Recent results in modelling solar radiative variability on long timescales

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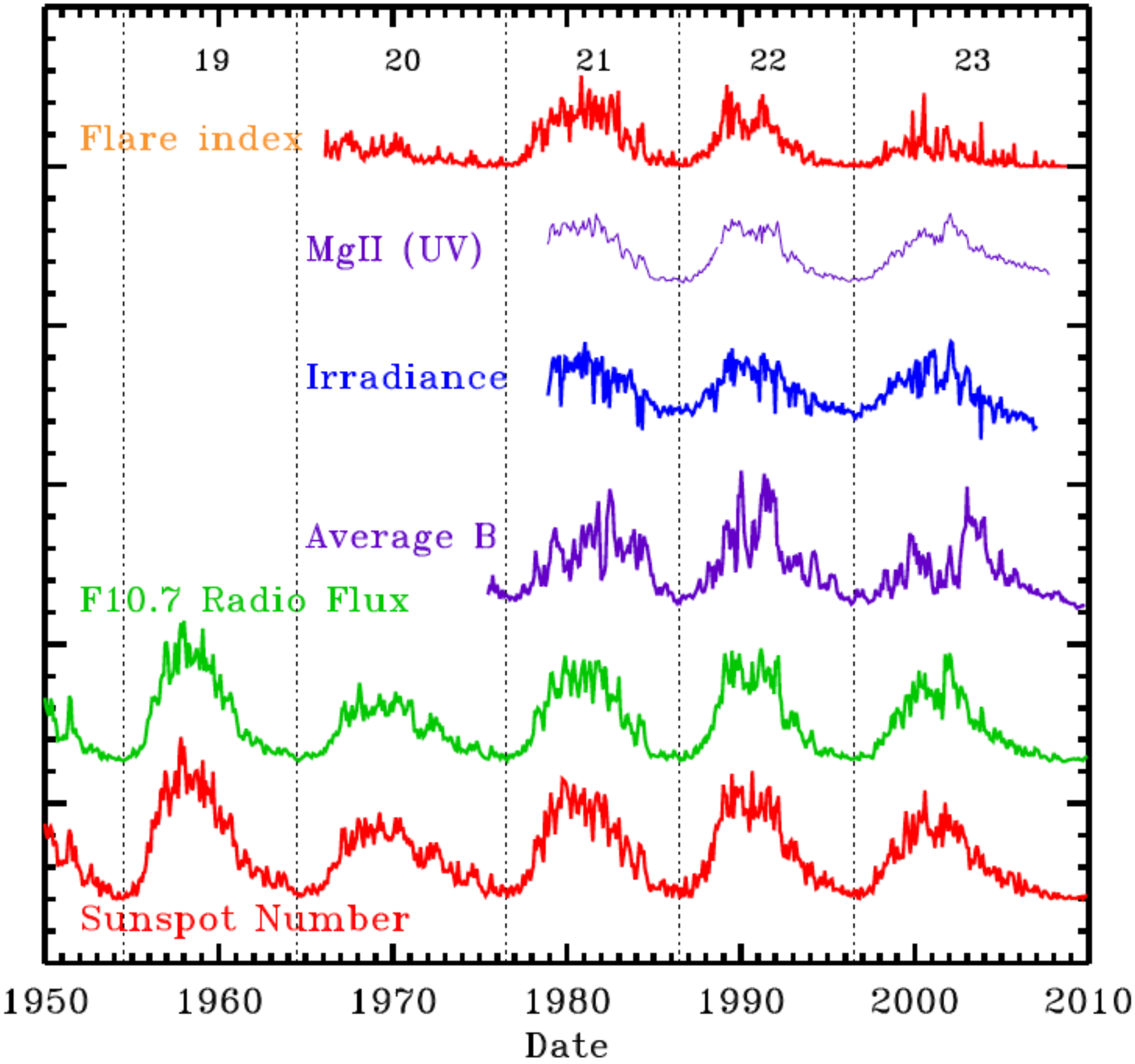
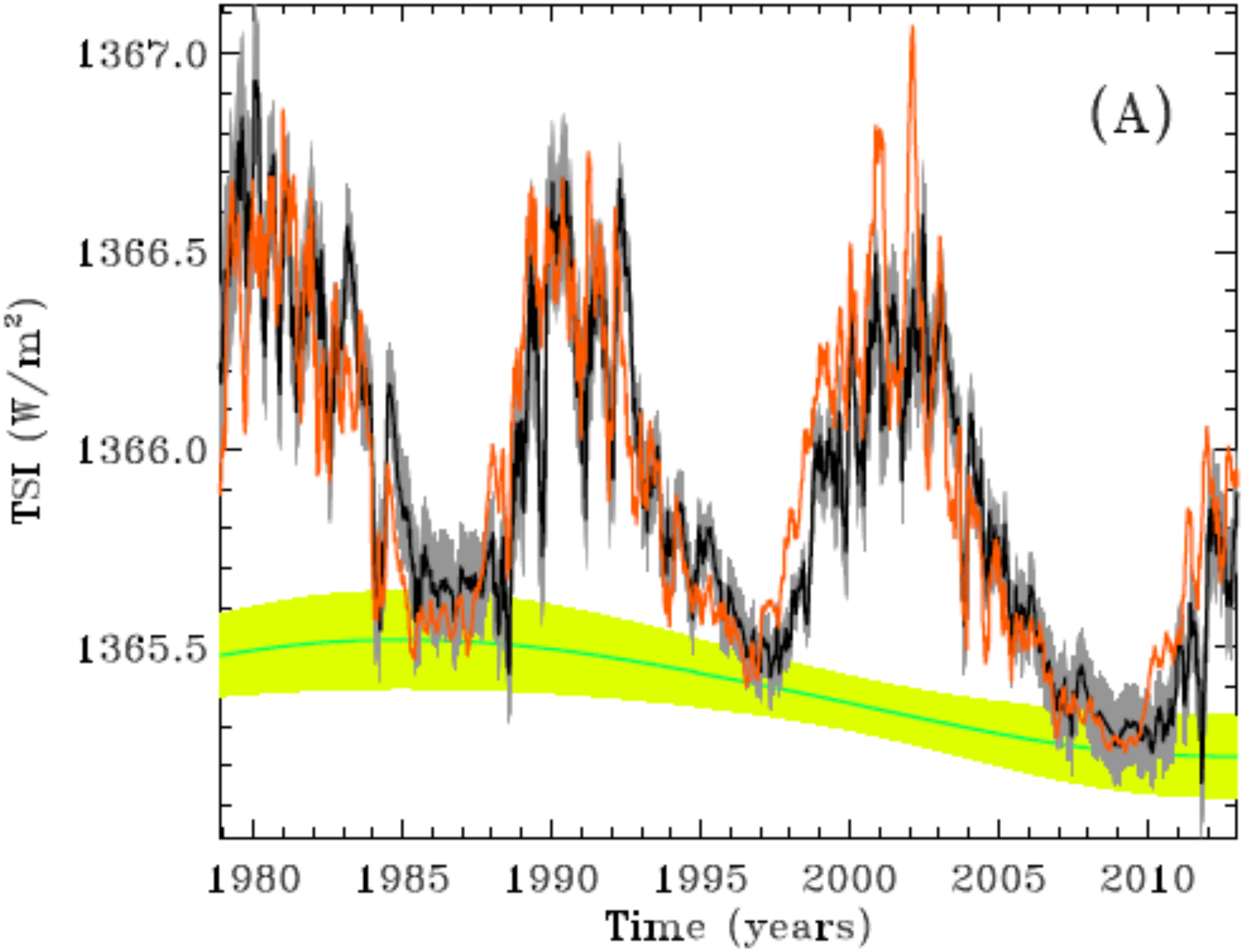
1. Solar radiative variability and the magnetic cycle
2. A model for the evolution of the magnetic network
3. Deep-seated, magneticaly-mediated modulation of the convective energy flux

Collaborators: Piotr Smolarkiewicz, Mihai Ghizaru, Dario Passos, Antoine Strugarek, Jean-François Cossette, Patrice Beaudoin, Cassandra Bolduc, Amélie Bouchat, Kim Thibault, Nicolas Lawson, Étienne Racine, Corinne Simard, Gustavo Guerrero, Roxane Barnabé, Ashley Crouch


19
20
21
22
23
Flare index
MgII (UV)
Irradiance
Average B
F10.7 Radio Flux
Sunspot Number
1950
1960
1970
1980
1990
2000
2010
Date

TSI reconstructions

[Bolduc et al. 2015, ApJ, submitted]



Two schools of thoughts

1. All TSI variation on all relevant timescales are due to varying surface coverage of magnetic features (spots, faculae, network, etc.). *Strongest evidence: reconstructions based on photospheric data can reproduce 95% of observed variance.*

2. Some TSI variations on timescales decadal and longer originate from deep inside the sun (changes in solar radius, photospheric temperature gradient, **magnetic modulation of convective energy flux**, etc.). *Strongest evidence: cyclic modulation of p-mode frequencies.*

A model for the solar magnetic network and its evolution over a solar cycle

[with A. Crouch, P. K. Thibault , M. Béland]

Diffusion-limited aggregation

[Crouch et al. 2007, ApJ, **677**, 723; Thibault et al. 2012, ApJ, **757**, 187]

A simulation of magnetic network formation and evolution through Diffusion-Limited Aggregation (DLA):

1. Elementary « flux tubes » are injected on a computational solar photosphere and left to random walk with step length corresponding to granulation.
2. Tubes coming closer than some preset interaction distance stick together (same polarities) or annihilate (opposite polarities).
3. Individual tubes and aggregates have a size-dependent probability of spontaneous diappearance (simulating convective submergence).

