

Differential rotation and convective dynamo in the solar convective envelope

Yuhong Fan (HAO/NCAR)

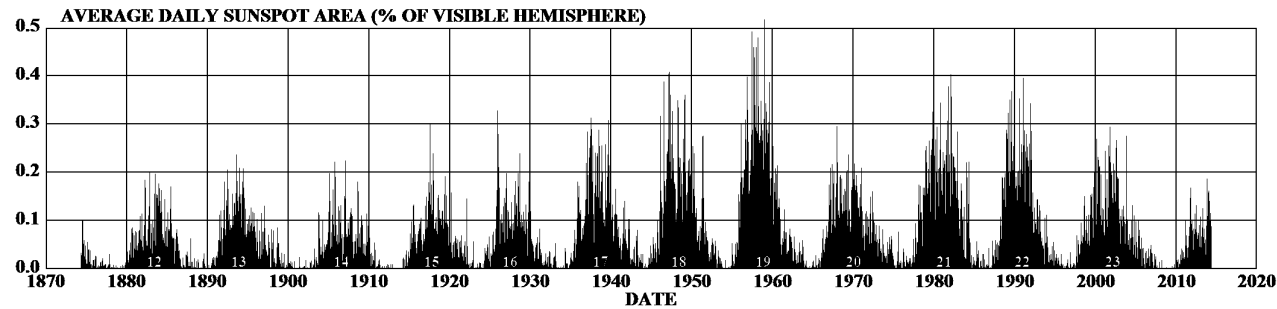
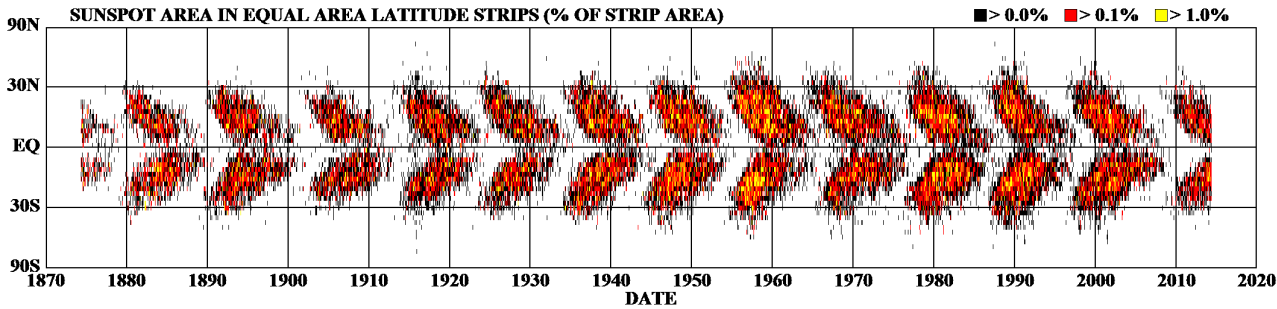
Collaborators: Fang Fang (LASP/CU), Feng Chen (ASP/NCAR), Matthias Rempel (HAO/NCAR), Mei Zhang (NAOC)

SOLARNET IV meeting

The High Altitude Observatory (HAO) at the National Center for Atmospheric Research (NCAR).

The Sun's magnetic cycle

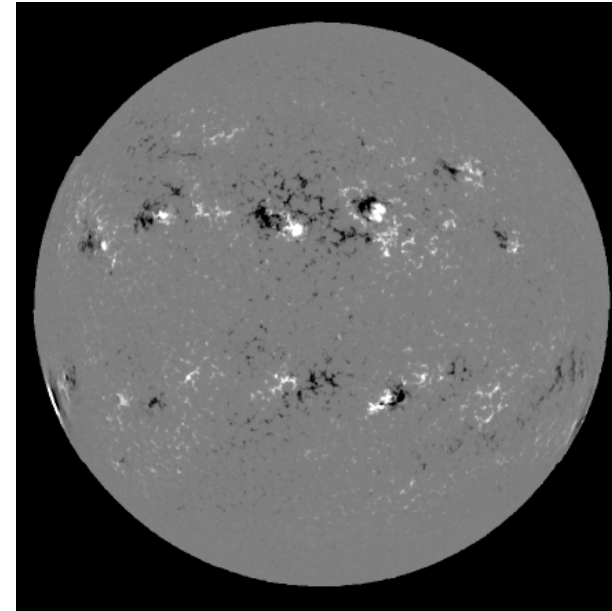
DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



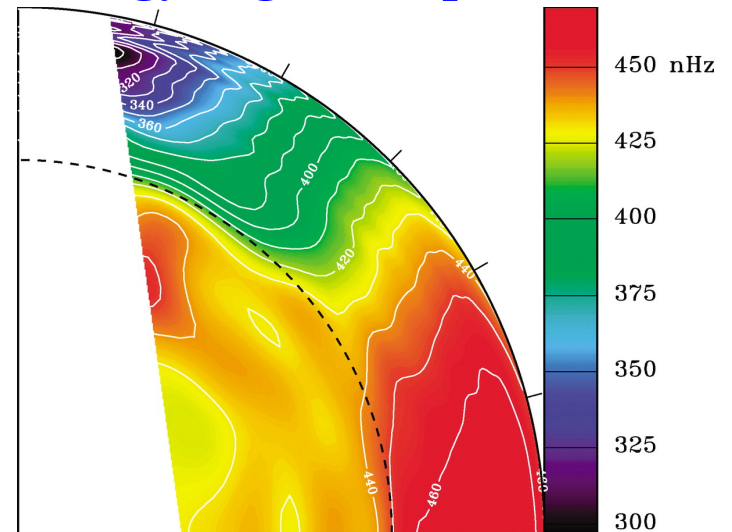
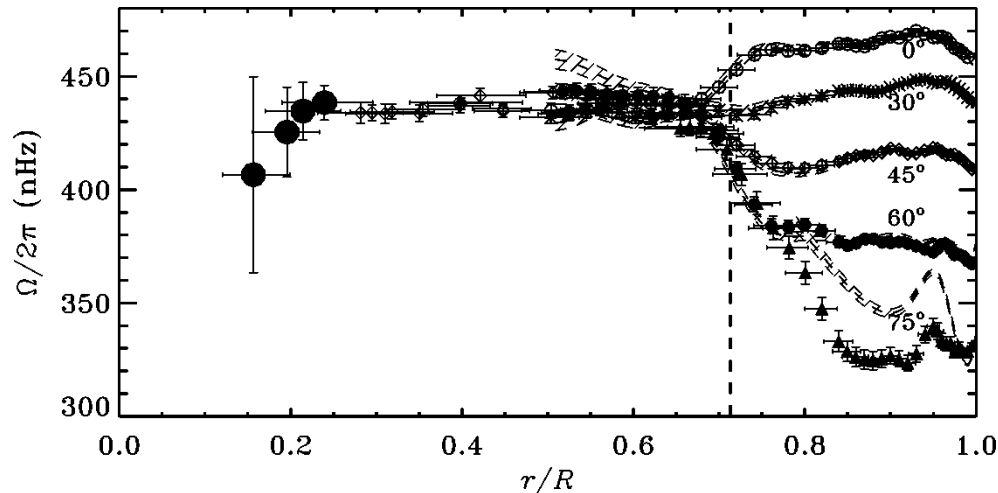
<http://solarscience.msfc.nasa.gov/>

HATHAWAY/NASA/MSFC 2014/06

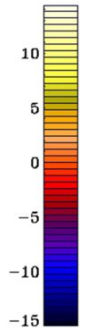
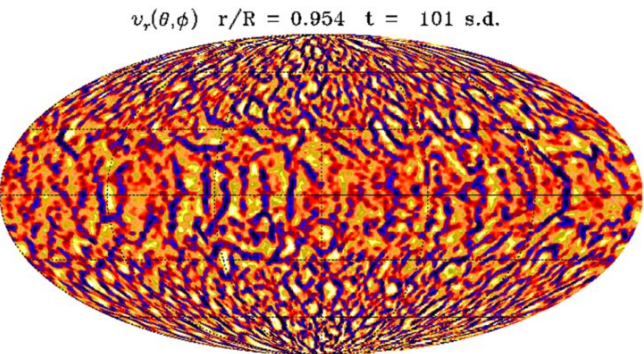
Full disk magnetogram from KPNO



Solar internal rotation inferred from Helioseismology (e.g. Thompson et al. 2003)

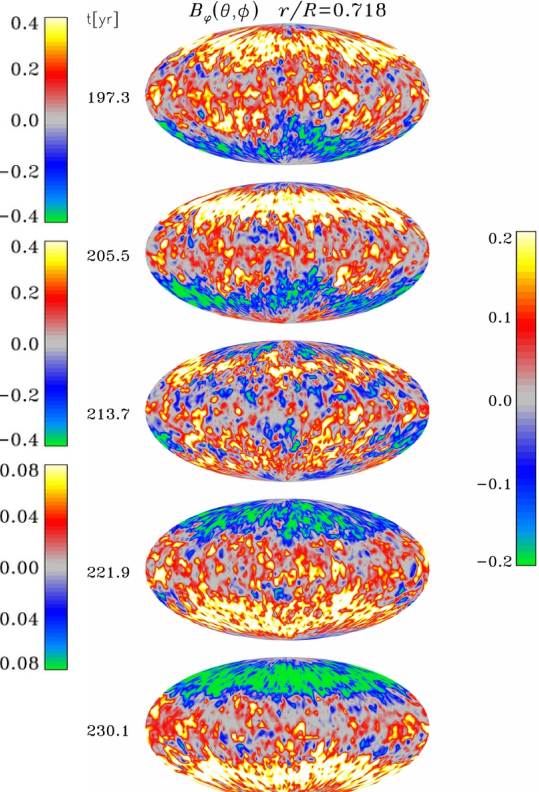
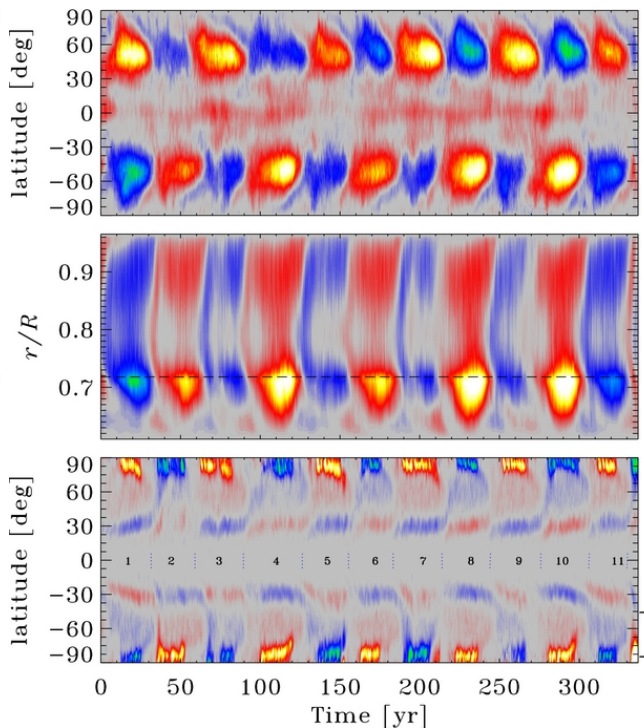
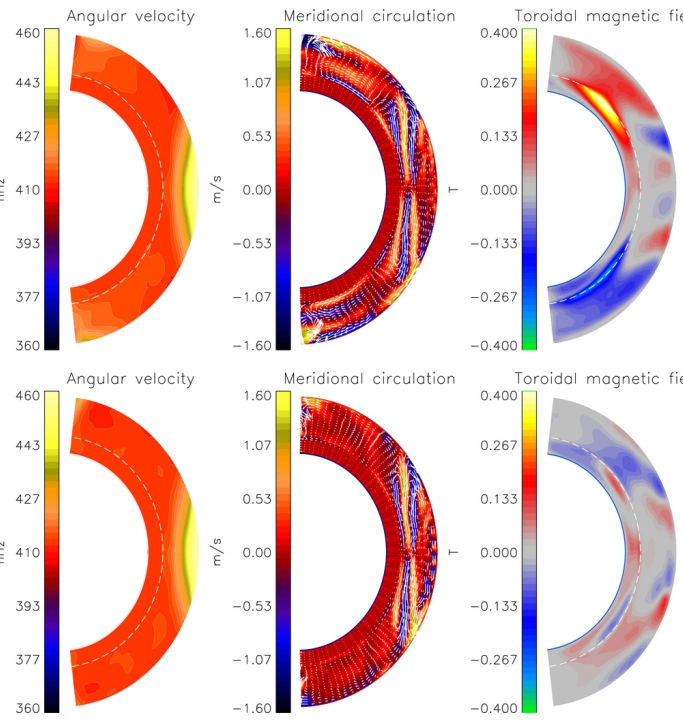


