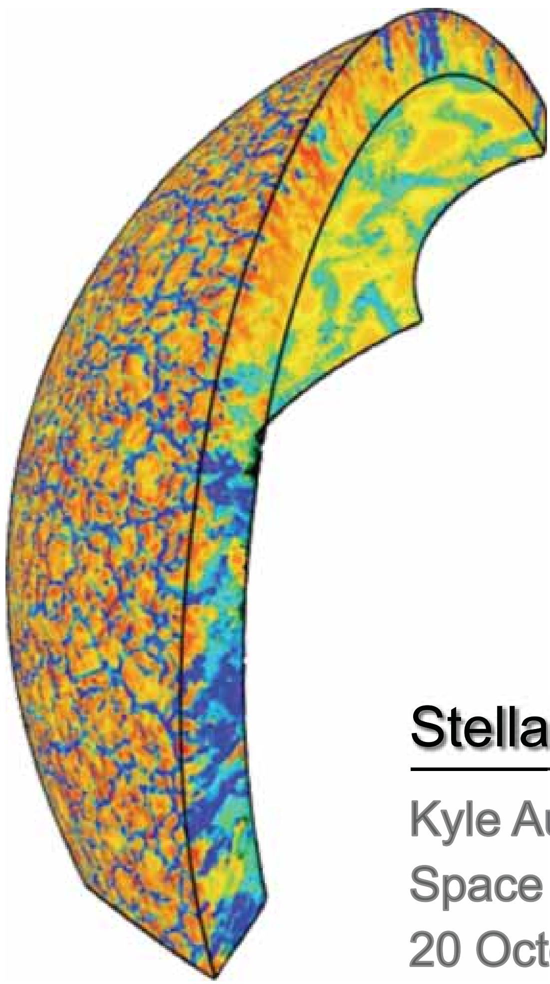
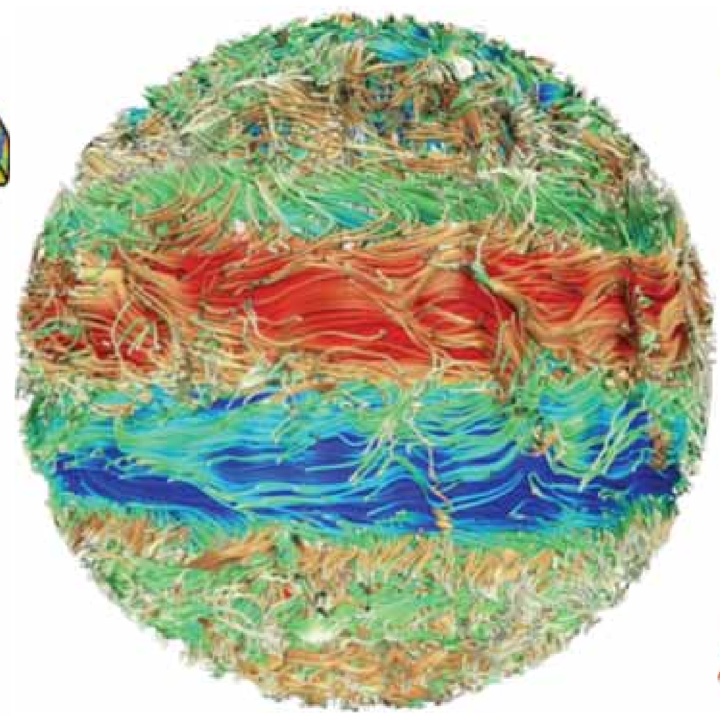


