Magnetic cycles in global MHD simulations of solar convection

1. Magnetism and the solar cycle
2. 3D MHD simulations of solar-like cycles
3. Solar and non-solar features
4. Conclusion

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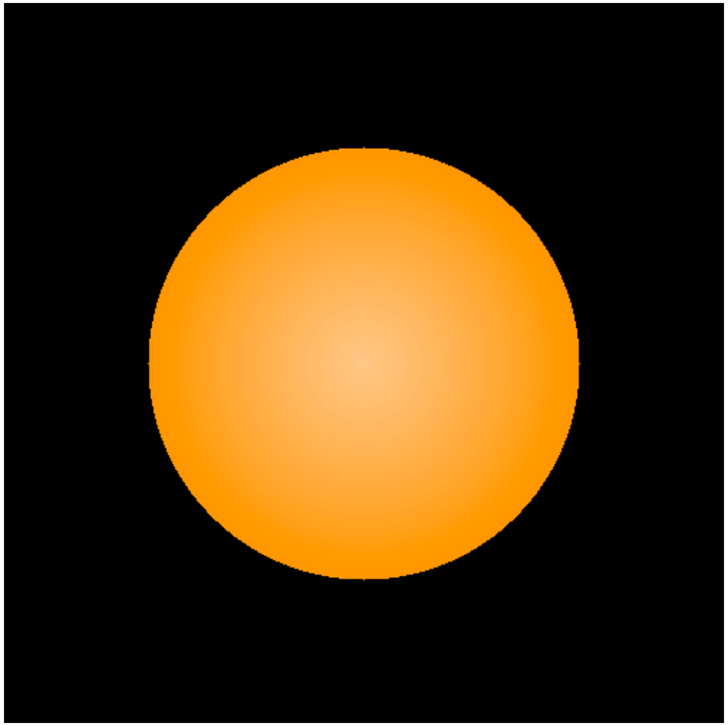
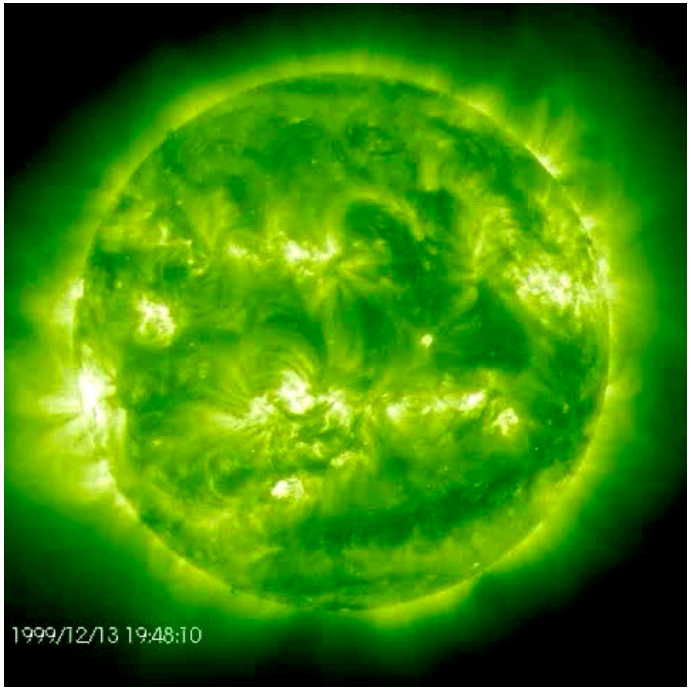
Second Eulag workshop, 13-16 sept. 2010

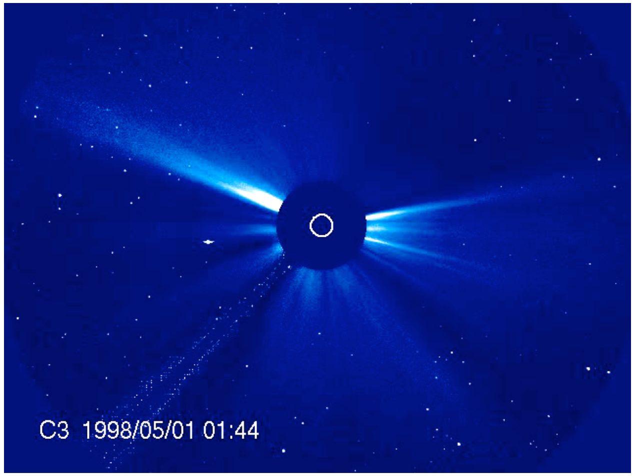
Solar magnetism





« If the sun did not have a magnetic field, it would be as boring a star as most astronomers believe it to be »

(Attributed to R.B. Leighton)



Harriot, Fabricius, Galileo, Scheiner, …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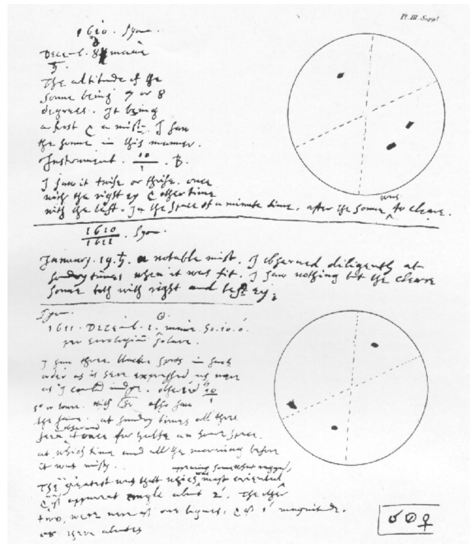
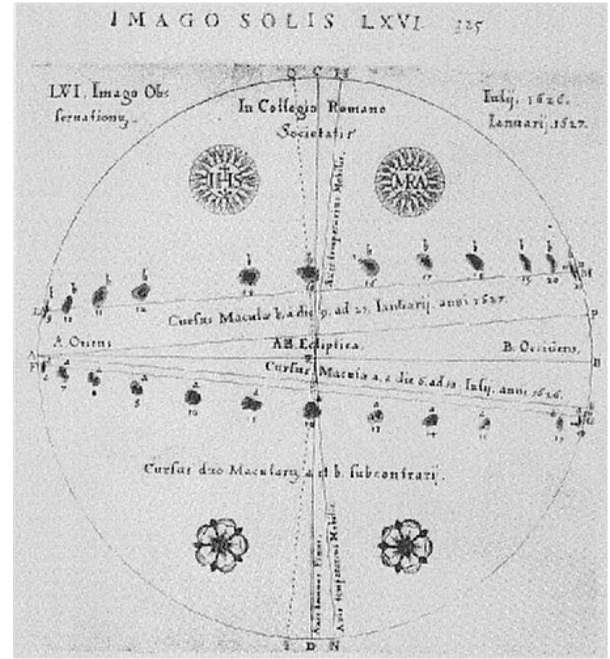
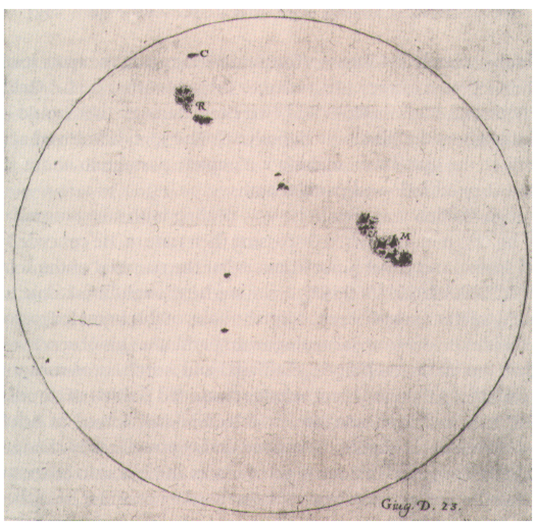
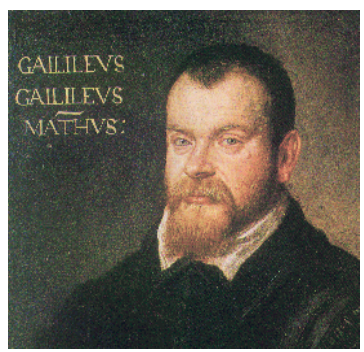