Local area DLA simulations (1)

[Crouch et al. 2007, ApJ **719**]

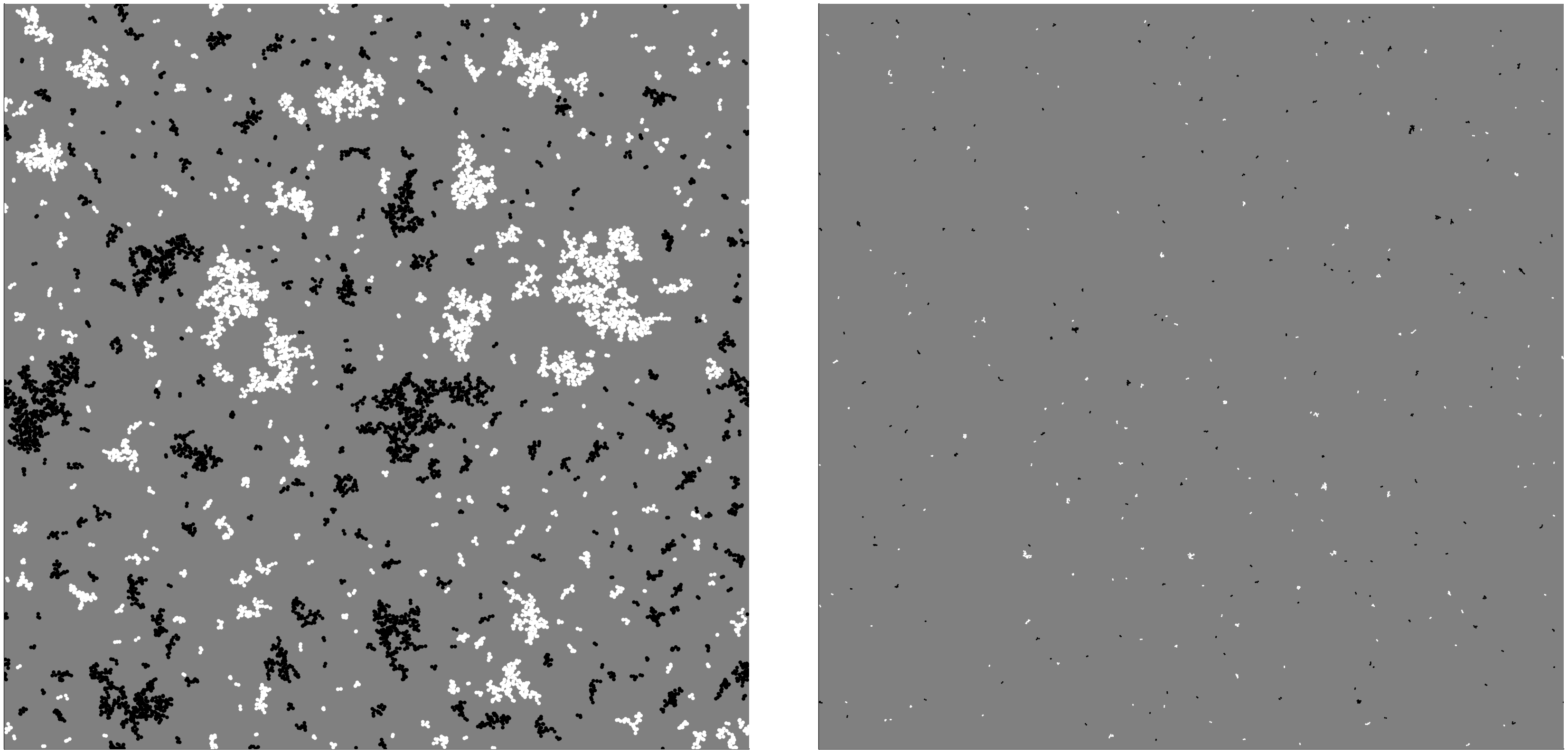


Fig. 4.—*Left*: Plot showing the position of the clustered magnetic elements after 5×10^4 time steps for a simulation with $d_w = 0.01$, $d_i = 0.005$, $n_{\rm in} = 400$, and $\tau = 4000$. *Right*: Plot showing the position of the clustered magnetic elements after 5×10^4 time steps for a simulation with $d_w = 0.01$, $d_i = 0.002$, $n_{\rm in} = 50$, and $\tau = 200$.

Sample solutions in « non-solar » parameter regimes

Local area DLA simulations (2)

[Crouch et al. 2007, ApJ **719**]

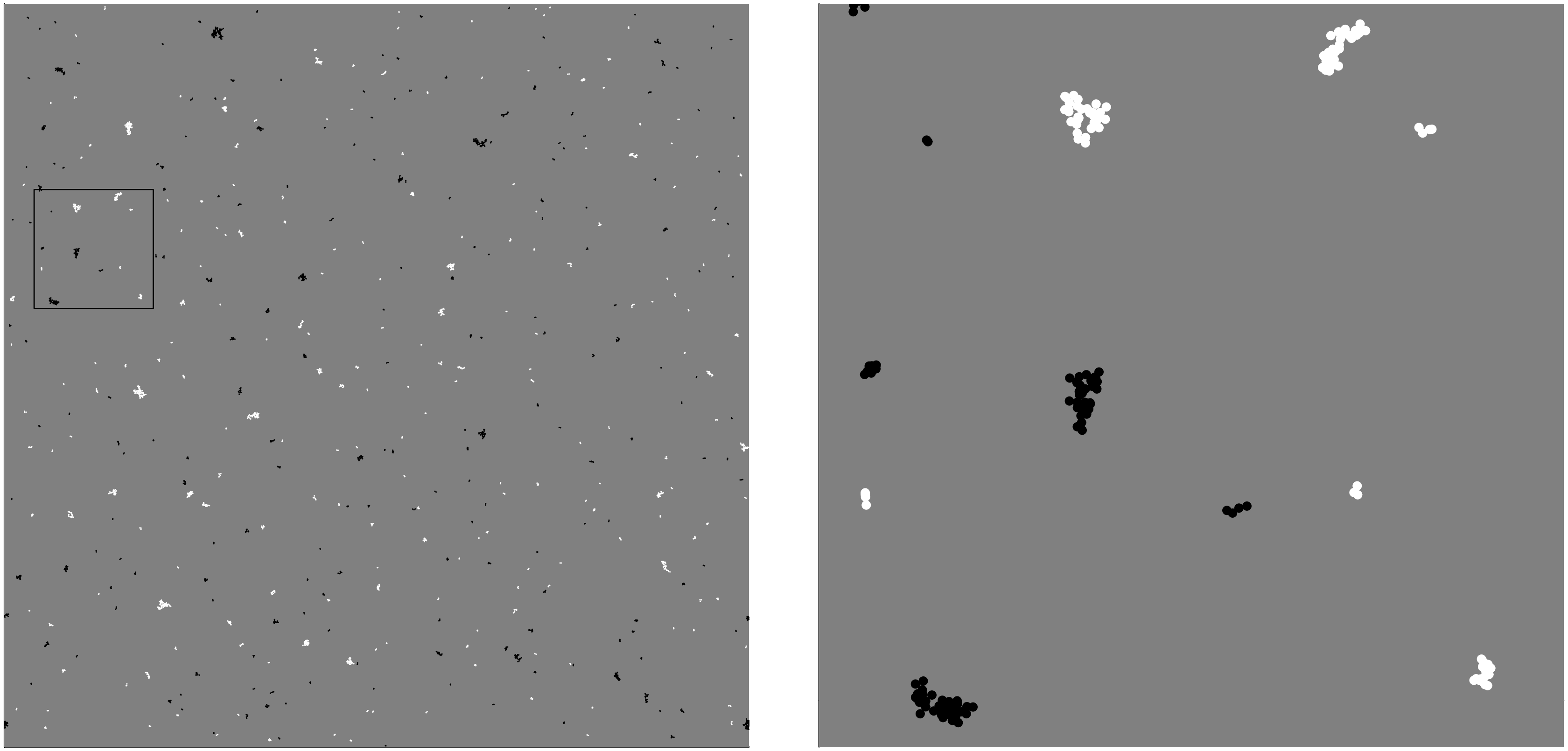
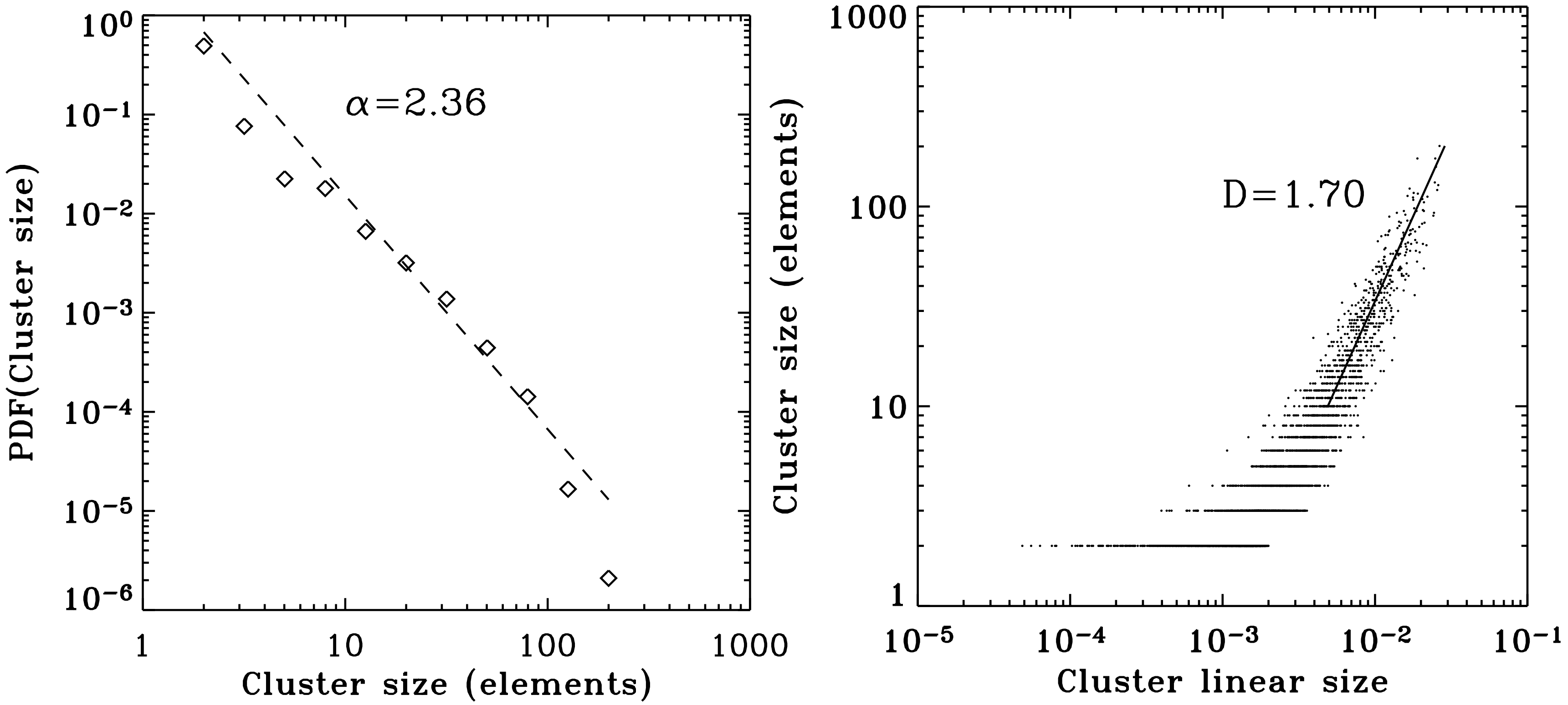


FIG. 3.—Position of the clustered magnetic elements after 5×10^4 time steps for a simulation with $d_w = 0.01$, $d_i = 0.002$, $n_{\rm in} = 50$, and $\tau = 1000$. *Left*: Entire domain (length and width of unity). *Right*: Enlargement of the area outlined on the left. Its length and width are 0.16. In both plots the individual elements are represented by filled circles with radius $d_i/2$. White points have negative polarity, and black ones have positive polarity.