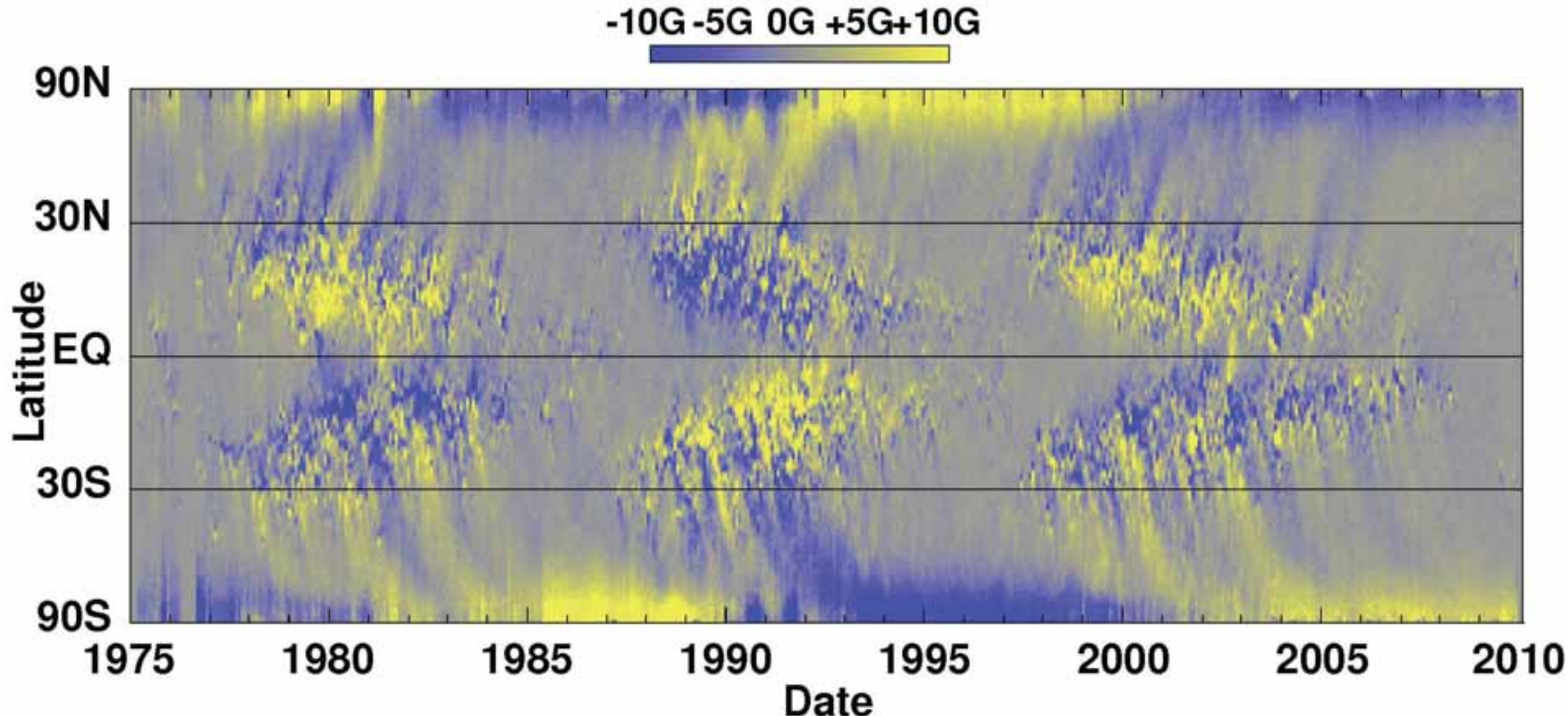


Stellar Convection, Dynamos, & Intrigue

Kyle Augustson - NCAR ASP @ HAO