• Cyclic dynamo in a global implicit large-eddy anelastic MHD simulation of the solar convective envelope with EULAG-MHD code (Ghizaru et al 2010, Racine et al. 2011)



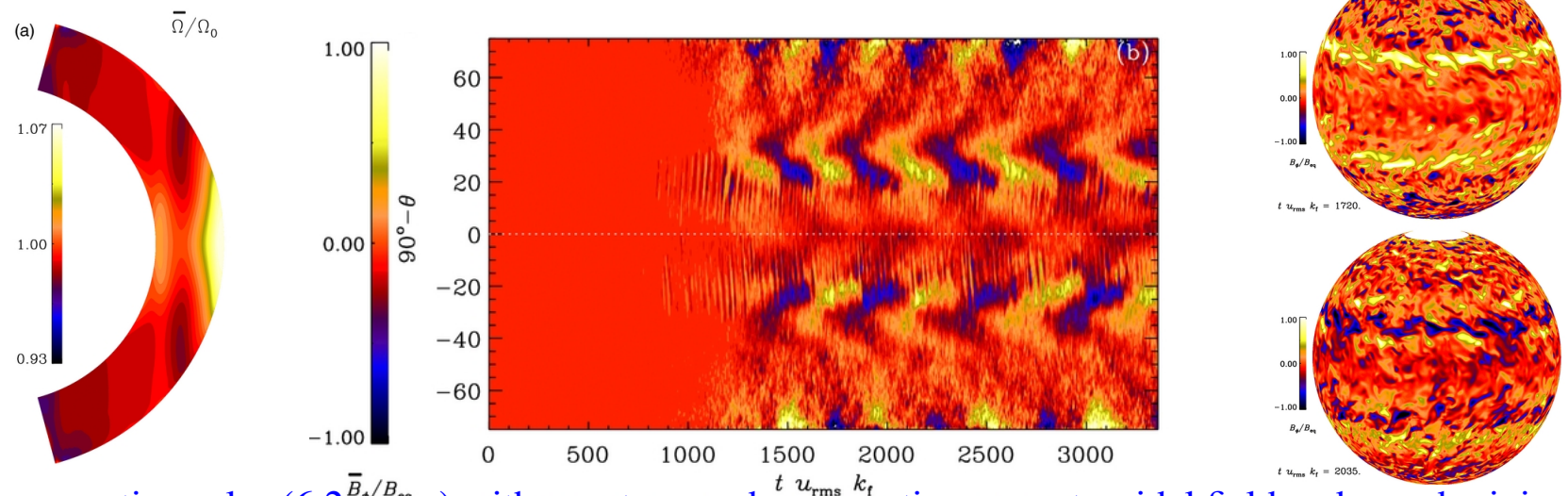
- Include a stable overshoot layer at the bottom of CZ
- Solar-like differential rotation in the CZ
- A strong and cyclic large-scale mean field component undergoing regular polarity reversals at a period of 30 years
- Convection maintained by an entropy gradient imposed by a Newtonian cooling term in the entropy equation.

Estimated $Co = 2\Omega / (u_{rms} 2\pi / \Delta r) \sim 6$



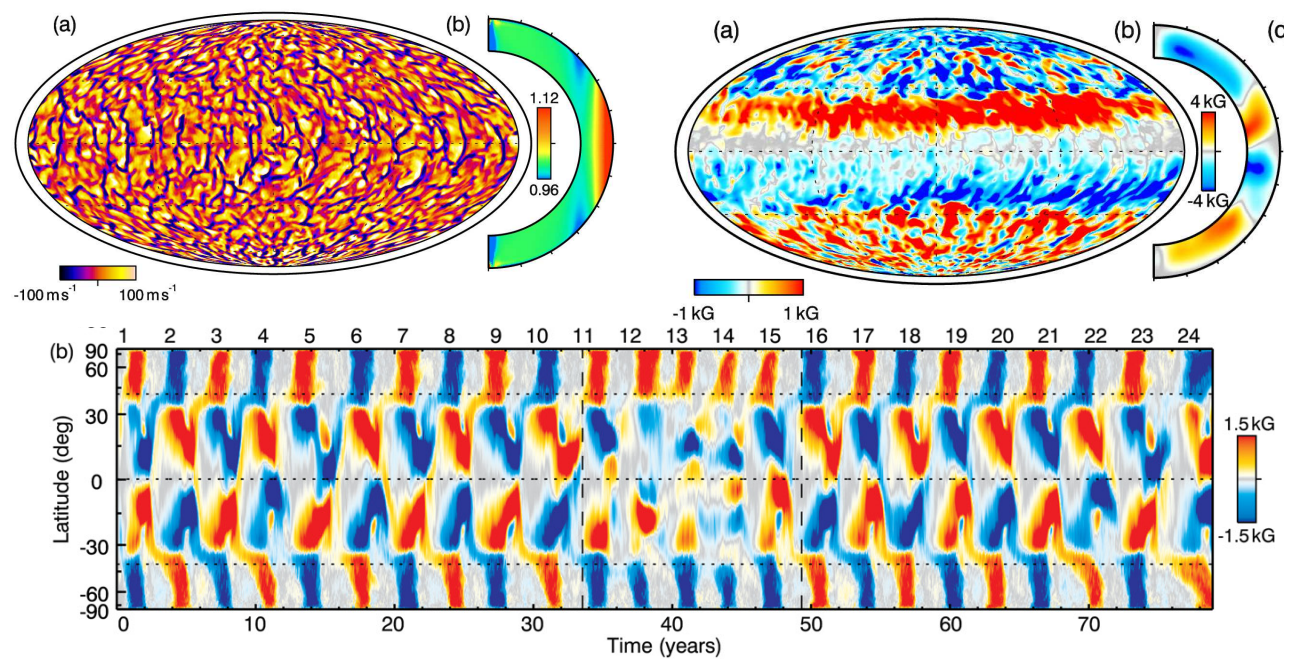
- Regular magnetic cycles with equator-ward-propagating mean toroidal field in compressible MHD simulations of convective dynamo (Käpylä et al. 2012, 2014, 2016, Warnecke et al. 2014):

$$Co = 2\Omega / (u_{rms} 2\pi / \Delta r) = 7.6$$



- Regular magnetic cycles (6.2 years) with equator-ward-propagating mean toroidal field and grand minima in a rapidly rotating young sun (3 times solar rotation rate) from Anelastic MHD global simulations (Augustson et al. 2015)

$$Co = 2\Omega / (u_{rms} 2\pi / \Delta r) \sim 4.5$$



- Convective dynamo driven by solar radiative diffusive heat flux and with the solar rotation rate, computed with the Finite-difference Spherical Anelastic MHD (FSAM) code (Fan and Fang 2014, 2016):

$$\nabla \cdot (\rho_0 \mathbf{v}) = 0,$$

$$\rho_0 \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = 2\rho_0 \mathbf{v} \times \boldsymbol{\Omega} - \nabla p_1 + \rho_1 \mathbf{g} + \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B} + \nabla \cdot \mathcal{D}$$

$$\rho_0 T_0 \left[\frac{\partial s_1}{\partial t} + (\mathbf{v} \cdot \nabla)(s_0 + s_1) \right] = \nabla \cdot (K \rho_0 T_0 \nabla s_1) - (\mathcal{D} \cdot \nabla) \cdot \mathbf{v} + \frac{1}{4\pi} \eta (\nabla \times \mathbf{B})^2 - \nabla \cdot \mathbf{F}_{\text{rad}}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \nabla \times \mathbf{B}),$$