A « solar magnetic network » solution

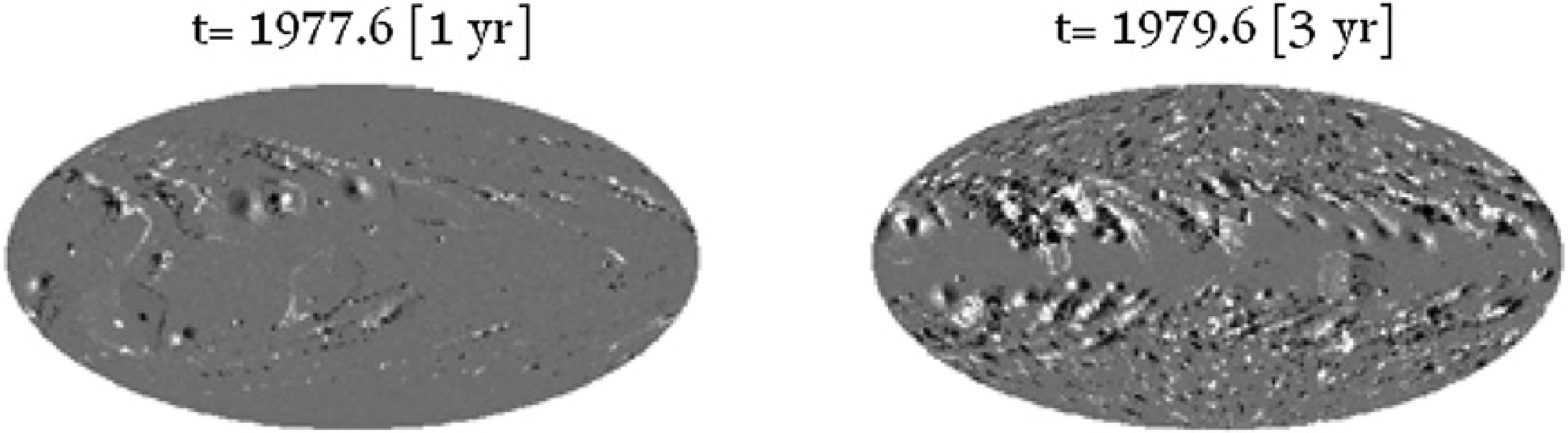
Local area DLA simulations (2)



This « solar » solution reproduces observed power-law shape and index of the size distribution of network elements (Parnell 2001, SolP **200**), as well as their observationally-inferred fractal dimension (Criscuoli et al. 2007, A&A **461**)

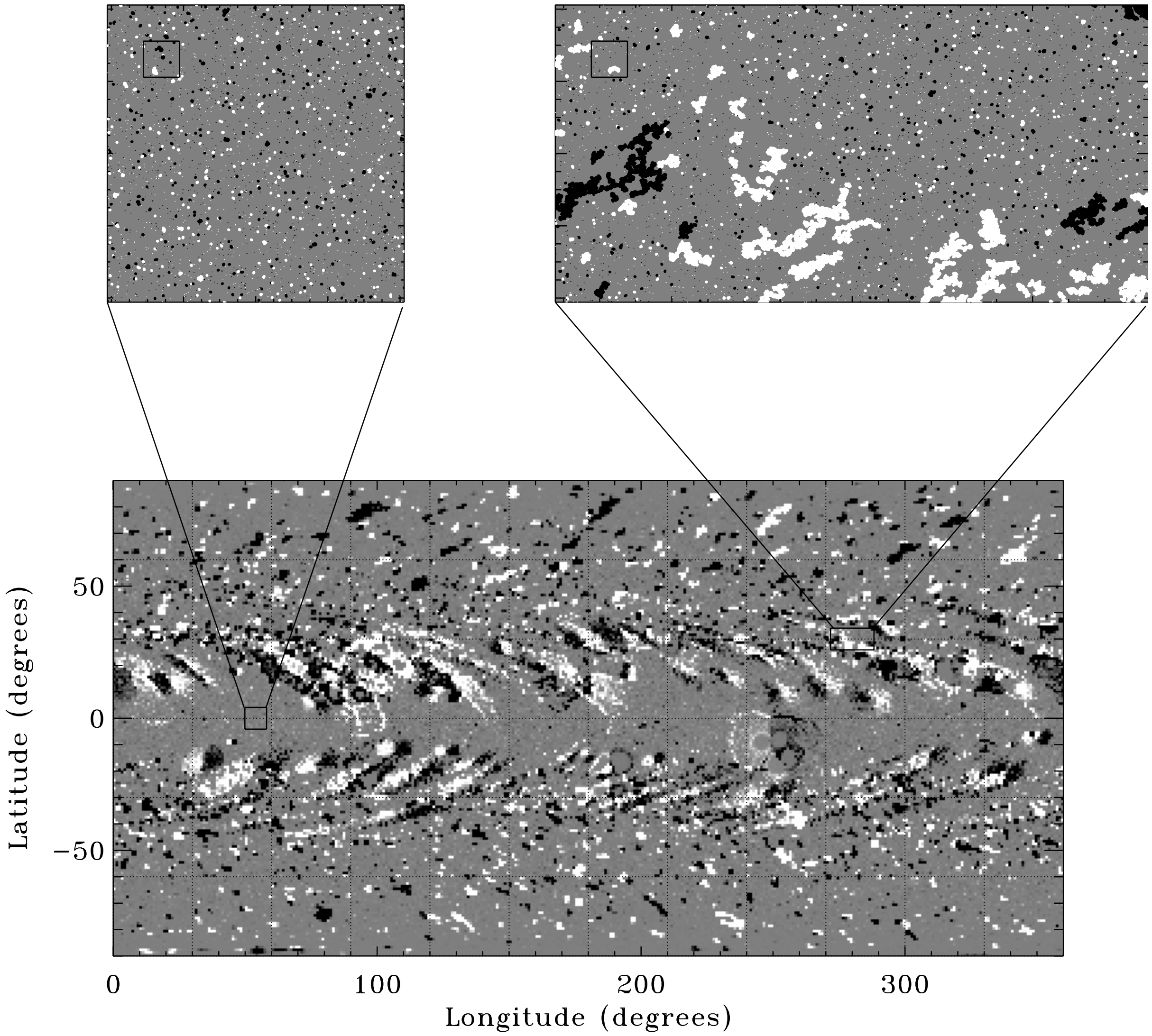
Global DLA simulation (1)

[Thibault et al. 2012, ApJ **757**; 2014, ApJ, **796**]



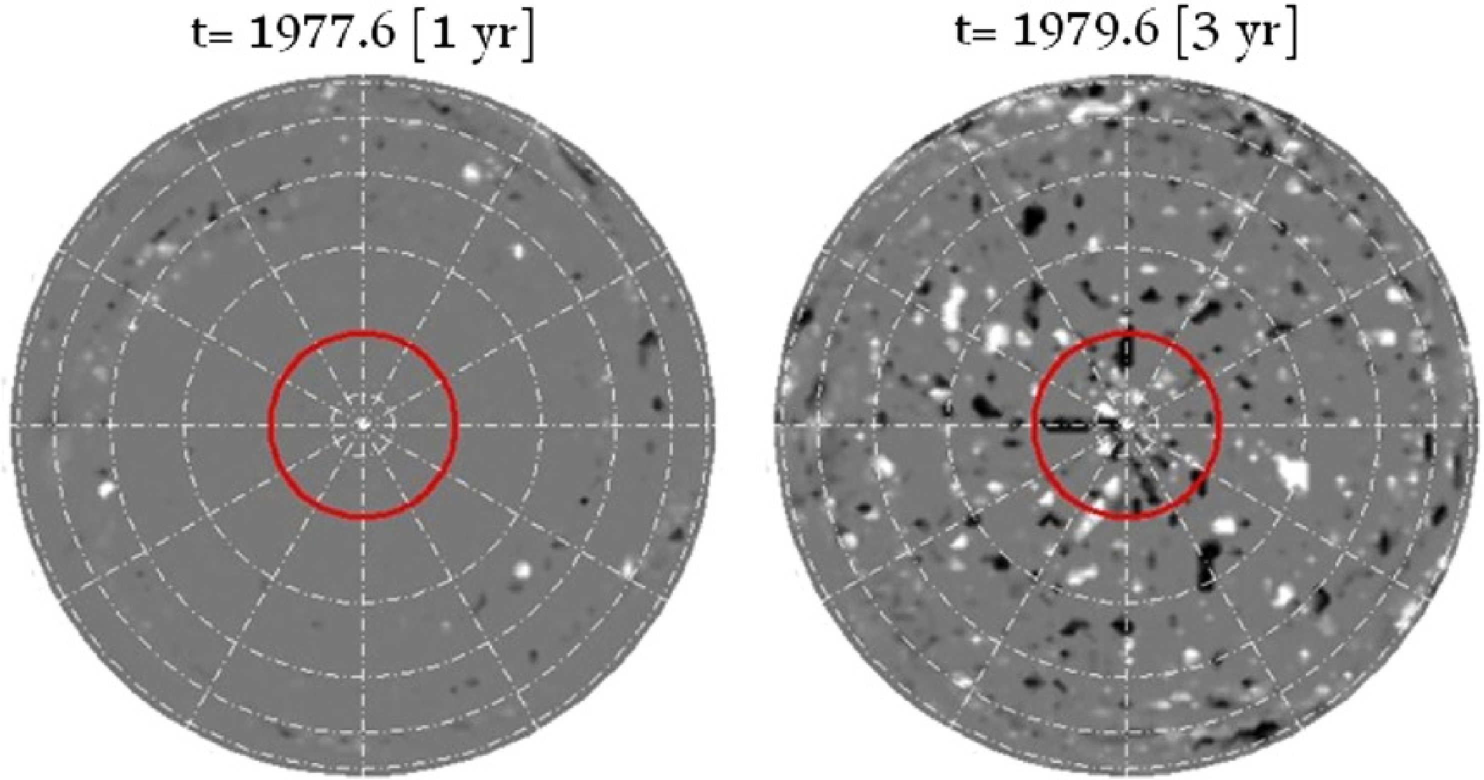
Global (full-sphere) version of local area DLA simulation: need to account or additional surface source of magnetic flux: decaying active regions; use Wang & Sheeley database for cycle 21; add also differential rotation and meridional flow.

