Solar Dynamo

RECENT PROGRESS WITH GLOBAL SIMULATIONS

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With Paul Charbonneau & the GRPS members

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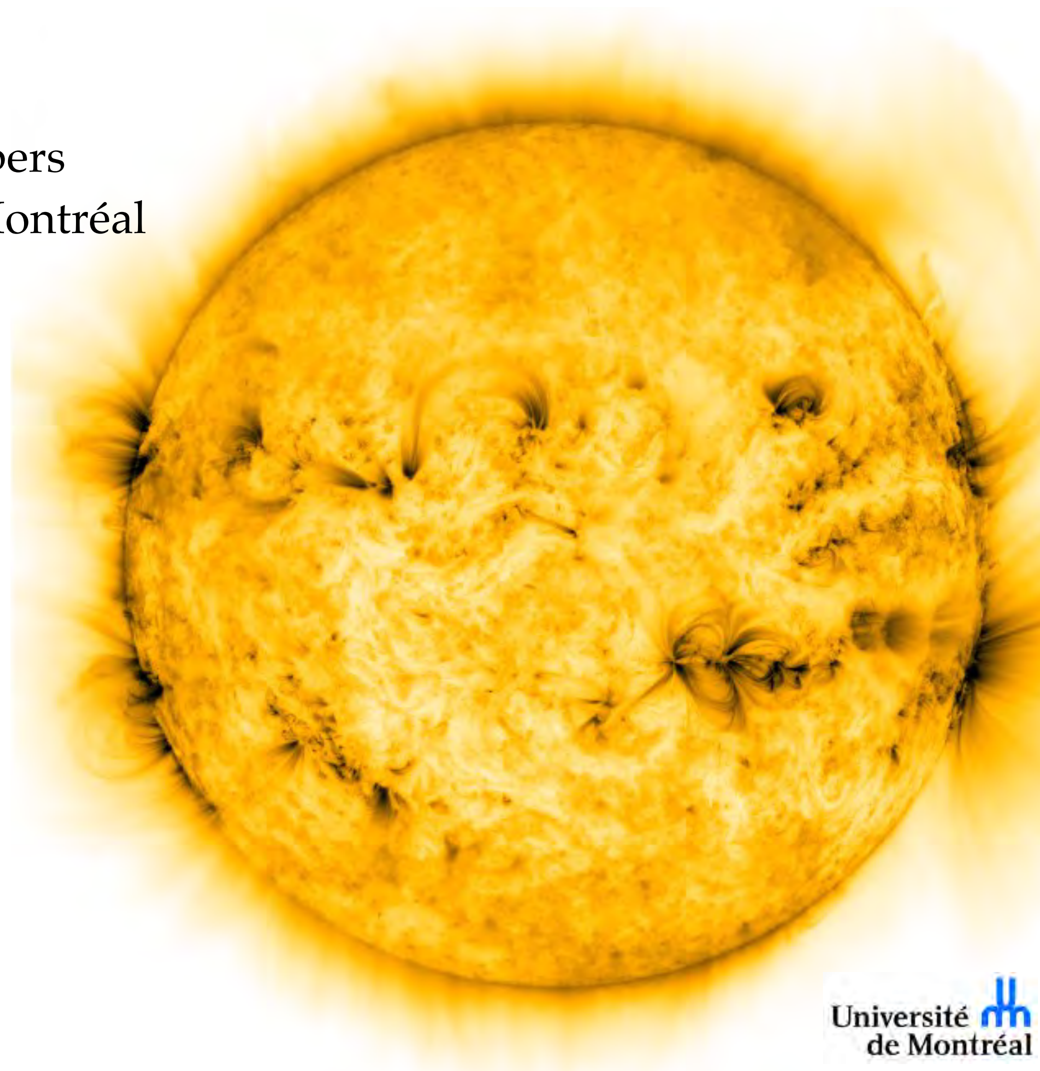
1. Introduction

2. The « millenium » simulation

3. Double-cycle dynamos

4. Conclusions



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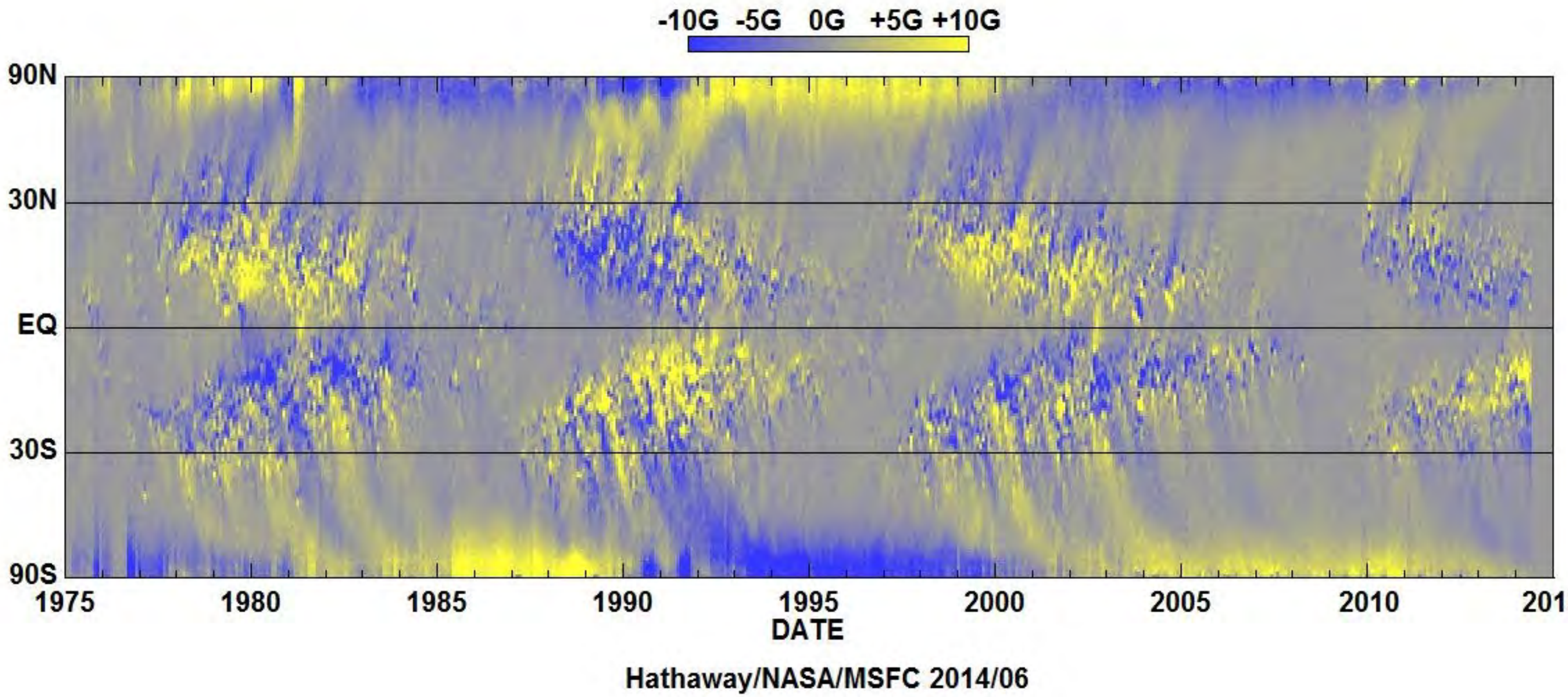
The solar magnetic cycle



Source: http://solarscience.msfc.nasa.gov/images/magbfly.jpg

Dynamo problems

The kinematic dynamo problem:

HARD

TURBULENCE

« To find a flow **u** that can lead to field amplification when substituted in the MHD equation »

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The solar/stellar dynamo problem(s):

HARDEST

????????

« To find a flow **u** that leads to a magnetic field amplification and evolution in agreement with observational inferences for the Sun and stars »

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 ??

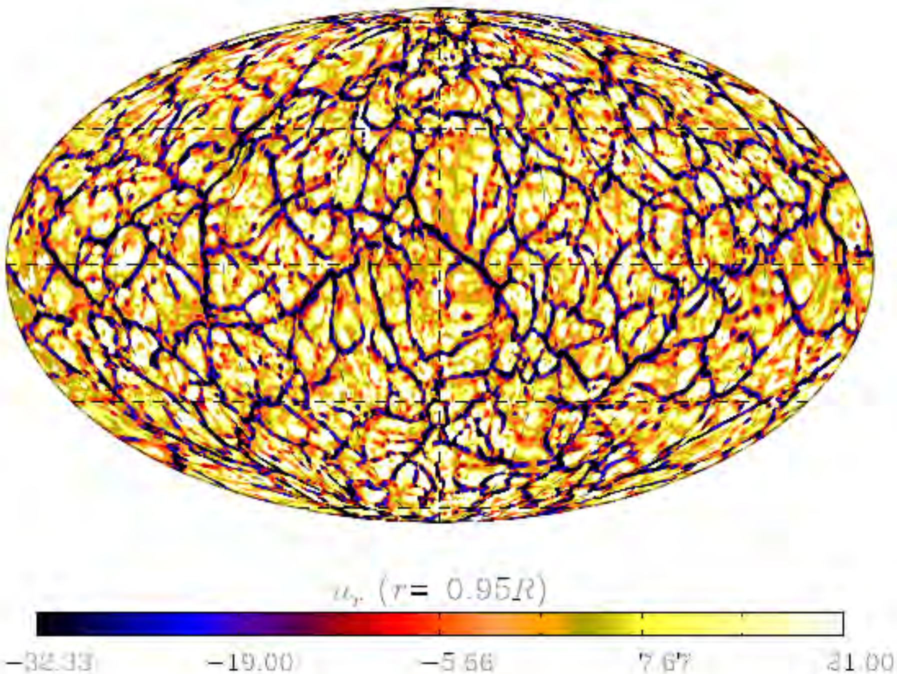
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Mechanism/Processes favoring organization on large spatial scales:

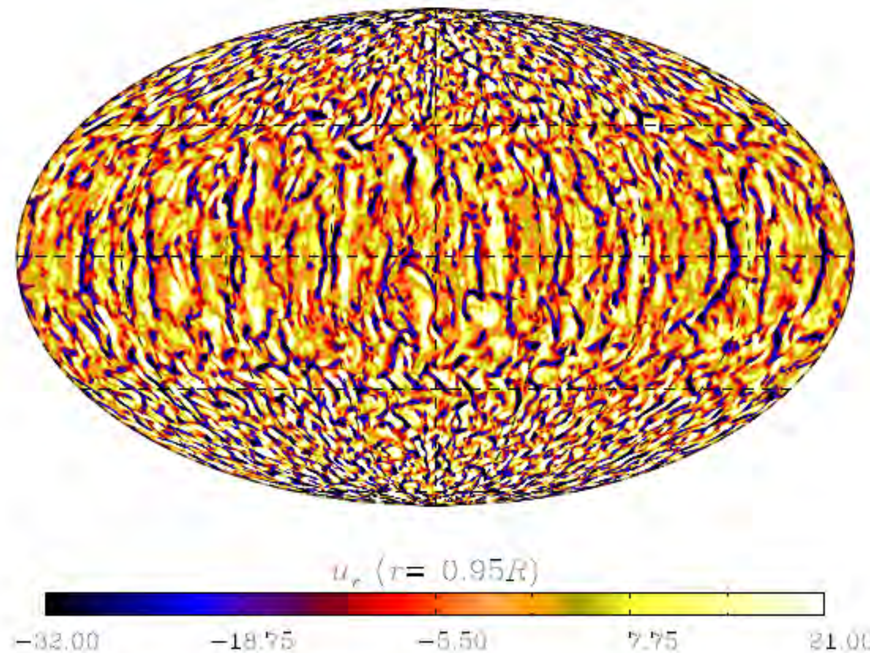
1. rotation (cyclonicity)
2. differential rotation (scale ~R)
3. turbulent inverse cascades

Rotation

No rotation



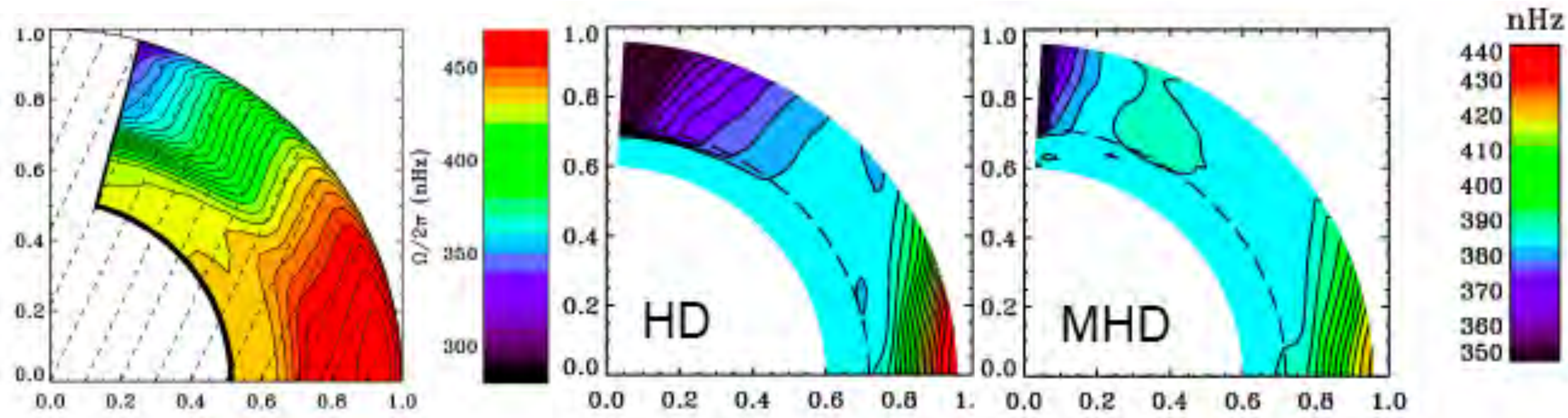
Rotation at solar rate



Vertical (radial) flow velocity, in Mollweide projection
[Guerrero et al. 2013, *Astrophys. J.*, **779**, 176]

Differential rotation

Helioseismology HD simulation MHD simulation



Angular velocity profiles, in meridional quadrant

Differential rotation in the Sun and solar-type stars is powered by turbulent Reynolds stresses, arising from rotationally-induced anisotropy in turbulent transport of momentum and heat

EULAG-MHD

EULAG: a robust, **general solver for geophysical flows**; developed by Piotr Smolarkiewicz and collaborators at MMM/NCAR

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

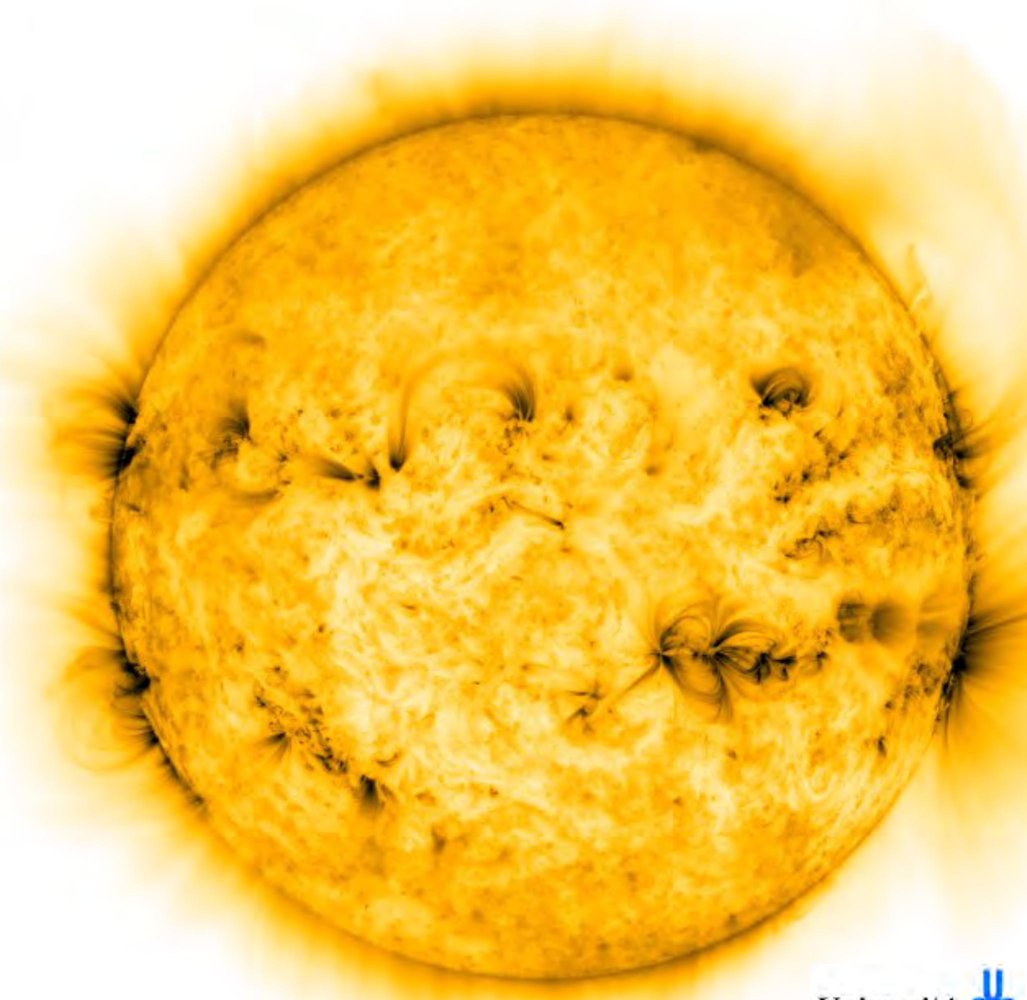
Core advection scheme: **MPDATA**, a **minimally dissipative** iterative upwind NFT scheme; equivalent to a dynamical, adaptive subgrid model.

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.