$$\frac{\rho_1}{\rho_0} = \frac{p_1}{p_0} - \frac{T_1}{T_0},$$

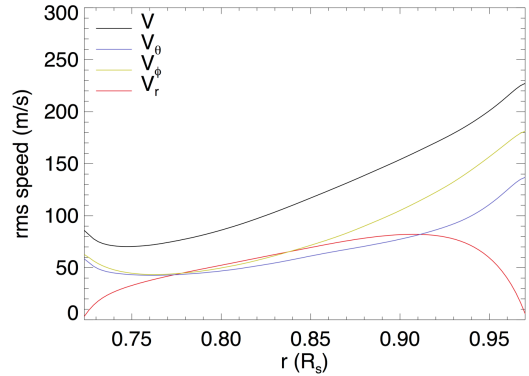
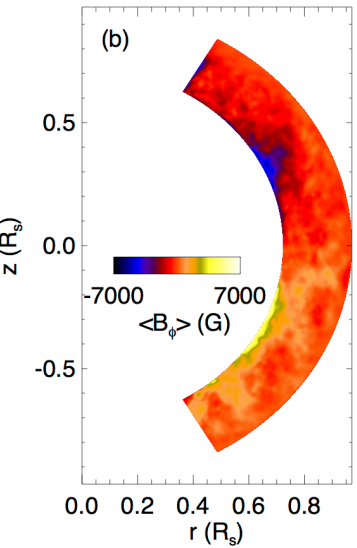
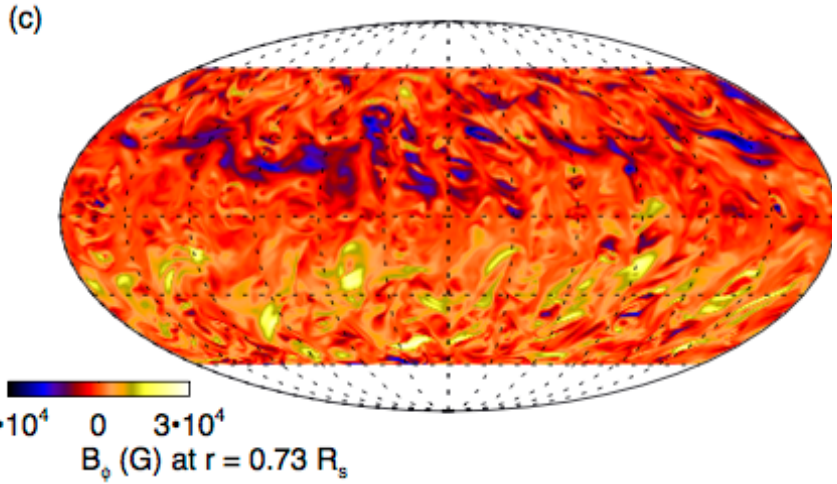
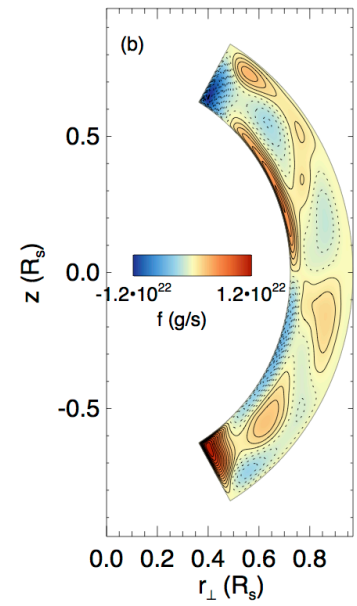
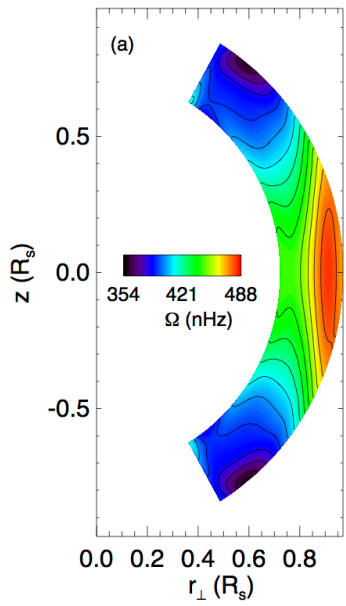
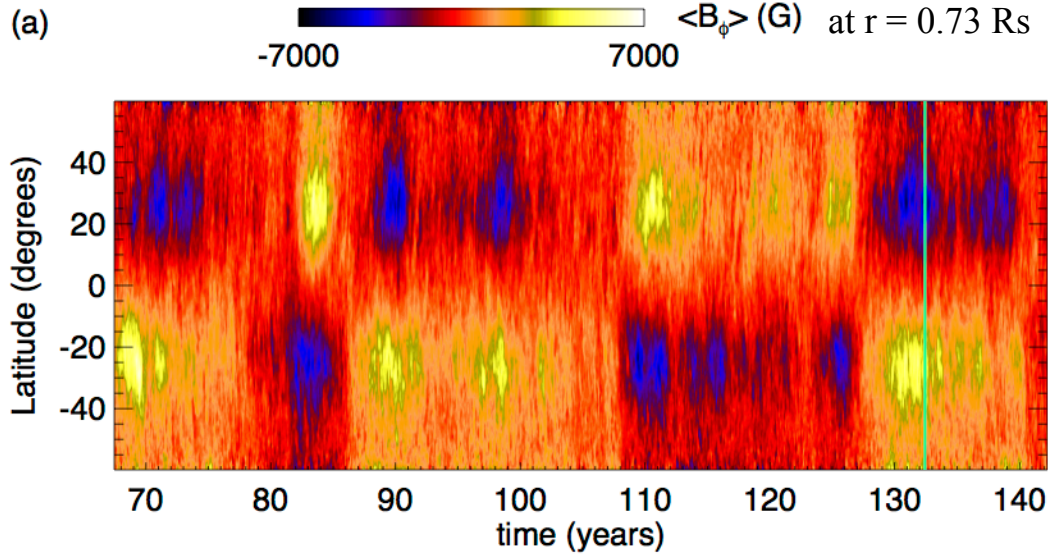
$$\frac{s_1}{c_p} = \frac{T_1}{T_0} - \frac{\gamma - 1}{\gamma} \frac{p_1}{p_0},$$

where D is the viscous stress tensor, and \mathbf{F}_{rad} is the radiative diffusive heat flux :

$$\mathbf{F}_{\text{rad}} = \frac{16\sigma_s T_0^3}{3\kappa\rho_0} \nabla T_0,$$

- Simulation domain $r \in (0.722R_s, 0.971R_s)$, $\theta \in (\pi/2 - \pi/3, \pi/2 + \pi/3)$, $\phi \in (0, 2\pi)$
- Grid: $96(r) \times 512(\theta) \times 768(\phi)$, horizontal res. at top boundary 2.8 Mm to 5.5 Mm, vertical res. 1.8 Mm
- $K = 3 \times 10^{13} \text{ cm}^2 \text{ s}^{-1}$, $\nu = 10^{12} \text{ cm}^2 \text{ s}^{-1}$, $\eta = 10^{12} \text{ cm}^2 \text{ s}^{-1}$, at top and decrease with depth as $1/\sqrt{\rho}$ (Fan and Fang 2014)
- K is the same as above but $\nu=0$, $\eta=0$ (Fan and Fang 2016)

Convective dynamo driven by solar radiative diffusive heat flux with solar rotation rate: irregular cyclic mean field and solar-like differential rotation (Fan and Fang 2014)



Estimated $Co = 2\Omega / (u_{rms} 2\pi / \Delta r) \sim 1.3$

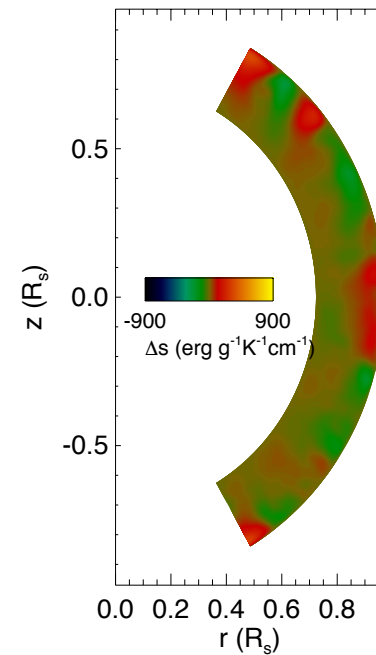
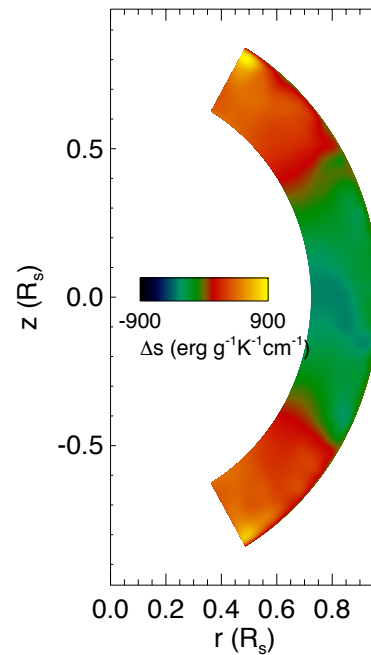
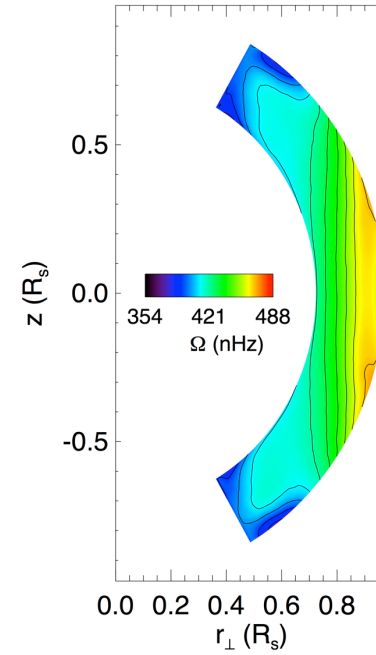
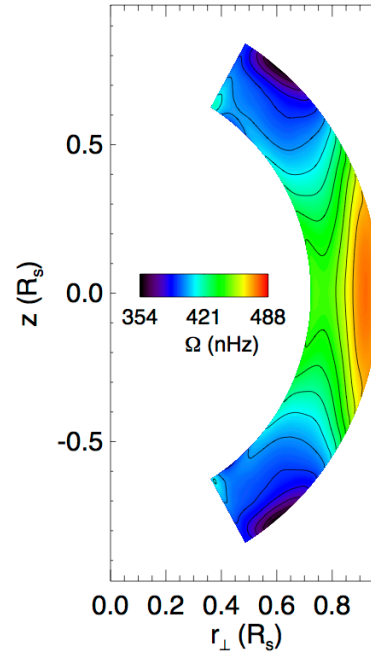
Our dynamo is in a much less rotationally constrained regime compared to Kapyla et al. (2012), Augustson et al. (2015).

with latitudinal gradient of s at base of CZ

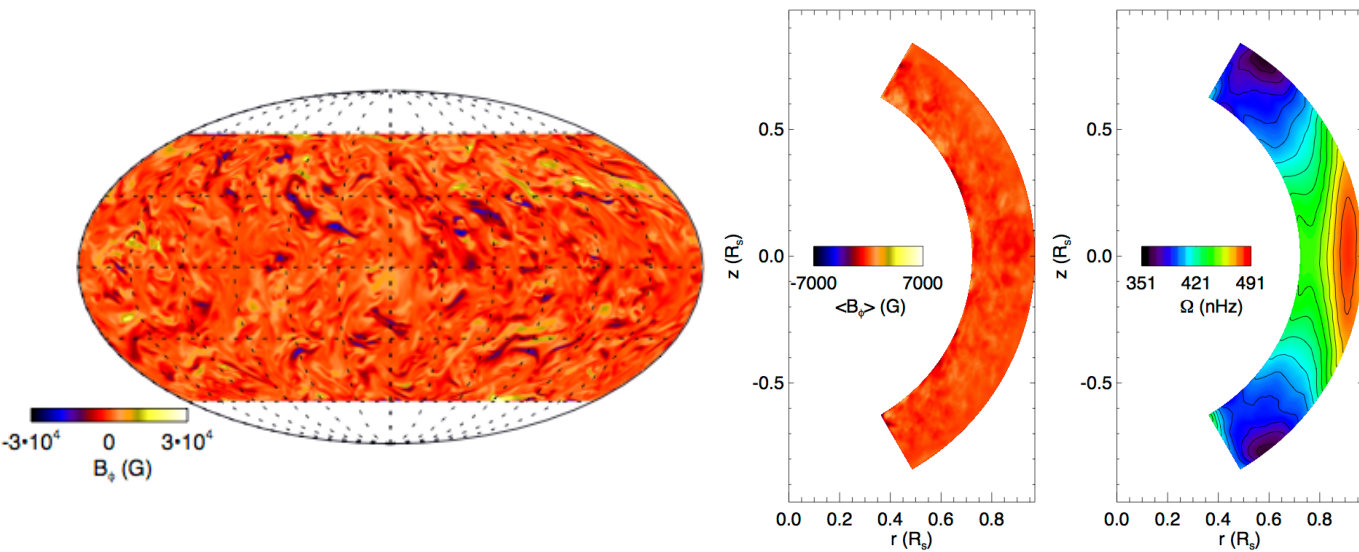
without latitudinal gradient of s at base of CZ

ϕ component of the vorticity equation: (Rempel 2005):

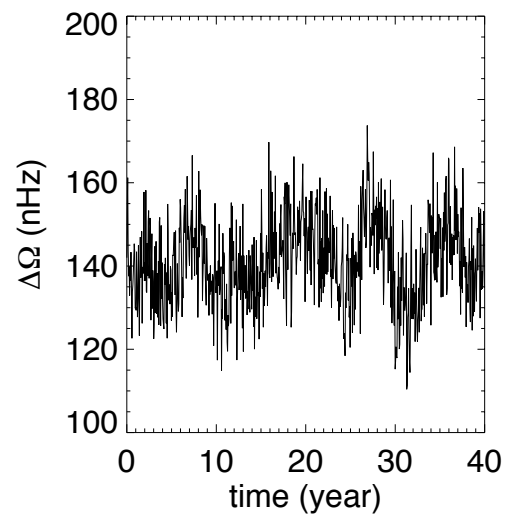
$$\frac{\partial \omega_\phi}{\partial t} = [\dots] + r \sin \theta \frac{\partial \Omega^2}{\partial z} - \frac{g}{rc_p} \frac{\partial s}{\partial \theta}$$