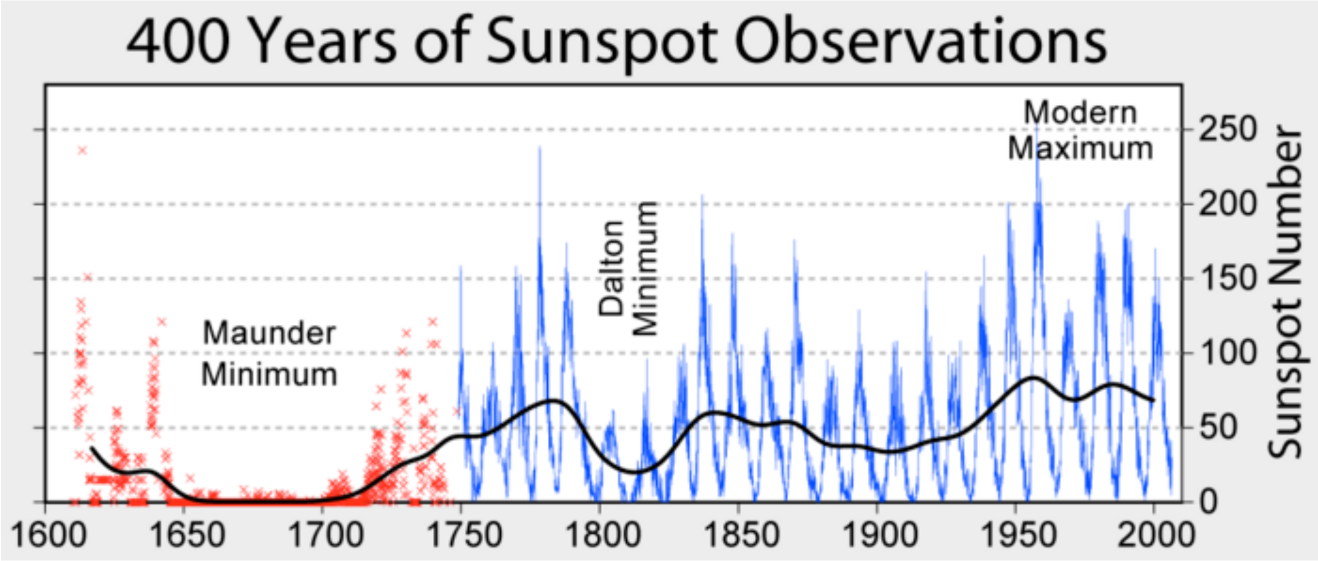






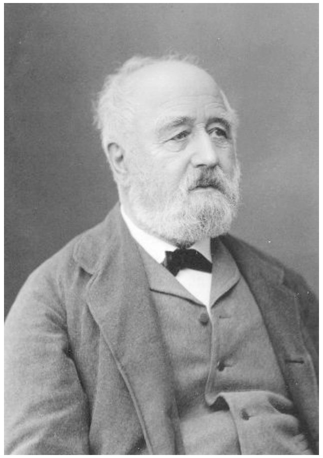
The sunspot cycle

Discovered in 1843 by an amateur astronomer, after 17 years of near-continuous sunspot observations

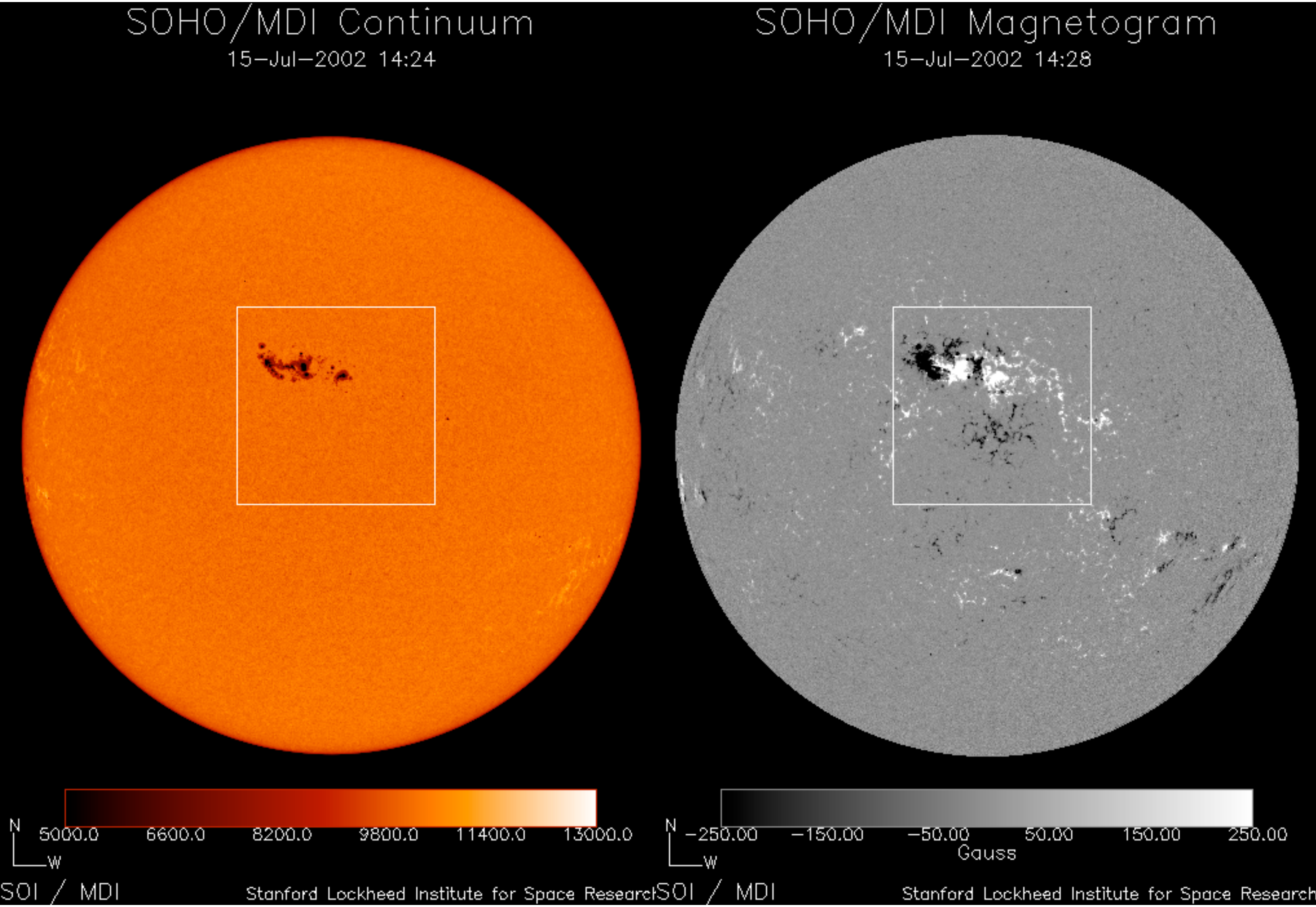


The sunspot cycle has a period of about 11 years, and its amplitude shows important cycle-to-cycle fluctuations

