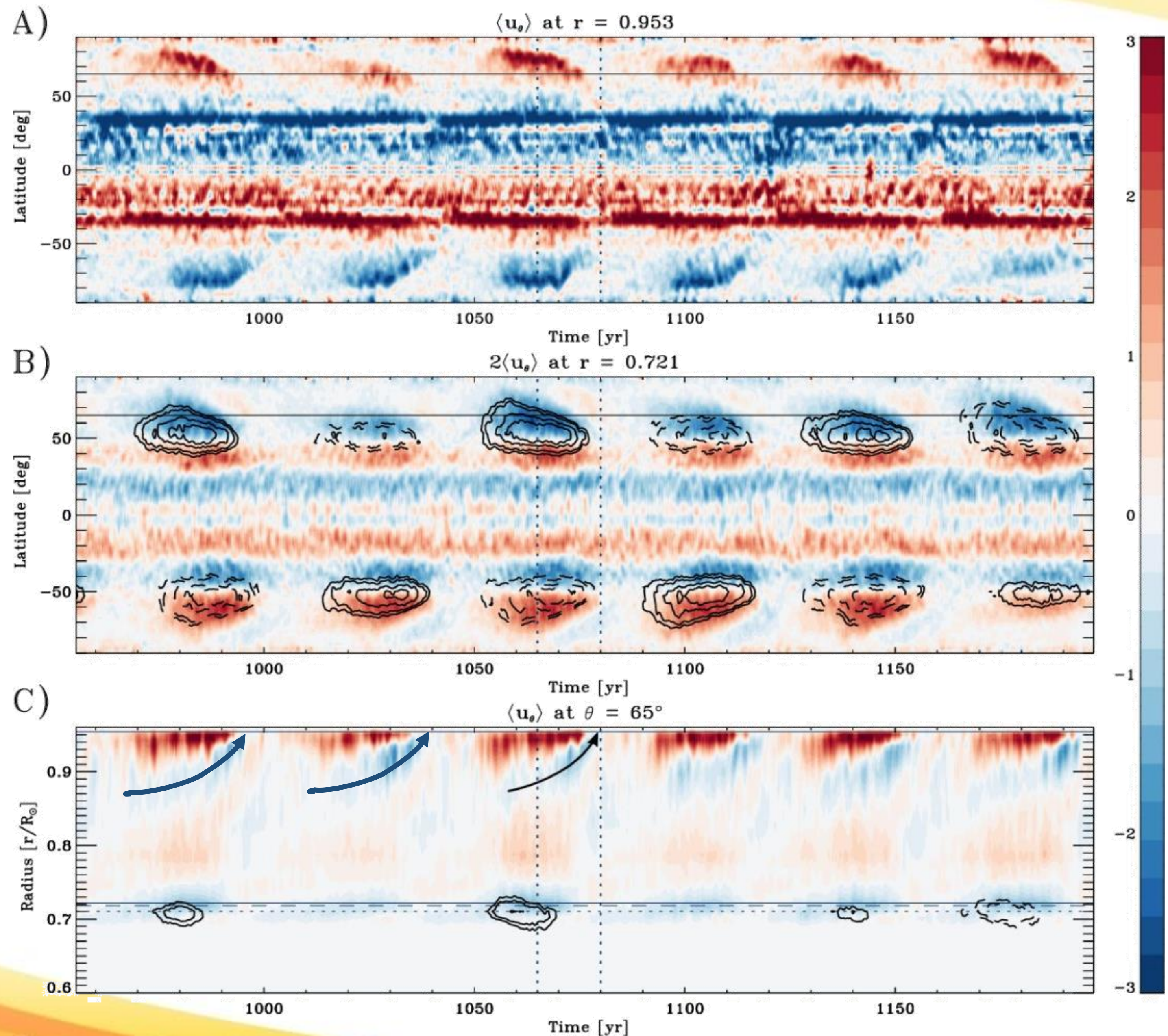
Cyclic evolution of MFB (main terms)



$$\left\langle -\frac{g(r)}{r}\frac{\partial}{\partial\theta}\left(\frac{\Theta'}{\Theta_0}\right)\right\rangle$$

Cossette et al 2013 (and Passos et al 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.