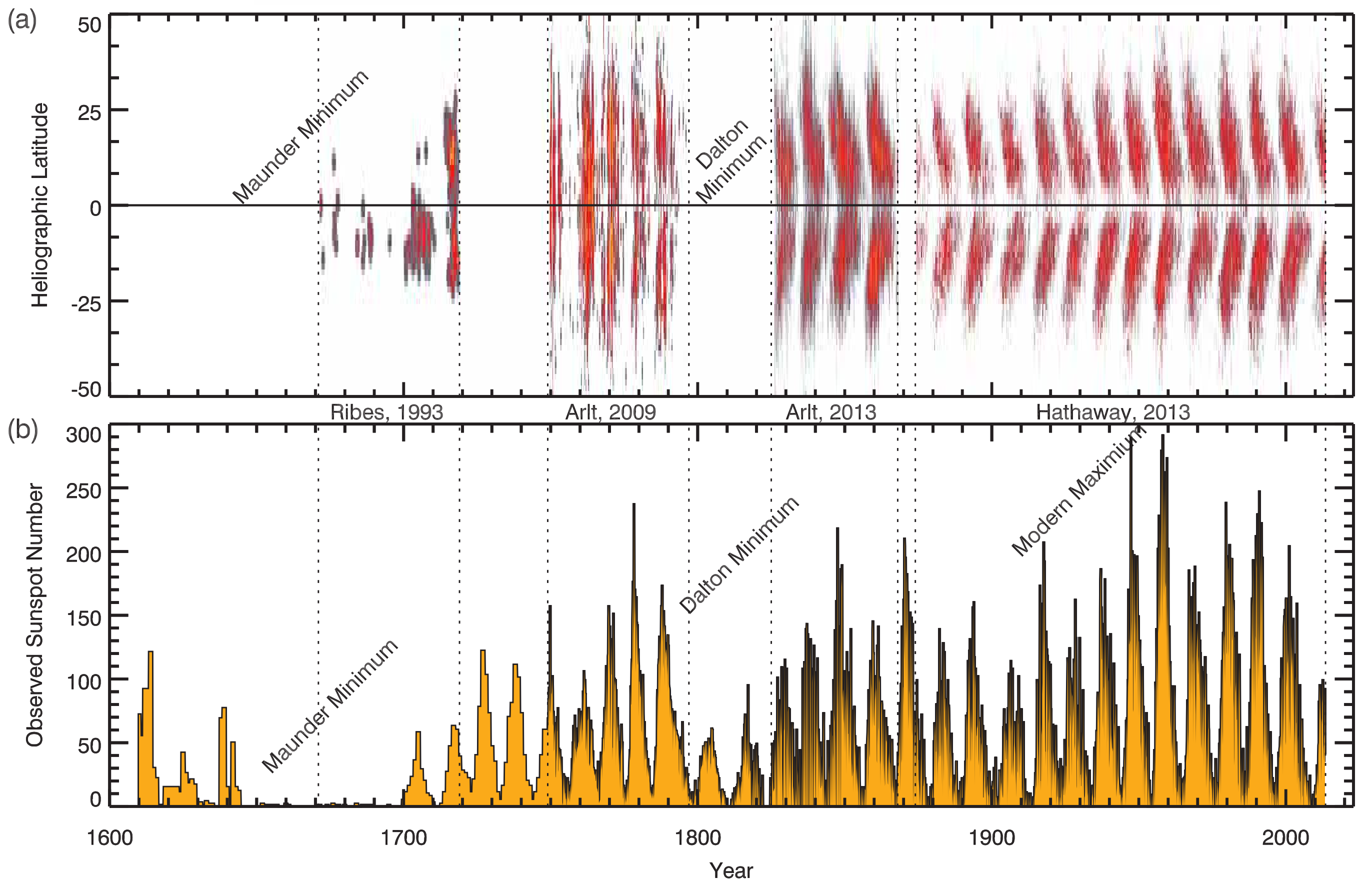
Space Weather & Young Suns Workshop
20 October 2014.