Heinrich Schwabe



Rudolf Wolf


SOHO/MDI Continuum
15-Jul-2002 14:24
SOHO/MDI Magnetogram
15-Jul-2002 14:28
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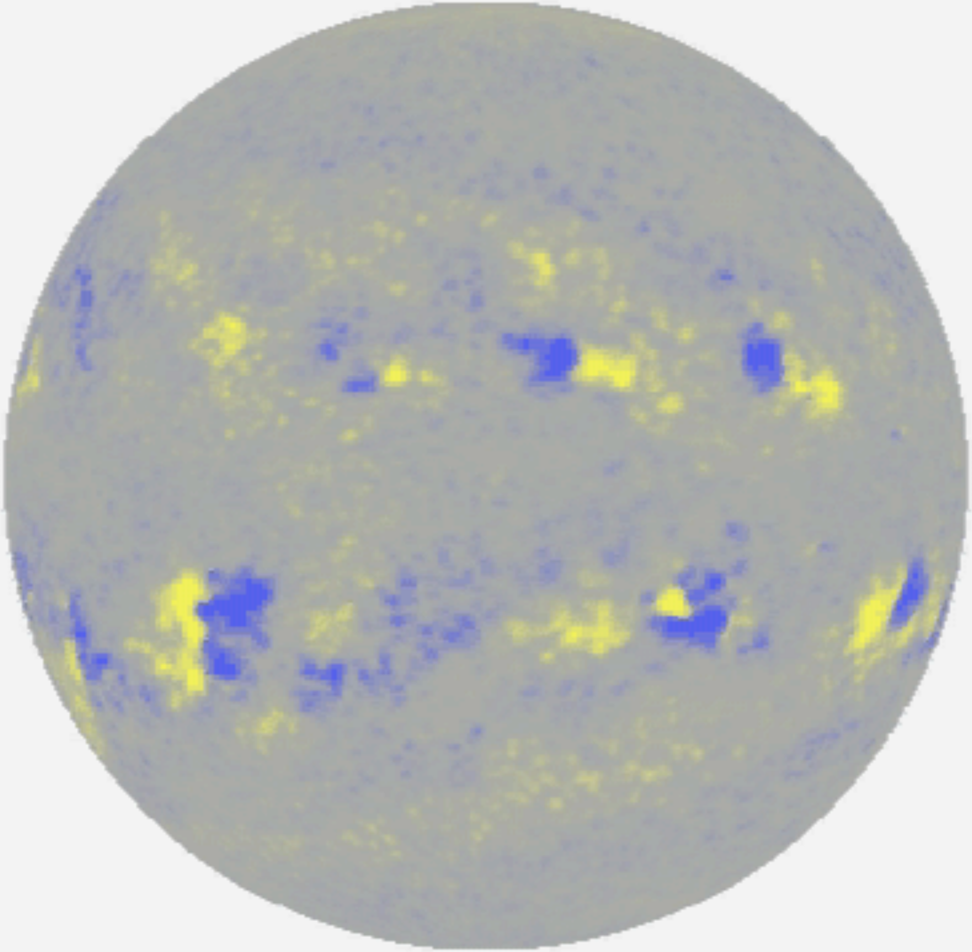
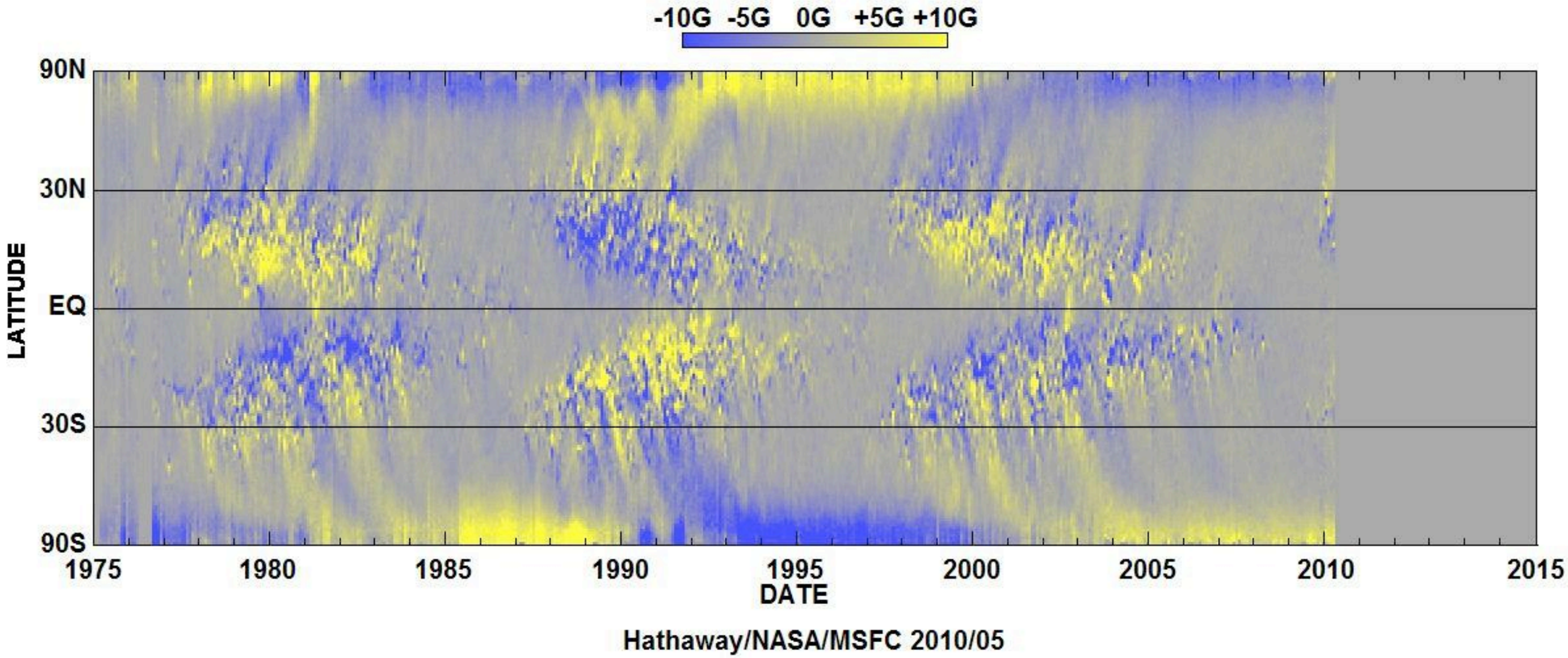
Stanford Lockheed Institute for Space Research
SOI / MDI
Stanford Lockheed Institute for Space Research



Data animation courtesy D. Hathaway, NASA/MSFC

The solar magnetic cycle



Synoptic magnetogram courtesy D. Hathaway, NASA/MSFC
http://solarscience.msfc.nasa.gov/images/magbfly.jpg

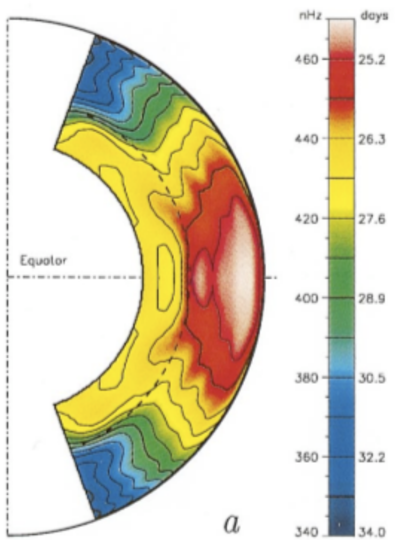
The evolution of the large-scale solar magnetic field may be thought of as a temporal sequence of the form

$$P(+) \to T(-) \to P(-) \to T(+) \to P(+) \to \dots$$

Modeling the Solar Cycle

$$P(+) \rightarrow T(-) \rightarrow P(-) \rightarrow T(+) \rightarrow P(+) \rightarrow \ldots$$

Poloidal to Toroidal : Shearing of Poloidal into Toroidal by differential rotation



Toroidal to Poloidal

- Babcock-Leighton dynamo
- alpha-effect (mean-field theory, mid 1950s)

Numerical models of solar convection; a vast range of scales:

Dissipation scale of smallest eddies (Kolmogorov scale) ~1cm

Largest scales involved (Sun's radius) ~ 1000 km

The anelastic MHD equations

Global acoustic modes ~ 1 hour or less

Implicit dissipation, 3rd order MPDATA

$$\frac{D\mathbf{v}}{Dt} = -\nabla\pi - \mathbf{g}\frac{\theta'}{\theta_o} + 2\mathbf{v}\times\mathbf{\Omega} + \frac{1}{\mu\rho_o}(\mathbf{B}\cdot\nabla)\mathbf{B} + \boxed{\mathcal{D}_\mathbf{v}},$$

$$\frac{D\theta'}{Dt} = -\mathbf{v}\cdot\nabla\theta_e + \boxed{\mathcal{H}} - \boxed{\alpha\theta'},$$

$$\frac{D\mathbf{B}}{Dt} = -\nabla\pi^* + (\mathbf{B}\cdot\nabla)\mathbf{v} - \mathbf{B}(\nabla\cdot\mathbf{v}) + \boxed{\mathcal{D}_\mathbf{B}},$$

$$\nabla\cdot(\rho_o\mathbf{v}) = 0\,, \quad \nabla\cdot\mathbf{B} = 0\,,$$

forces the system towards an unstable ambient stratification

Implicitly forcing the system towards an unstable ambient state avoids the need for an eddy thermal diffusivity that accounts for energy transport by the unresolved motions as well as specification of top and bottom heat fluxes.

Selected milestones

Gilman 1983: Boussinesq MHD simulation, producing large-scale magnetic fields with polarity reversals on yearly timescale; but non-solar large-scale organization.

Glatzmaier 1984, 1985: Anelastic model including stratification, large-scale fields with polarity reversals within a factor 2 of solar period; tendency for equatorward migration of the large-scale magnetic field. Approximately cylindrical isocontours of internal rotation.

Miesch et al. 2000: Strongly turbulent HD simulation, producing a reasonably solar-like internal differential rotation profile.

Brun et al. 2004: Strongly turbulent MHD simulation, producing copious small-scale magnetic field but no large-scale magnetic component.

Browning et al. 2006: Demonstrate the importance of an underlying, convectively stable fluid layer below the convection zone in producing a large-scale magnetic component in the turbulent regime.

Brown et al. 2009, 2010: Obtain polarity reversals of thin, intense toroidal field structure in a turbulent simulation rotating at 3X solar.