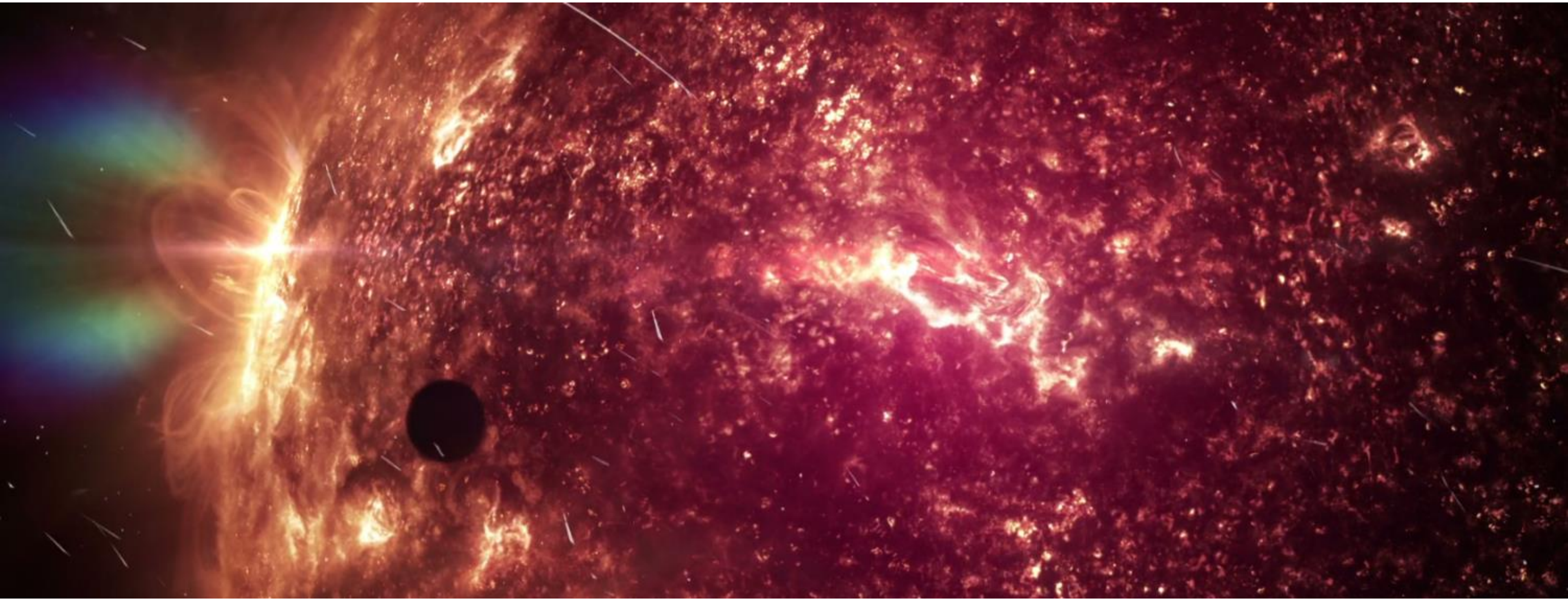
• Model based predictions:

- 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

$$\mathbf{u}(r,\theta,\phi,t) = \langle\mathbf{u}\rangle(r,\theta,t) + \mathbf{u}'(r,\theta,\phi,t))$$

Quantities averaged over the ϕ 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