Basic Aspects of Solar Magnetism

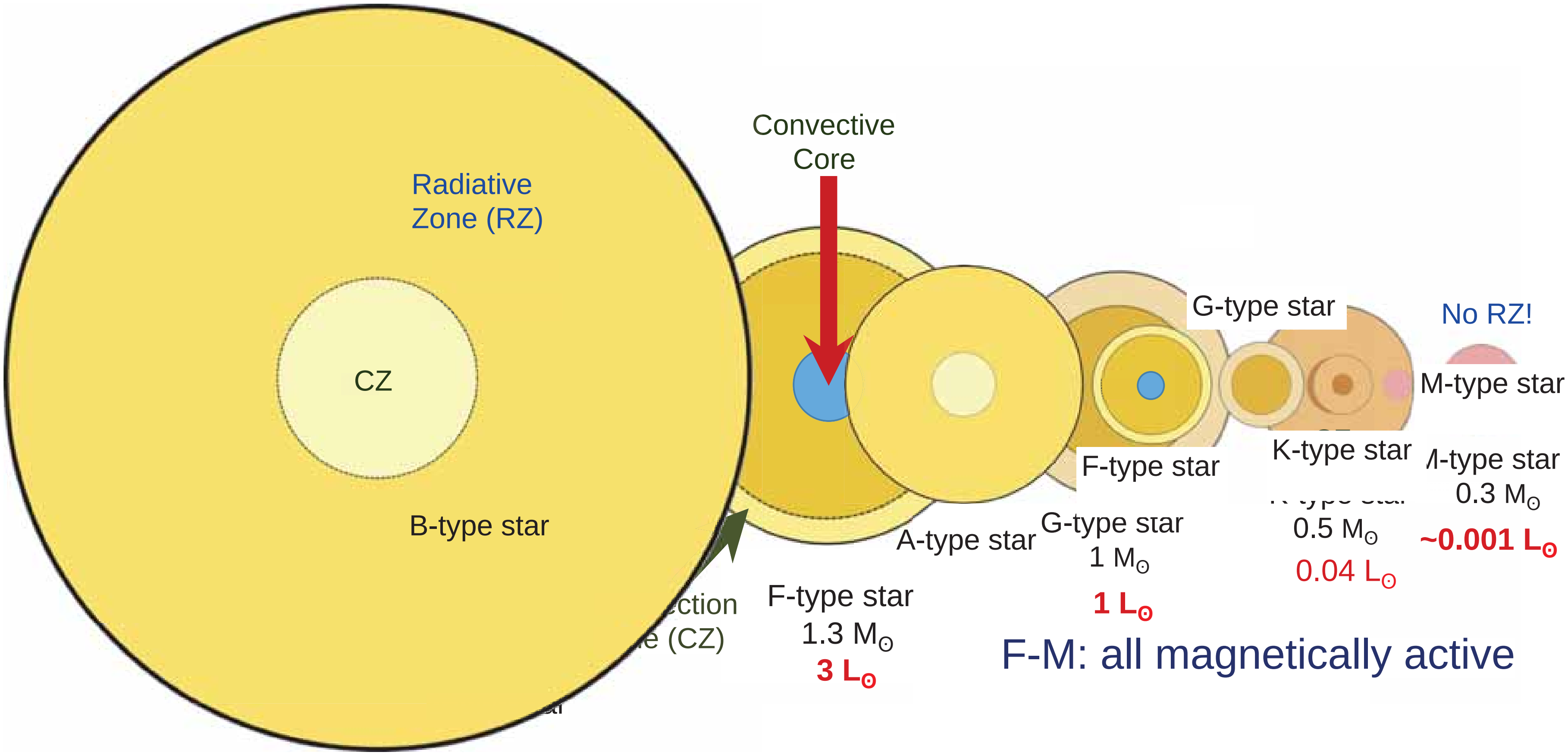


Hathaway 2010

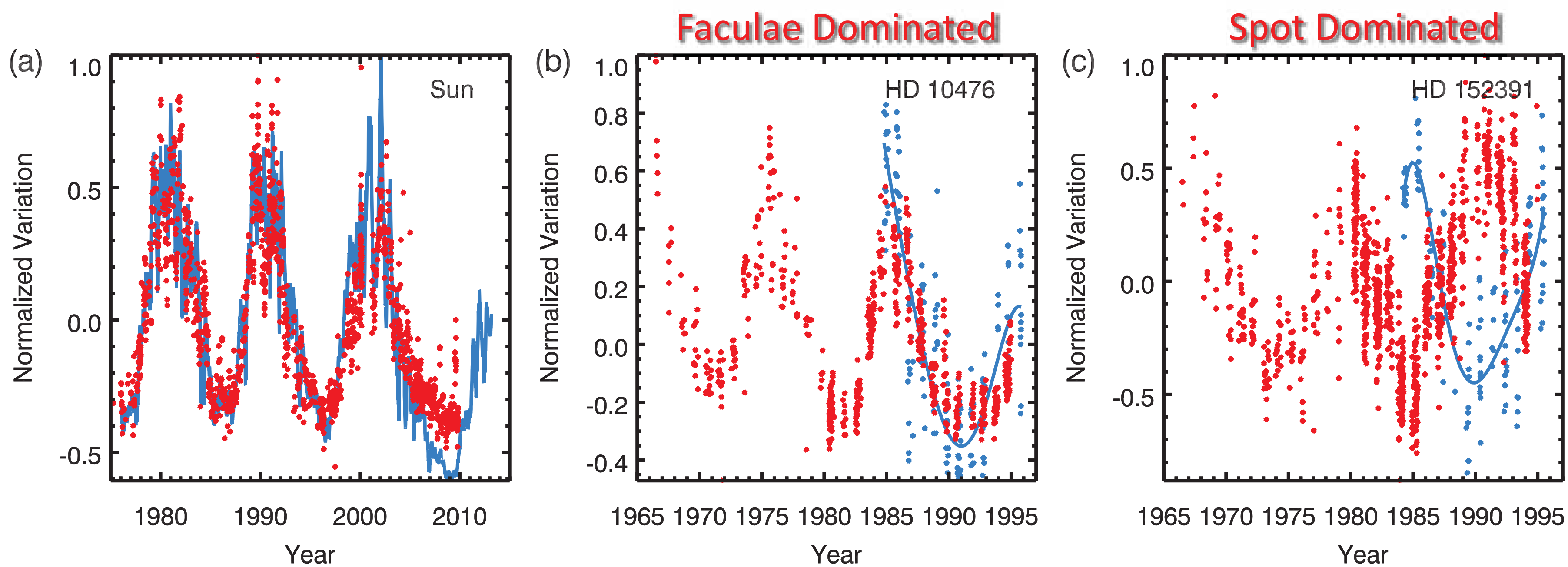
Basic Aspects of Solar Magnetism