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MAGNETIC CYCLES IN GLOBAL LARGE-EDDY SIMULATIONS OF SOLAR CONVECTION

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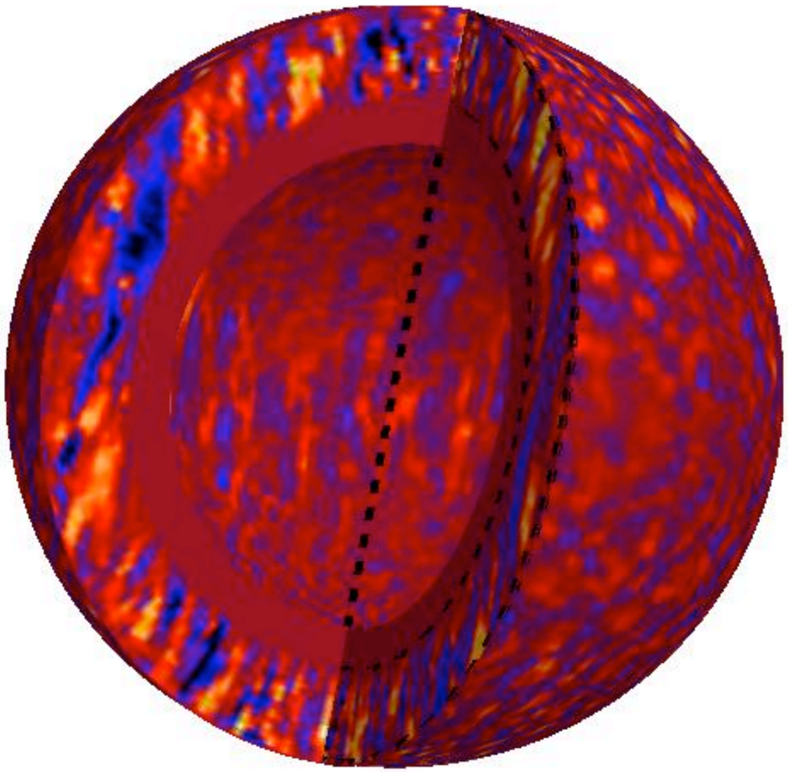
ABSTRACT

We report on a global magnetohydrodynamical simulation of the solar convection zone, which succeeds in generating a large-scale axisymmetric magnetic component, antisymmetric about the equatorial plane and undergoing regular polarity reversals on decadal timescales. We focus on a specific simulation run covering 255 years, during which 8 polarity reversals are observed, with a mean period of 30 years. Time–latitude slices of the zonally averaged toroidal magnetic component at the base of the convecting envelope show a well-organized toroidal flux system building up in each solar hemisphere, peaking at mid-latitudes and migrating toward the equator in the course of each cycle, in remarkable agreement with inferences based on the sunspot butterfly diagram. The simulation also produces a large-scale dipole moment, varying in phase with the internal toroidal component, suggesting that the simulation may be operating as what is known in mean-field theory as an $\alpha\Omega$ dynamo.

Key words: convection – magnetohydrodynamics (MHD) – Sun: activity – Sun: dynamo

For updates on simulation results, see GRPS Web Page:
http://www.astro.umontreal.ca/~paulchar/grps

Simulation setup:



Domain is a rotating stratified shell of electrically conducting fluid 0.61 to 0.96 solar radius thick, with the solar luminosity forced across the shell.

The background stratification is convectively unstable in 0.71< r/R <0.96, and stable below (important!).

Initial condition: unmagnetized hydrostatic, random flow and field perturbations introduced at *t*=0.

Numerical approximations

In addition to the usual advective nonlinearity, nonlinear forcing terms that couple the velocity and magnetic fields deserve special treatment when integrals are being constructed

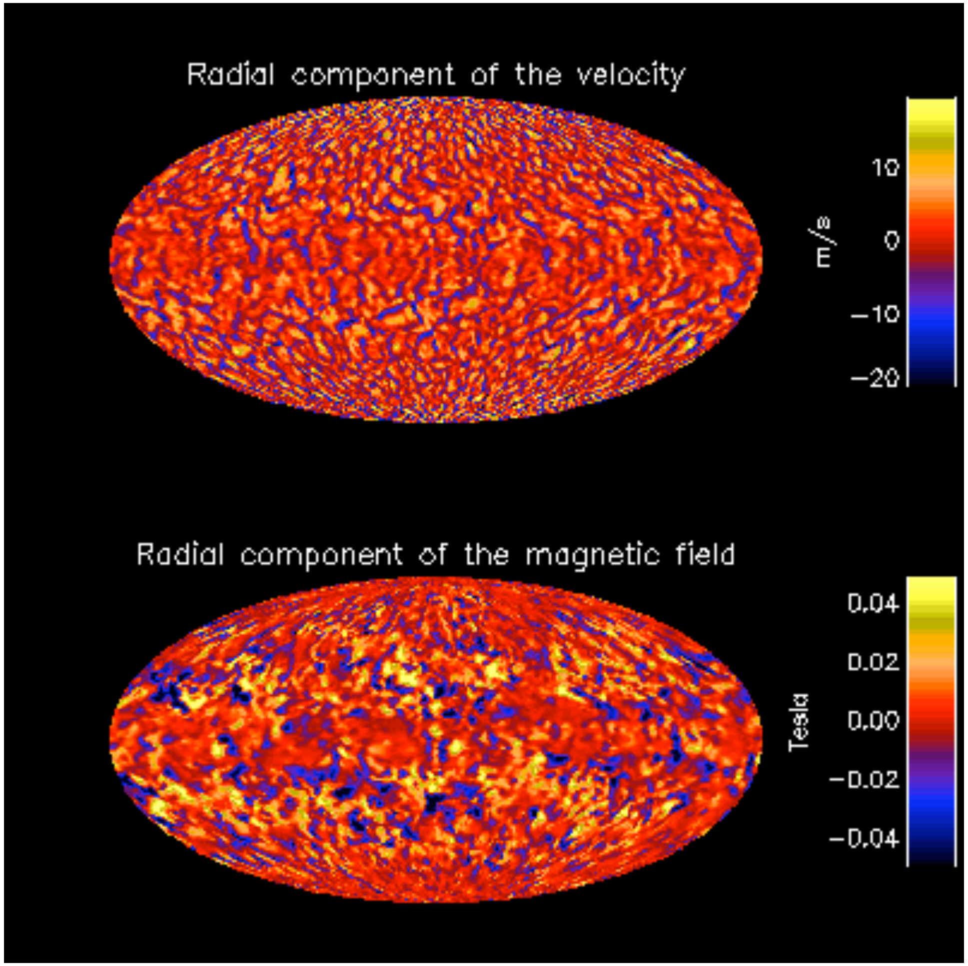
$$\mathbf{\Psi}_{\mathbf{i}}^{n,\nu} = \widehat{\mathbf{\Psi}}_{\mathbf{i}} + \frac{\delta t}{2}\mathbf{L}\mathbf{\Psi}\Big|_{\mathbf{i}}^{n,\nu} + \frac{\delta t}{2}\mathbf{N}\mathbf{\Psi}\Big|_{\mathbf{i}}^{n,\nu-1} - \nabla\mathbf{\Phi}\Big|_{\mathbf{i}}^{n,\nu}$$

$$\widehat{\mathbf{\Psi}}_{\mathbf{i}} \equiv \mathcal{A}_{\mathbf{i}}(\mathbf{\Psi}^{n-1} + 0.5\delta t\mathbf{R}^{n-1}, \widetilde{\mathbf{V}}^{*})$$

Boundary conditions: top: stress-free and purely radial field;
bottom: perfect conductor and rigid rotation

Numerics: Implicit LES based on MPDATA high-order upwind advection scheme; minimally diffusive, finite volumes, divergence cleaning

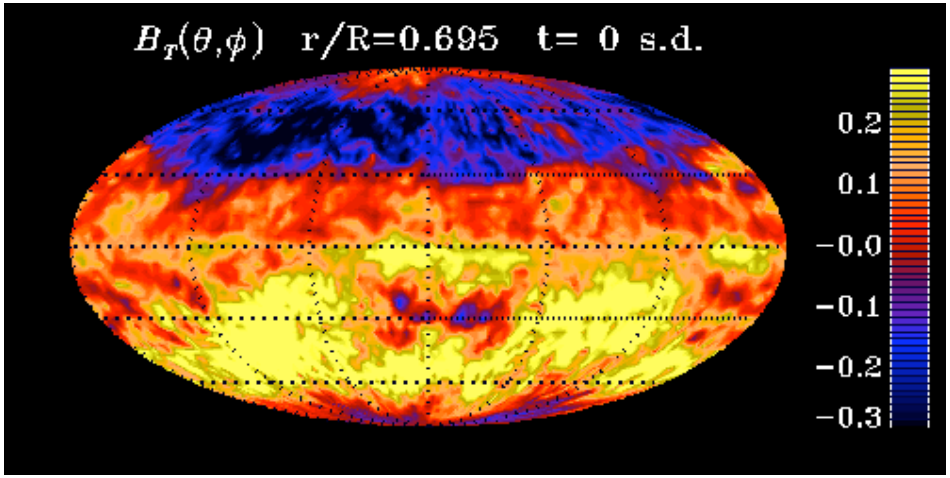
Convection and small-scale magnetic fields



Turbulent convection, in itself, produces a lot of magnetic field, but very little net magnetic flux on the larger spatial scales

The large-scale magnetic fields (1)

Mollweide projection of toroidal magnetic component immediately beneath core-envelope interface