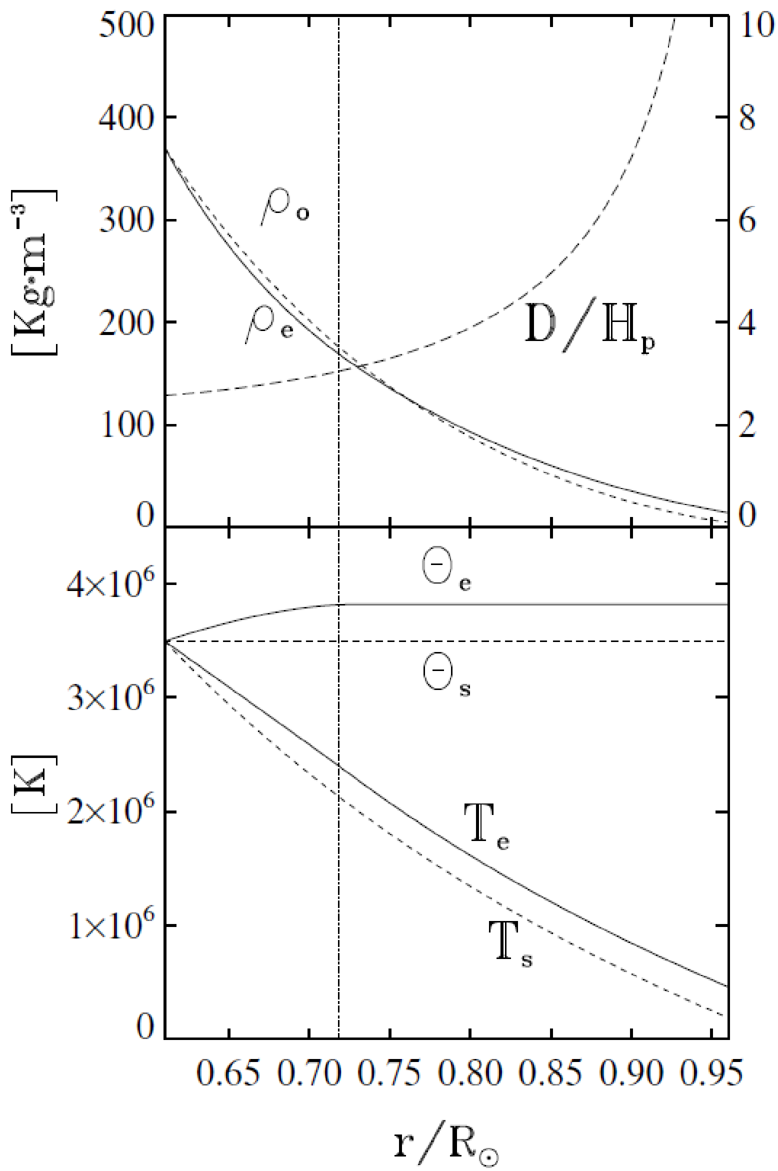
EULAG Radiative Diffusion

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

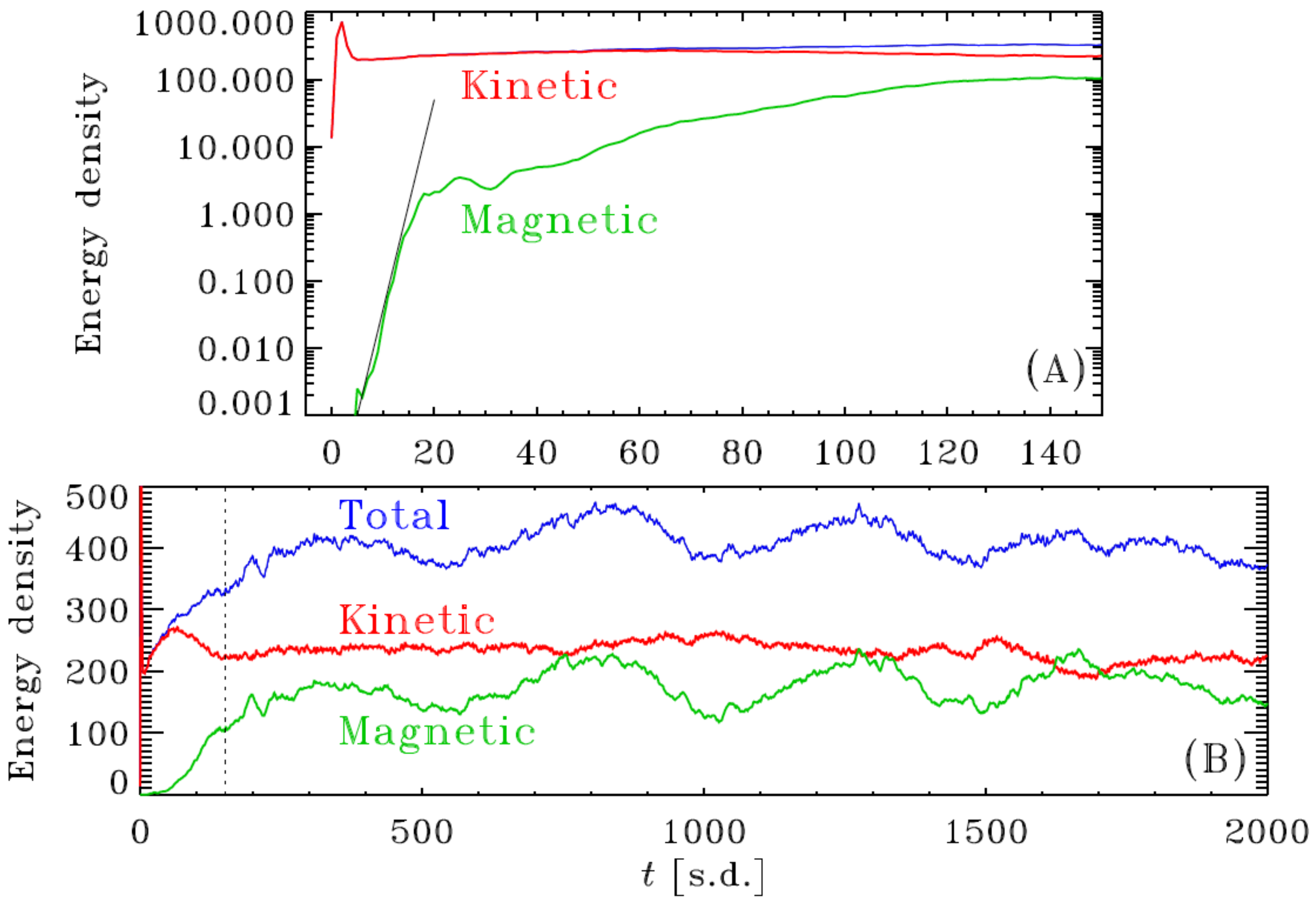
EULAG Ambient Potential Temperature

$$\Theta_e \equiv T_e \left(\frac{\rho_b T_b}{\rho_e T_e} \right)^{1-1/\gamma}$$

Density and temperatures profiles



Energetics

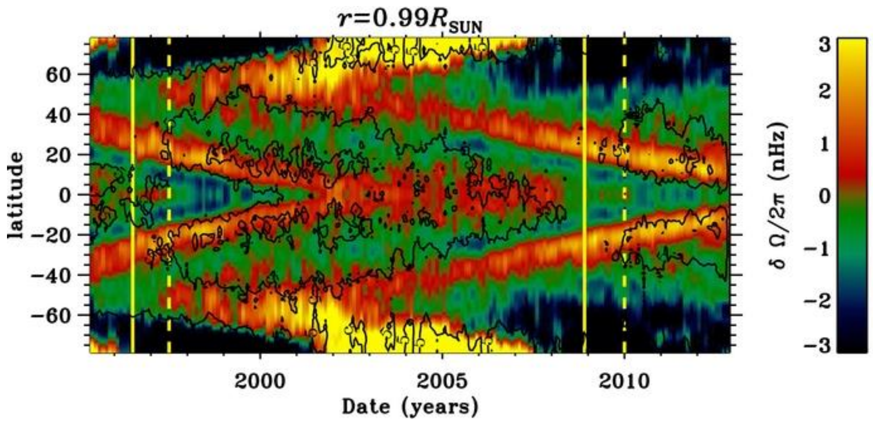

1000.000
100.000
10.000
1.000
0.100
0.010
0.001
Energy density
Kinetic
Magnetic
(A)
0
20
40
60
80
100