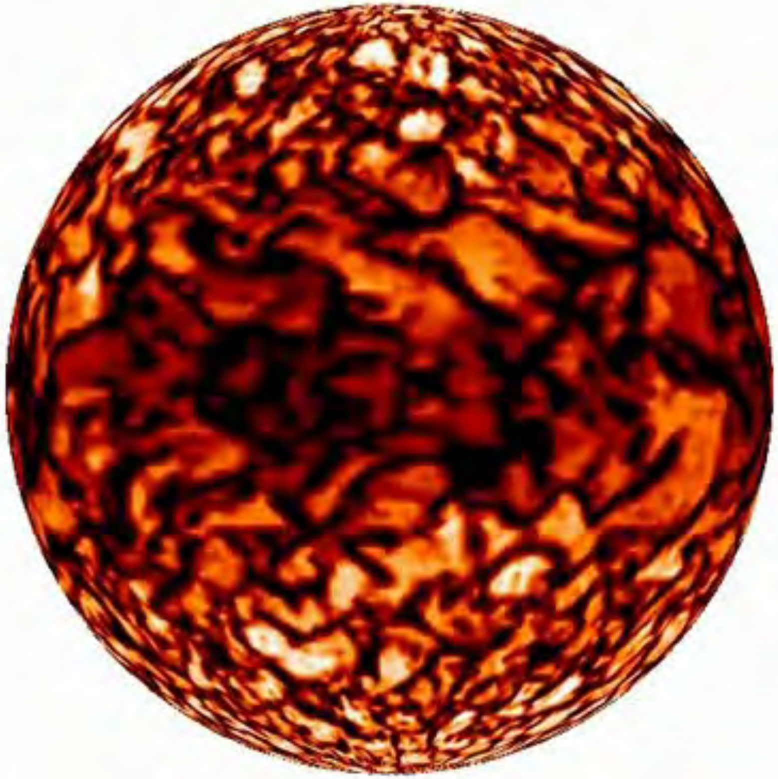
Model can operate as LES or **ILES**

The « millenium » simulation



Simulated magnetic cycles

[Ghizaru+ 2010, ApJL]



The self-organization of the magnetic field is produced at the base of the convective layer, with a field accumulation inside the underlying stable zone

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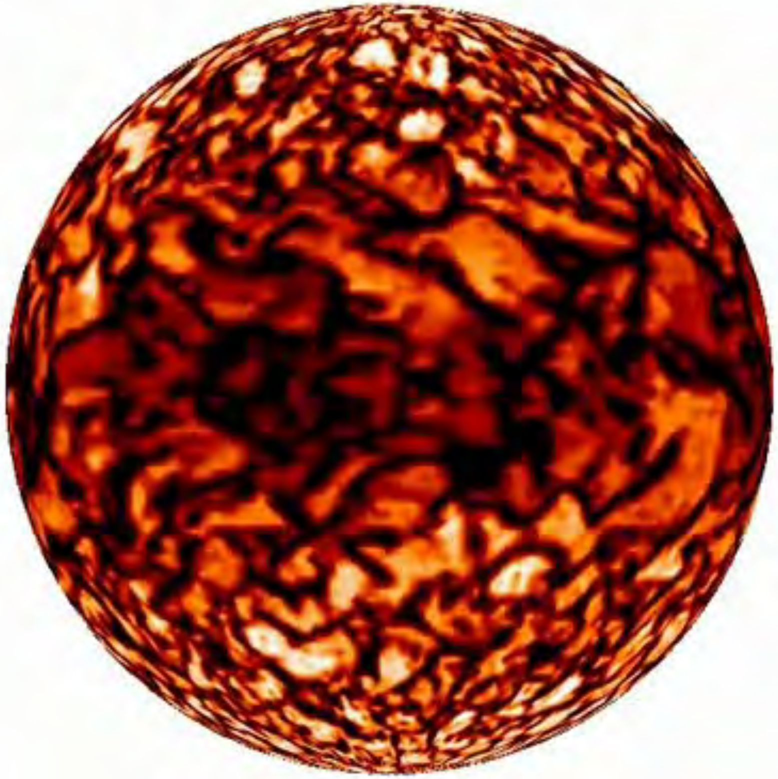

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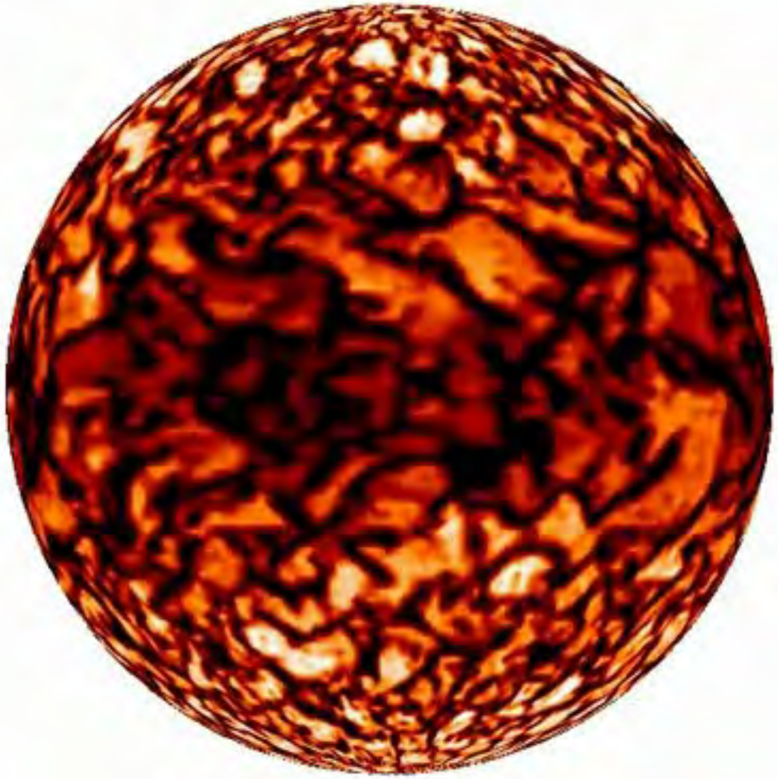

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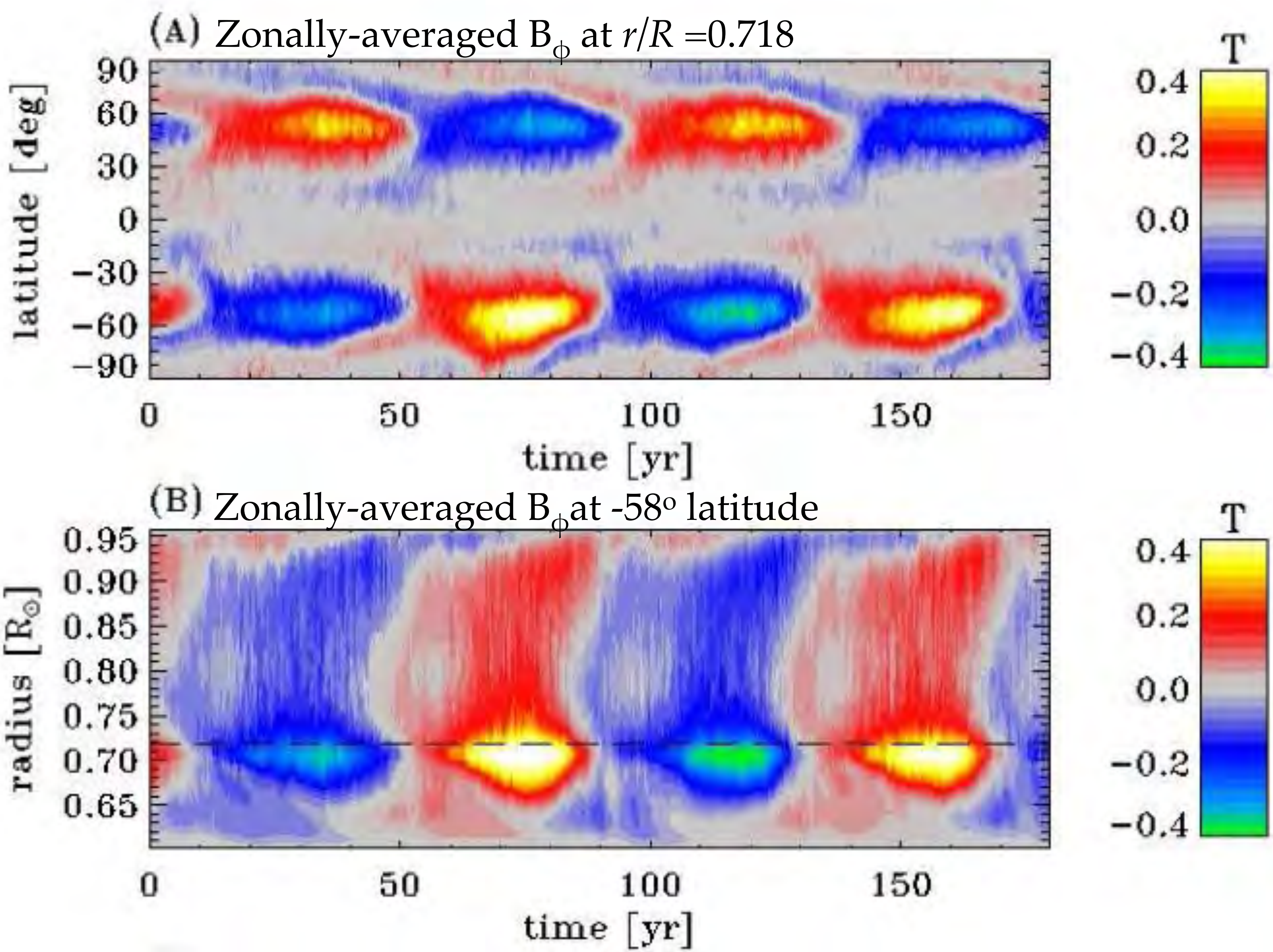
(A) Zonally-averaged B_ϕ at r/R =0.718
latitude [deg]
90
60
30
0
−30
−60
−90
0
50
100
150
time [yr]
T
0.4
0.2
0.0
−0.2
−0.4
(B) Zonally-averaged B_ϕ at -58° latitude
radius [$R_\odot$]
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0
50
100
150
time [yr]
T
0.4
0.2
0.0
−0.2
−0.4

Successes and problems

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

Cycle period **4 times too long**, strong fields concentrated at **mid-latitudes**

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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**

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

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Does the statistics of the modelled dynamo coincide with the solar statistics?

Well-defined

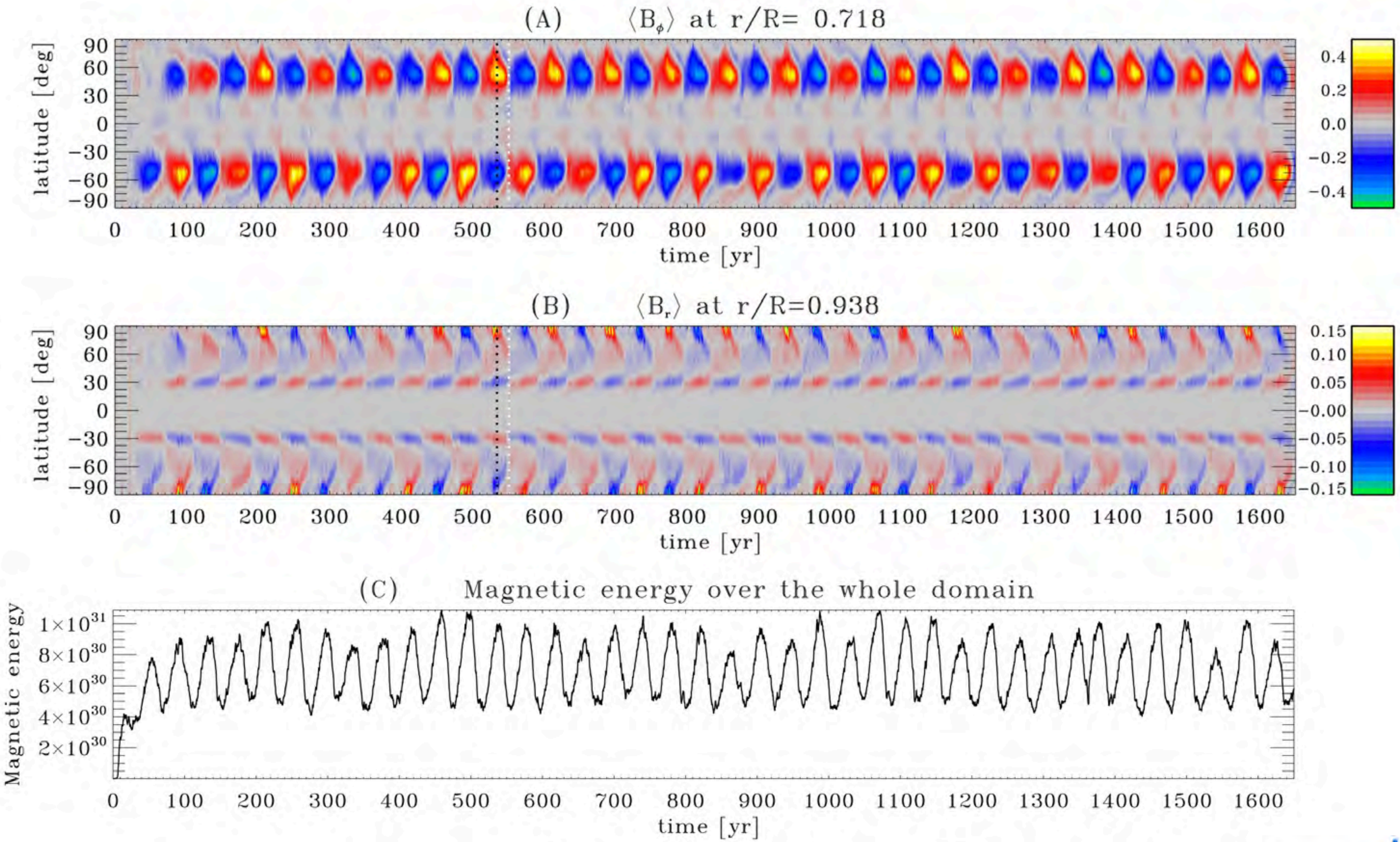
Reasonably solar-like internal **differential rotation**, and solar-like cyclic **torsional oscillations** (correct amplitude and phasing)

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

Cyclic modulation

The « millenium » simulation

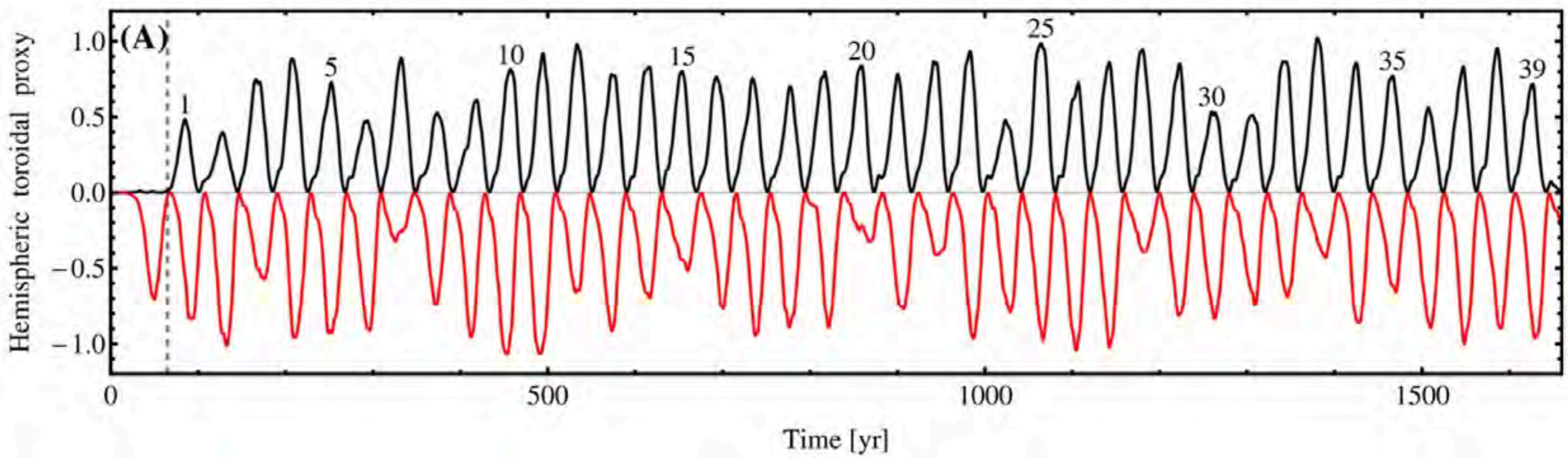
[Passos & Charbonneau 2014, A&A]

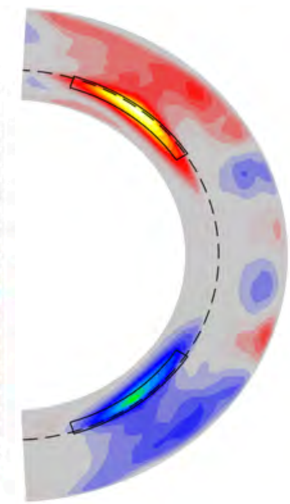


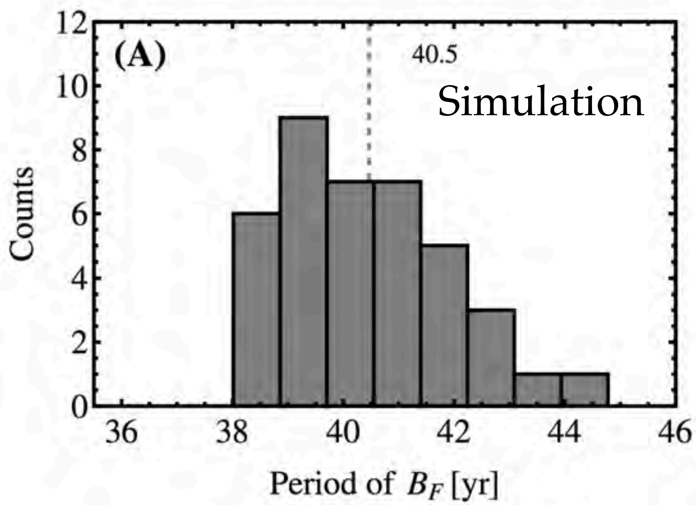
Simulated solar cycles: SSN

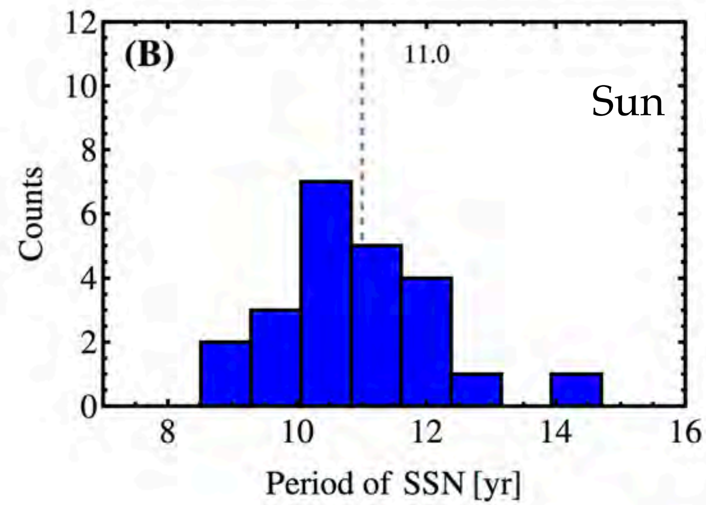
[Passos & Charbonneau 2014, A&A]

Define a SSN proxy, measure cycle characteristics (period, amplitude…) and compare to observational record