Global DLA simulation(2)



DLA simulation of surface flux evolution

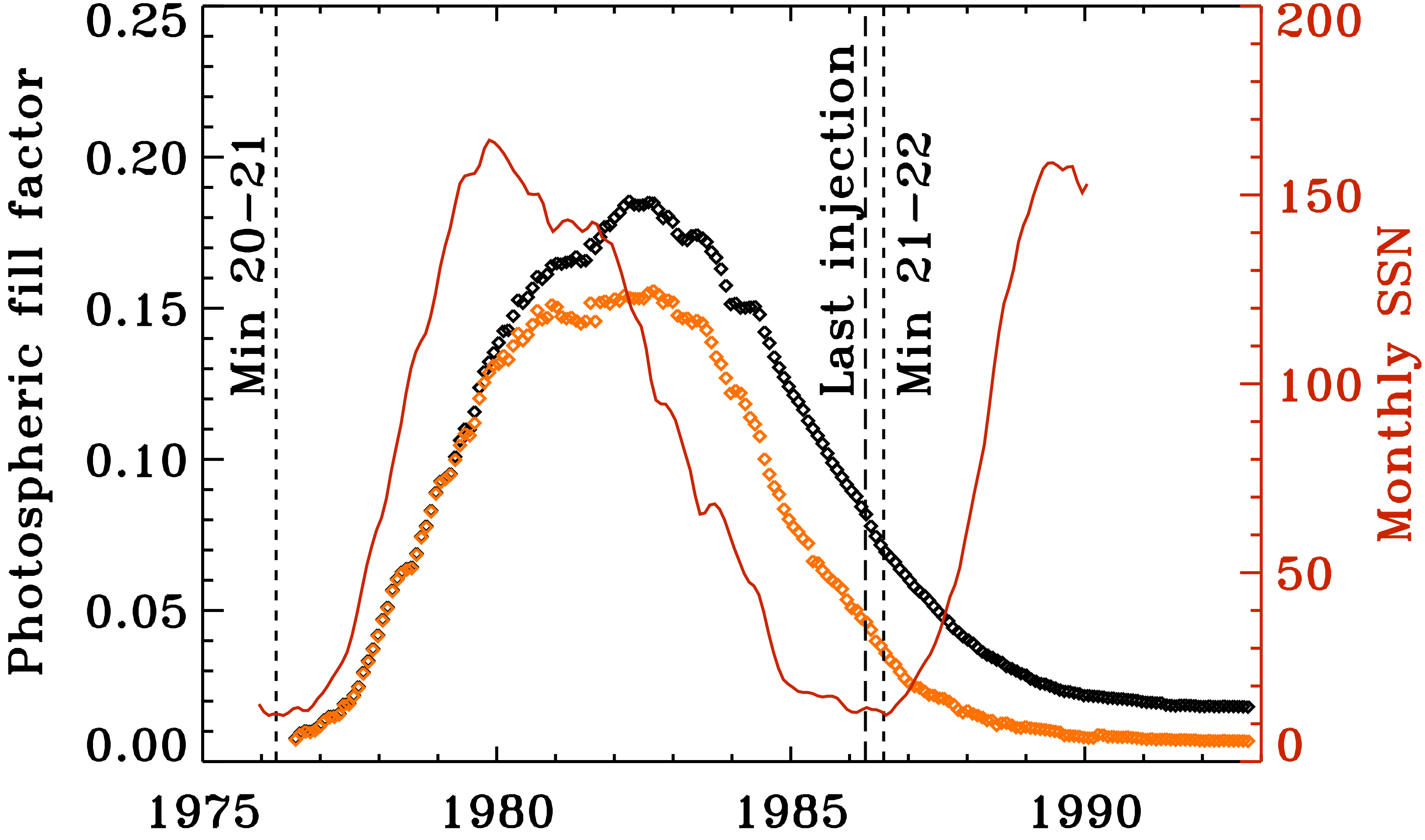
[Thibault et al. 2014, ApJ, **796**]



Polar behavior offer validation (of sorts): dominance of large clusters of mixed polarities containing the bulk of polar cap magnetic flux, with one polarity slightly dominating the other (as revealed by Hinode !)

Network evolution over a solar cycle

[Thibault et al. 2014, ApJ, **796**]



Magnetic network relaxation timescale: 2.9 yr

Magnetically-mediated cyclic modulation of convective energy transport

[with J.-F. Cossette, P. Smolarkiewicz, M. Ghizaru]

EULAG-MHD

[Smolarkiewicz & Charbonneau, *J. Comput. Phys*. **236**, 608-623 (2013)]

EULAG: a robust, general solver for multiscale geophysical flows

EULAG-MHD: MHD generalization of above; developed mostly at UdeM in close collaboration with Piotr Smolarkiewicz

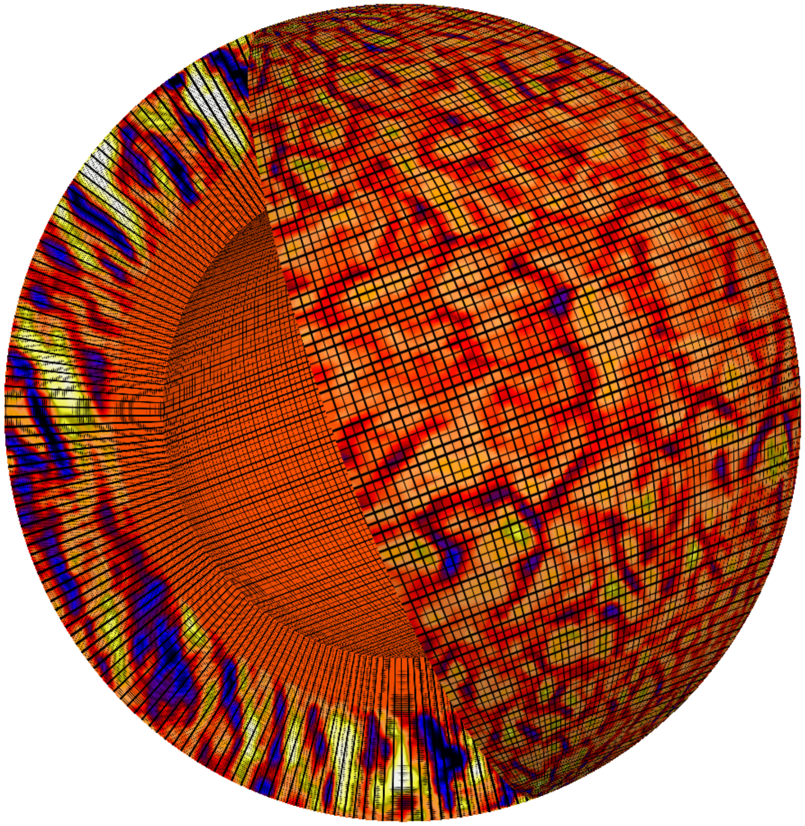
Core advection scheme: MPDATA, a minimally dissipative iterative upwind NFT scheme; equivalent to a dynamical, adaptive subgrid model.

Thermal forcing of convection via volumetric Newtonian cooling term in energy equation, pushing reference adiabatic profile towards a very slightly superadiabatic ambiant profile

Strongly stable stratification in fluid layers underlying convecting layers.