120
140
500
400
300
200
100
0
Energy density
Total
Kinetic
Magnetic
(B)
0
500
1000
1500
2000
t [s.d.]

Differential rotation and torsional oscillations in 3D simulations

Simulated Differential Rotation

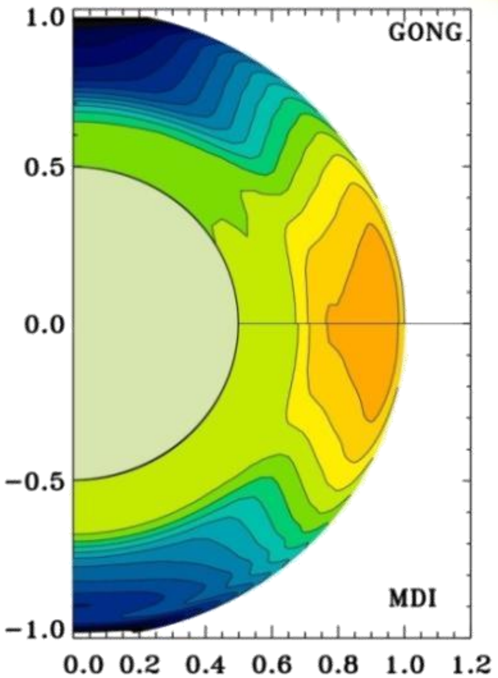
(Racine et al 2011, ApJ 735)

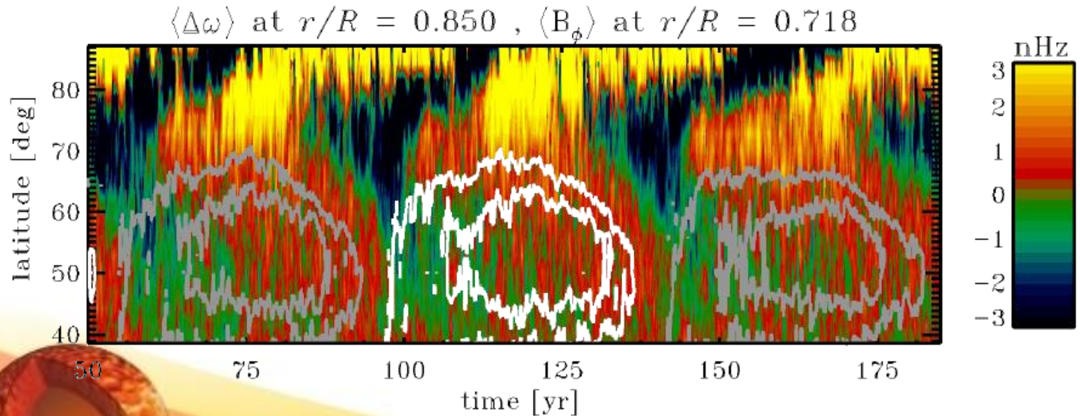
Solar like-differential rotation (slower poles and faster equator) but 3 times less intense then in the Sun. Columnar structures at low latitudes, not radial.