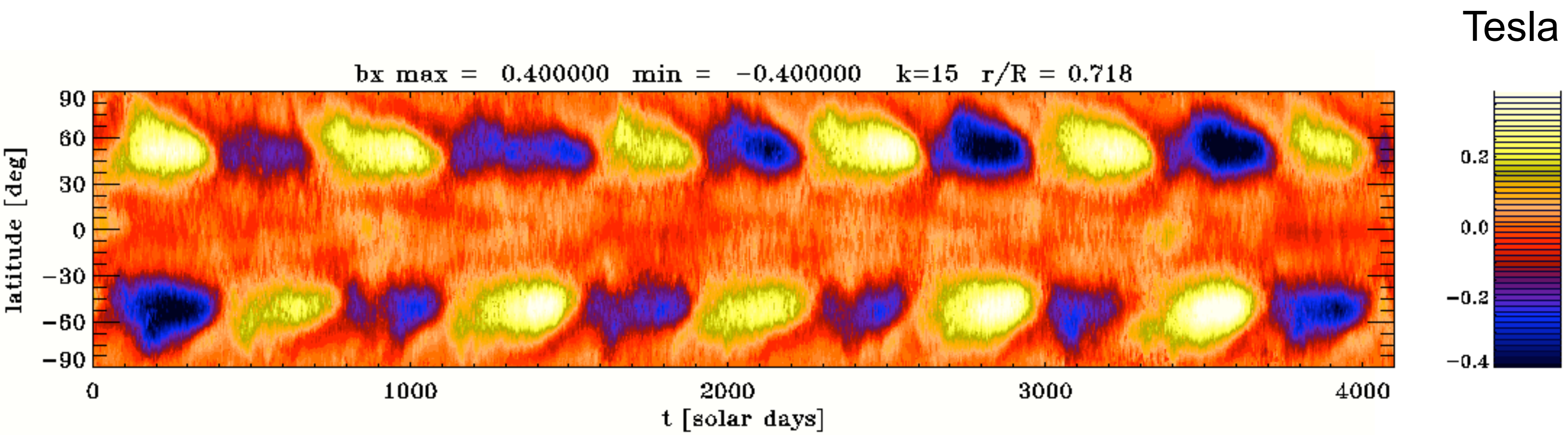
Field is very « turbulent », due to convective undershoot;

Fairly well-defined axisymmetric component, antisymmetric about equatorial plane;

Hemispherically synchronous polarity reversals on ~30 yr timescale.

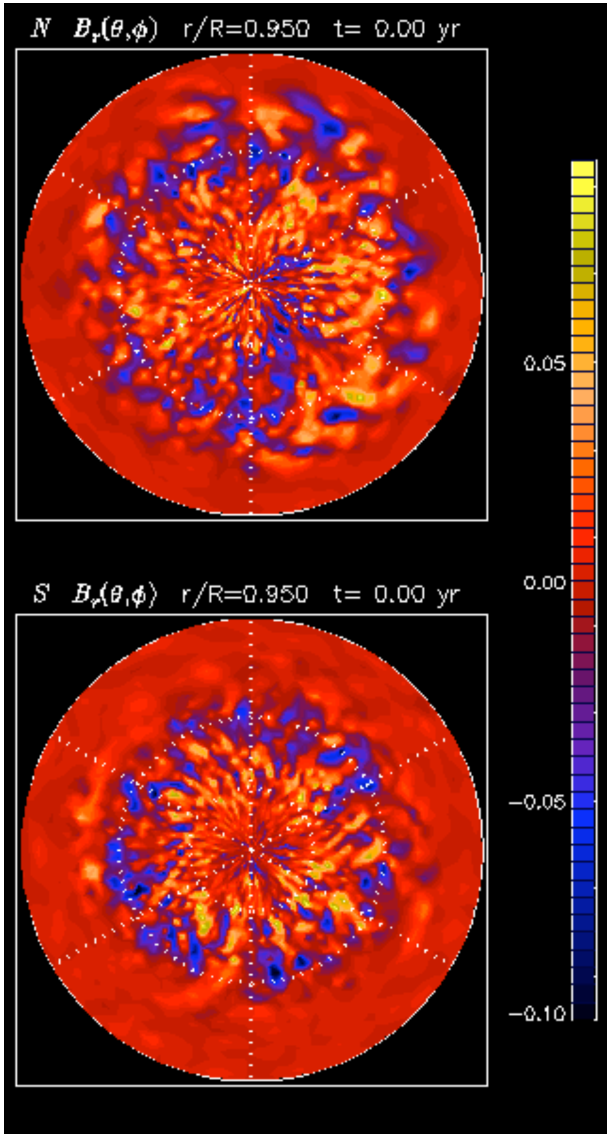
Magnetic cycles (1)

Time-latitude diagram of zonally-averaged toroidal component at core-envelope interface (r/R=0.718)



IF flux rope formation is proportional to toroidal field strength, and **IF** flux ropes rise radially through convective envelope, then this is the simulation's analog to the sunspot butterfly diagram

Magnetic cycles (2)



Surface radial magnetic field over North and South polar caps

Magnetic field is very intermittent spatiotemporally

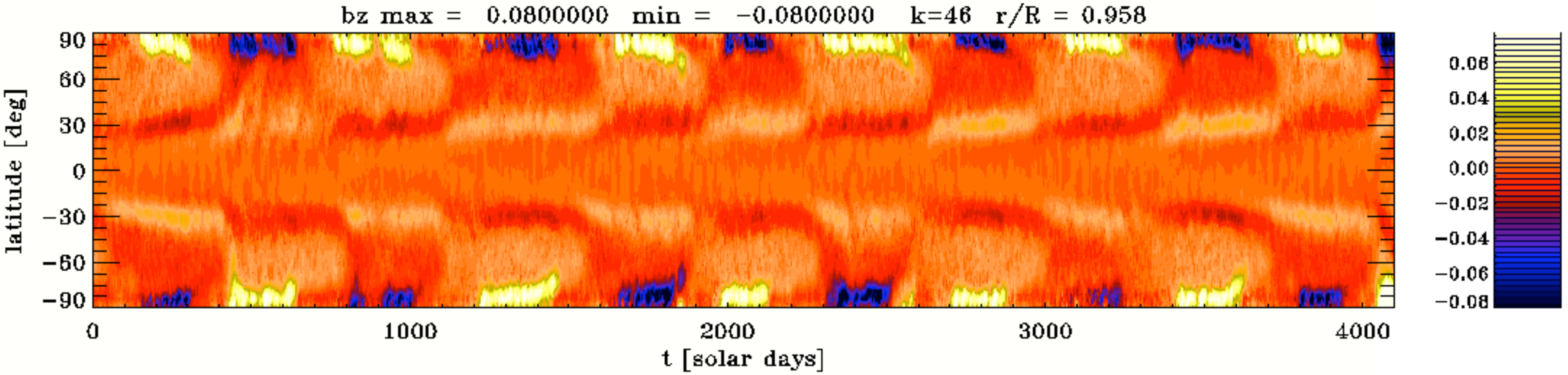
Nonetheless, there is a clear axisymmetric component on the larger spatial scales.

Pattern of polar cap B_r shows a very well-defined dipole moment, very well aligned with rotation axis.

Polarity reversals begin at mid-latitude and proceeds towards pole.

Magnetic cycles (3)

Time-latitude diagram of zonally-averaged surface radial component



Hint of surface fields migrating from low-latitudes to polar regions

Large-scale surface magnetic field strongly peaked at high latitudes

Very high degree of hemispheric symmetry

Other interesting simulation features

Solar-like differential rotation: equatorial acceleration, with tachocline-like shear layer at core-envelope interface.

Torsional oscillations originating at high latitudes and migrating equatorward to mid-latitudes, with 2-cycle overlap.

Magnetically-mediated cyclic modulation of large-scale meridional flow in convection zone.

Azimuthal turbulent electromotive force sustaining axisymmetric large-scale poloidal magnetic component.

Magnetically-mediated cyclic modulation of convective energy transport.

The alpha-effect

Expressing the velocity and magnetic fields as the sum of a small-scale and a large-scale component,

$$\mathbf{U} = \langle \mathbf{U} \rangle + \mathbf{u} \qquad \mathbf{B} = \langle \mathbf{B} \rangle + \mathbf{b}$$

one obtains the induction equation for the evolution of a large-scale magnetic field involving the curl of the product of small-scale fluctuations

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times \left(\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle \right) + \nabla \times \boldsymbol{\mathcal{E}} + \eta \nabla^2 \langle \mathbf{B} \rangle$$

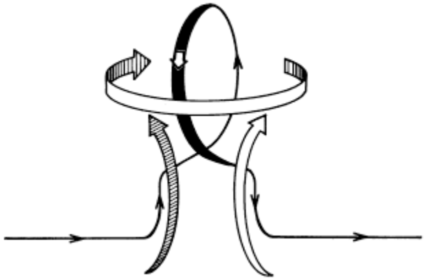
The so-called mean-field electro-motive force (EMF)