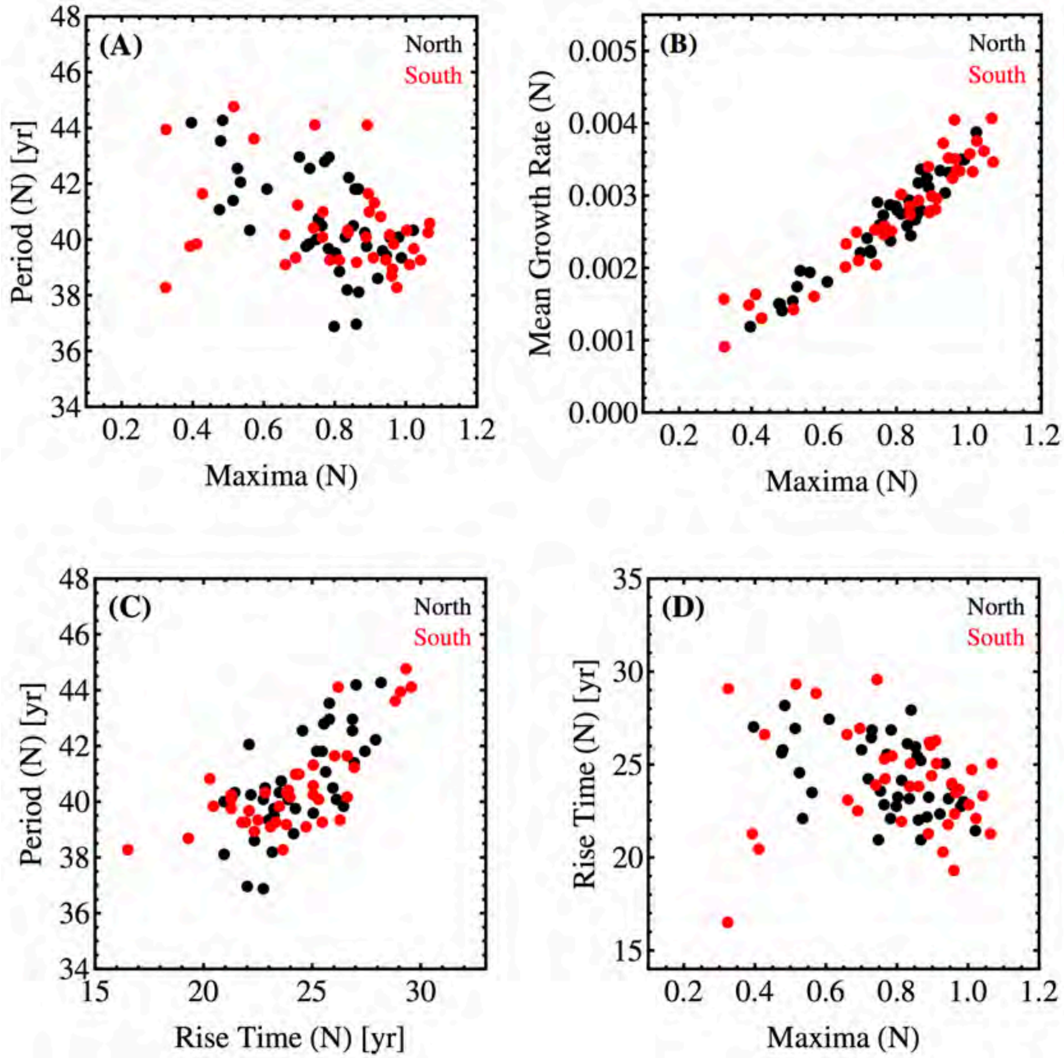


SIMULATED SOLAR CYCLES: CORRELATIONS

[PASSOS & CHARBONNEAU 2014, A&A]

-0.395 / -0.147
[-0.552 / -0.320]

0.957 / 0.947
[0.763 / 0.841]



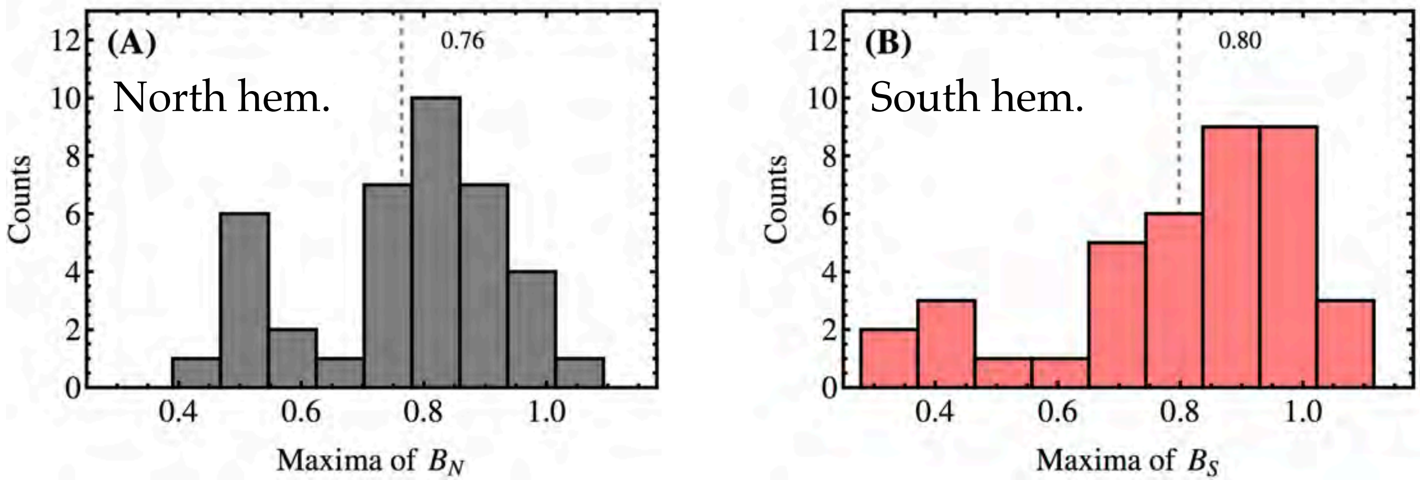
0.688 / 0.738
[0.322 / 0.451]

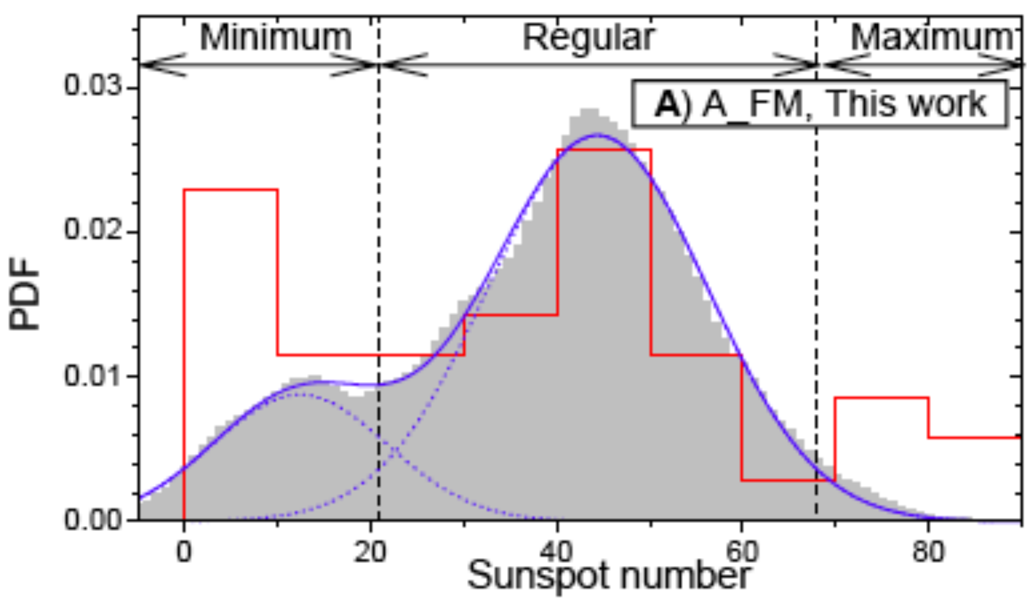
-0.465 / -0.143
[0.185 / -0.117]

Simulated solar cycles: Bimodality

[Passos & Charbonneau 2014, A&A]

Hemispheric cycle amplitude show a hint of bimodality



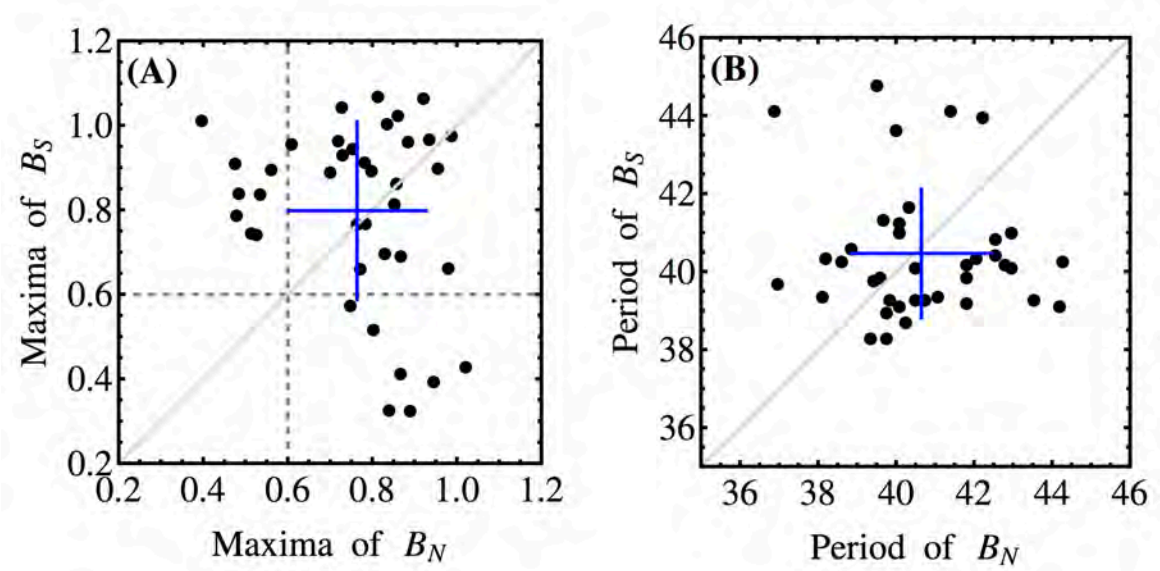


Usoskin et al. 2014, *A&A* **562**, L10;

From 3000yr 14C time series

Simulated solar cycles: Hemispheric lag

[Passos & Charbonneau 2014, A&A]



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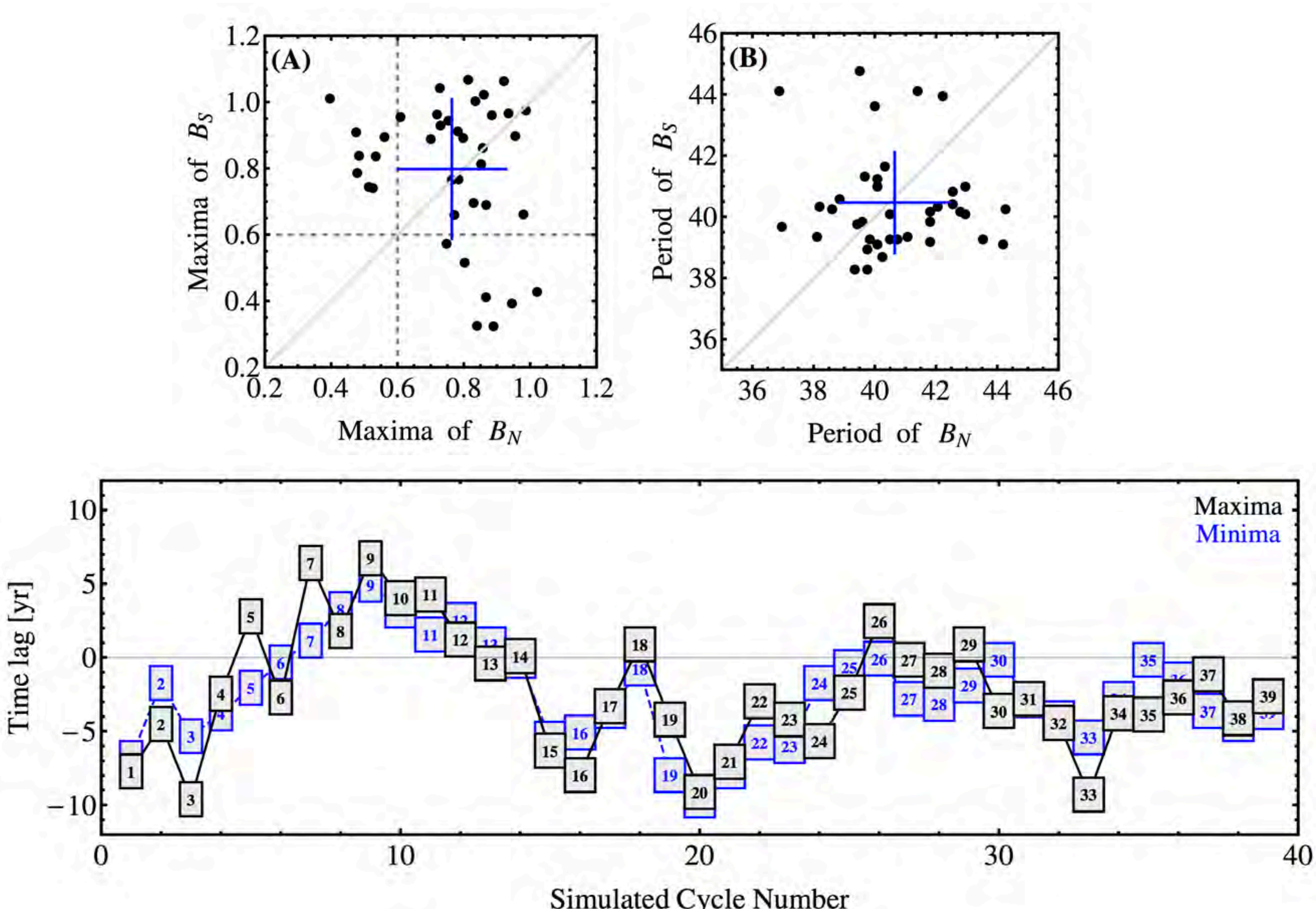
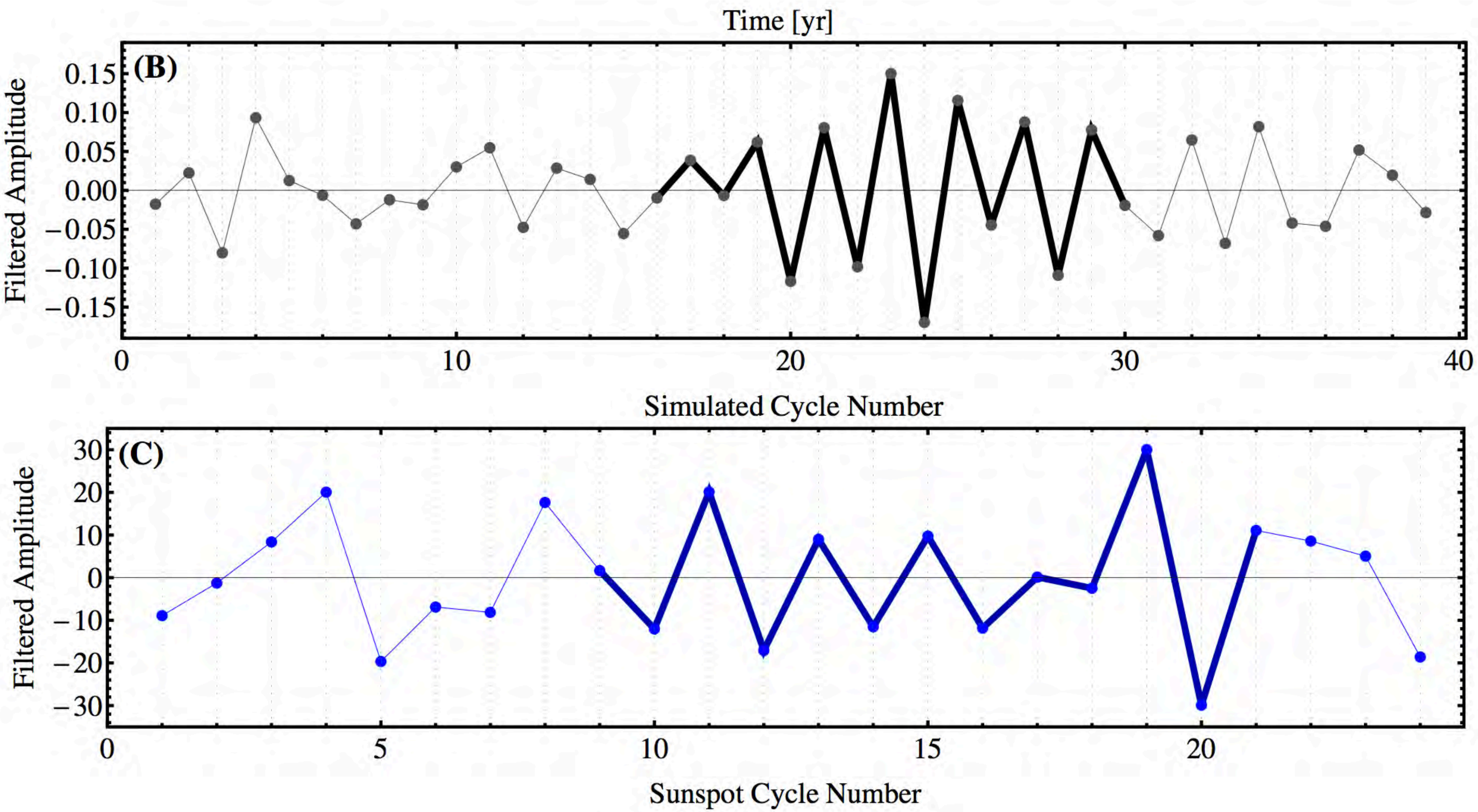
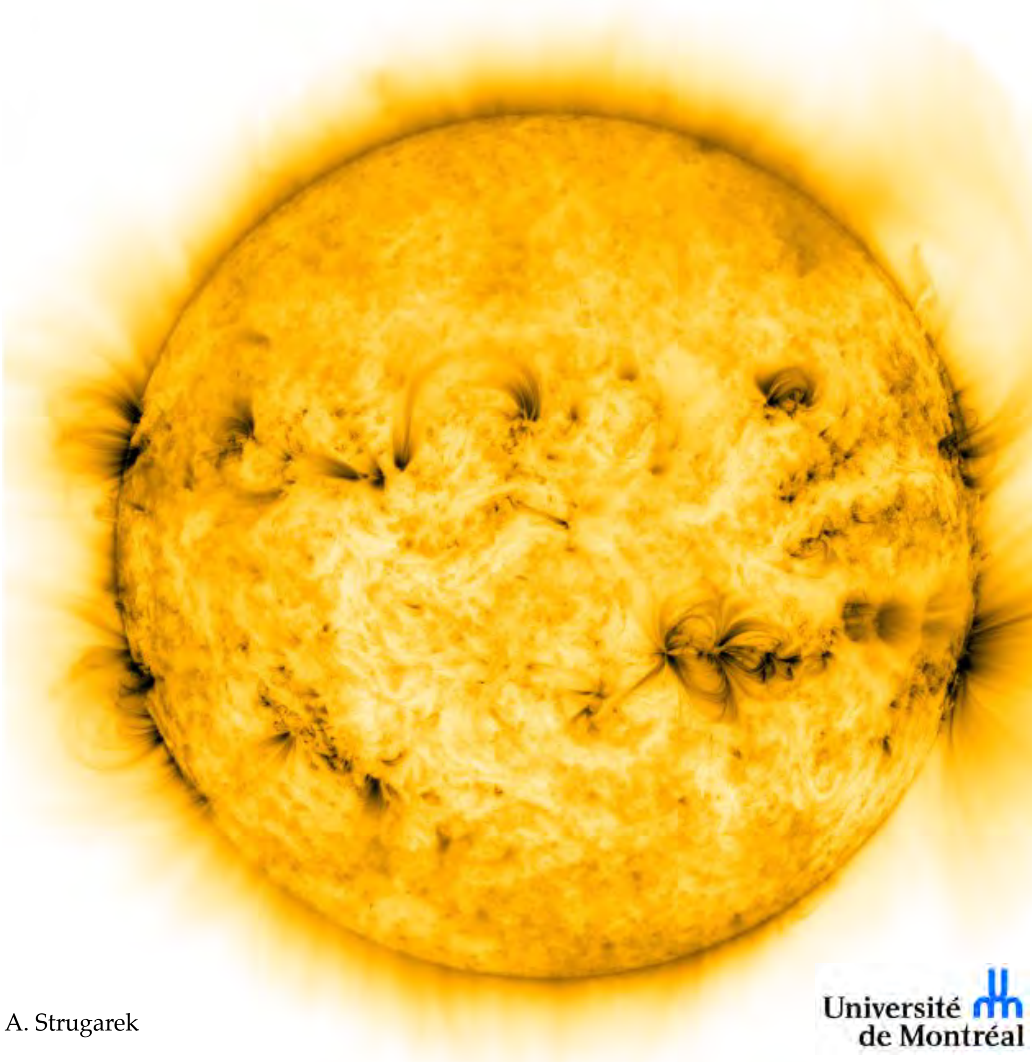