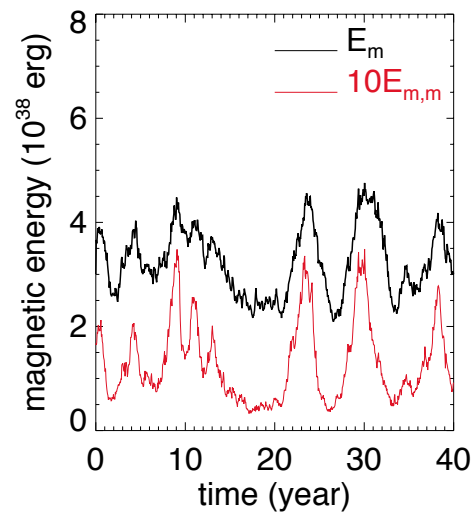
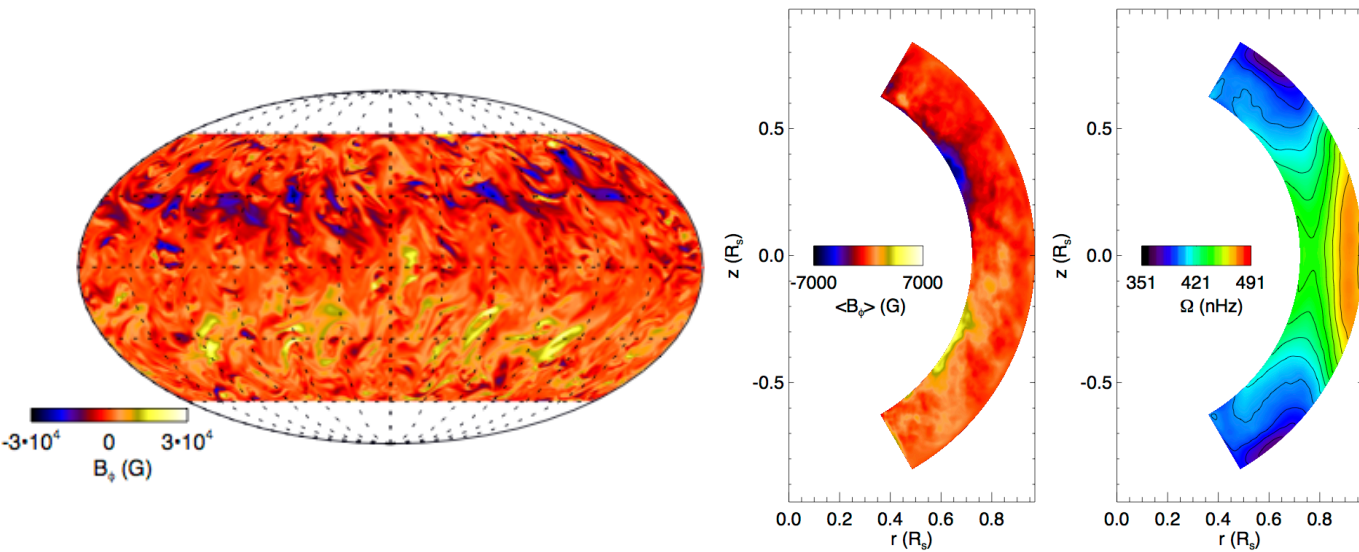
minimum

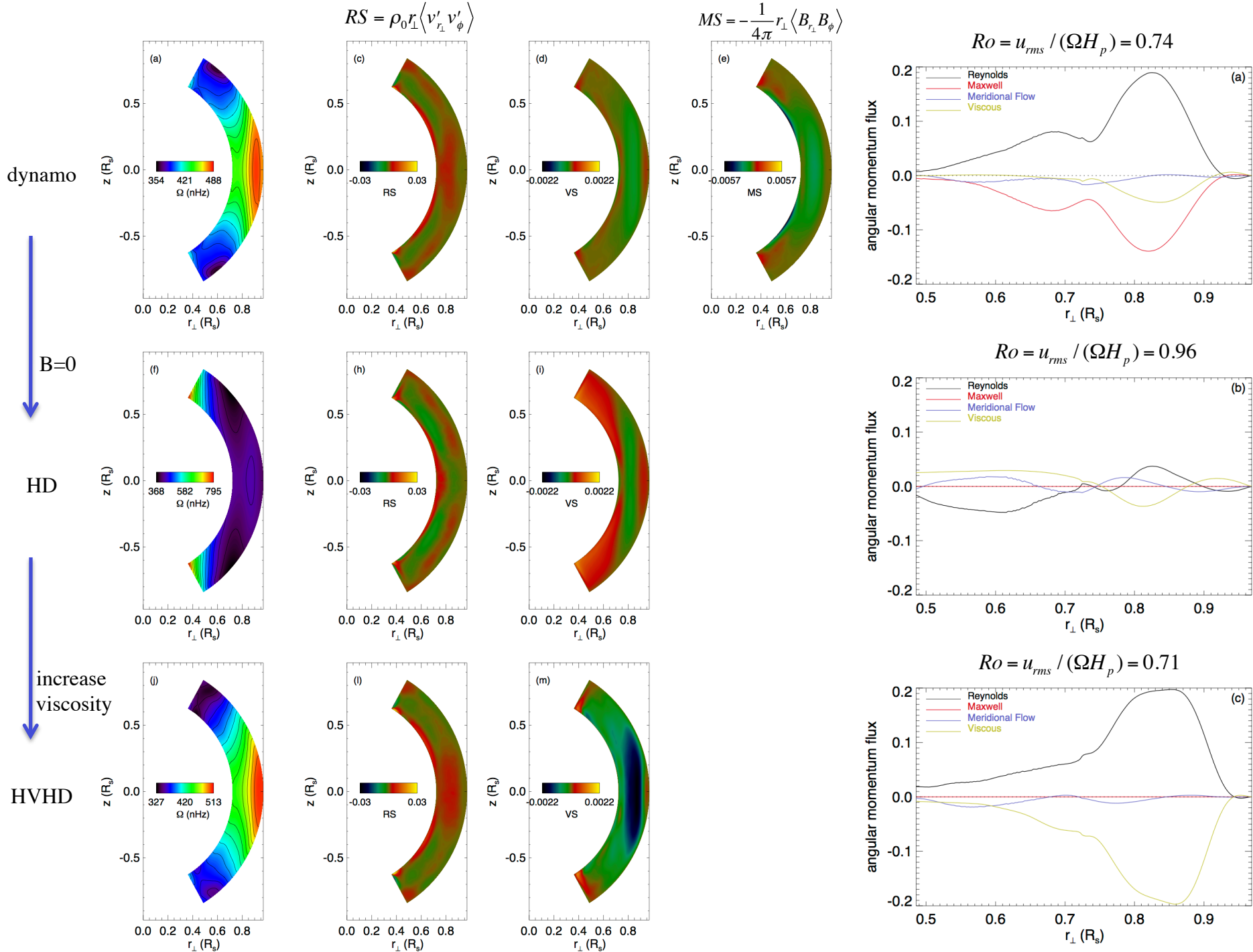


Cycle variation of
differential rotation
contrast $\Delta\Omega$



maximum





Angular momentum flux density due to meridional circulation:

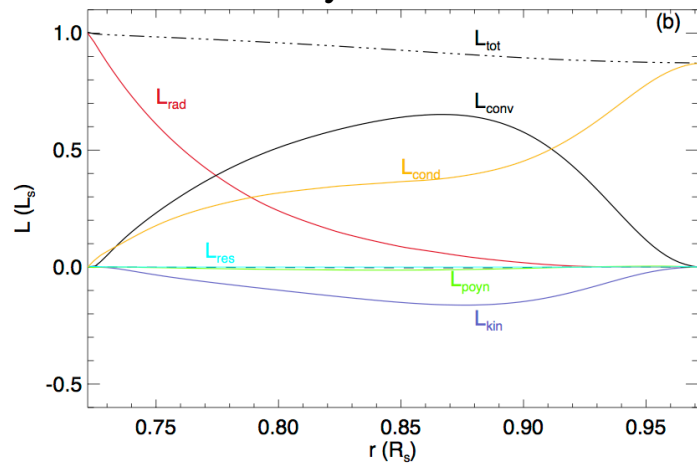
$$\mathbf{F}_{\text{MC}} = \rho_0 L \langle \mathbf{v}_m \rangle, \text{ where } L = r_\perp^2 \Omega$$

If $L \approx L(r_\perp)$, then the net angular momentum flux across a constant r_\perp cylinder (e.g. Miesch 2005, Rempel 2005):

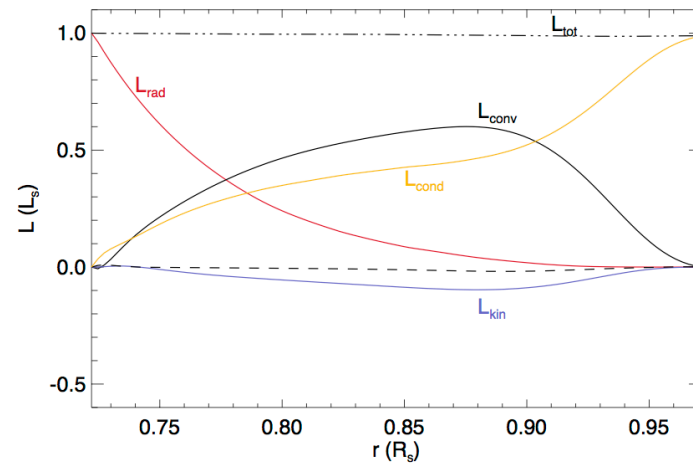
$$f(r_\perp) = \int_{s(r_\perp)} \rho_0 L(r_\perp) \langle \mathbf{v}_m \rangle dS \approx L(r_\perp) \int_{s(r_\perp)} \rho_0 \langle \mathbf{v}_m \rangle dS = 0$$

- Meridional circulation does not transport a net angular momentum flux across the cylinders, but only redistributes it along the cylinders
- A net angular momentum flux across the cylinders by the Reynolds stress cannot be balanced by meridional circulation \rightarrow differential rotation