$$\boldsymbol{\mathcal{E}} = \langle \mathbf{u} \times \mathbf{b} \rangle$$

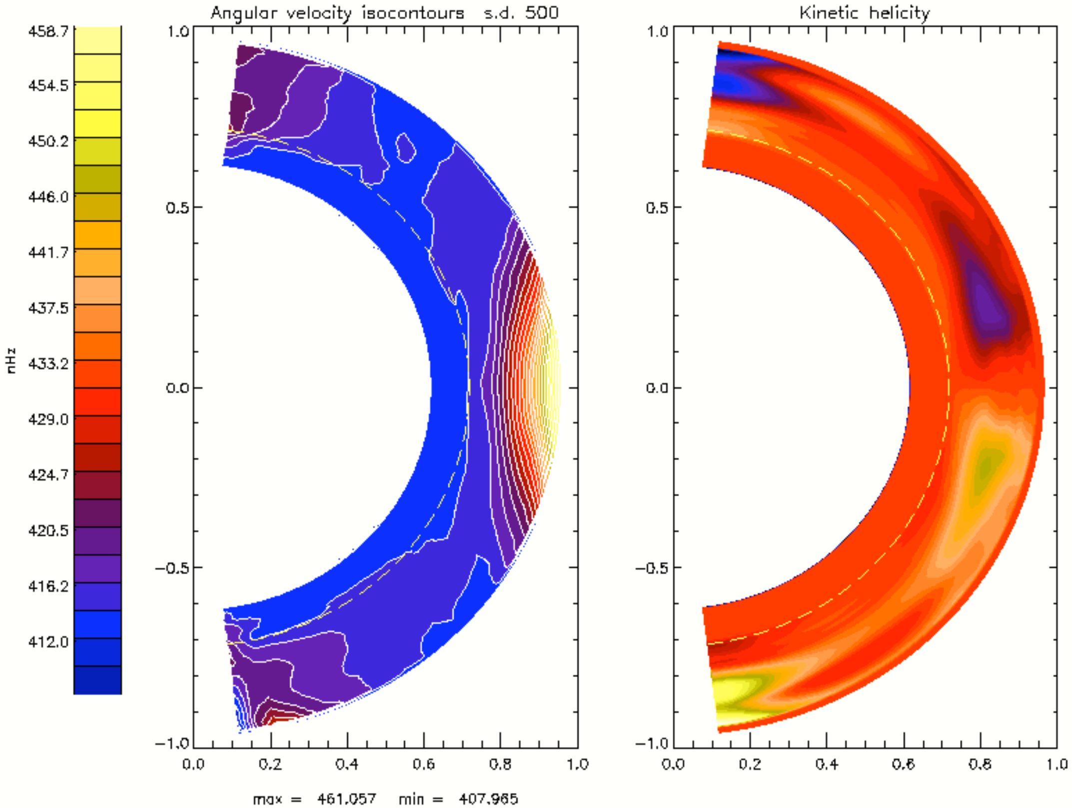
provides a mechanism for the production of a large-scale poloidal magnetic field from the toroidal component induced by differential rotation.

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

Ampère’s Law, pre-Maxwellian from (non-relativistic MHD)



Differential rotation and kinetic helicity



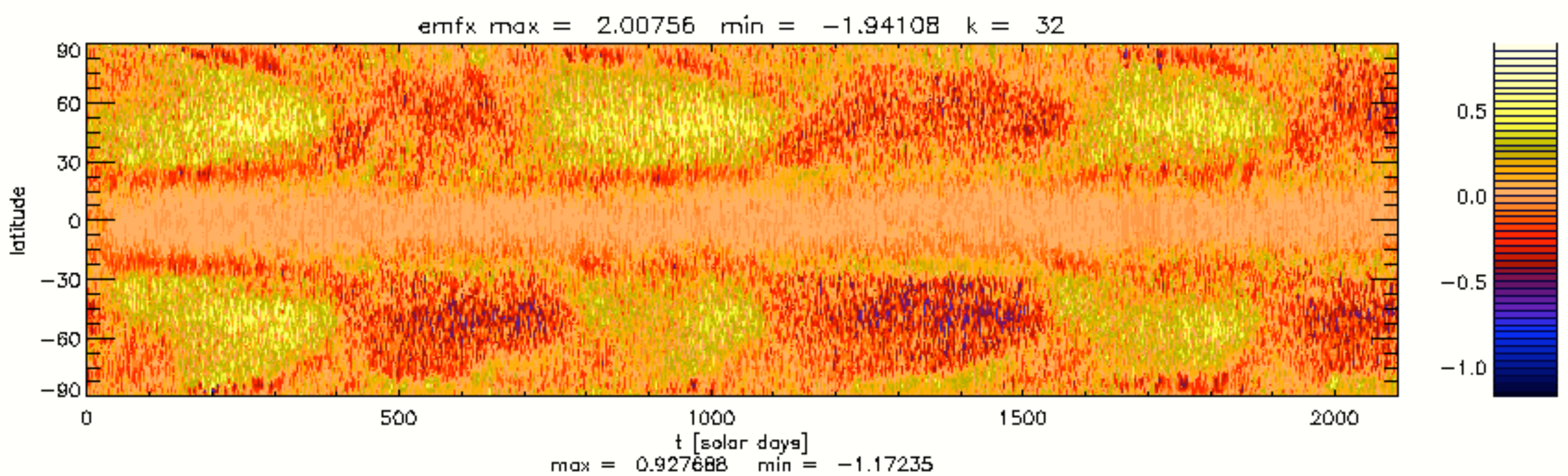
$$\mathbf{u} \cdot (\nabla \times \mathbf{u})$$

Differential rotation is reasonably solar-like, with shear layer at core-envelope interface.

Kinetic helicity is negative in bulk of N-hemisphere, as expected from action of Coriolis force.

Mode of dynamo action
[Lead: Étienne Racine]

Time-latitude diagram of phi-component of the turbulent emf < **u**' x **b** '> at mid-depth in the convective envelope.