Simulated solar cycles: Gnevyshev-Ohl Pattern

[Passos & Charbonneau 2014, A&A]



Double-cycle dynamo



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Short quasi-periodic variability in the Sun

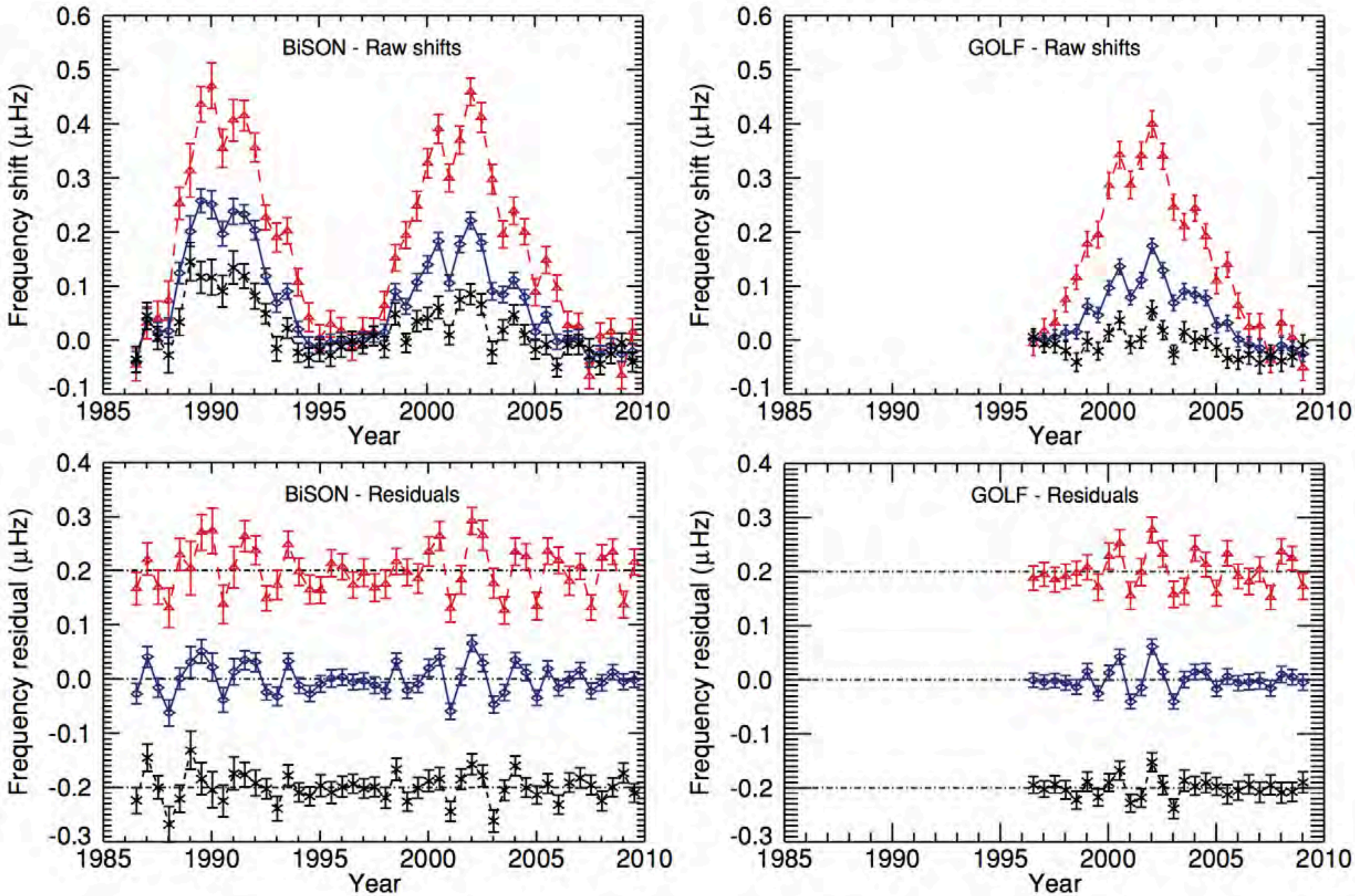
Evidence for **short-term (~0.5 – 2 yr) quasi-periodic variability** is found is a great many indicators of solar activity:

- Sunspot number and area
- Radio flux
- Total and spectral irradiance
- *p*-mode acoustic frequencies
- Interplanetary magnetic field
- Flaring rate
- Solar wind speed

The Astrophysical Journal Letters, 718:L19–L22, 2010 July 20 doi:10.1088/2041-8205/718/1/L19

A SEISMIC SIGNATURE OF A SECOND DYNAMO?

Stephen T. Fletcher[1], Anne-Marie Broomhall[2], David Salabert[3,6], Sarbani Basu[4], William J. Chaplin[2], Yvonne Elsworth[2], Rafael A. Garcia[5], and Roger New[1]



The Astrophysical Journal, 765:100 (8pp), 2013 March 10 doi:10.1088/0004-637X/765/2/100

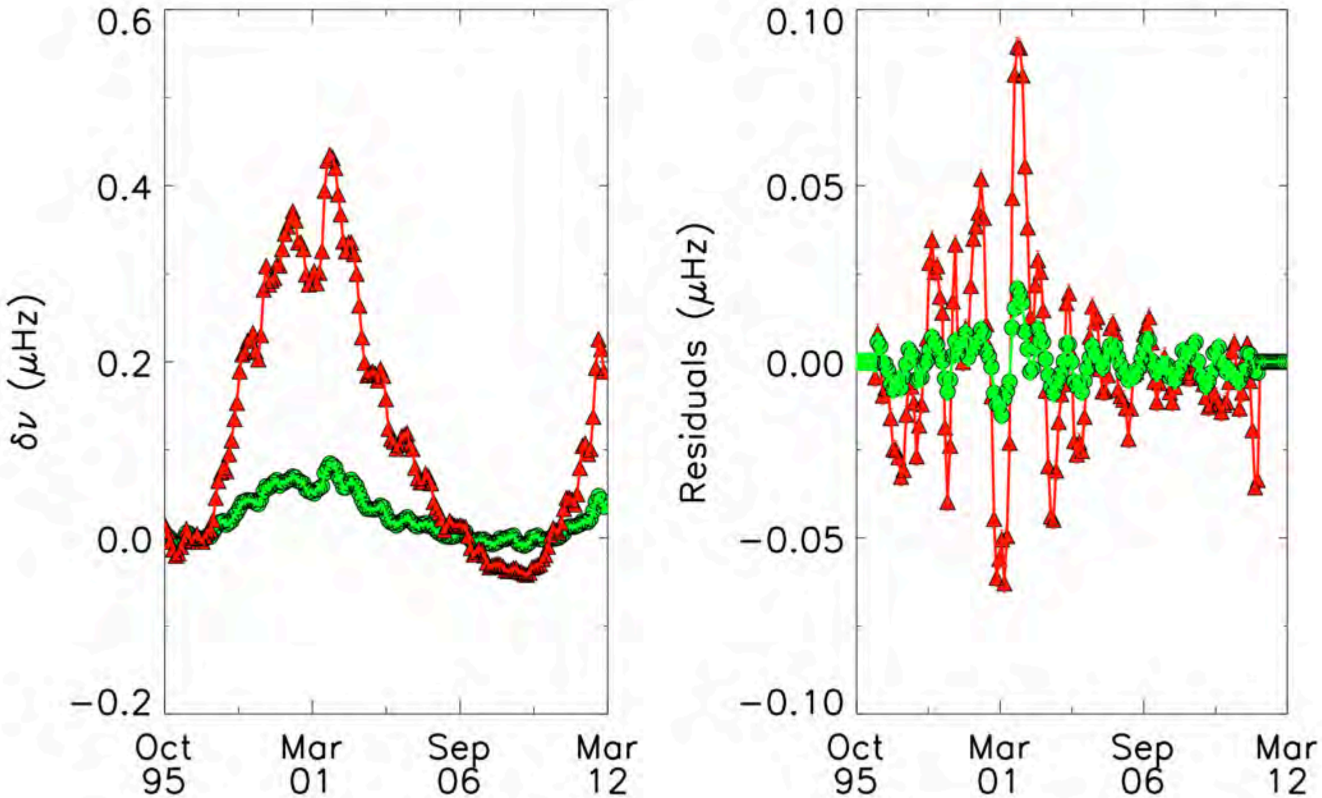
THE QUASI-BIENNIAL PERIODICITY AS A WINDOW ON THE SOLAR MAGNETIC DYNAMO CONFIGURATION

R. Simoniello[1,2], K. Jain[3], S. C. Tripathy[3], S. Turck-Chièze[1], C. Baldner[4], W. Finsterle[2], F. Hill[3], and M. Roth[5]
[1] Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, CEA, IRFU, SAp, Centre de Saclay, F-91191 Gif-sur-Yvette, France; rosaria.simoniello@cea.fr
[2] PMOD/WRC Physikalisch-Meteorologisches Observatorium Davos-World Radiation Center, 7260 Davos Dorf, Switzerland
[3] National Solar Observatory, Tucson, AZ 85719, USA
[4] W. W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305-4085, USA
[5] Kiepenheuer Institute for Solar Physics, Freiburg, Germany
Received 2012 October 24; accepted 2013 January 18; published 2013 February 21

GONG

1.6-2.5 nHz

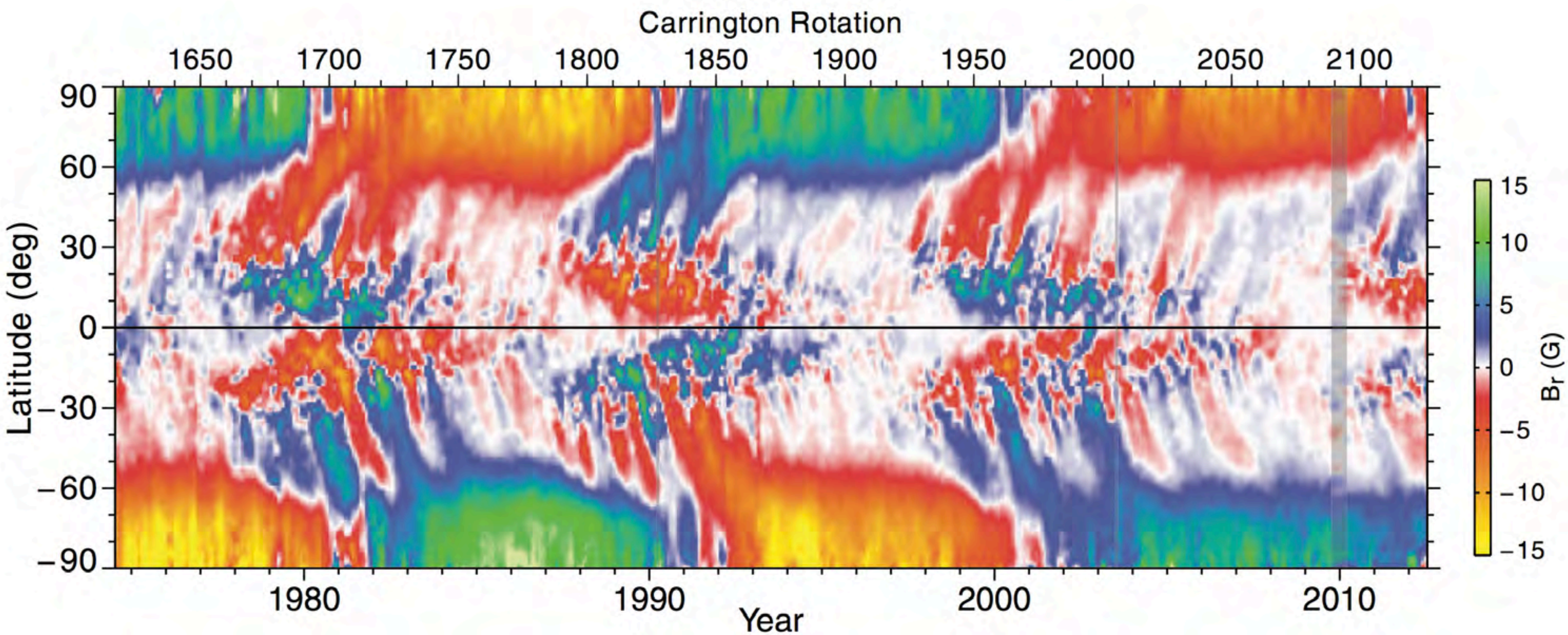
2.5-3.5 nHz

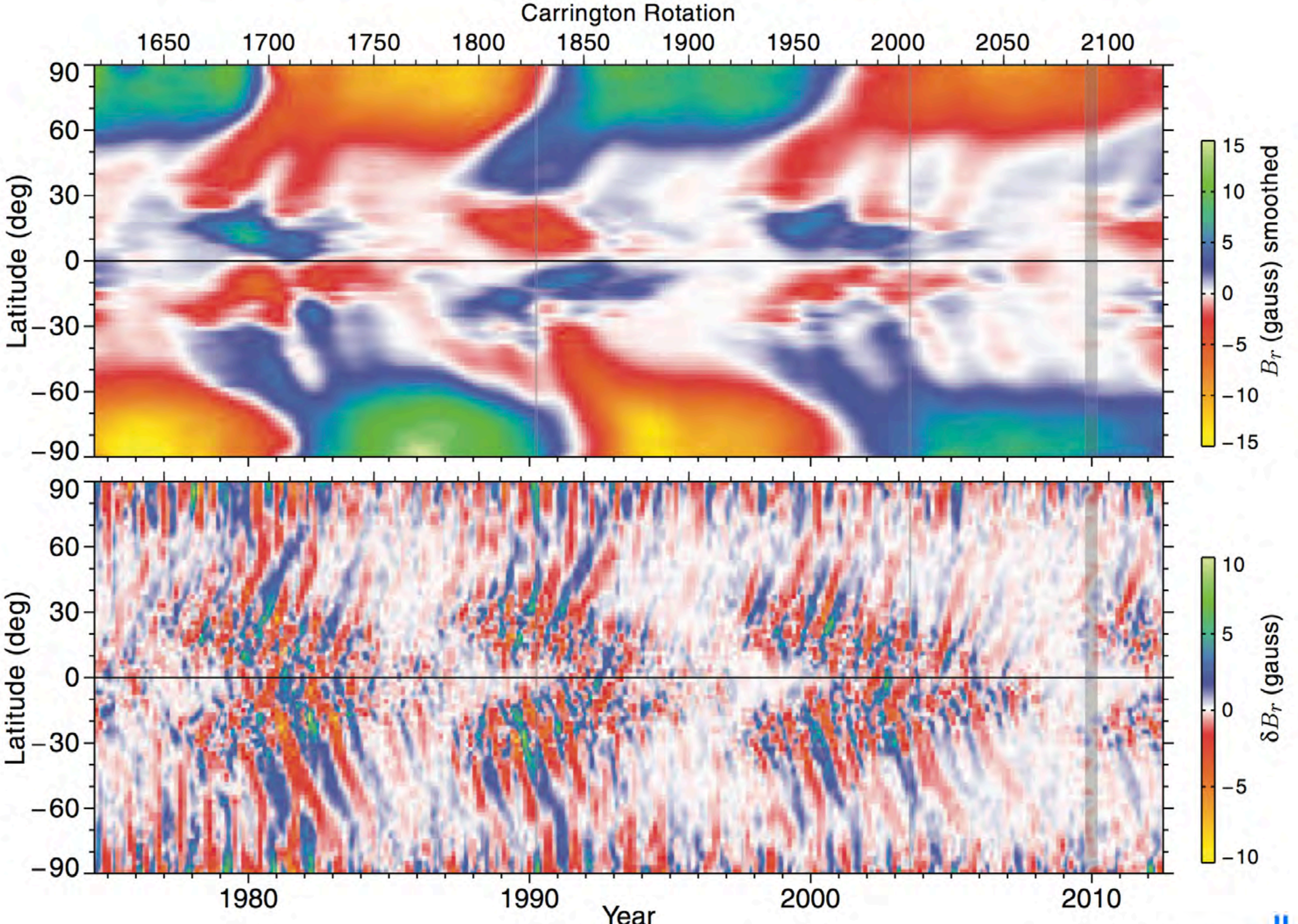


THE ASTROPHYSICAL JOURNAL, 768:189 (12pp), 2013 May 10 doi:10.1088/0004-637X/768/2/189