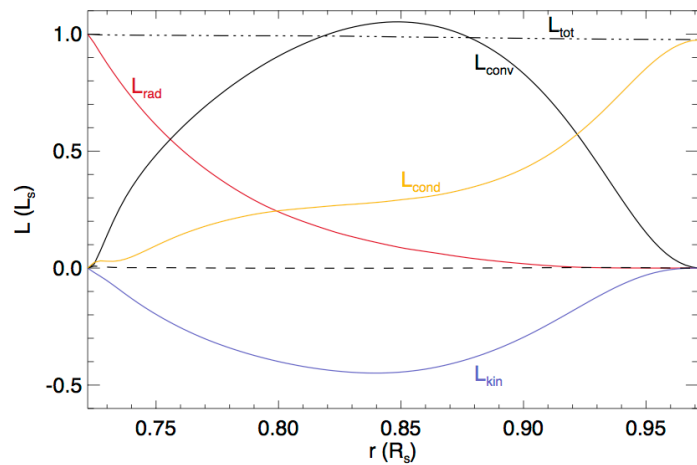
dynamo



HVHD

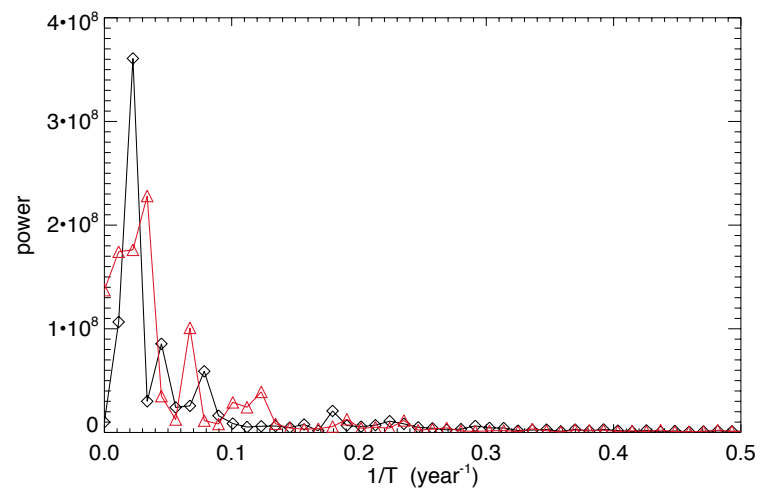
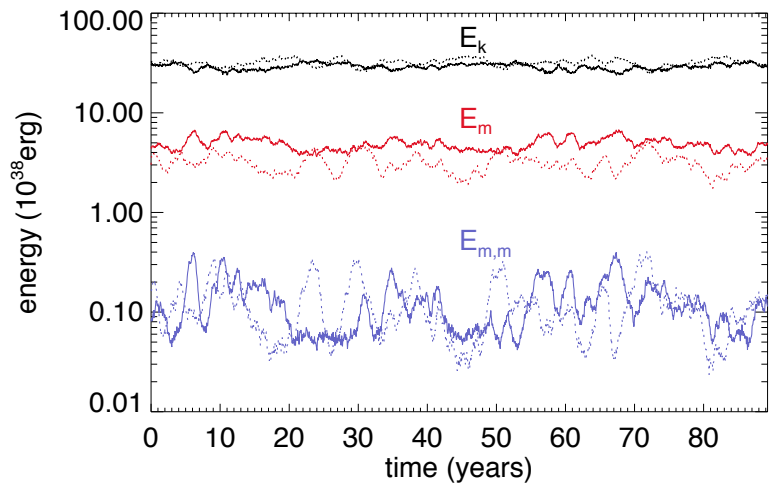
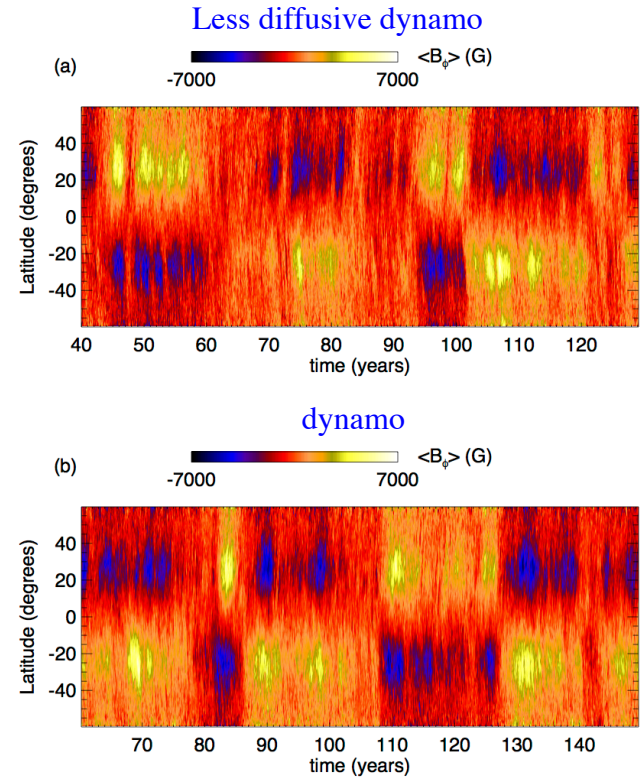
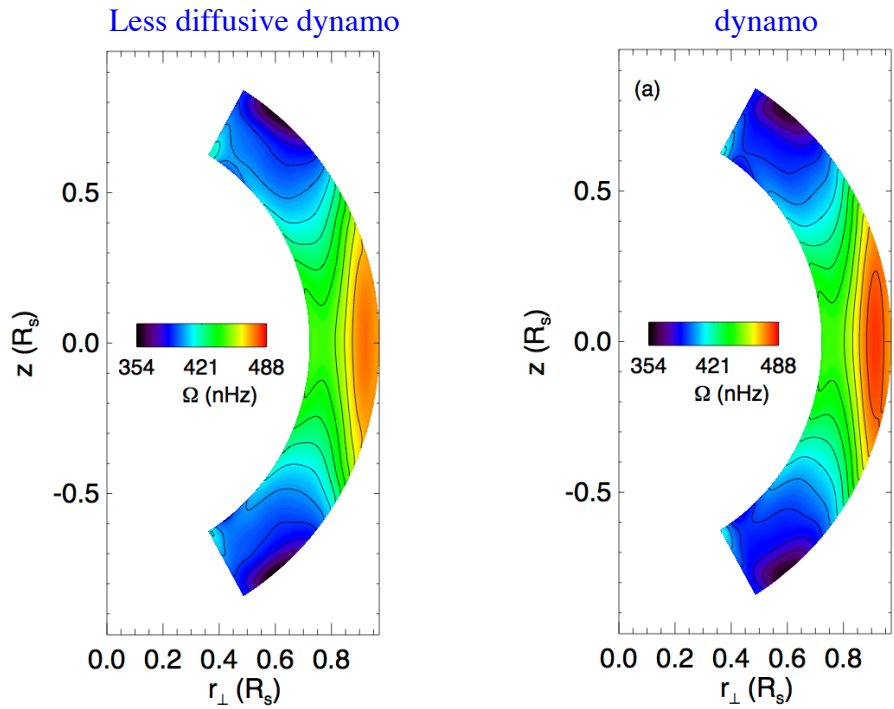


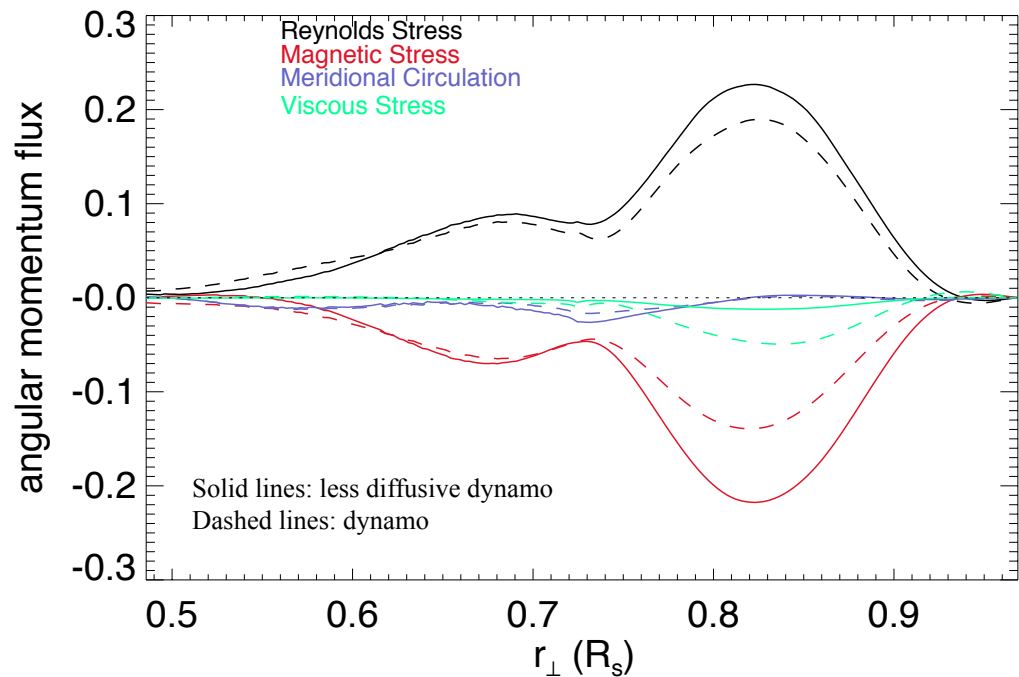
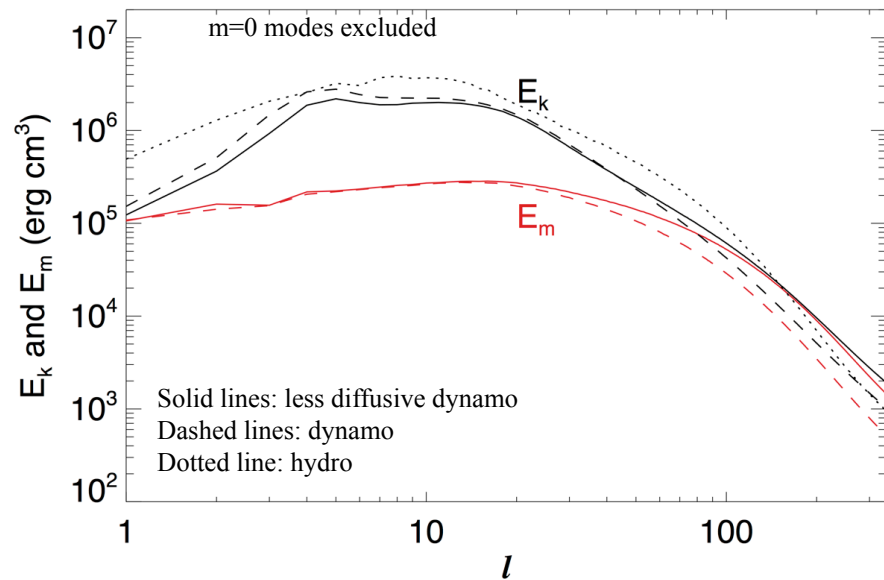
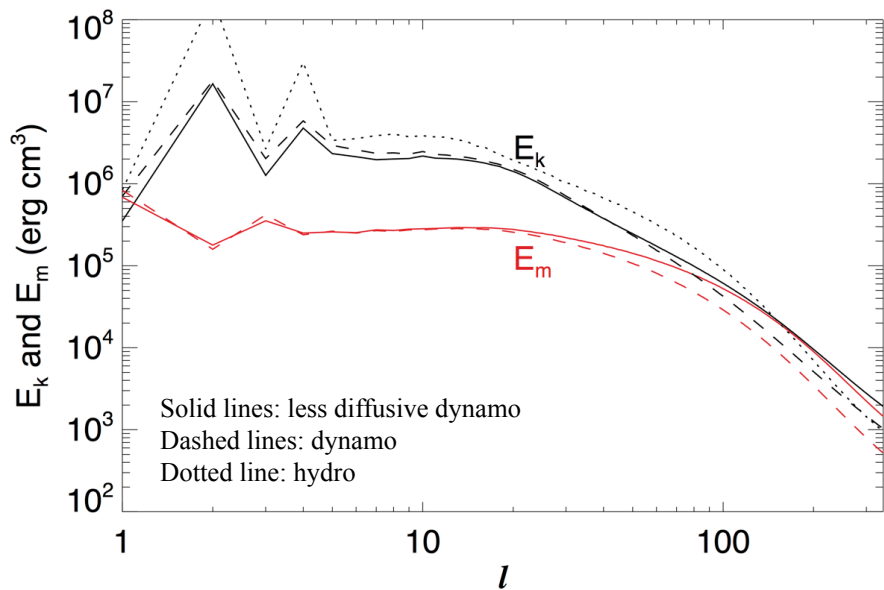
HD



Dynamo (Fan and Fang 2014): $K = 3 \times 10^{13} \text{ cm}^2 \text{ s}^{-1}$, $\nu = 10^{12} \text{ cm}^2 \text{ s}^{-1}$, $\eta = 10^{12} \text{ cm}^2 \text{ s}^{-1}$, at top and decrease with depth as $1/\sqrt{\rho}$

Less diffusive dynamo (Fan and Fang 2016): $K = 3 \times 10^{13} \text{ cm}^2 \text{ s}^{-1}$ at top and decrease with depth as $1/\sqrt{\rho}$, $\nu = 0$, $\eta = 0$