Observed TO pattern

Howe et al (2014)



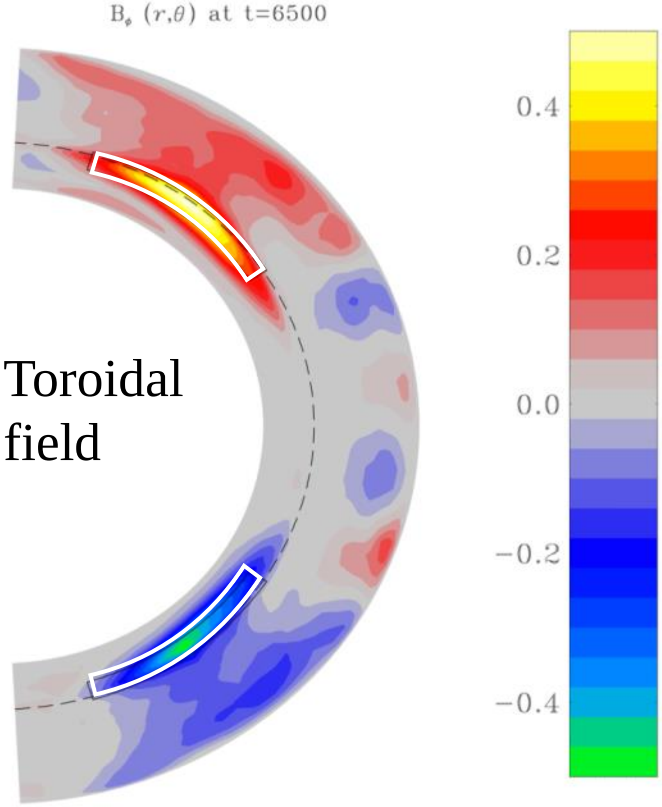


Simulated torsional oscillations

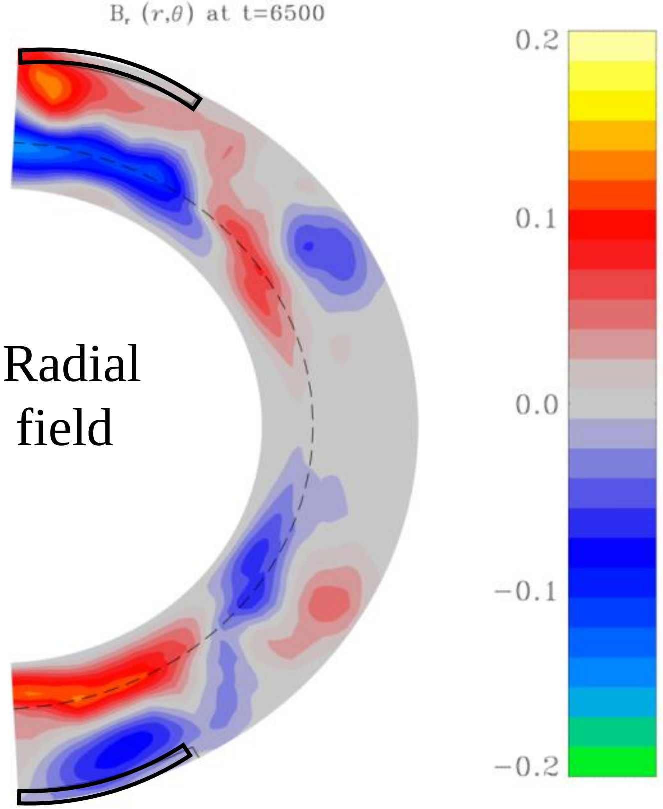
(Beaudoin et al 2013, Sol.Phys. 828)

Appear at higher latitudes but with correct phase and amplitude in respect to the magnetic cycle.