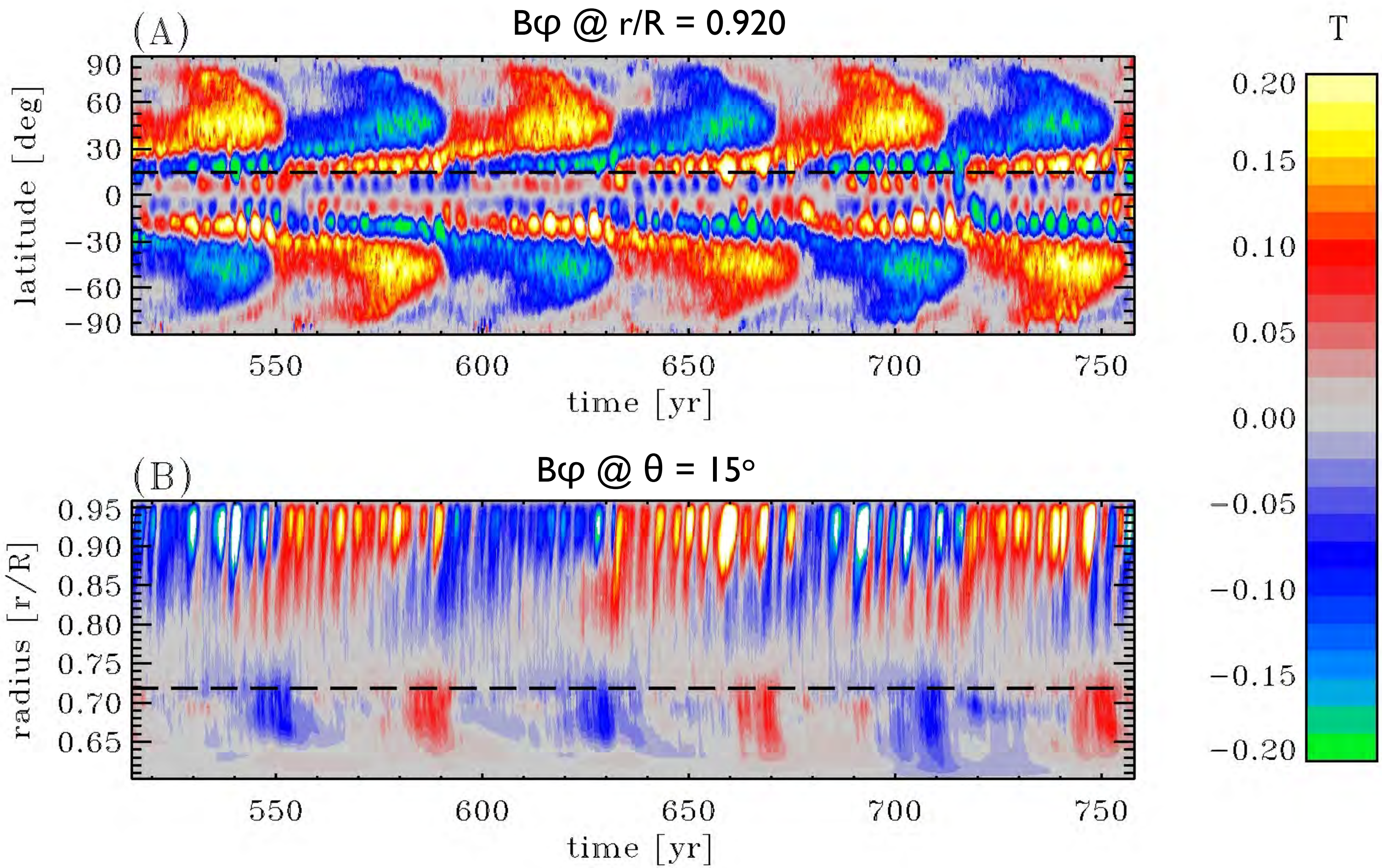
THE GLOBAL SOLAR MAGNETIC FIELD—IDENTIFICATION OF TRAVELING, LONG-LIVED RIPPLES

R. K. ULRICH AND THAM TRAN
Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA; ulrich@astro.ucla.edu
Received 2012 November 24; accepted 2013 April 3; published 2013 April 26




Carrington Rotation
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
Latitude (deg)
90
60
30
0
−30
−60
−90
B_r (gauss) smoothed
15
10
5
0
−5
−10
−15
δB_r (gauss)
1980
1990
2000
2010
Year

Short quasi-periodic variability in simulations
[Beaudoin+ 2014, in prep]



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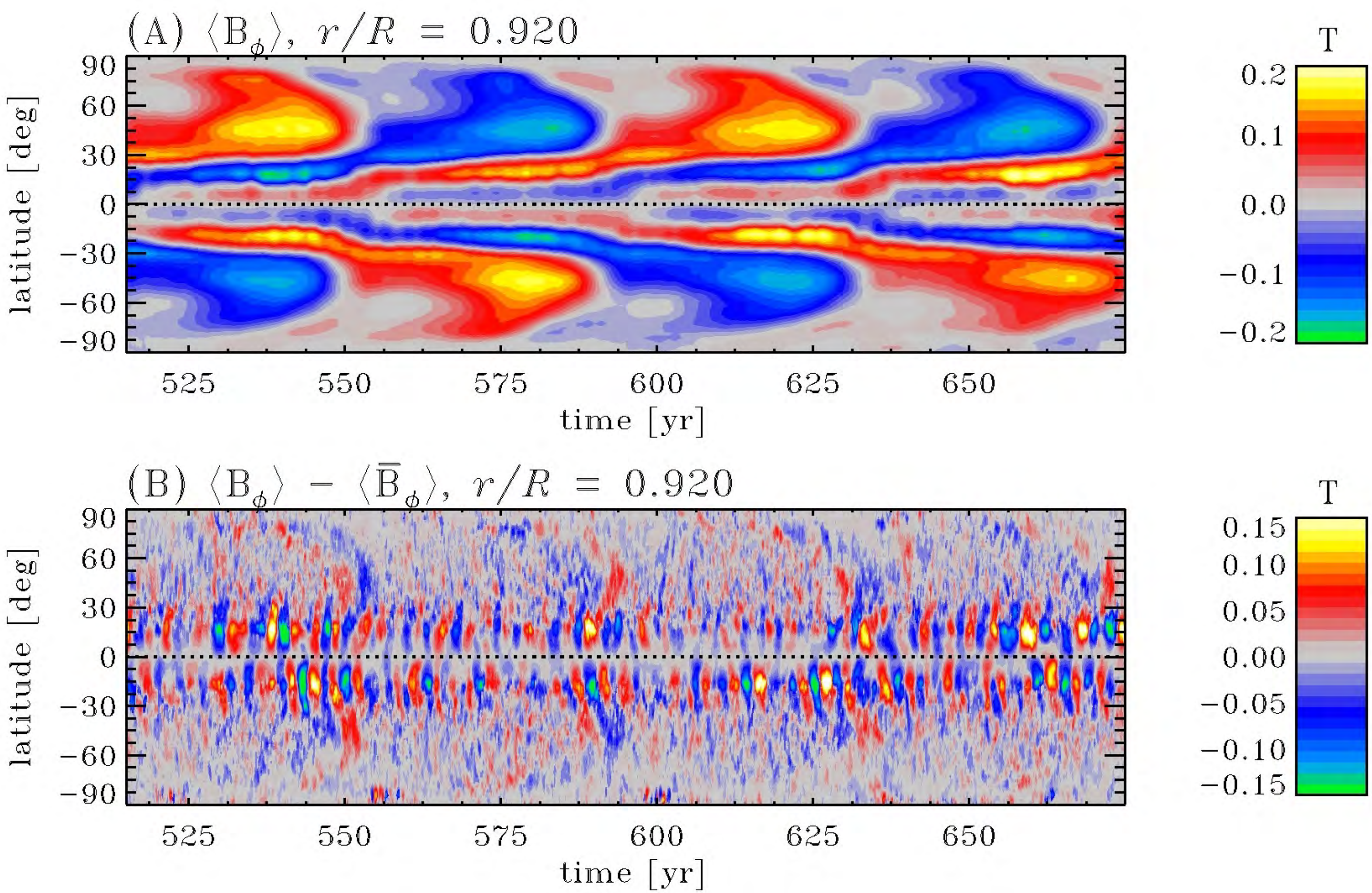
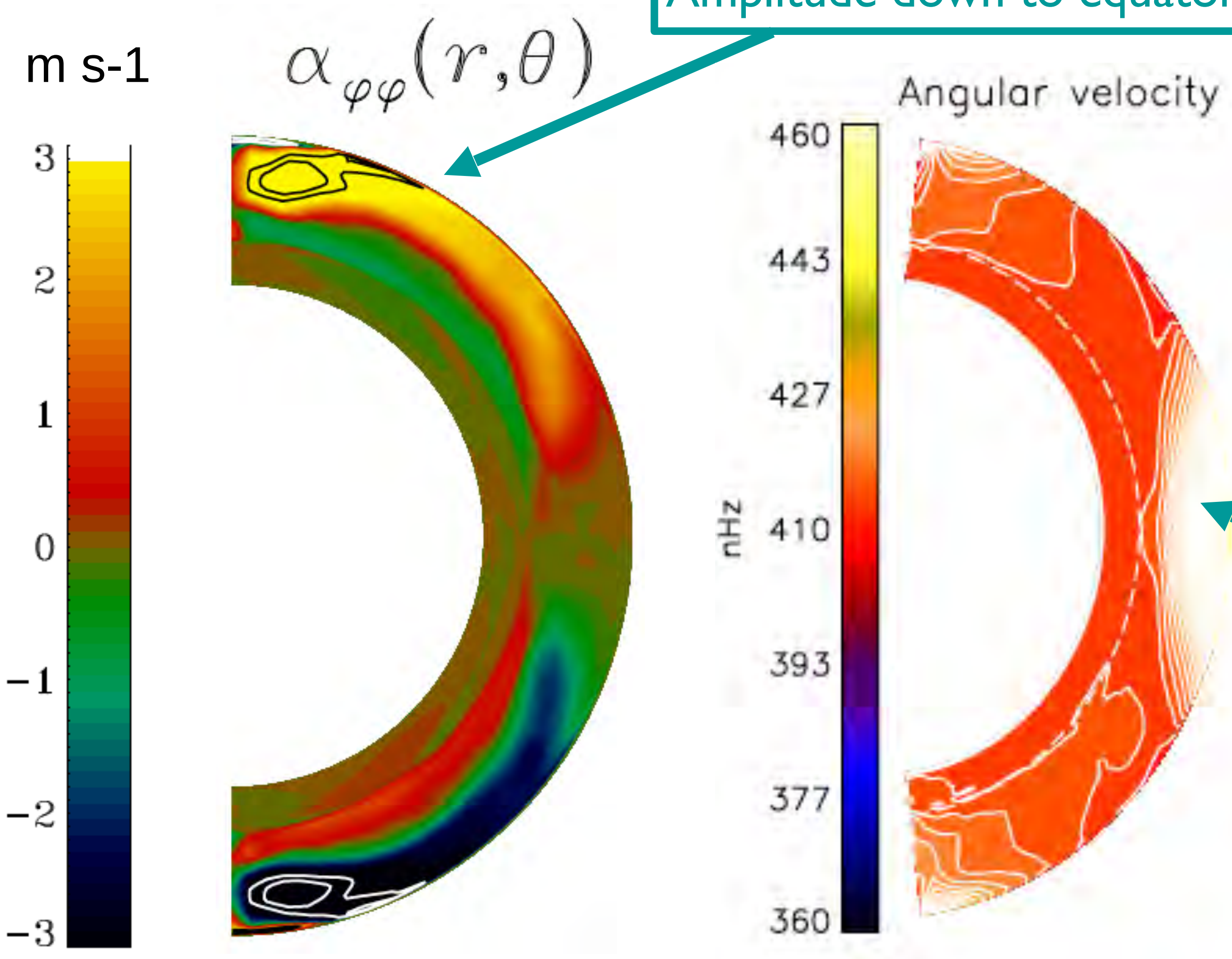


Double cycle origin

Peaks at high latitude, but significant Amplitude down to equatorial regions



Peaks at low latitudes within convection zone; tachocline mostly at high latitudes.

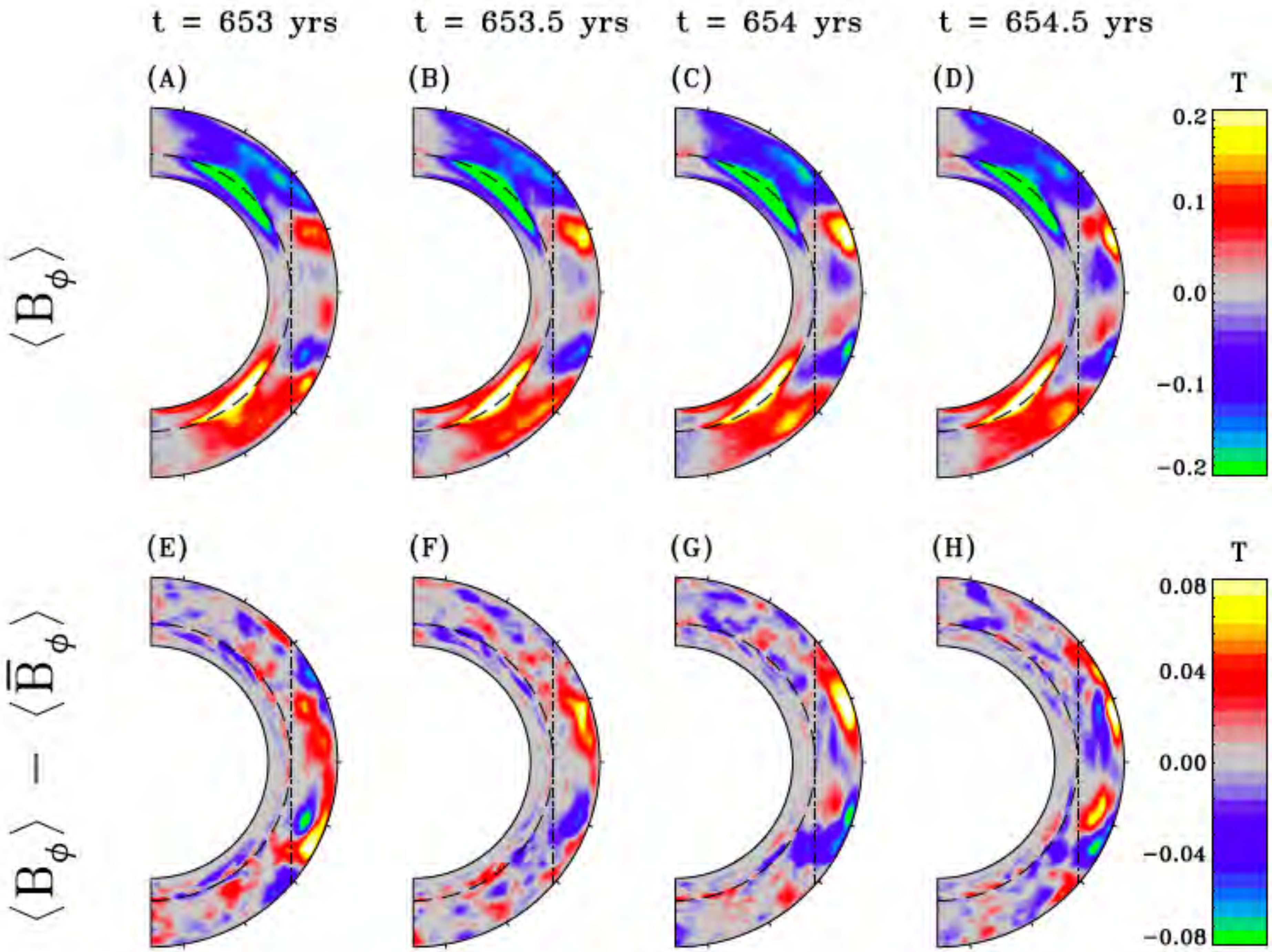
Double cycle origin

Scenario:

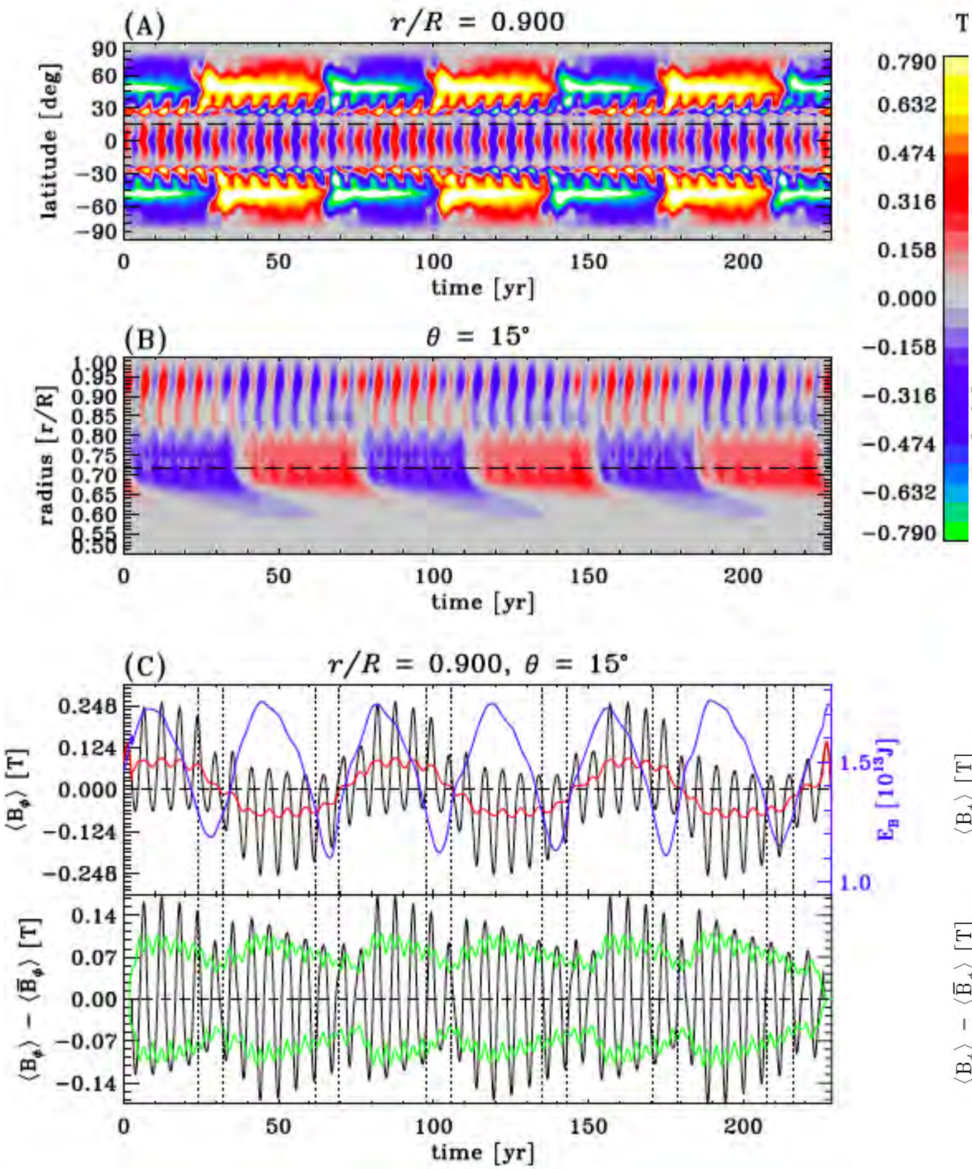
« Long » dynamo mode powered by turbulent emf
($\alpha^2\Omega$ dynamo mode) [Racine+ 2010, ApJ]