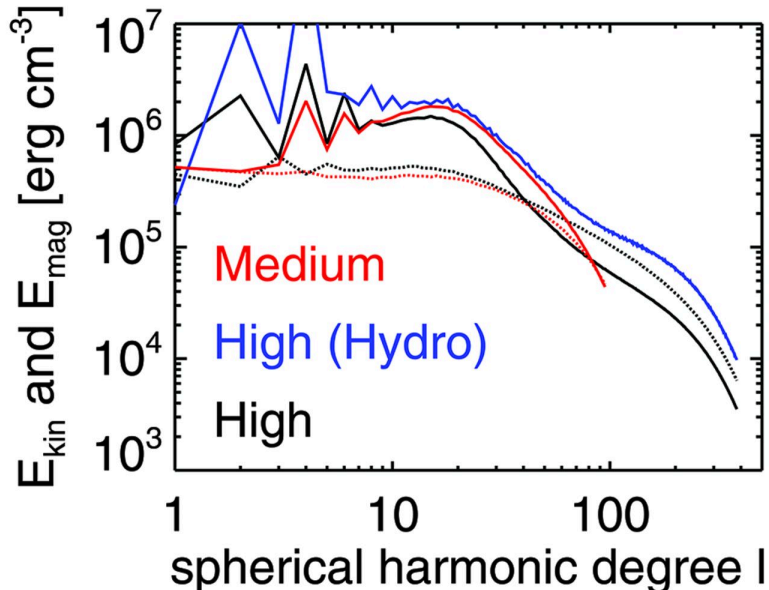
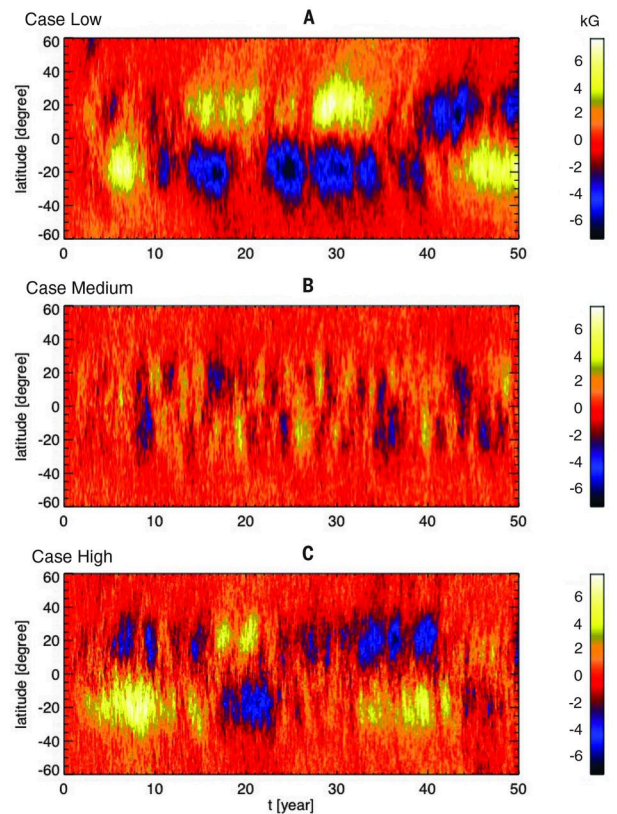
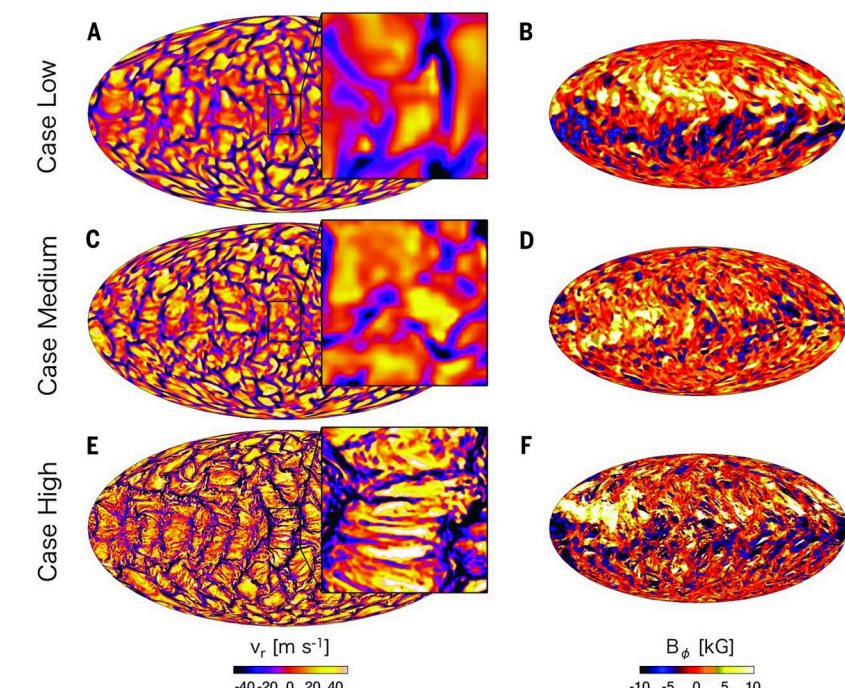


	Less diffusive dynamo	dynamo
W_{buoyancy}	0.782 L_{sol}	0.777 L_{sol}
W_{lorentz}	0.330 L_{sol}	0.256 L_{sol}

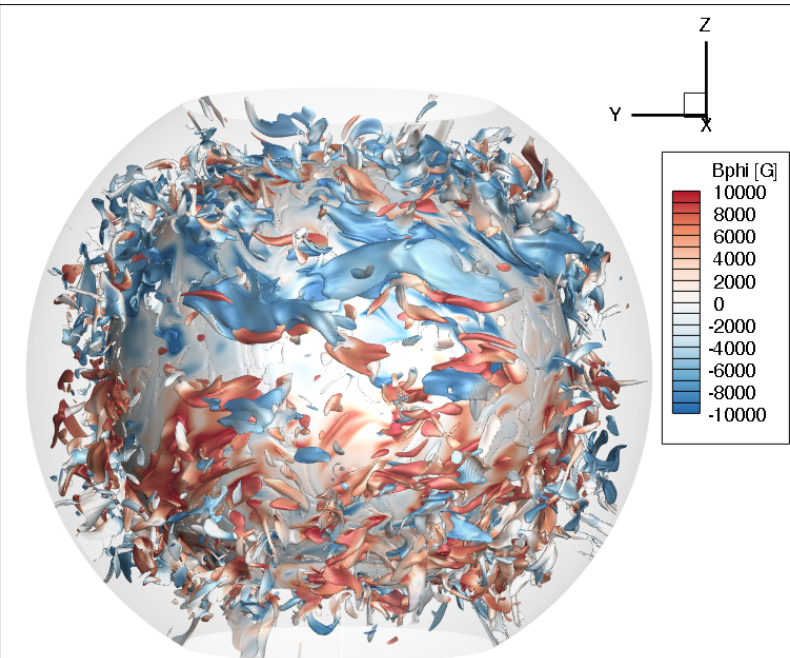
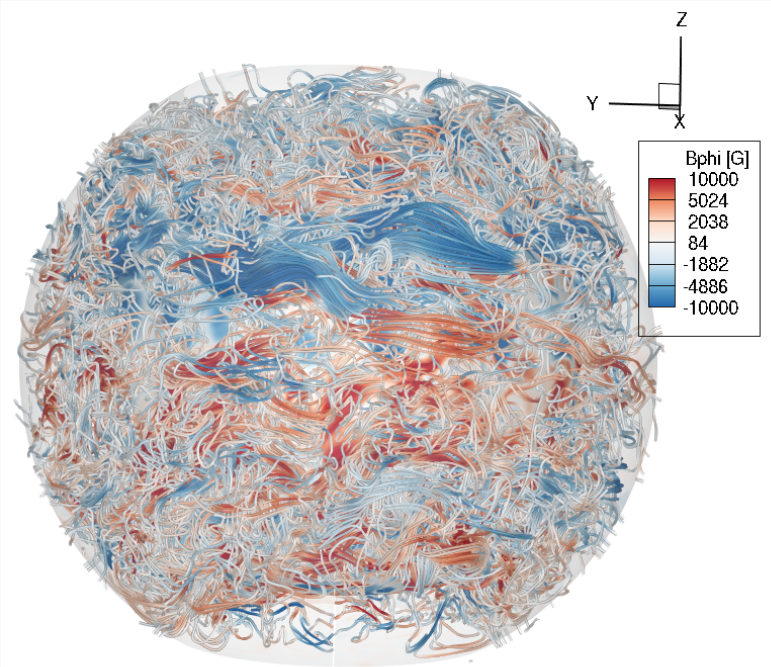
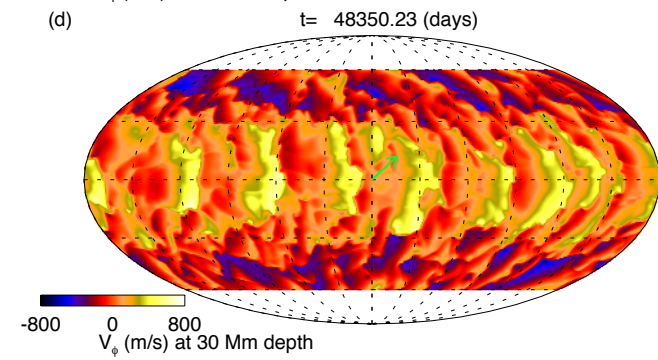
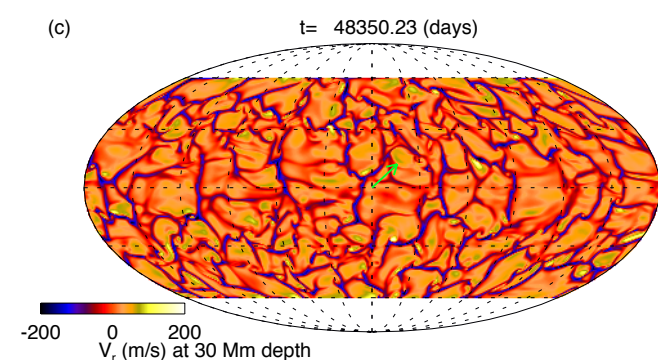
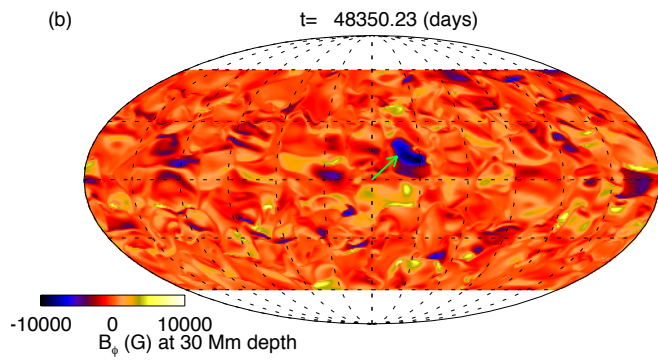
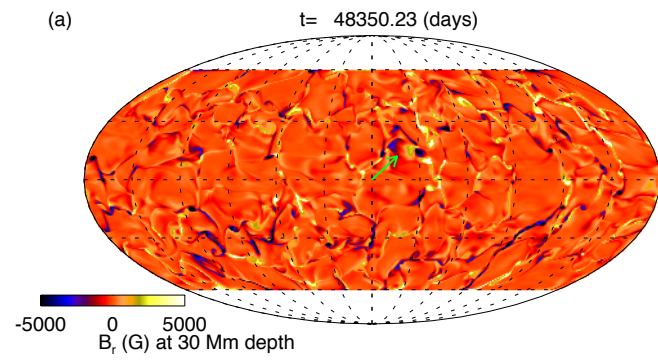
$$W_{\text{Buoyancy}} = \left\langle \int_V \rho_0 g_0 v_r \frac{s_1}{c_p} dV \right\rangle,$$

$$W_{\text{Lorentz}} = - \left\langle \int_V \mathbf{v} \cdot \left[\frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B} \right] dV \right\rangle,$$