Building Proxies of solar activity

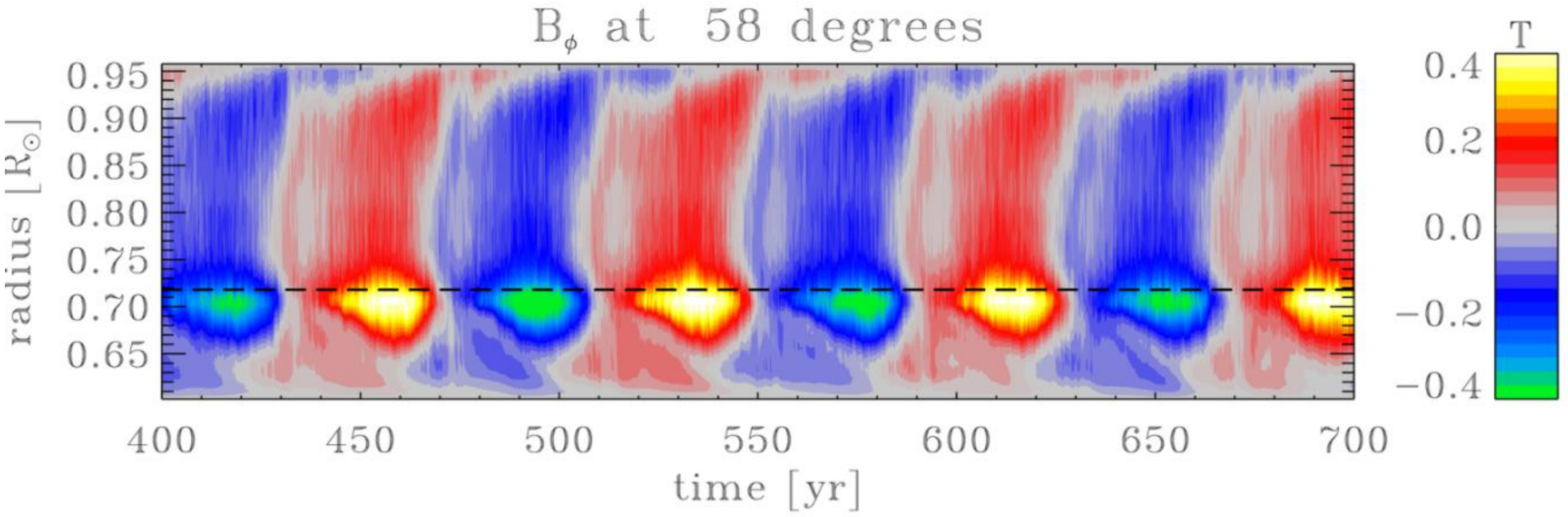


Toroidal
field



Radial
field

Toroidal field radial profile