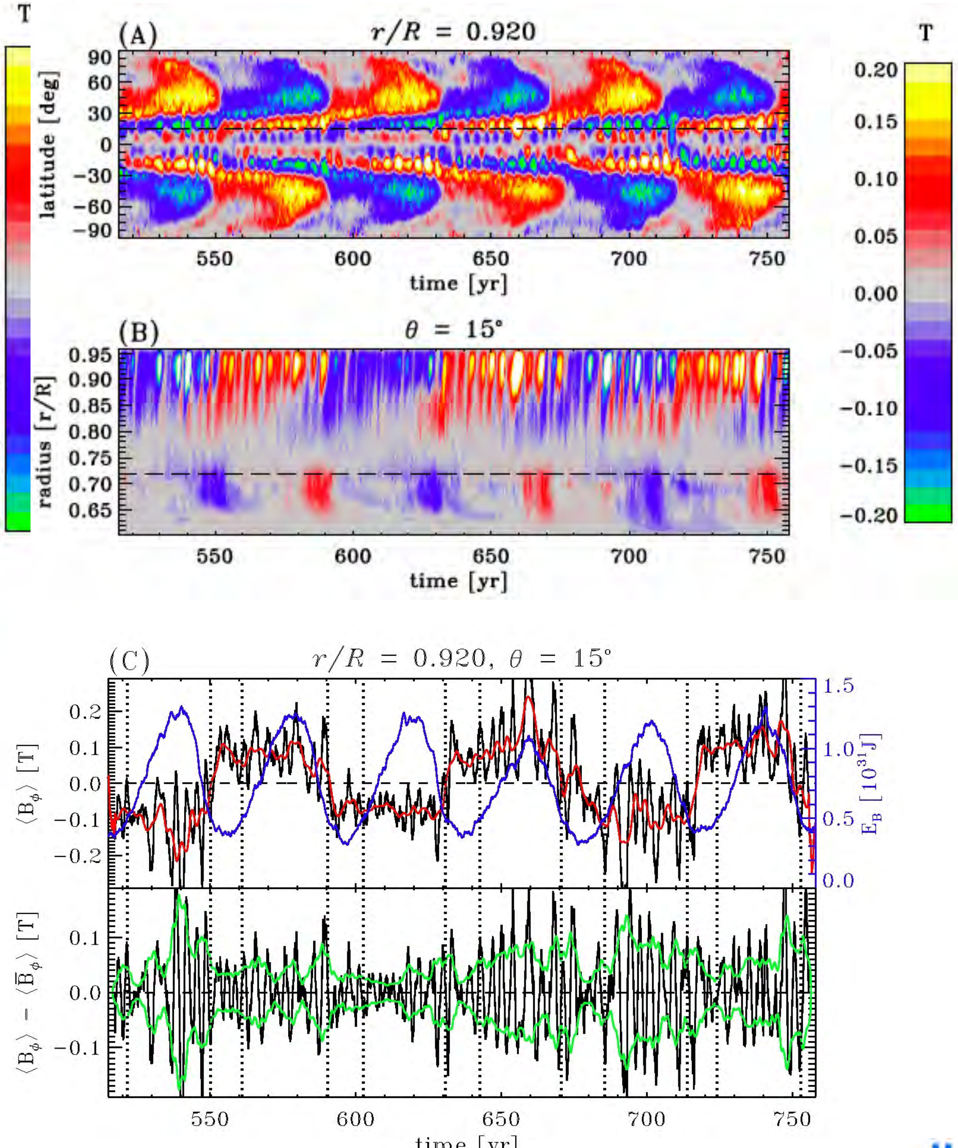
« Short » dynamo mode powered by rotational shear
in equatorial portion of convection zone ($\alpha\Omega$ dynamo mode)

A Parker-Yoshimura sign rule should apply:
dynamo wave propagates away from equatorial plane
along iso-contours of Ω

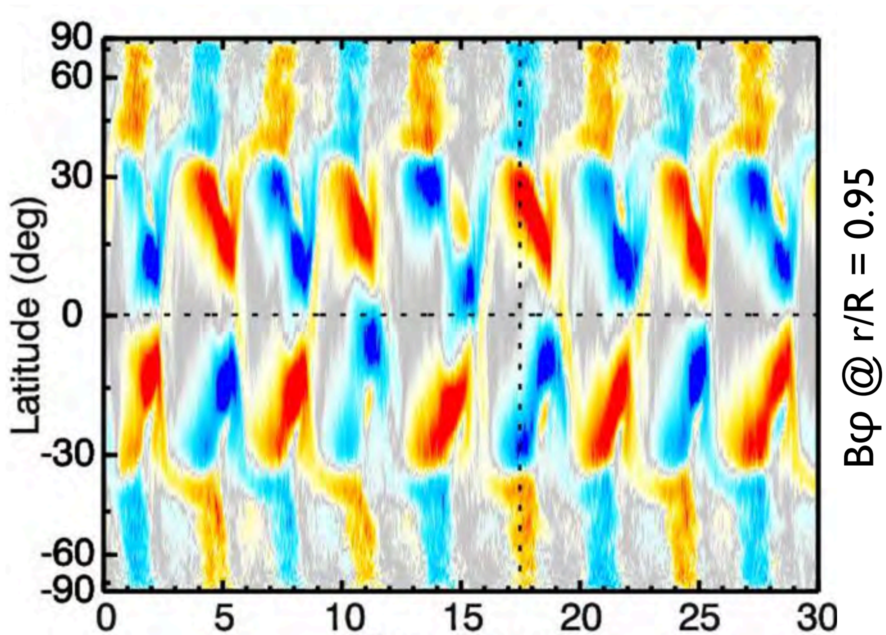

t = 653 yrs
t = 653.5 yrs
t = 654 yrs
t = 654.5 yrs
(A)
(B)
(C)
(D)
(E)
(F)
(G)
(H)
$\langle B_\phi \rangle$
$\langle B_\phi \rangle - \langle \bar{B}_\phi \rangle$
T
0.2
0.1
0.0
-0.1
-0.2
T
0.08
0.04
0.00
-0.04
-0.08

Validation against mean-field model





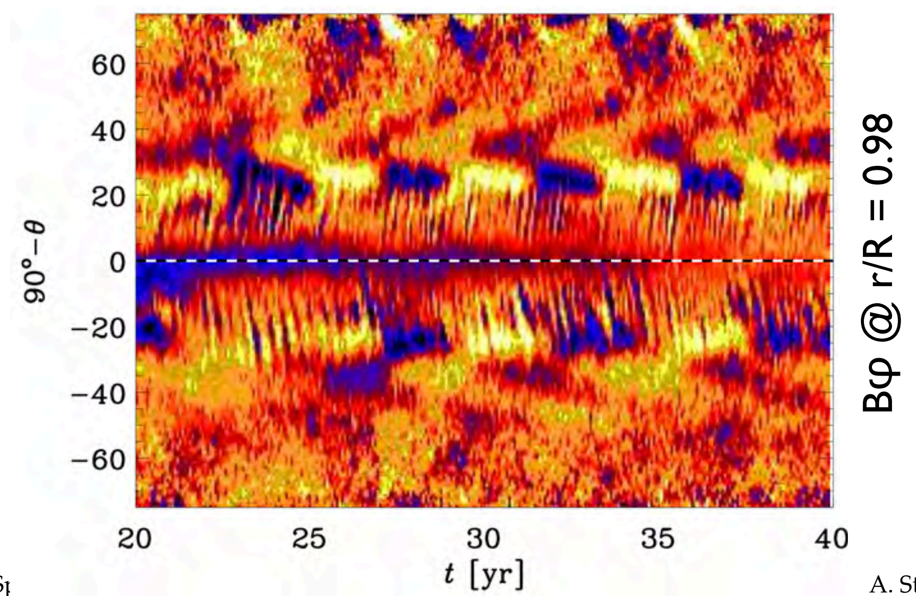
Related « short » cycles in other simulations?



[Augustson+ 2014] ASH Code

Cycle period ~ 3.1 yr

(+ grand minima)



[Warnecke+ 2014] Pencil Code

Cycle period ~ 2.5 yr

Interpretation as a $\alpha\Omega$ dynamo mode

Conclusions and Open questions

EULAG-MHD simulations unveils double-cycle dynamos running in solar-like interior

The two cycles appear to originate from different locations in the interior

At least one of the two cycles seems akin cycles found with other simulation codes

Can we identify physical parameter(s) that set the cycle(s) period ?

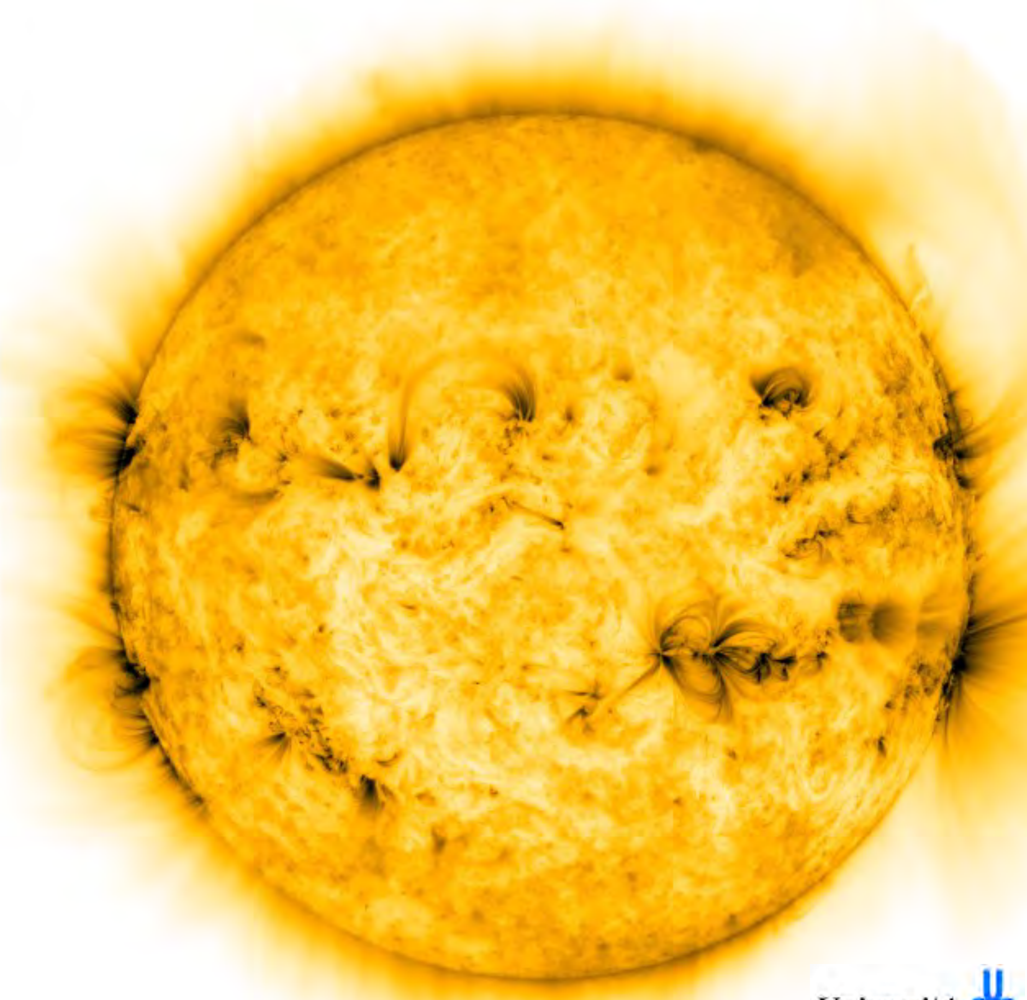
What is the exact role of the tachocline for the longer cycle?

Can we get the longer cycle, seated in the upper tachocline, to produce flux emergence throughout the convection zone?

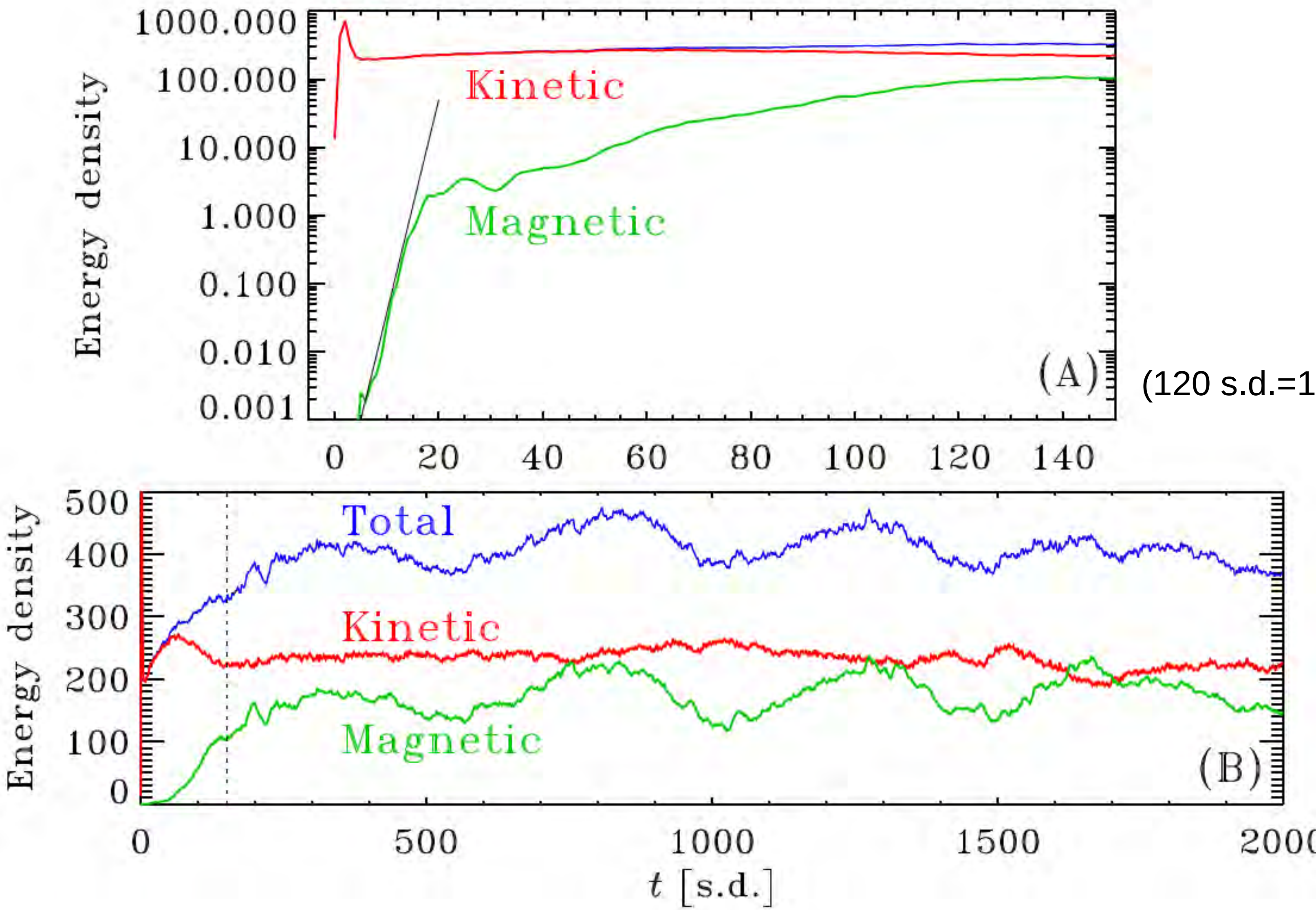
How to obtain regular cycles in high-Re simulations?

☛ Direct comparison runs between ASH and EULAG-MHD ongoing…

Supplemental material



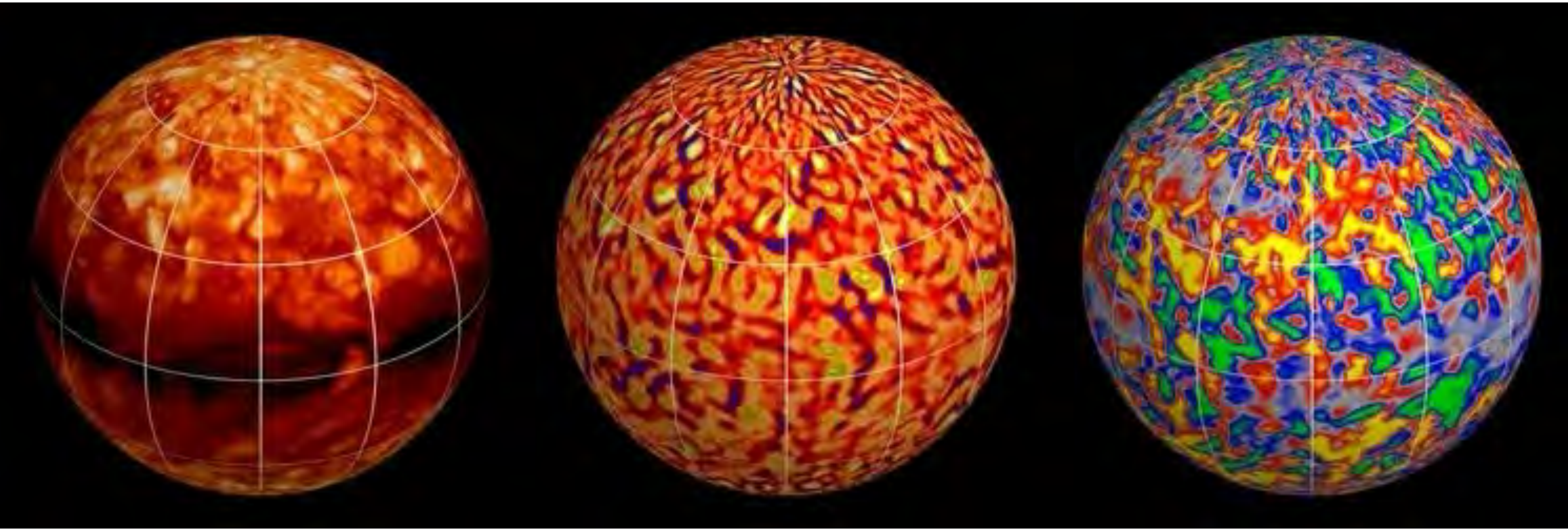
KINETIC AND MAGNETIC ENERGIES



(120 s.d.=10 yr)

Simulation of the solar dynamo

[Ghizaru et al. 2010, ApJL]



http://www.astro.umontreal.ca/~paulchar/grps

Electromagnetic induction by internal flows is the engine powering the solar magnetic cycle. The challenge is to produce a magnetic field well-structured on spatial and temporal scales much larger/longer than those associated with convection itself. This is the **magnetic self-organisation problem**.