- High resolution convective dynamo simulations of the solar convective envelope using Reduced Speed of Sound Technique with MHD (Hotta, Rempel, and Yokoyama 2016)



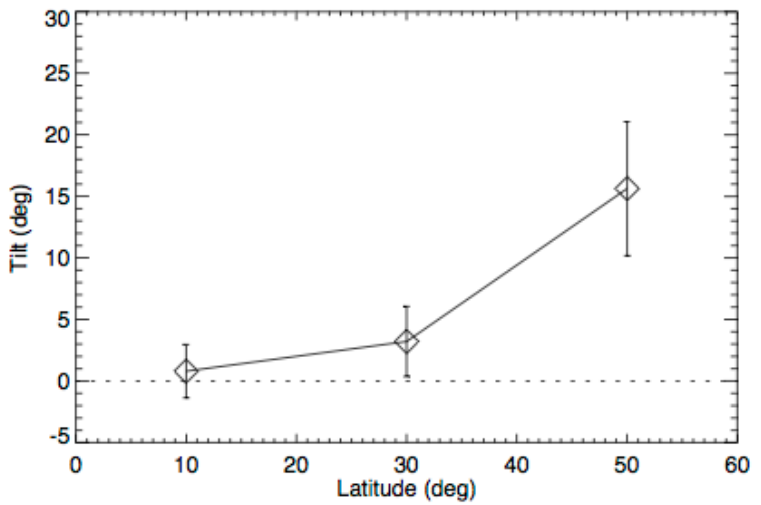
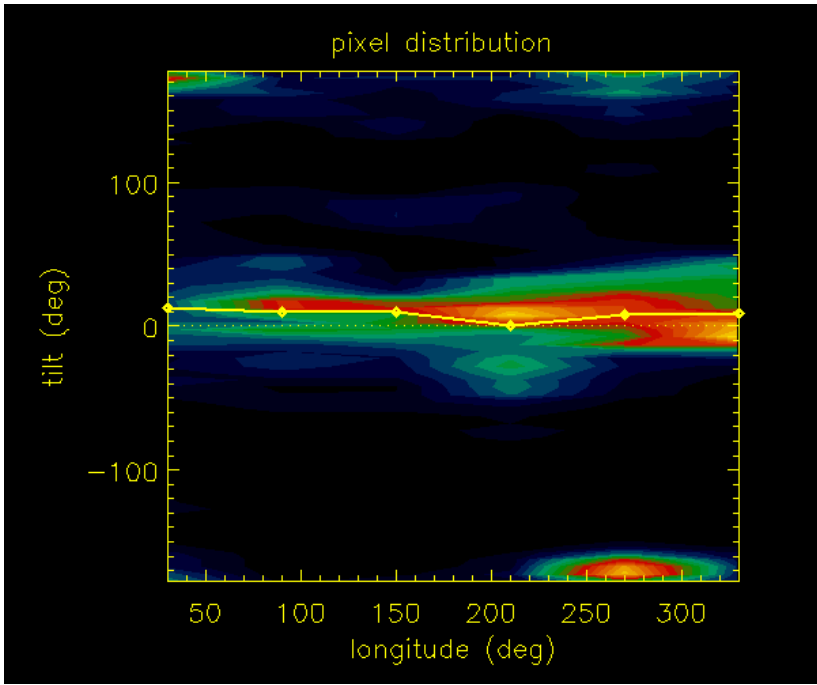
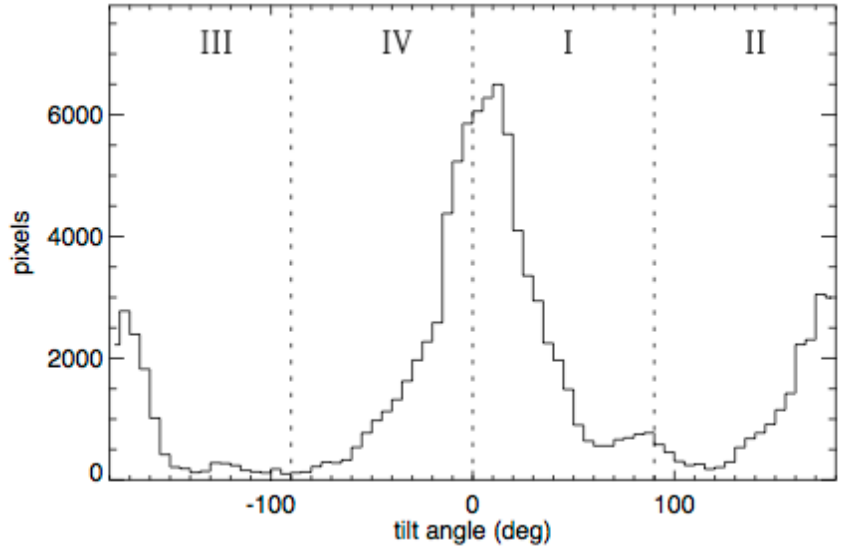
- An efficient small-scale dynamo that suppresses small-scale convective flows, acting as a large viscosity. As a result, the large scale mean-field is maintained even in the regime of large Reynolds numbers.



Fan and Fang (2014)

• Tilt angles of super-equipartition flux emergence areas at $0.957 R_s$:

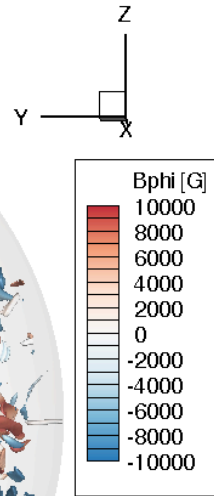
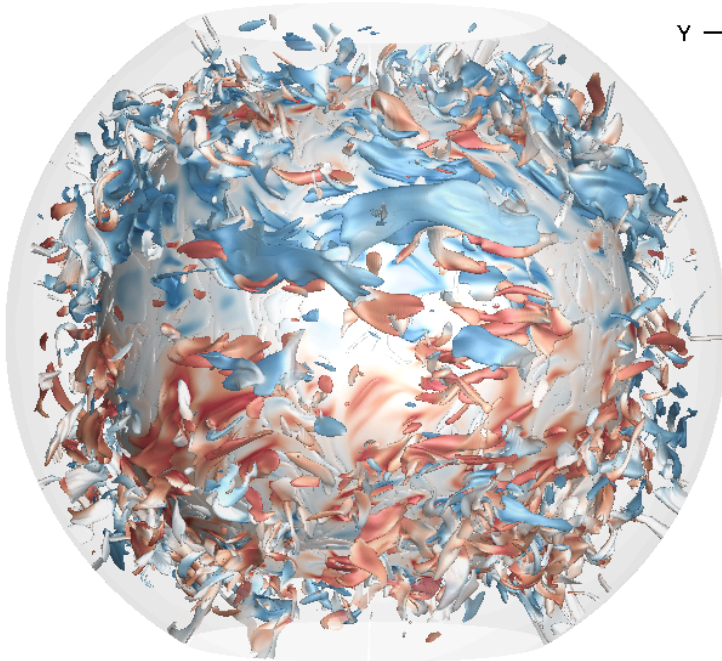
- Conform to Hale's rule by 2.4 to 1 in area
- Statistically significant mean tilt angle: $7.5^\circ \pm 1.6^\circ$
- Weak Joy's law trend



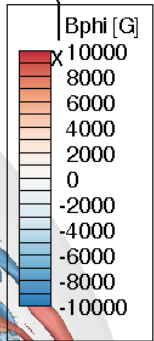
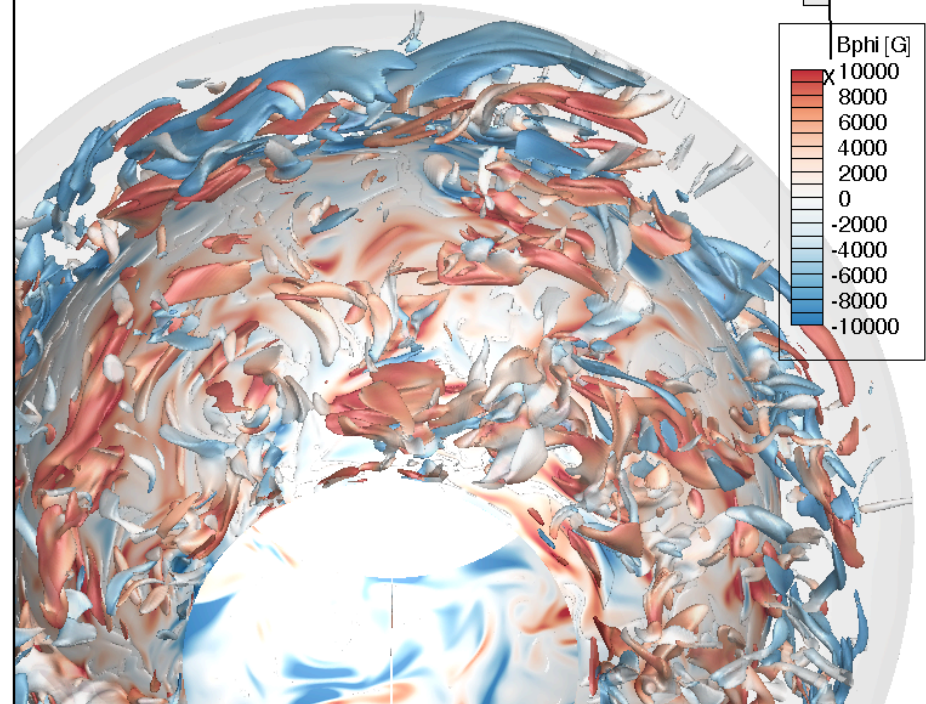
Strong emerging flux bundles sheared by giant cell convection