Poloidal field at 4 cycle phases

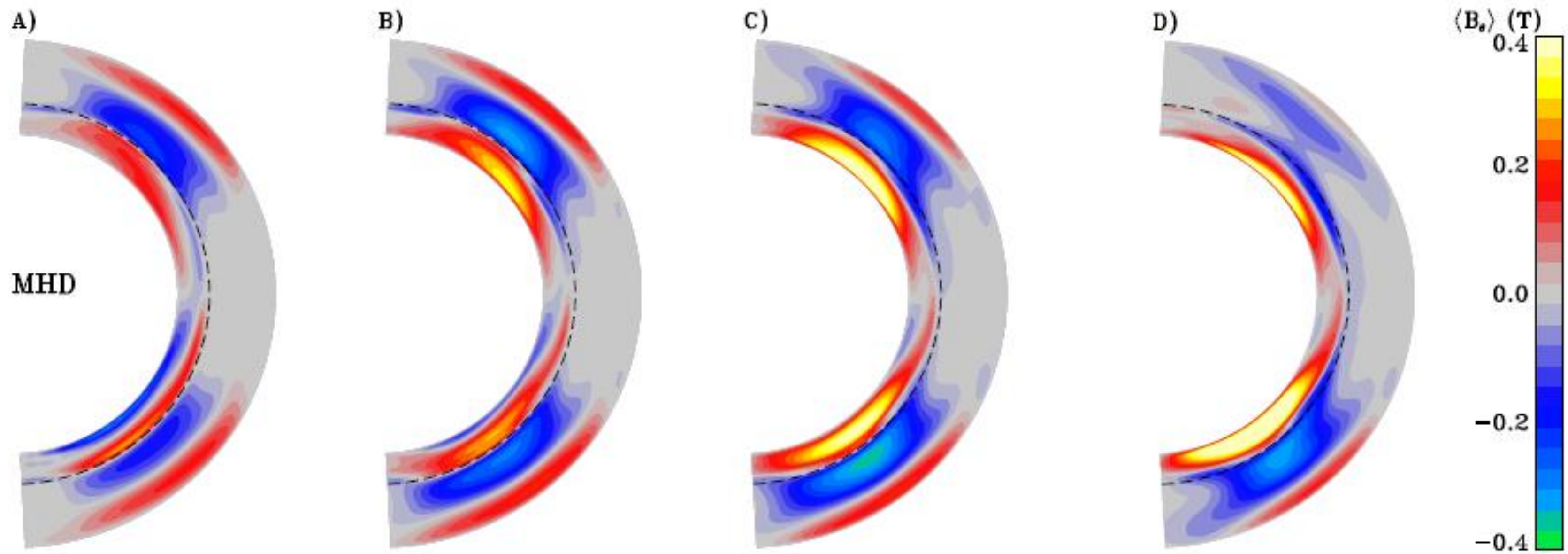
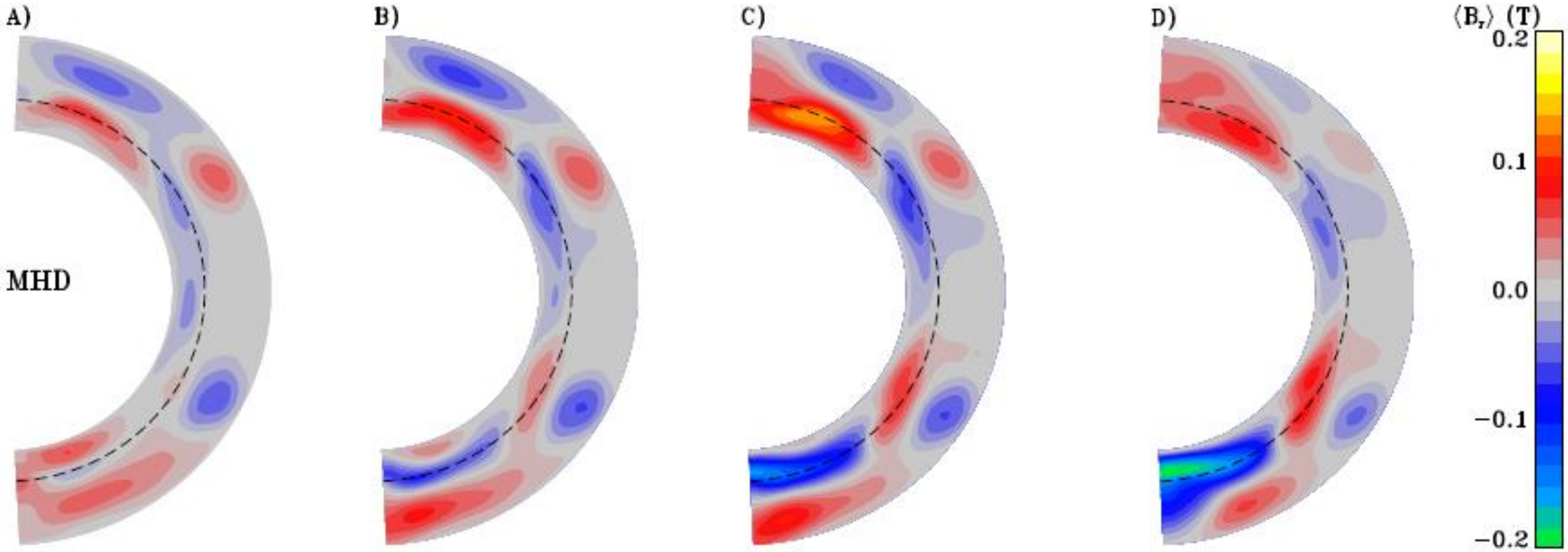
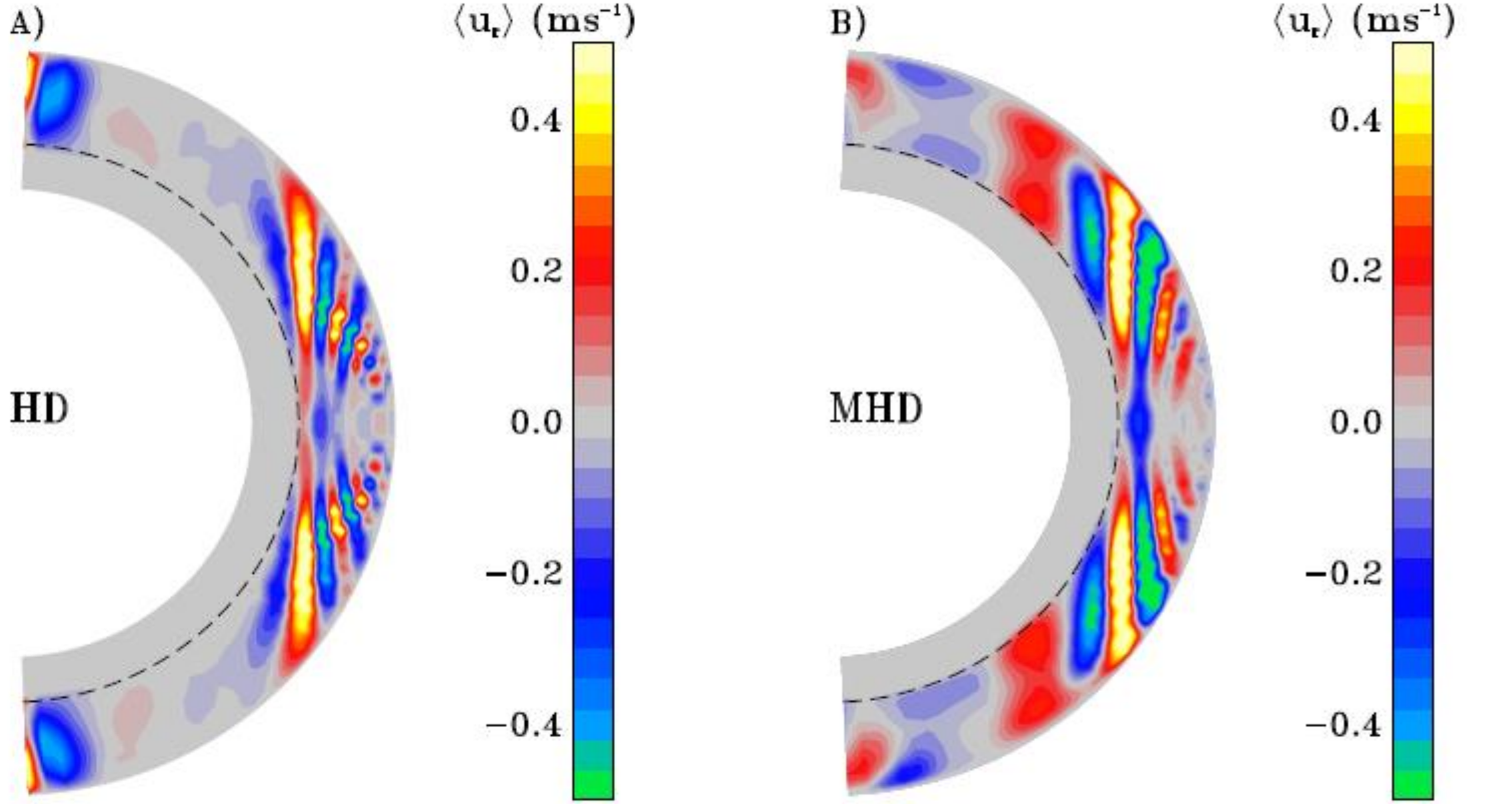