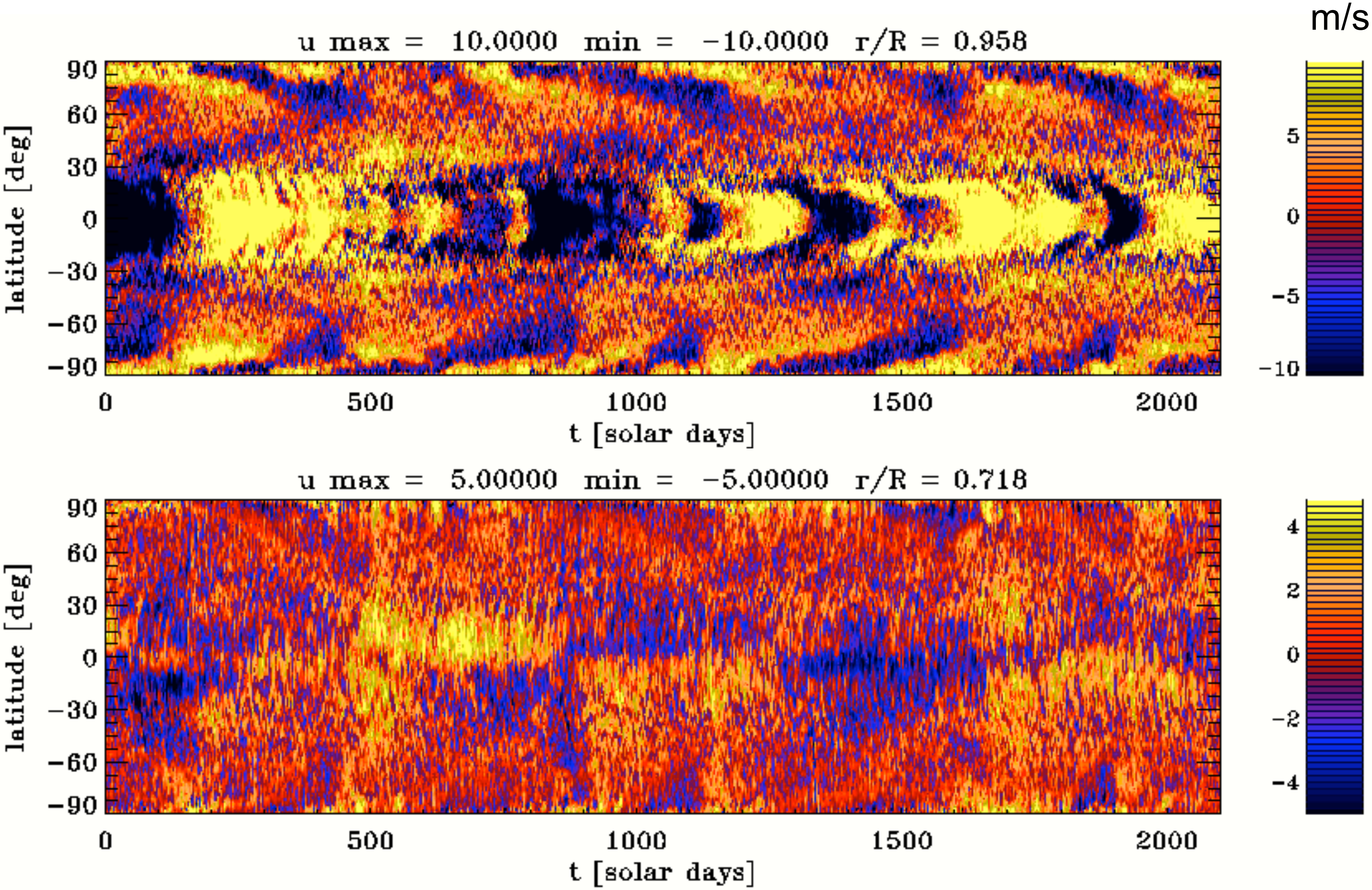


Turbulent emf has same sign in each hemisphere

Turbulent emf changes sign from one cycle to the next

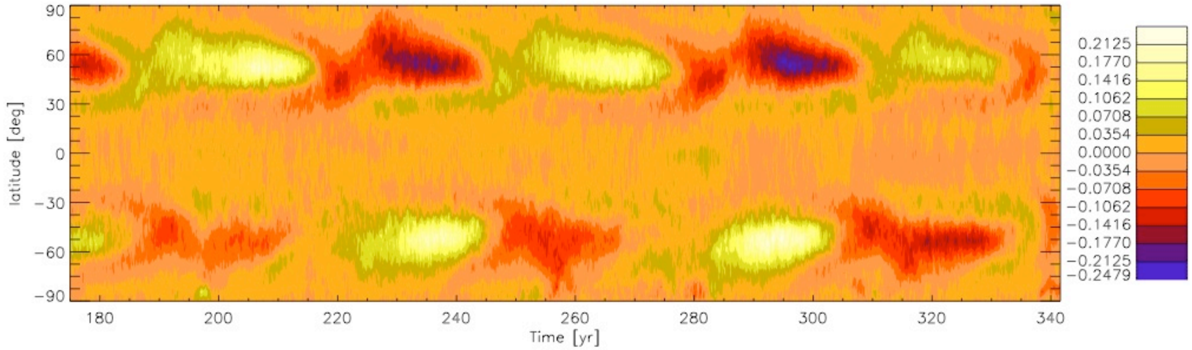
This is consistent with the idea of a turbulent alpha-effect producing the observed dipole moment

Torsional oscillations
[Lead: Patrice Beaudoin (M.Sc.)]



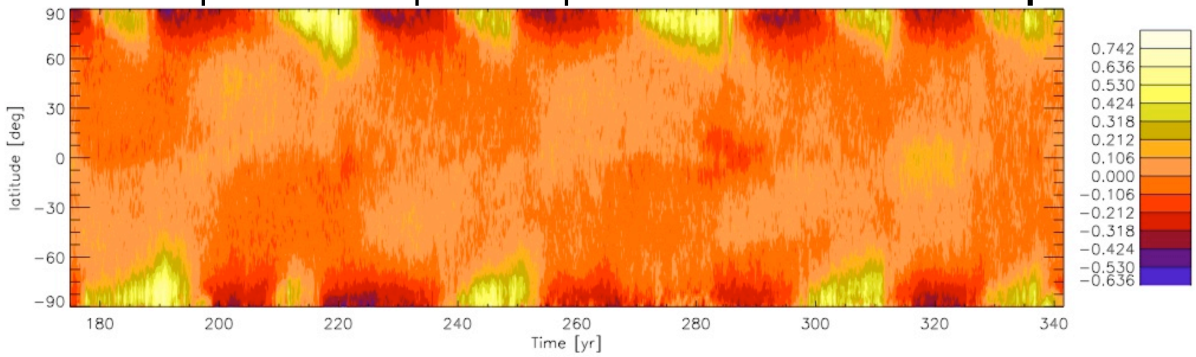
Impact on convective energy transport

Zonal mean toroidal magnetic field **at core-envelop interface** (r/R=0.718)



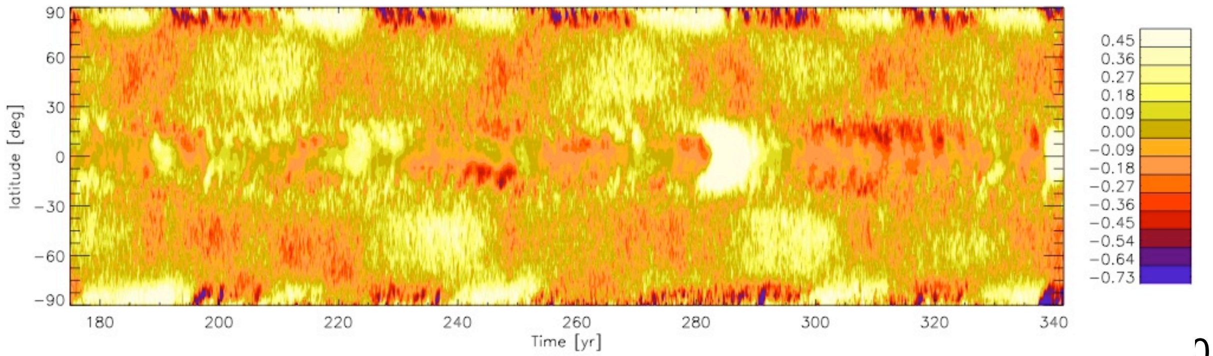
Preliminary results;
Lead: Jean-François Cossette (Ph.D.)

Zonal mean of potential temperature perturbation **at core-envelop interface**



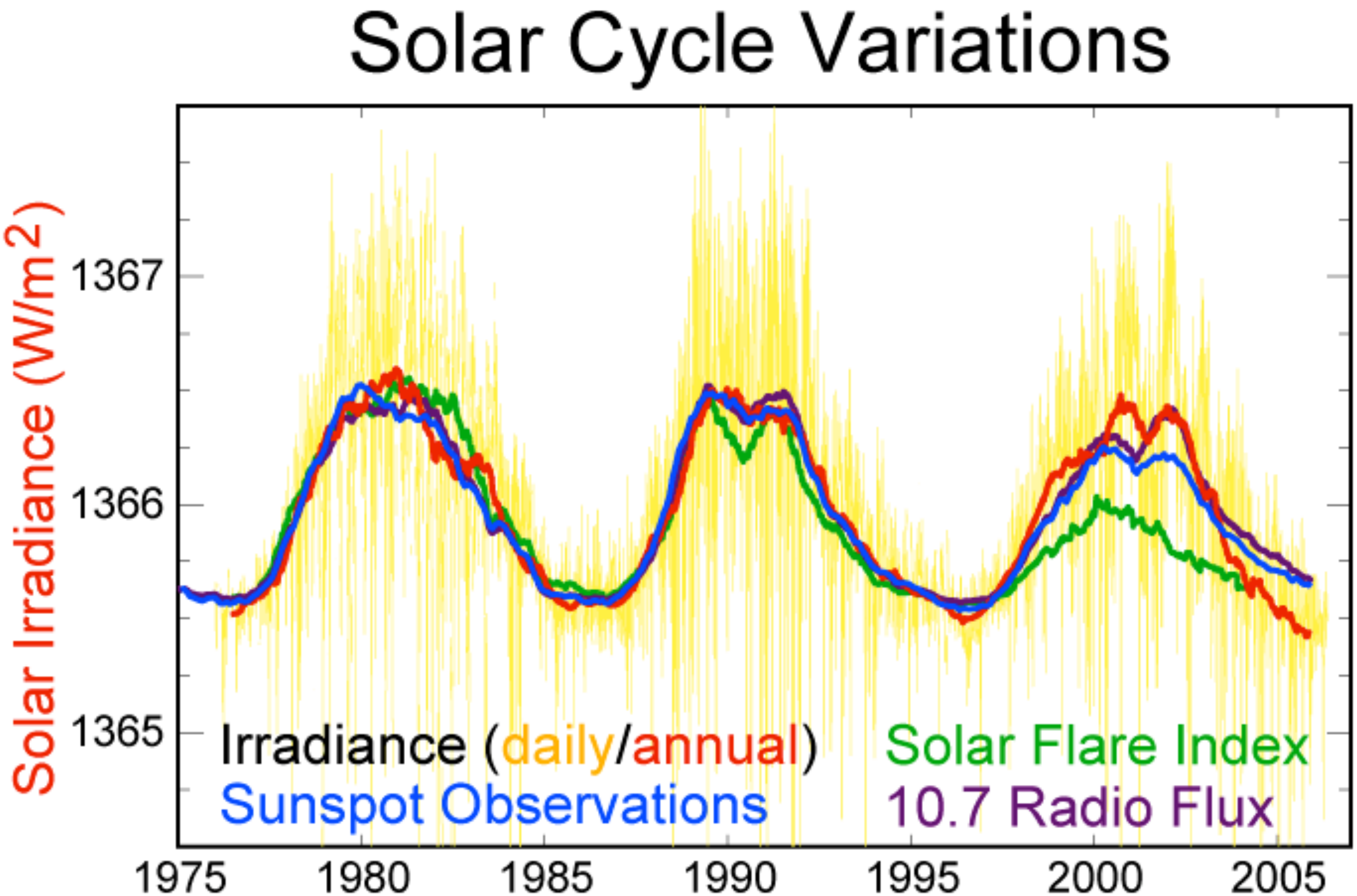
Temperature modulation already present at the base of the convective envelope, varying in phase with the cycle.

Zonal mean of potential temperature perturbation **below the model surface** (r/R=0.96).



Weak but significant temperature excess at the top of the simulation domain, at « maximum » phase of cycle.

Link with total solar irradiance variations



Conclusions

3D global MHD simulations of solar-like cycles have landed.