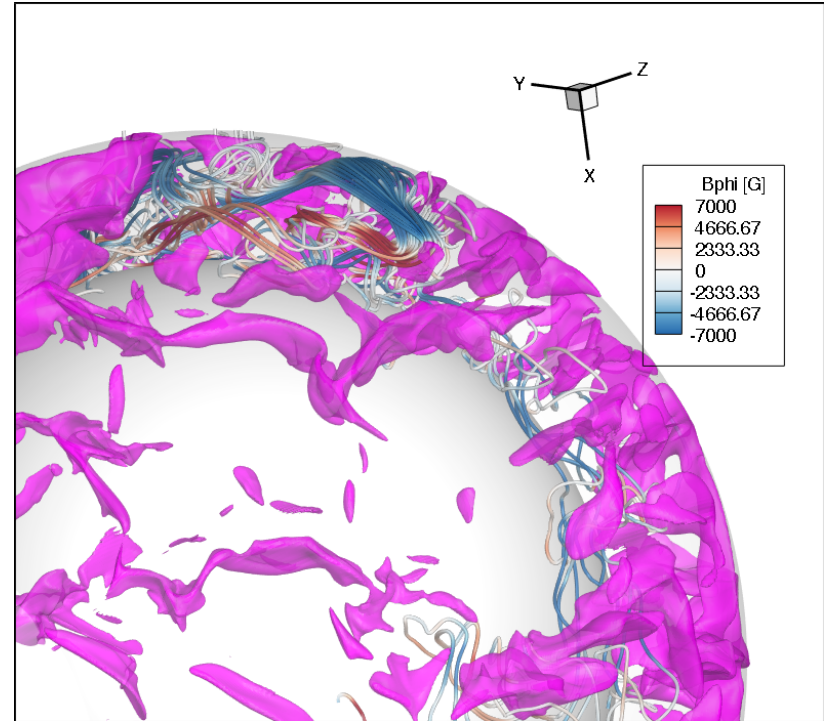
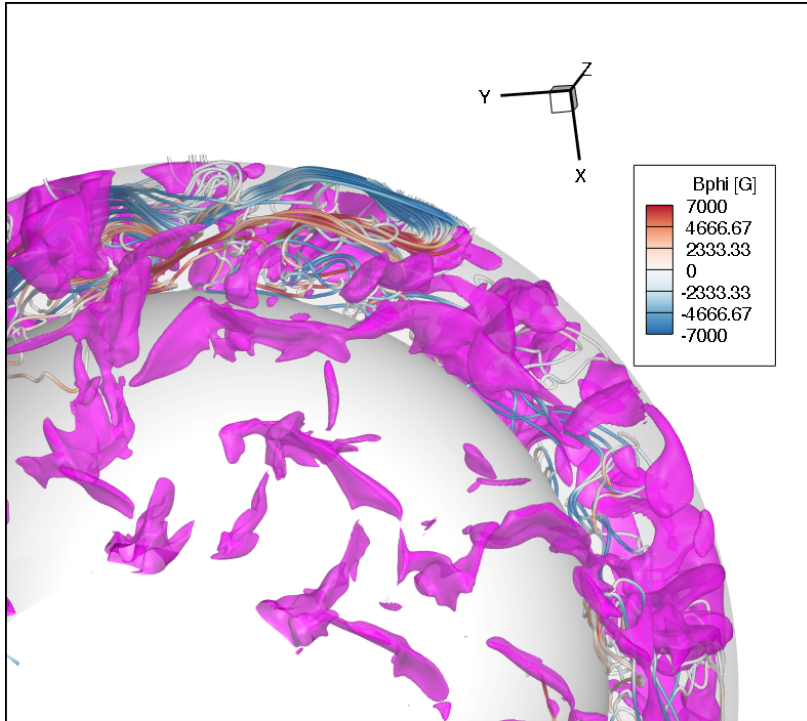
- Emerging flux bundles are not isolated flux tubes rising from the bottom of the CZ, but are continually formed in the bulk of the CZ through sheared amplification by the giant-cell convection
- The prograde flow in the giant cell shears the emerging flux bundle into a hairpin shape with the leading end pushed up against the down flow lane of the giant cell.

48348.81 days

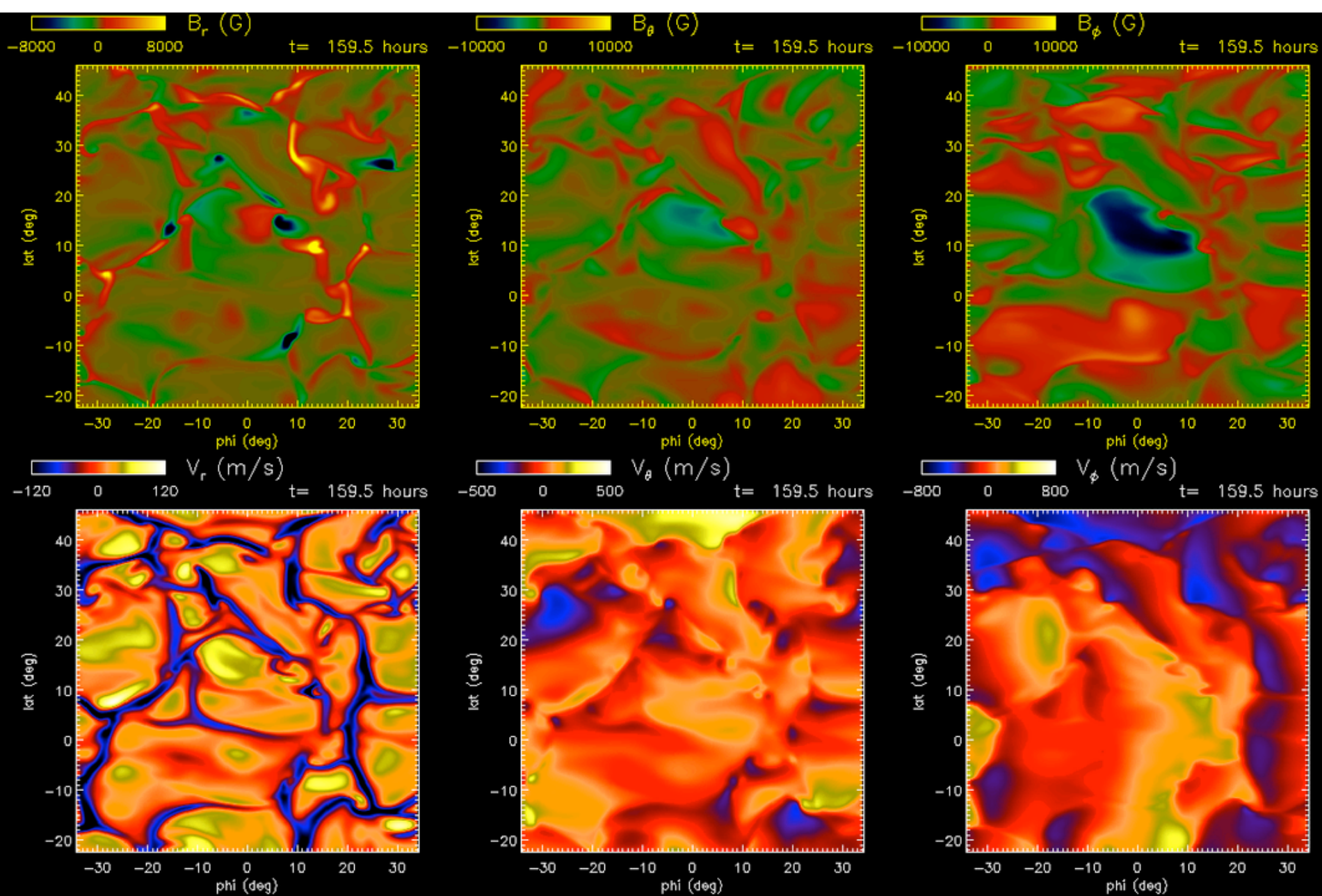


48348.81 days





- Horizontal slices of B and V fields centered on the strong emerging flux region, extracted at the depth of 30 Mm to be used for driving near surface layer flux emergence simulations



- Near surface layer flux emergence simulations with MURaM driven at the lower boundary by the B and V fields extracted from the convective dynamo simulation (Chen, Rempel and Fan 2017) → Asymmetric formation of active regions with earlier formation and more coherent leading sunspots.

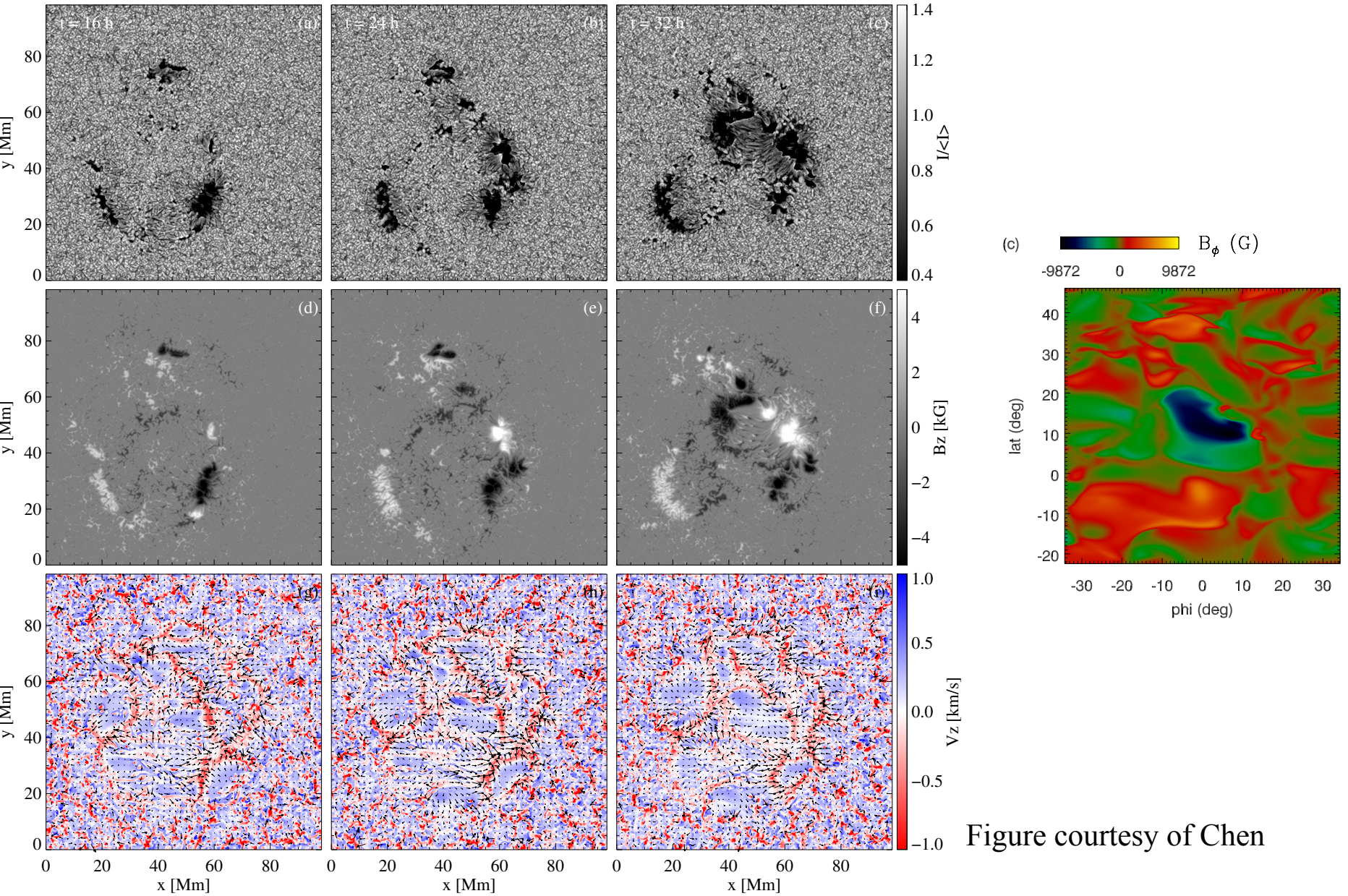


Figure courtesy of Chen

Summary

- Simulations of convective dynamo in rotationally constrained regime have produced large-scale mean field with regular magnetic cycles and equator-ward migration of the strong toroidal fields in the bulk of CZ.
- Simulations of convective dynamo at the solar rotation rate and driven by the solar radiative heat flux:
 - produce a large-scale mean magnetic field that exhibits irregular cyclic behavior with polarity reversals.
 - The presence of the magnetic fields are necessary for the self-consistent maintenance of the solar-like differential rotation. In several ways it acts like an enhanced viscosity.
 - With further reduced magnetic diffusivity and viscosity, we find an enhanced magnetic energy, and a reduced kinetic energy in the large scales. This results in a further enhanced outward transport (away from the rotation axis) of angular momentum by the Reynolds stress, balanced by an increased inward transport by the magnetic stress, with the transport by the viscous stress reduced to a negligible level
 - Produce emergence of coherent super-equipartition toroidal flux bundles with properties similar to solar active regions: following Hale's rule by 2.4:1, a weak Joy's law trend.
- Near surface layer flux emergence simulations driven at the lower boundary by the emerging B and V fields from the convective dynamo:
 - The asymmetric emerging flux bundle with a strong down flow at its leading end can cause formation of active regions with earlier formation and more coherent, stronger leading sunspots.