Fig. 17.— Zonal poloidal field $\langle B_\theta \rangle$ averaged over the 4 phases of magnetic cycle 1.

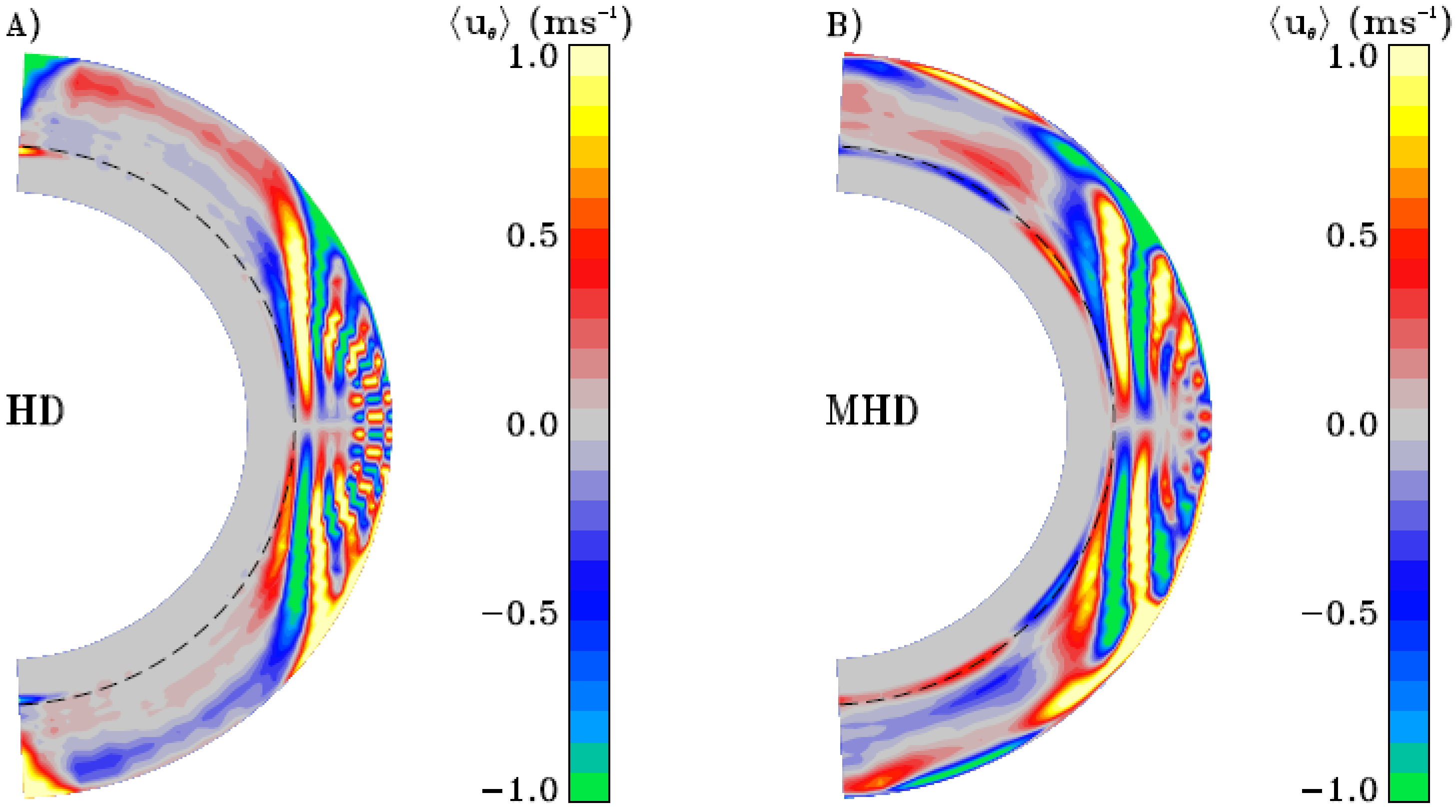
Radial field at 4 cycle phases



Radial velocity component (HD and MHD)



Latitudinal (θ) velocity component (HD and MHD)



Meridional Circulation Stream function (HD and MHD)