Model can operate as LES or ILES

Simulation design

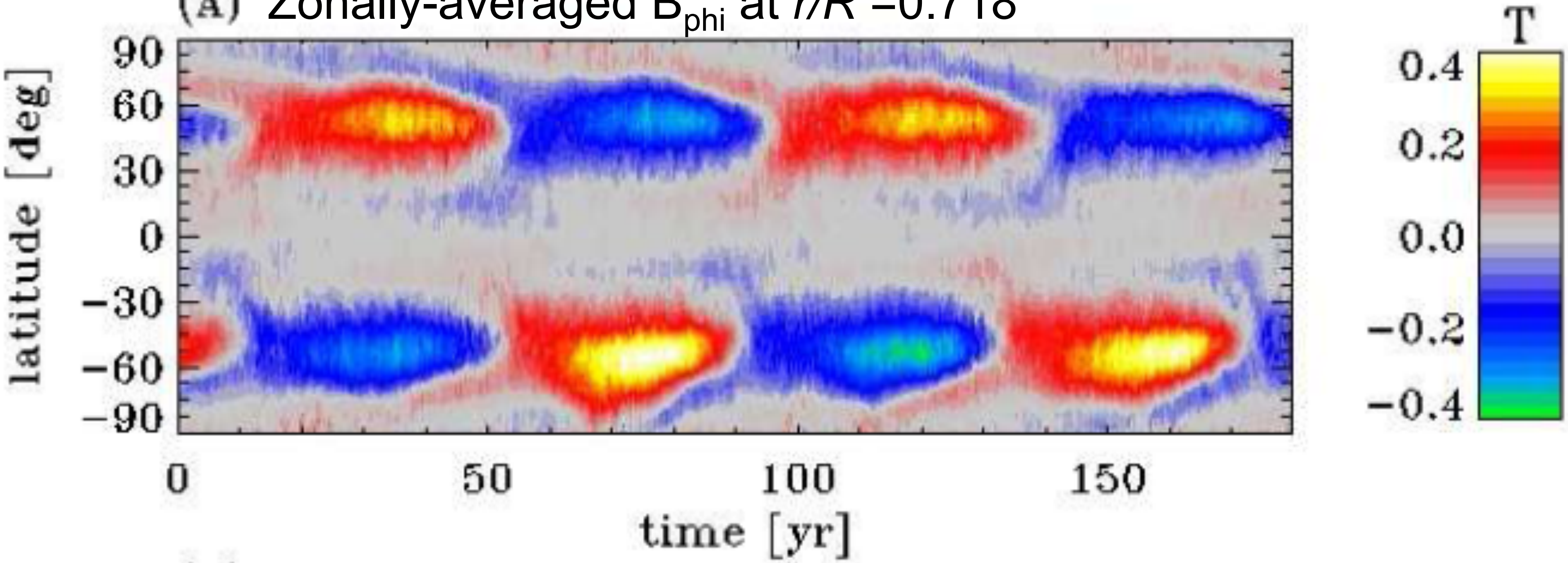


Simulate anelastic convection in thick, **rotating** and unstably **stratified** fluid shell of electrically conducting fluid, overlaying a stably stratified fluid shell.

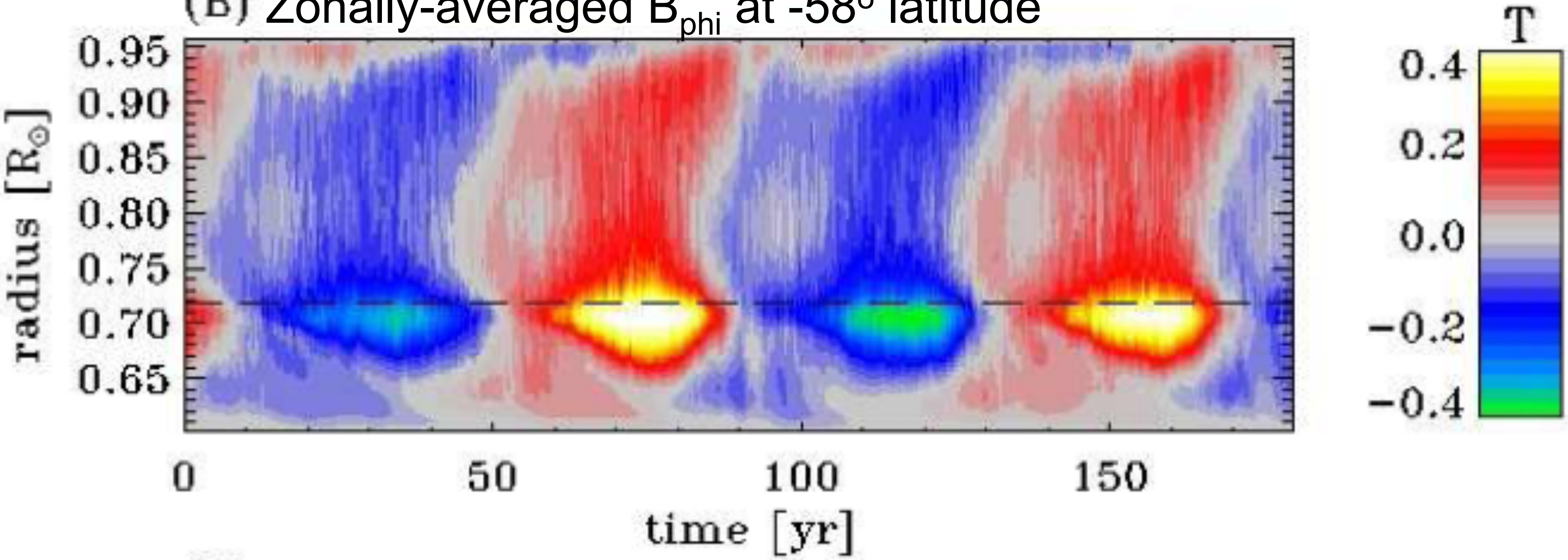
Recent such simulations manage to reach Re, Rm ~10^2-10^3, at best; a long way from the solar/stellar parameter regime.

Throughout the bulk of the convecting layers, **convection is influenced by rotation**, leading to alignment of convective cells parallel to the rotation axis.

Stratification leads to **downward pumping of the magnetic field** throughout the convecting layers.



(A) Zonally-averaged B_{phi} at r/R =0.718



(B) Zonally-averaged B_{phi} at -58° latitude

Successes and problems

KiloGauss-strength large-scale magnetic fields, antisymmetric about equator and undergoing regular polarity reversals on decadal timescales.

Cycle period four times too long, and strong fields concentrated at mid-latitudes, rather than low latitudes.

Internal magnetic field dominated by toroidal component and strongly concentrated immediately beneath core-envelope interface.

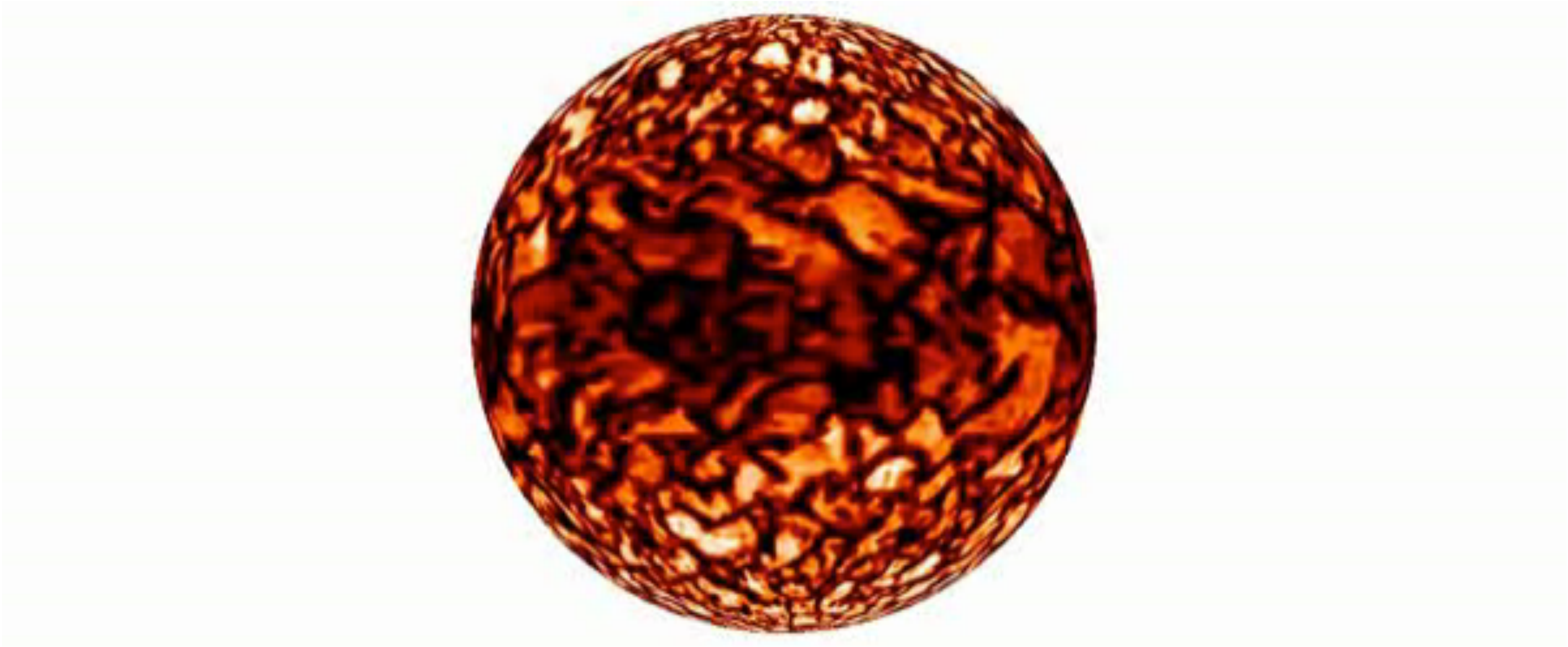
Well-defined dipole moment, well-aligned with rotation axis, but oscillating in phase with internal toroidal component.

Reasonably solar-like internal differential rotation, and solar-like cyclic torsional oscillations (correct amplitude and phasing).

On long timescales, tendency for hemispheric decoupling, and/or transitions to non-axisymmetric oscillatory modes.

Cyclic modulation of the convective energy flux, in phase with the magnetic cycle.