Stellar Convection Zones



Stellar Cycles & Magnetism



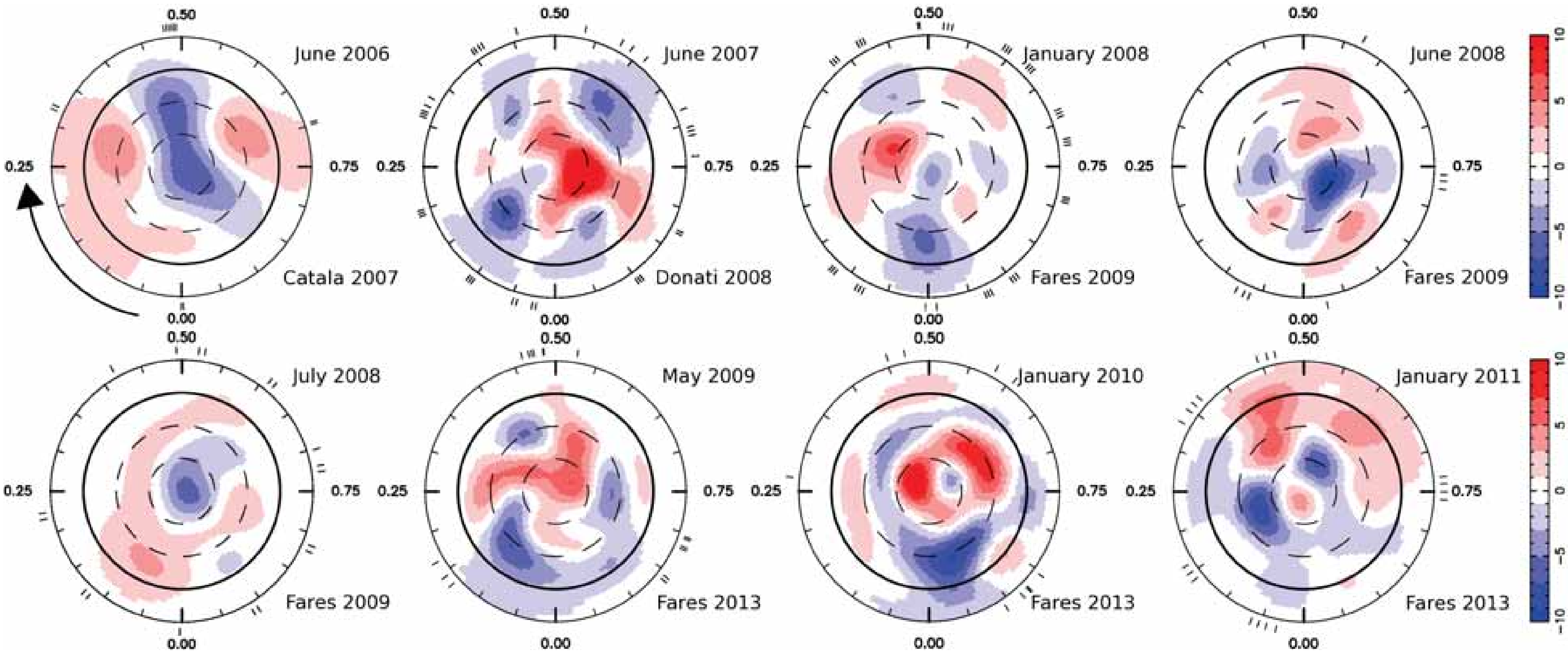
Froehlich 2013,
Livingston 2007

Radick 1998