1. We do not understand the origin of fluctuations in solar cycle amplitude and duration

2. We currently do not understand what sets our 30 yr cycle period, nor why we get cycles and others do not …

3. A weak but clear cyclic modulation of convective energy transport is present in the simulations.

Conclusions

In ideal MHD systems, total magnetic helicity is conserved:

$$\int_V \mathbf{A} \cdot \mathbf{B} \; d\mathbf{x}$$

Generation of a large-scale magnetic component (and therefore a large-scale helicity) therefore requires that small-scale helicity is either

1.stored at small-scales in opposite sign to that of large-scale helicity (inhibits alpha effect, Brandenburg &Subramanian 2007)

or

2. expelled out of the domain (demands proper boundary conditions)

or

3. dissipated

FIN

Three fundamental issues

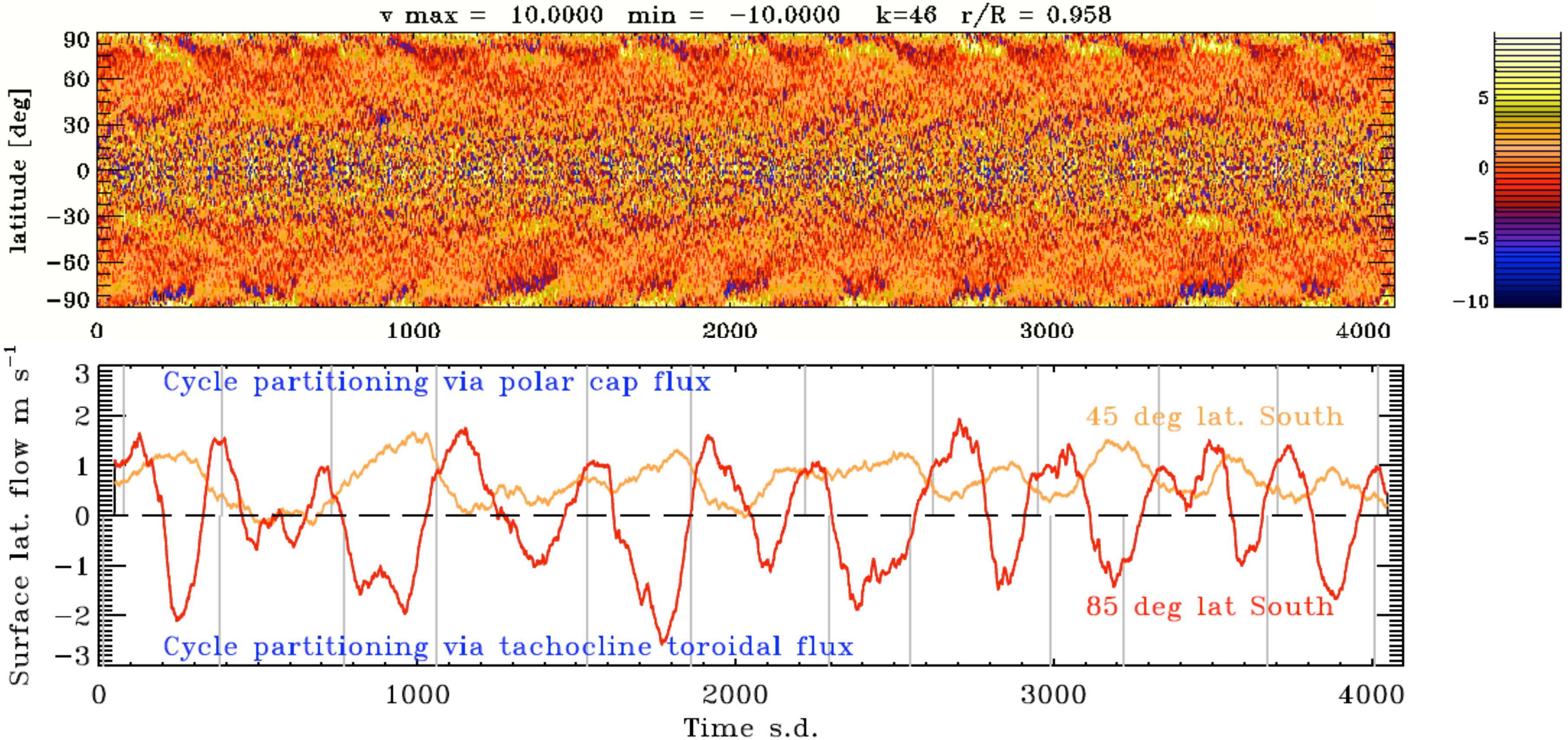
1. What kind of dynamo model best describes the solar cycle: mean-field alpha-Omega? With or without meridional circulation? Babcock-Leighton? something else?

2. What is the mechanism responsible for saturation and observed cycle fluctuations: stochastic forcing? Backreaction by Lorentz force? Time delay modulation? Combination of above and/or something else?

3. How do we « predict » sunspot number from a numerical model that provides the spatiotemporal evolution of a large-scale magnetic field?

Cyclic modulation of meridional flow (1)

Time-latitude diagram of zonally-averaged surface latitudinal flow

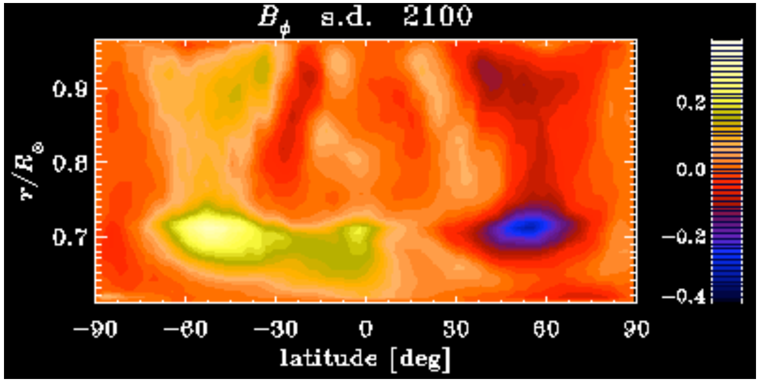


Surface meridional flow generally poleward from mid-latitudes to poles

Counterrotating high-latitude flow cells in descending phase of cycles

The large-scale magnetic fields (2)

Radius-latitude animation of zonally-averaged toroidal magnetic component



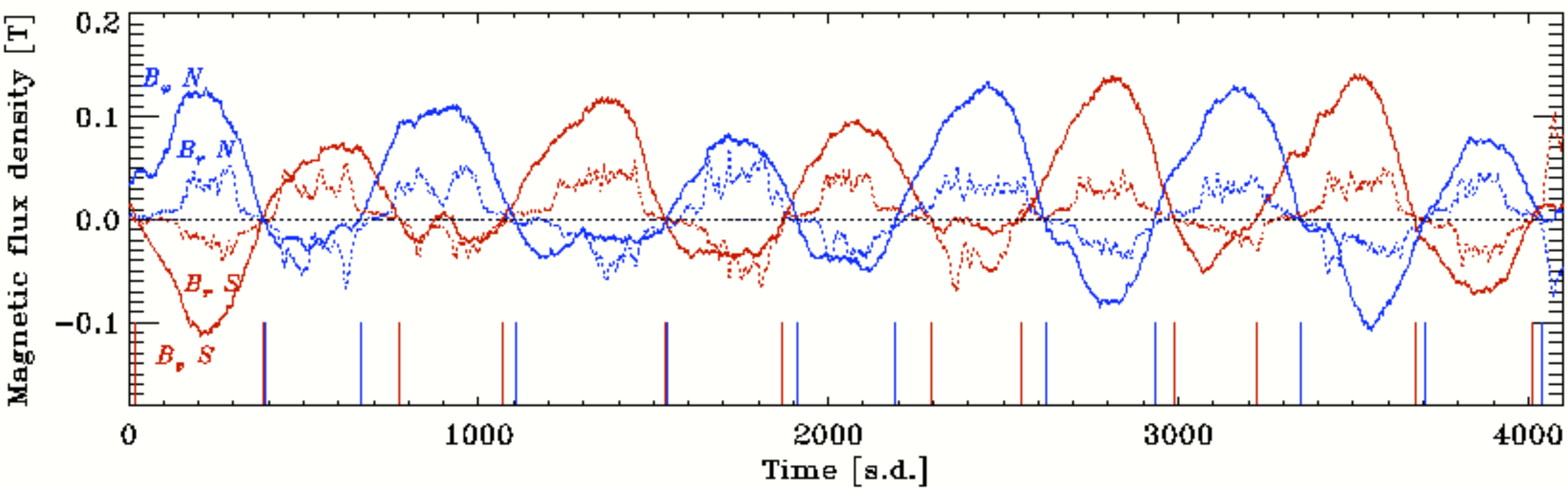
Cycles « begin » in bottom half of convection zone;

Field accumulates at core-envelope interface, in part via turbulent pumping, reaching ~0.4T at peak of cycle;

Dynamo action also taking place in subsurface layers, shorter period.

Magnetic cycles (4)

Polar cap magnetic flux (dotted lines), interface toroidal flux (solid lines)



Good hemispheric synchrony, despite strong cycle-to-cycle fluctuations

Well-defined dipole moment, oscillating in phase with toroidal component (Sun has pi/2 phase lag)

Cycle (half-) period is fairly regular, here ~30 yr instead of the solar 11