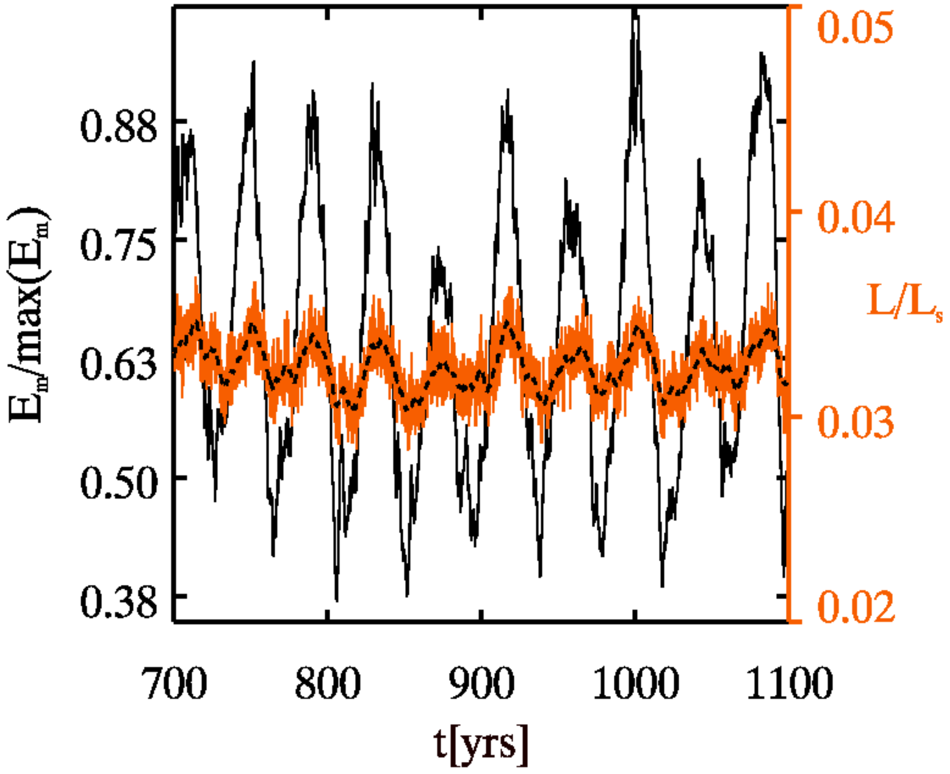
Simulated magnetic cycles (1)

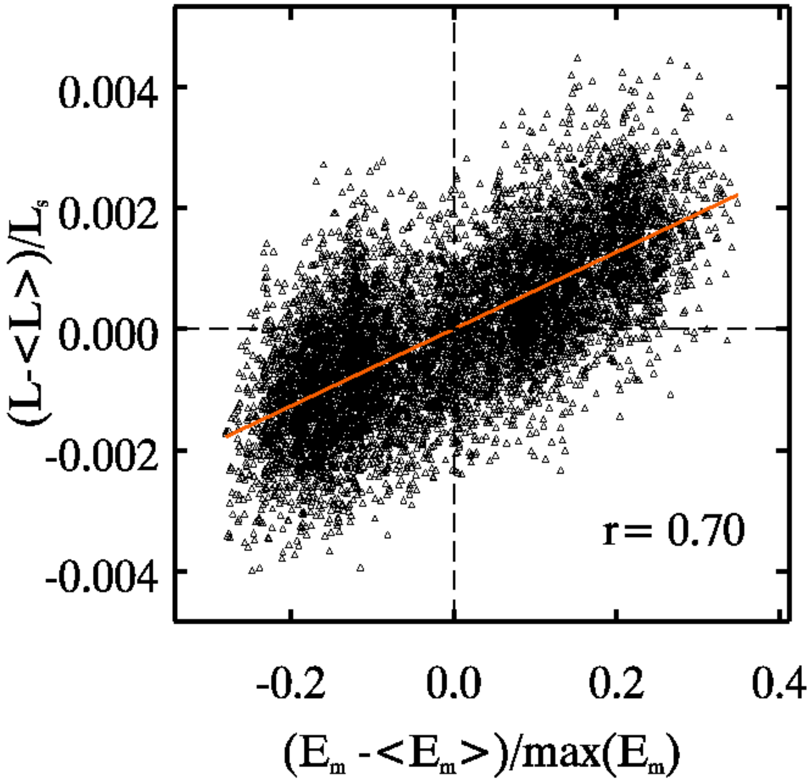


Large-scale organisation of the magnetic field takes place primarily at and immediately below the base of the convecting fluid layers

Magnetic modulation of convective energy transport in EULAG-MHD simulation

[Cossette et al. 2013, ApJL, **777**, L29]





The simulation is more « luminous » at magnetic cycle maximum, by a solar-like 0.2% L_{sol} !

How to modulate convective energy transport

$$L_{\rm cv} \equiv \int F d\sigma \qquad\qquad F \equiv c_p \rho_o u_r \widetilde{T}$$

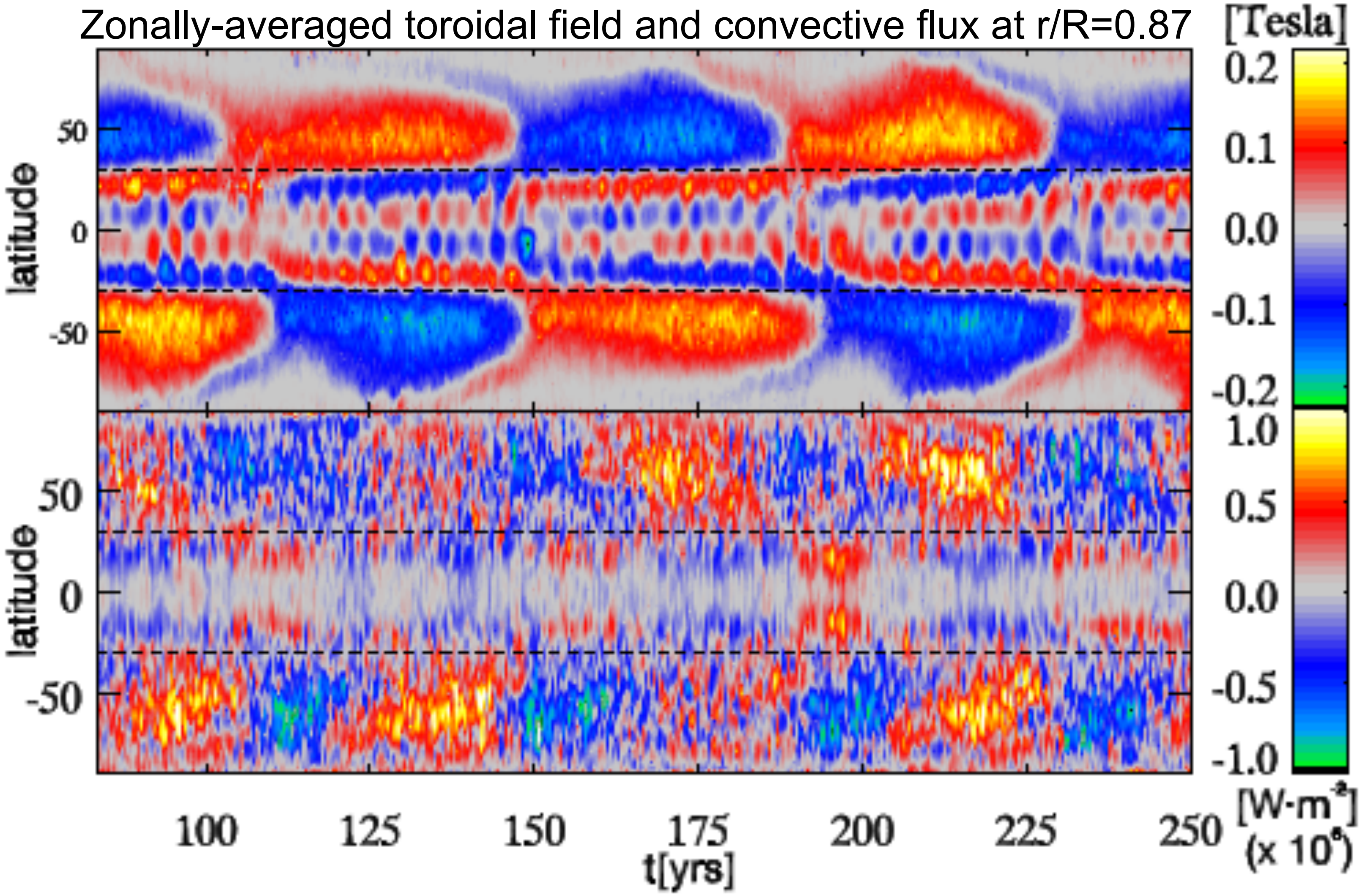
Vertical flow speed

Temperature deviation from horizontal mean

1. Lorentz force modulates convective velocity u_r ;
2. Change in magnitude of temperature perturbations;
3. Change in degree of correlation between the two;
4. Change in latitudinal distribution of F .
5. All of above ? And/or something else … ?

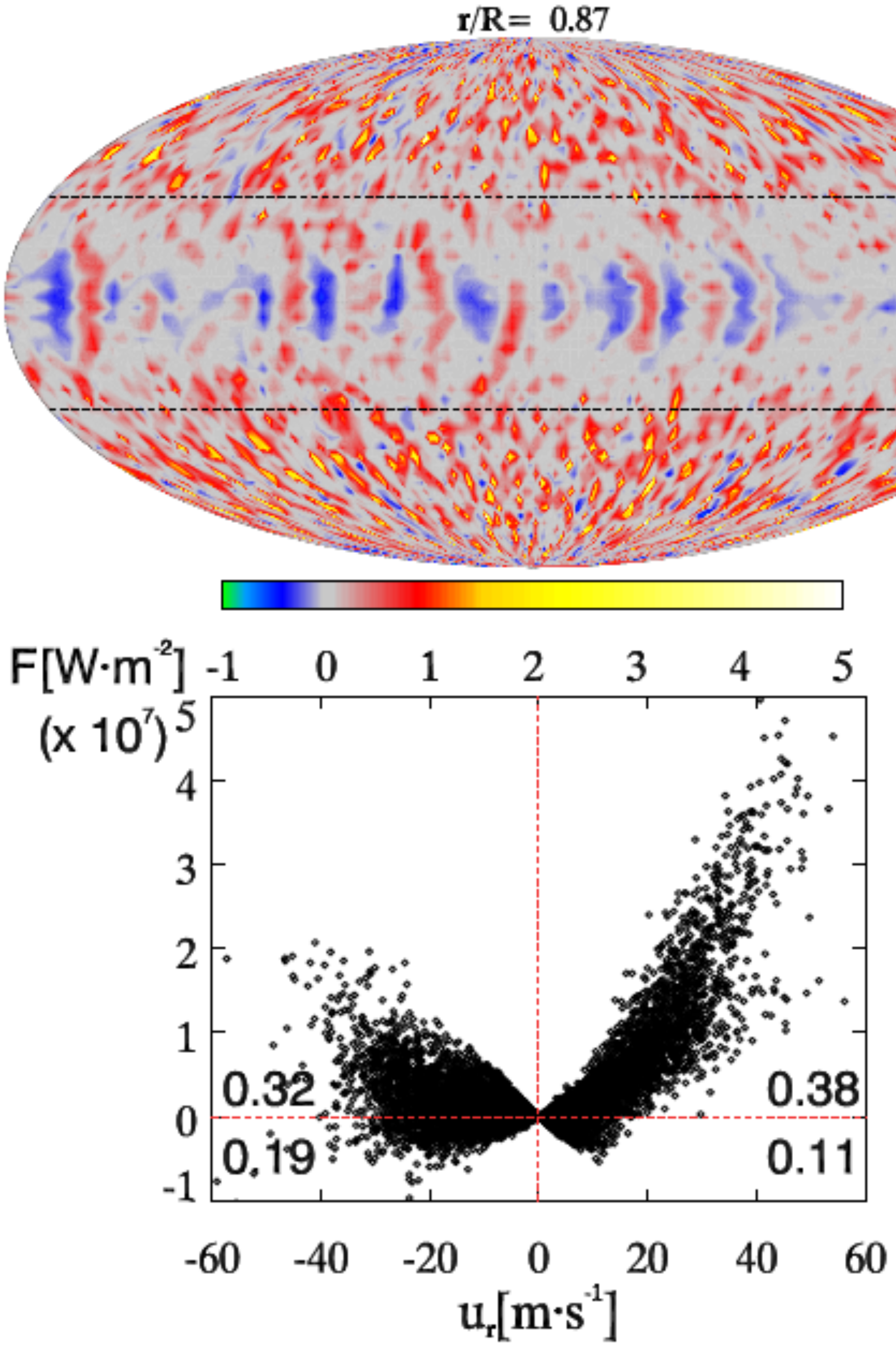
Spatiotemporal variability of the convective flux