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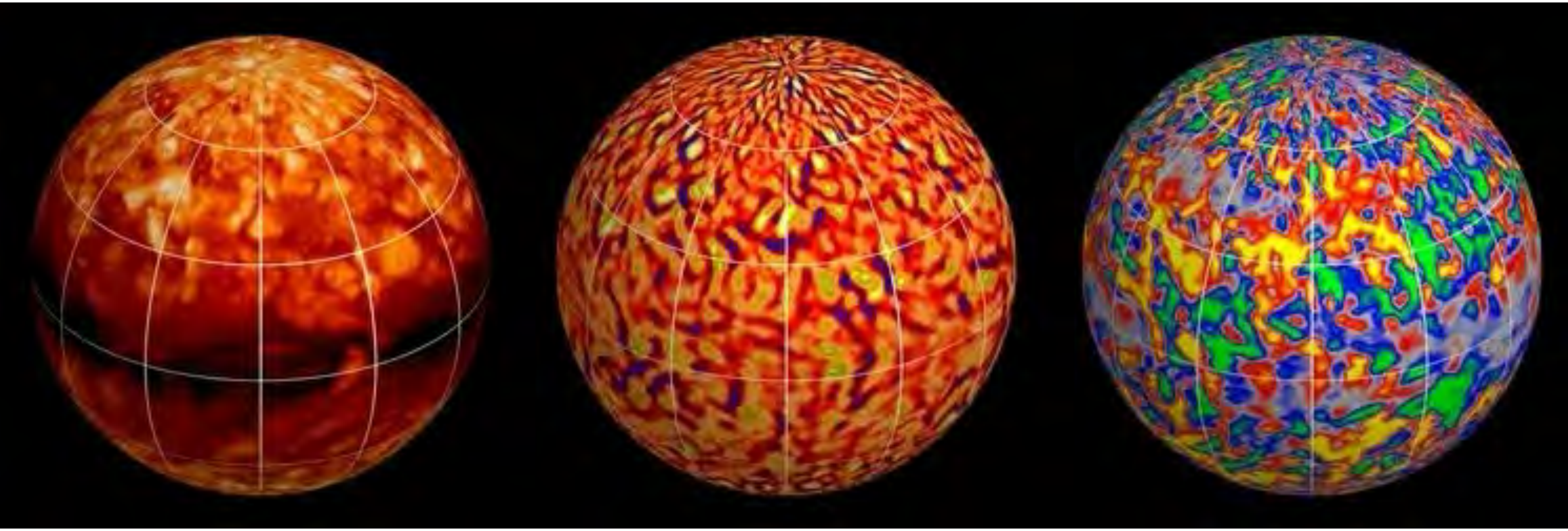

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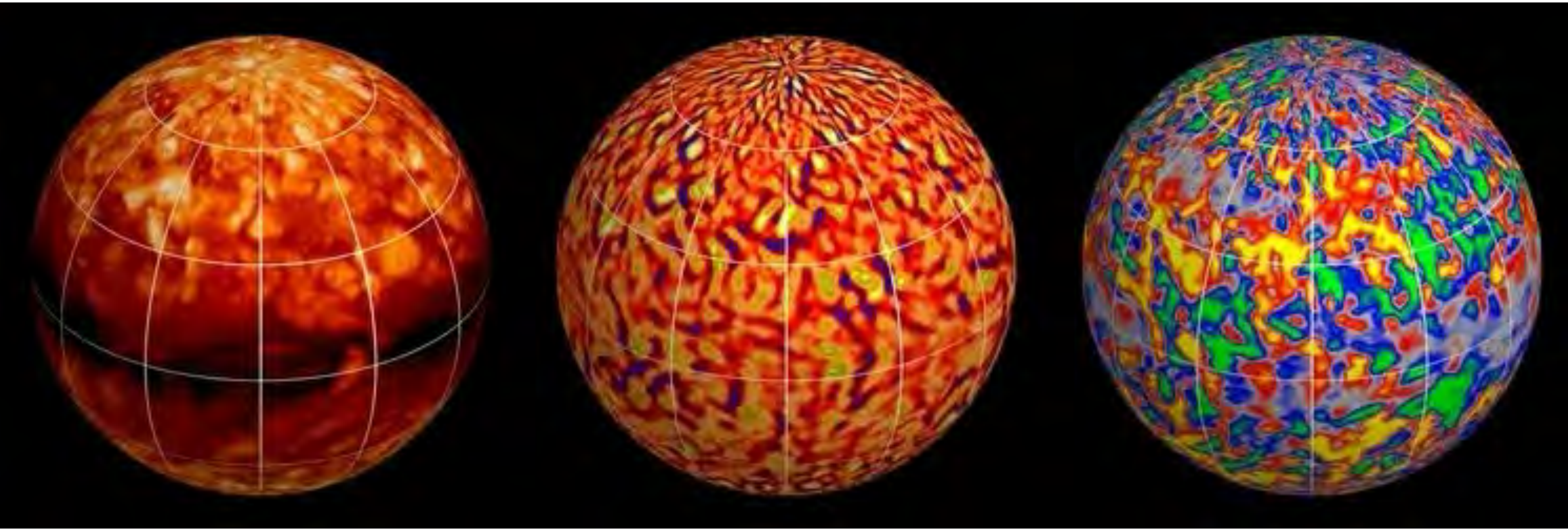
Simulation of the solar dynamo

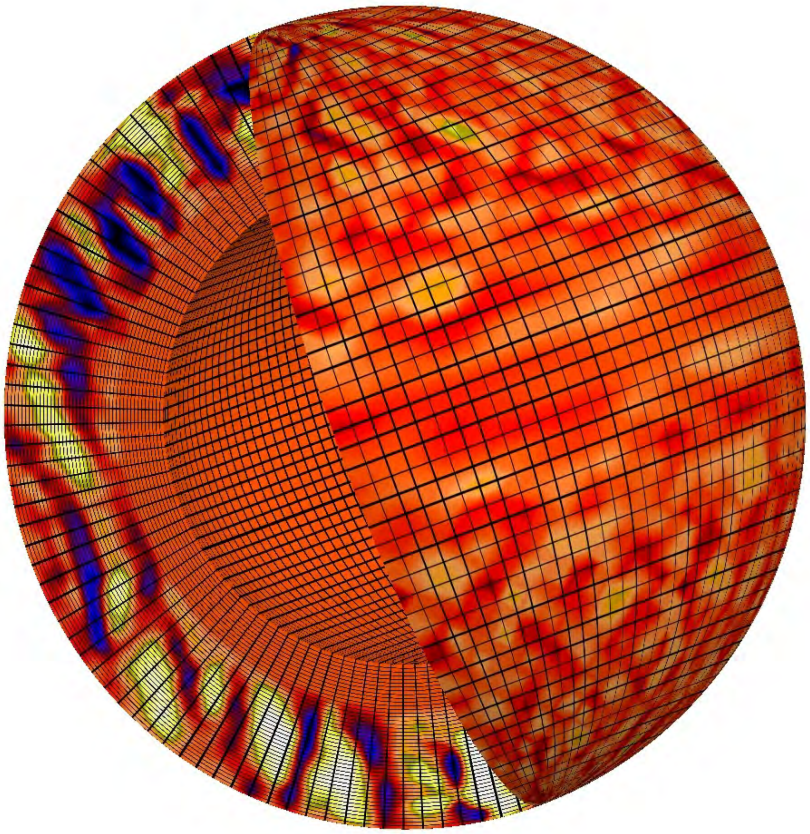
[Ghizaru et al. 2010, ApJL]



http://www.astro.umontreal.ca/~paulchar/grps

Electromagnetic induction by internal flows is the engine powering the solar magnetic cycle. The challenge is to produce a magnetic field well-structured on spatial and temporal scales much larger/longer than those associated with convection itself. This is the **magnetic self-organisation problem**.

Simulation framework



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.

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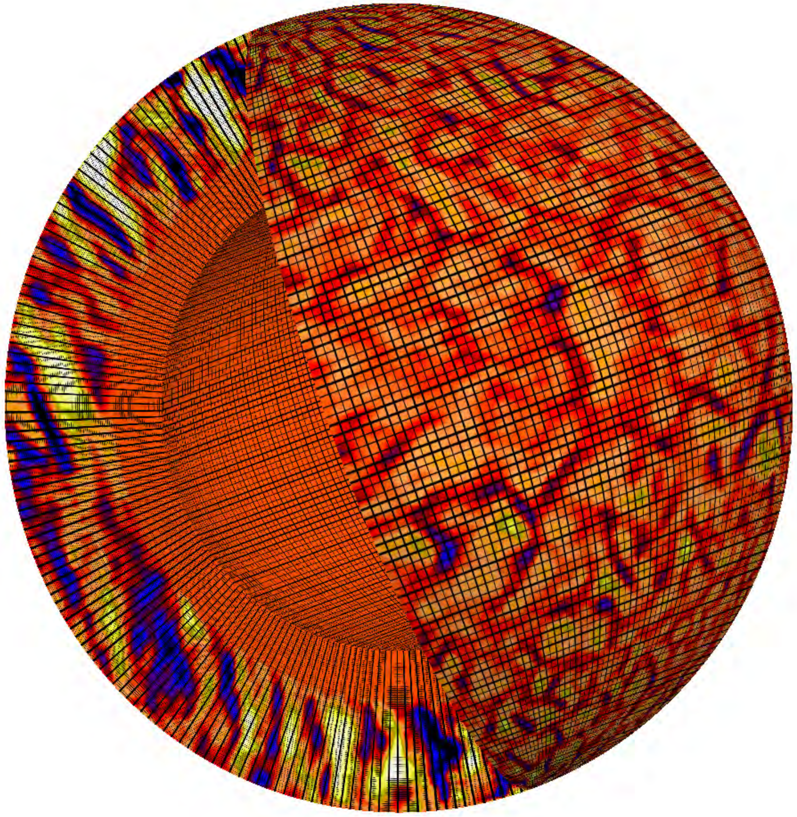

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$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \ ,$$

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\frac{1}{\rho}\nabla p + \mathbf{g} + \frac{1}{\mu_0 \rho}(\nabla \times \mathbf{B}) \times \mathbf{B} + \frac{1}{\rho}\nabla \cdot \boldsymbol{\tau} \ ,$$

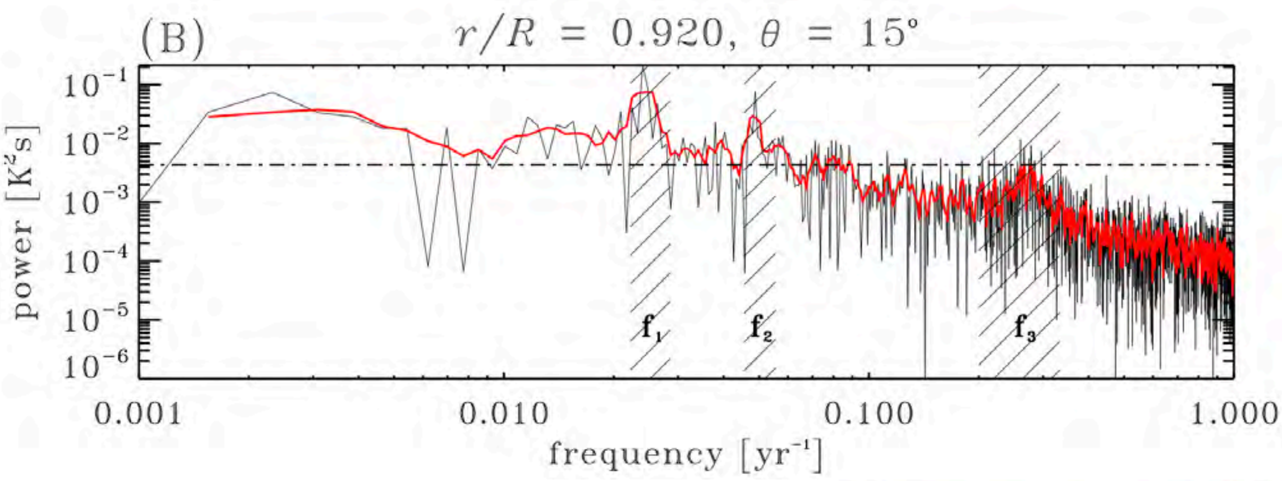
$$\frac{\mathrm{D}e}{\mathrm{D}t} + (\gamma - 1)e\nabla \cdot \mathbf{u} = \frac{1}{\rho}\left[\nabla \cdot \Big((\chi + \chi_r)\nabla T\Big) + \phi_\nu + \phi_B\right] \ ,$$

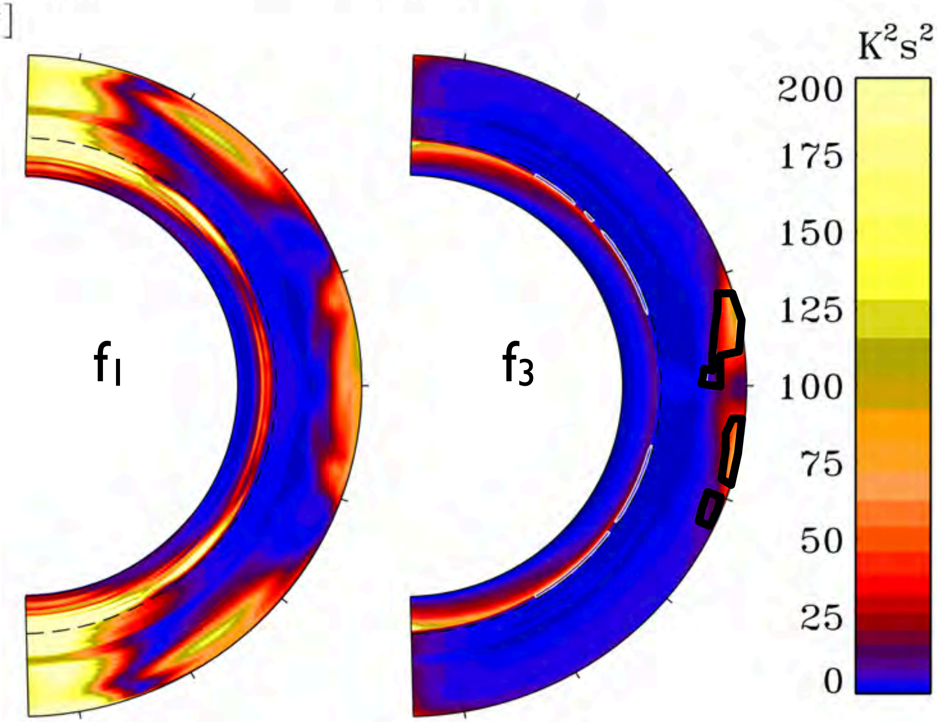
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B} - \eta \nabla \times \mathbf{B}) \ .$$

Correlations for each hemisphere

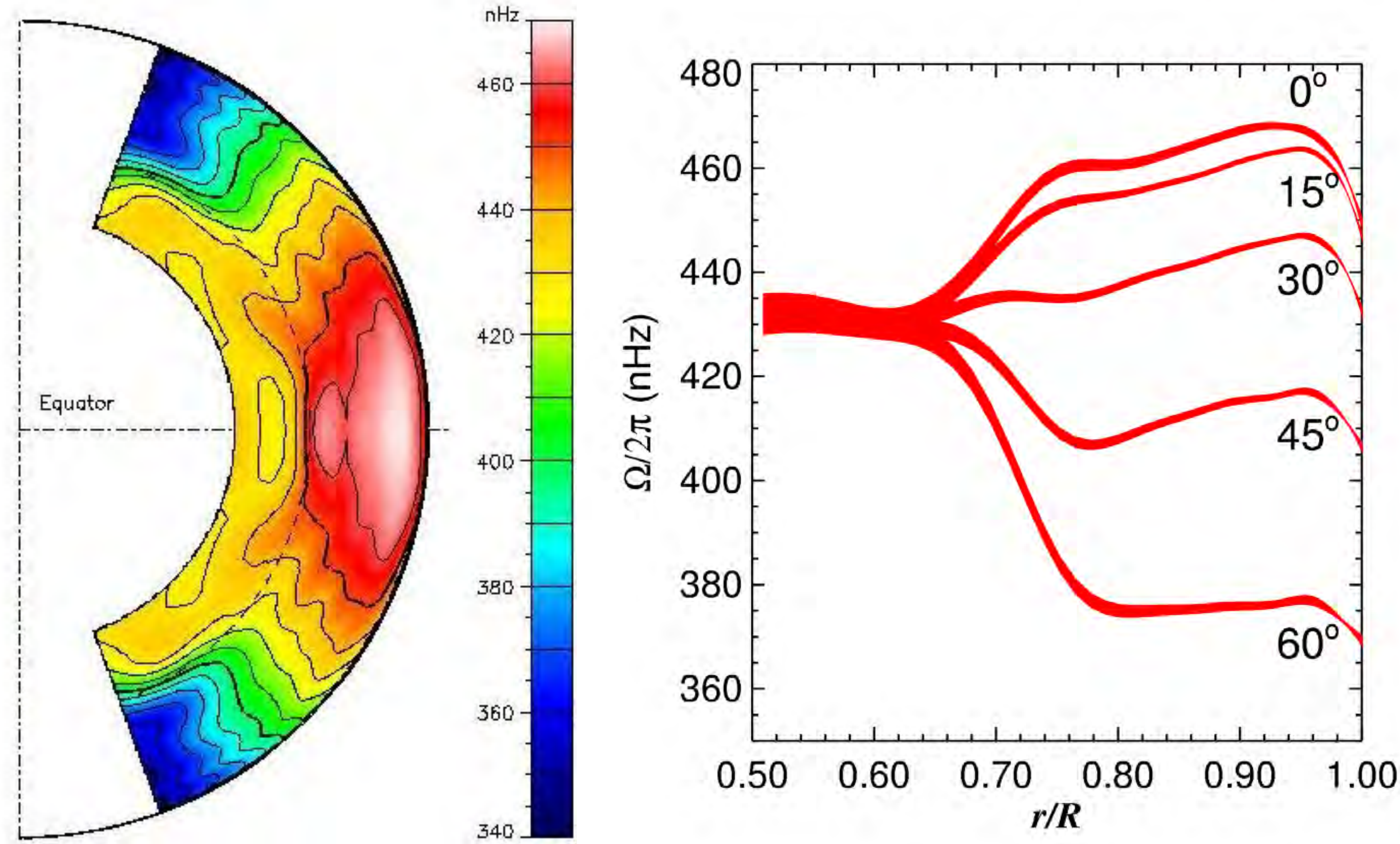
Quantity	Simulation N	Simulation S	Observational N	Observational S
Period (*N*) vs. maxima (*N*)	–0.597	–0.307	–0.217	–0.183
Period (*N*) vs. maxima (*N*+1)	–0.395	–0.147	–0.552	–0.320
Period (*N*) vs. rise time (*N*)	0.688	0.738	0.322	0.451
Period (*N*) vs. mean growth rate (*N*)	–0.696	–0.475	–0.416	–0.328
Rise time (*N*) vs. maxima (*N*)	–0.465	–0.143	0.185	–0.117
Rise time (*N*) vs. maxima (*N*+1)	–0.284	–0.095	0.025	0.311
Mean growth rate (*N*) vs. maxima (*N*)	0.957	0.943	0.763	0.841
Mean growth rate (*N*) vs. maxima (*N*+1)	0.192	0.040	0.285	0.157

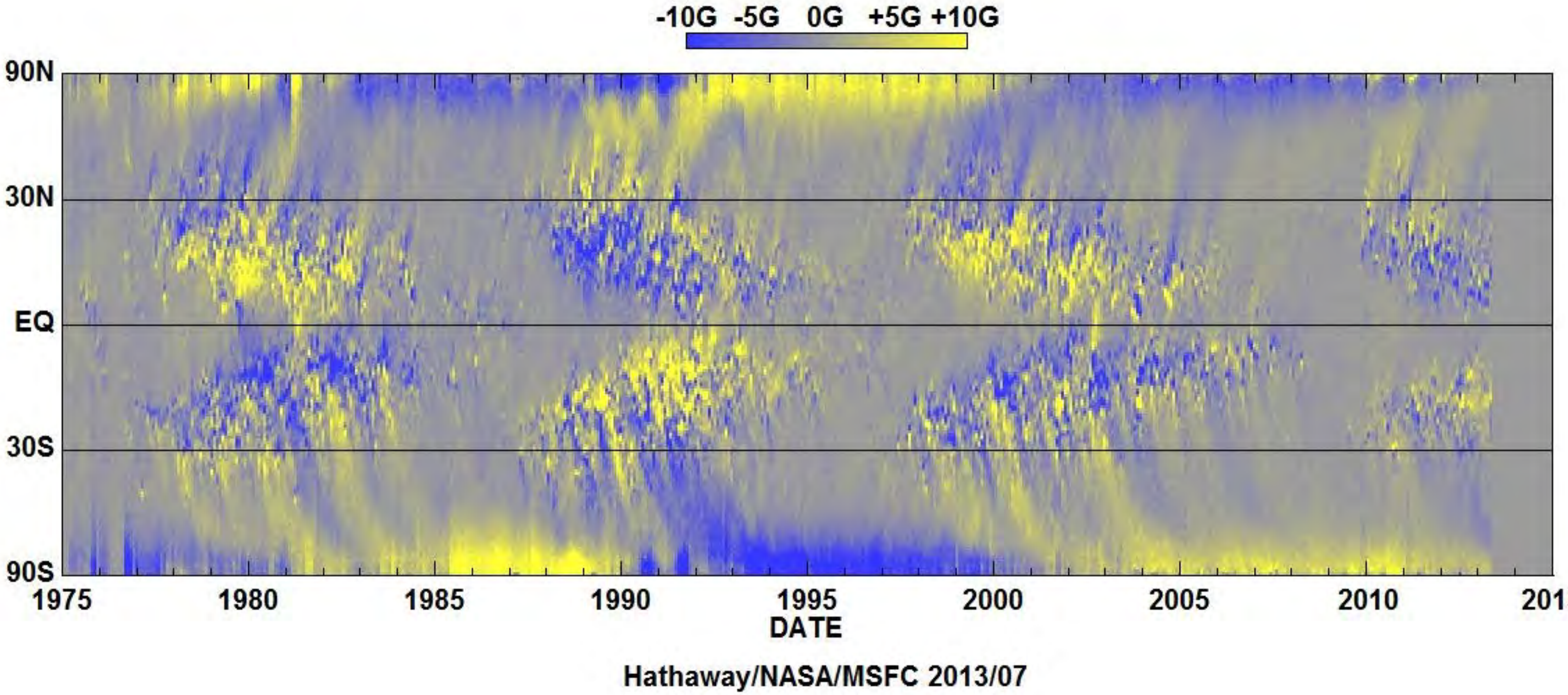
TEMPERATURE SIGNATURE OF THE TWO CYCLES

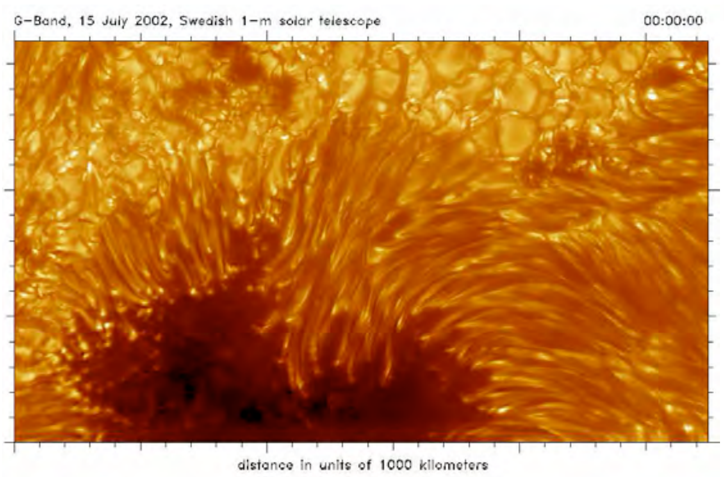


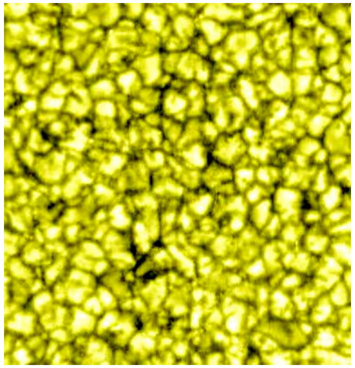


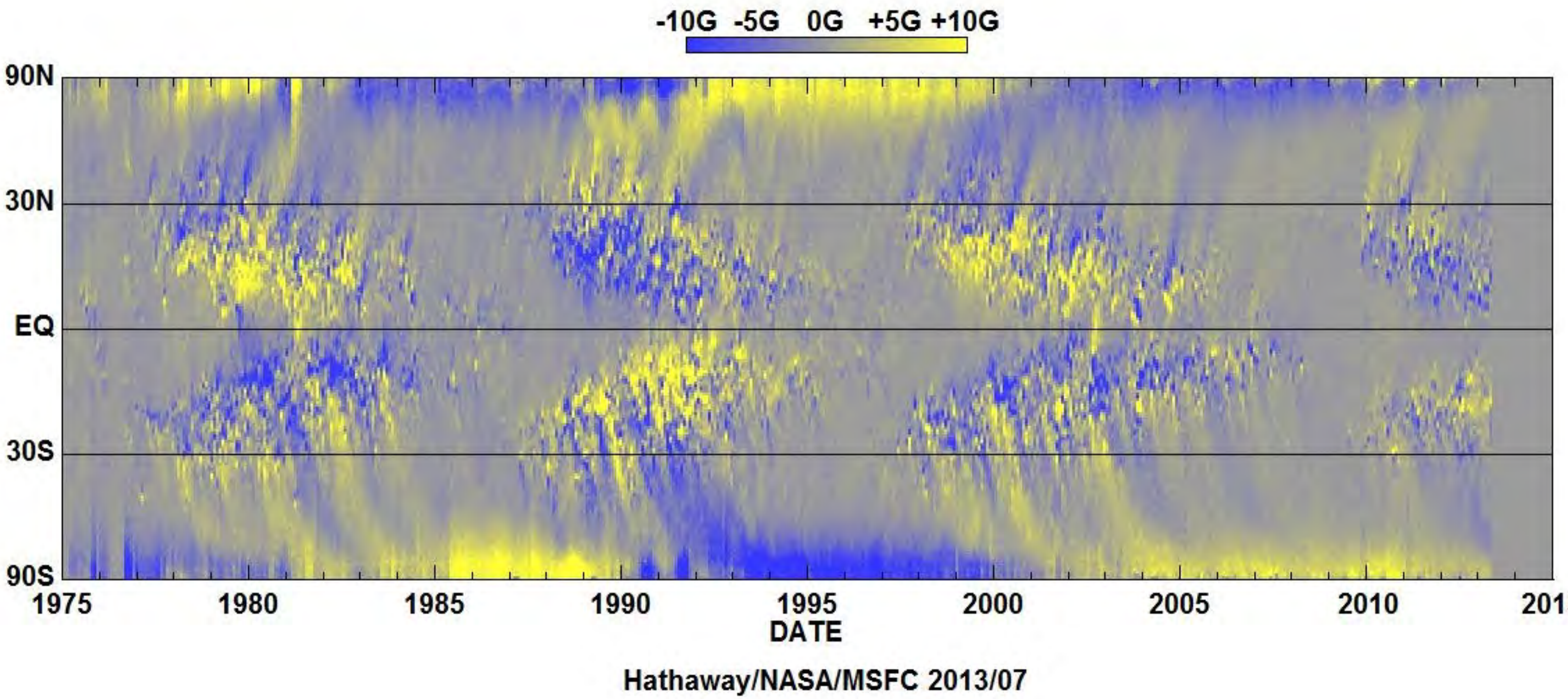
Solar differential rotation




-10G -5G 0G +5G +10G
90N
30N
EQ
30S
90S
1975
1980
1985
1990
1995
2000
2005
2010
2015
DATE
Hathaway/NASA/MSFC 2013/07


G-Band, 15 July 2002, Swedish 1-m solar telescope
00:00:00
distance in units of 1000 kilometers

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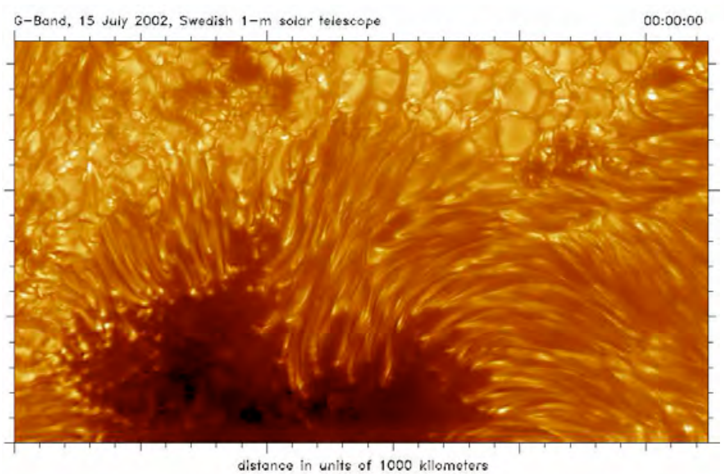
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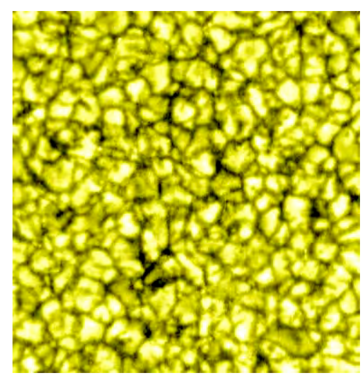

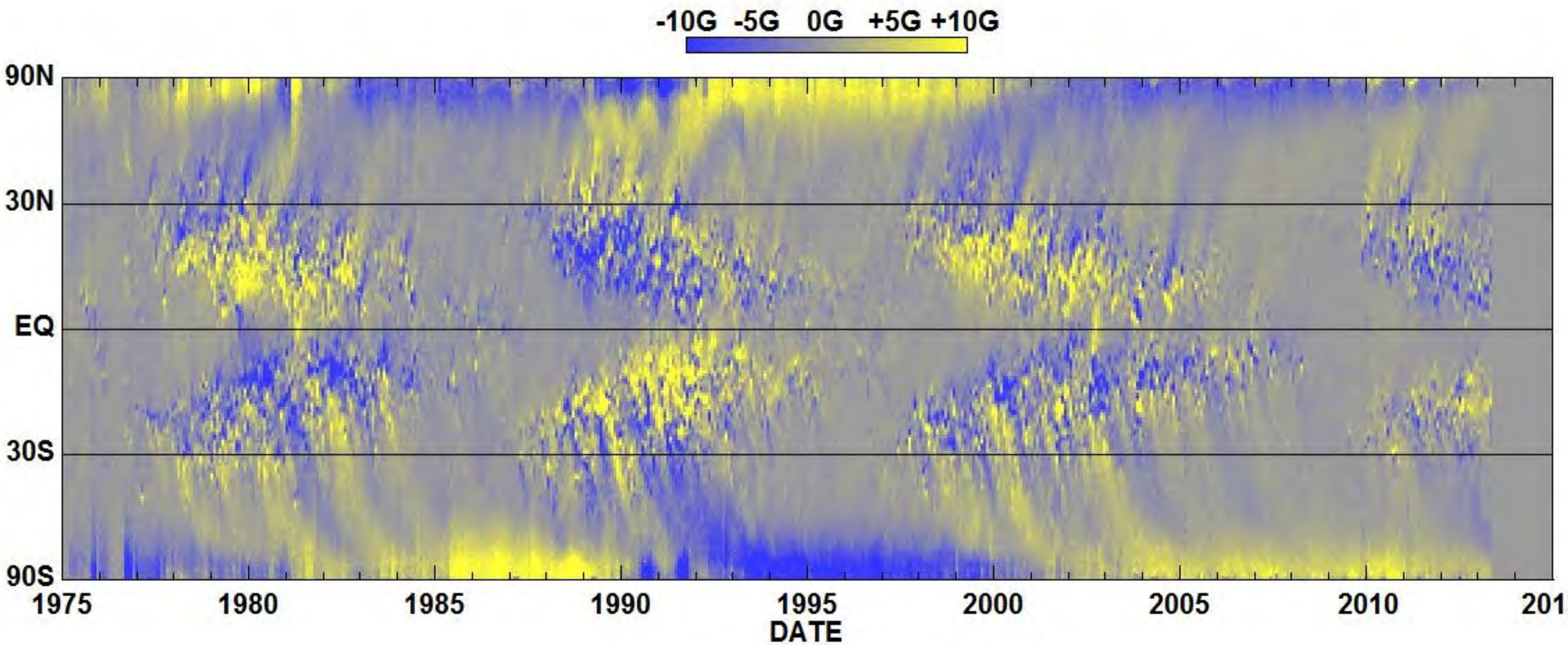

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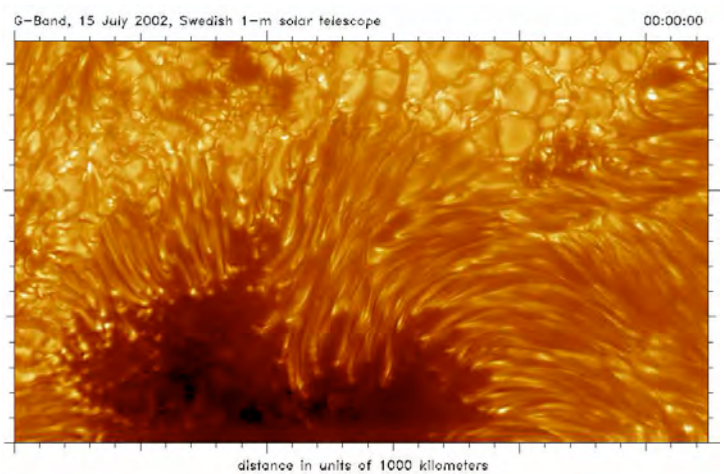

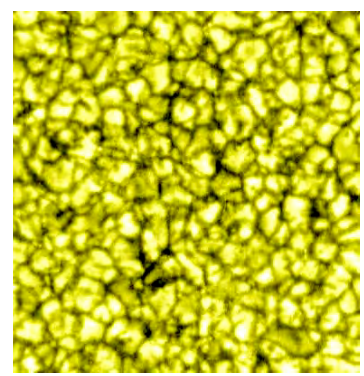

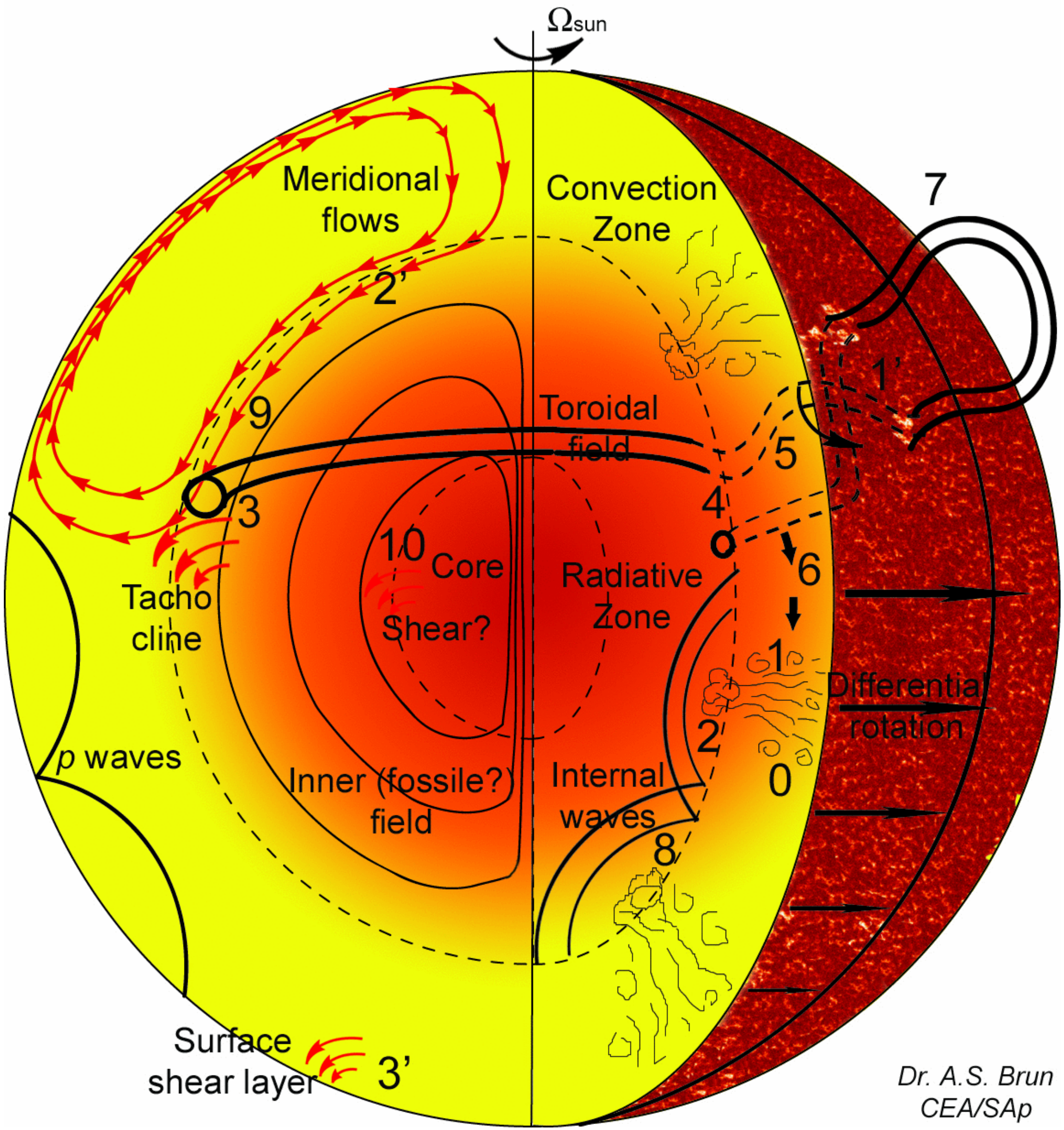

Ω_{sun}
Meridional flows
Convection Zone
7
2'
1'
9
Toroidal field
5
3
4
10
Core
Radiative Zone
6
Tacho cline
Shear?
1
Differential rotation
2
p waves
Inner (fossile?) field
Internal waves
0
8
Surface shear layer
3'
Dr. A.S. Brun
CEA/SAp