[Cossette et al. 2013, ApJL, **777**, L29]



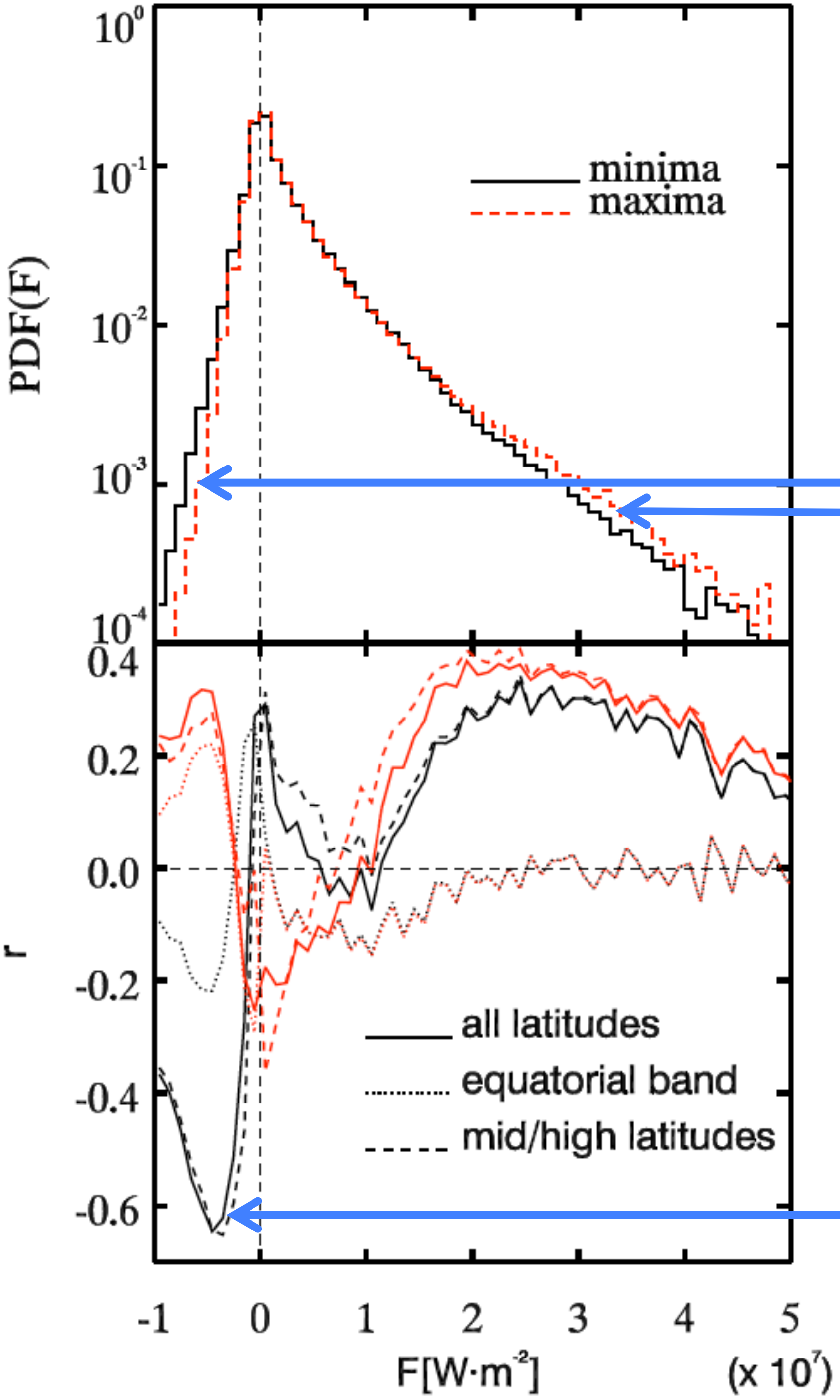
Zonally-averaged toroidal field and convective flux at r/R=0.87

Convective entrainment and « hot spots »



Pinning it down…

[Cossette et al. 2013, ApJL, **777**, L29]

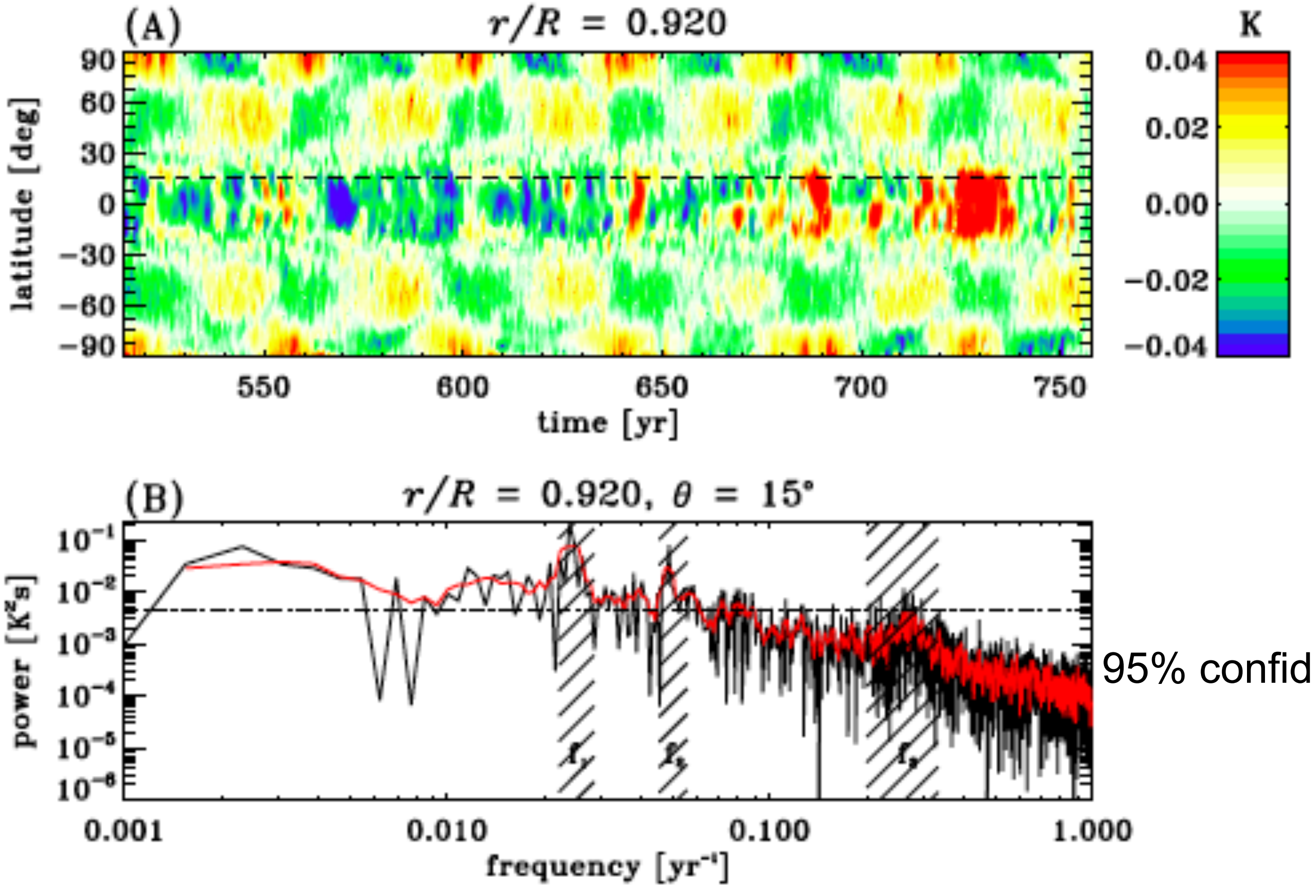


Differences are in the tails of the flux distributions: hot spots are enhanced, turbulent entrainment is suppressed.

The strongest (anti)correlations with the magnetic cycle are for the negative convective fluxes.

Small (multi)periodic signal in temperature

[Beaudoin et al. 2015, submitted.]



95% confidence

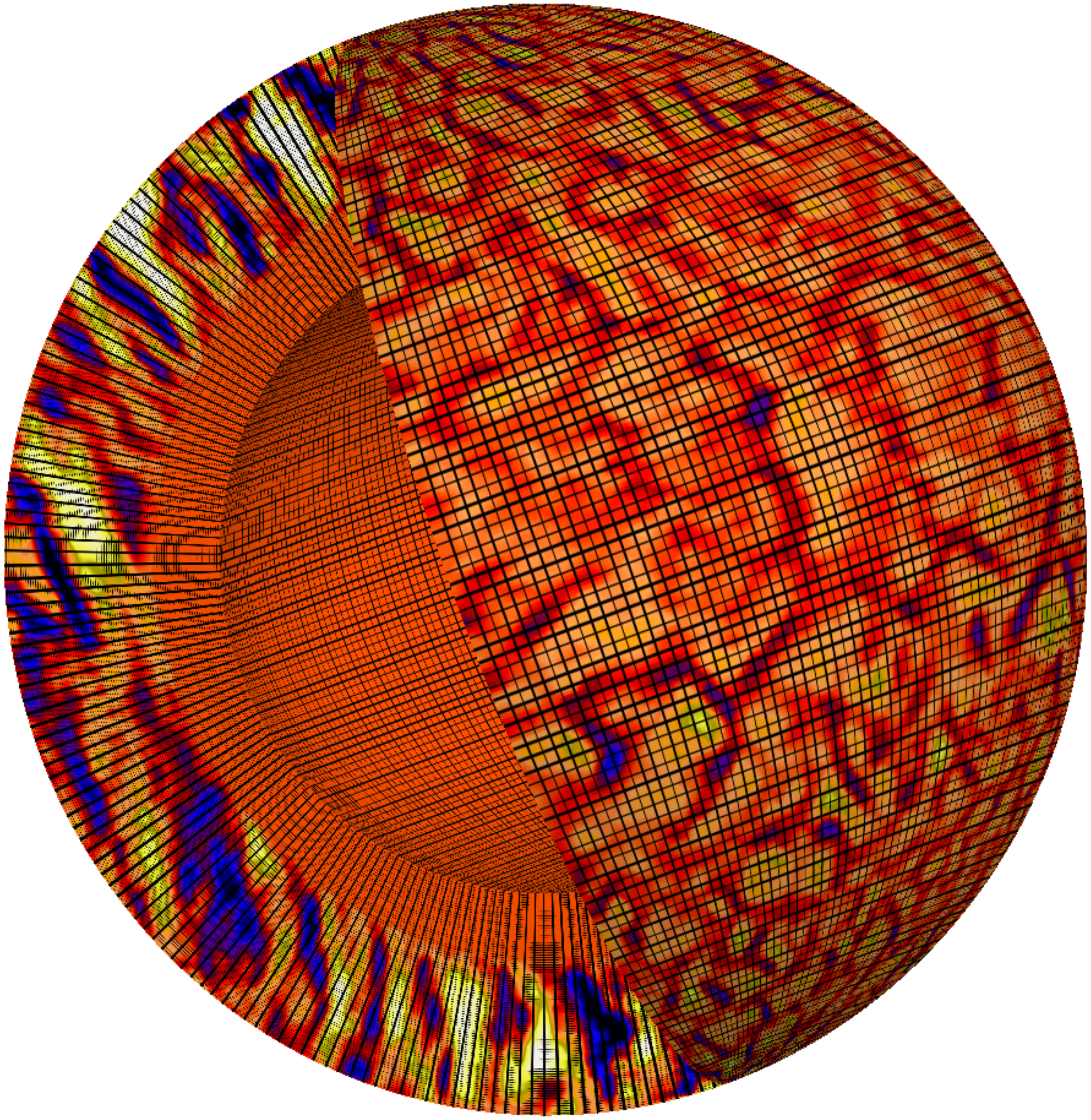
Foukal et al. 2006, *Nature* **443,** 161-166: this cannot produce TSI variations !

Convection is NOT diffusion !

1. The Newtonian diffusive heat flux is proportional to the temperature gradient; the heat flux is entirely determined by **local** conditions.

2. The convective heat flux is proportional to temperature at point of origin of upflows and downflows; for strongly turbulent convection, these flow structures can cross many scale heights; the heat flux is strongly **non-local**.

Convection is NOT diffusion !



A few bits to remember from this talk

Diffusion-limited aggregation can serve as the basis of a simple model of the magnetic network which properly reproduces many of its geometrical properties

Augmented by magnetic flux injection due to decaying active regions, it becomes possible to construct a simple model for the evolution of the magnetic network over a solar cycle.

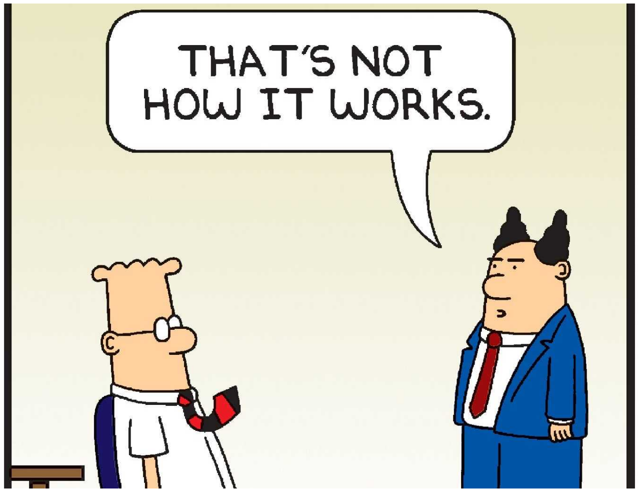
Such a model suggests a network relaxation time of 2.9yr after active region injection ceases, suggesting that the cycle 23-24 minimum was not long enough for the network to reach it basal state.

On long timescales (decadal and up), deep-seated, magnetically-driven modulation of heat transport may play a significant role in TSI variations.

Global MHD numerical simulations now allow quantitative investigations of these effects; but need to get closer to the surface to allow detailed comparison to observations

The ones who did the real work

Jean-François Cossette
PhD granted November 2014
Now Hale postdoctoral Fellow at the University of Colorado/Boulder, U.S.A.



Kim Thibault
PhD granted April 2014
Later MITACS postdoc in industry, Montréal

CRSNG
NSERC

FIN

CSA ASC

Fondation canadienne
pour l'innovation

Canada Foundation
for Innovation

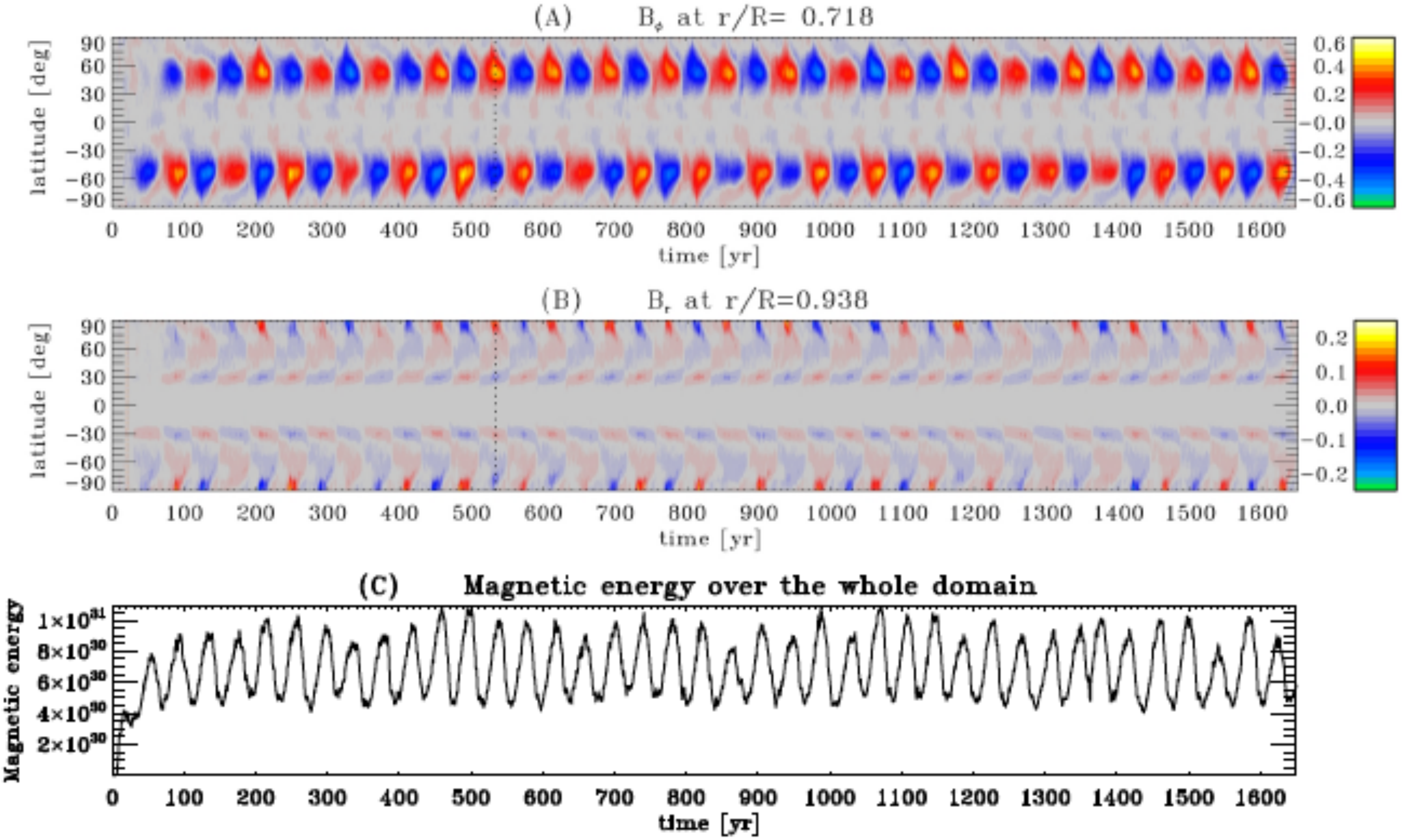
Calcul Québec

Fonds de recherche
sur la nature
et les technologies
Québec

Collaborators: Piotr Smolarkiewicz (ECMWF), Mihai Ghizaru, Étienne Racine (CSA), Jean-François Cossette, Patrice Beaudoin, Nicolas Lawson, Amélie Bouchat, Corinne Simard, Caroline Dubé, Dario Passos, Kim Thibault, Cassandra Bolduc, Antoine Strugarek

The « millenium simulation »

[Passos & Charbonneau 2014, A&A, in press]



The magnetic self-organization conundrum

How can turbulent convection, a flow with a length scale <<R and coherence time of ~month, generate a magnetic component with scale ~R varying on a timescale of ~decade ??

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

Mechanism/Processes favoring organization on large spatial scales: 1. rotation (cyclonicity); 2. differential rotation (scale ~R); and 3. turbulent inverse cascades.