Ca H & K Emission

Long-term Activity Cycles

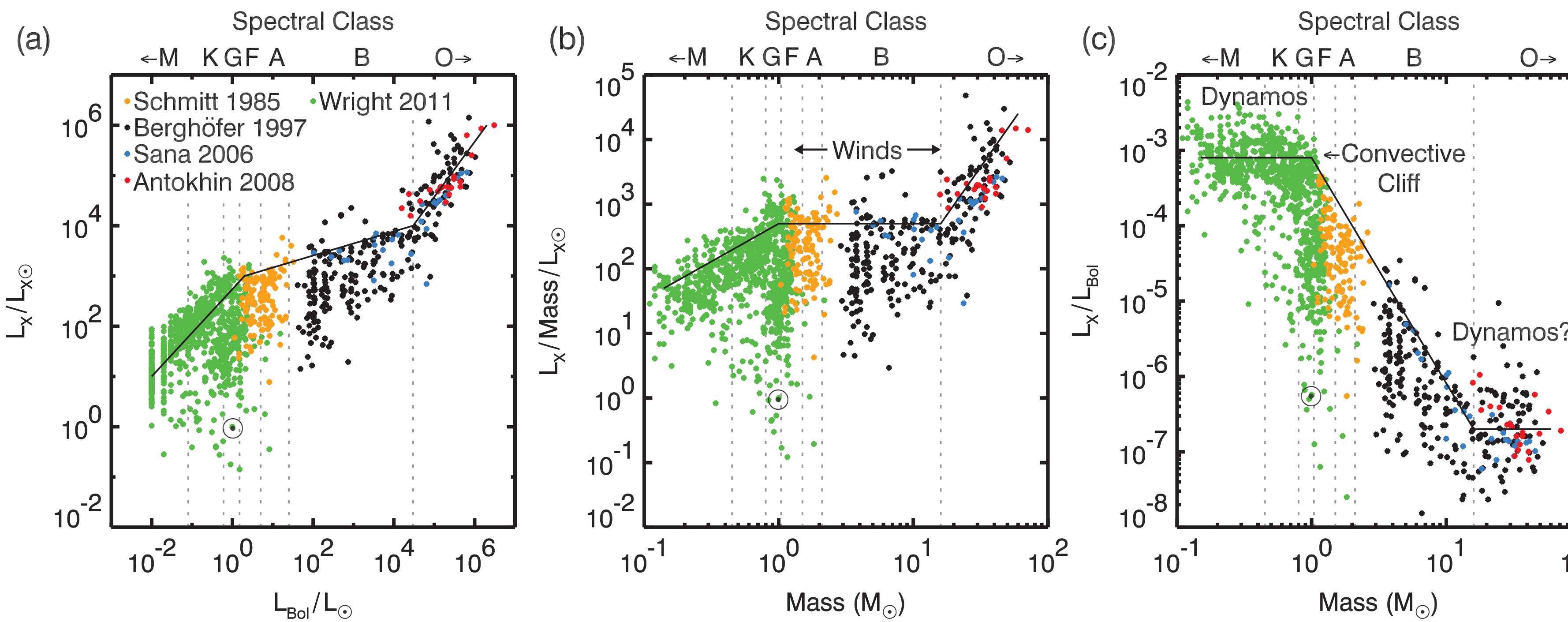
Stellar Cycles & Magnetism



Spectropolarimetry

Tau-Bootis F-type Star

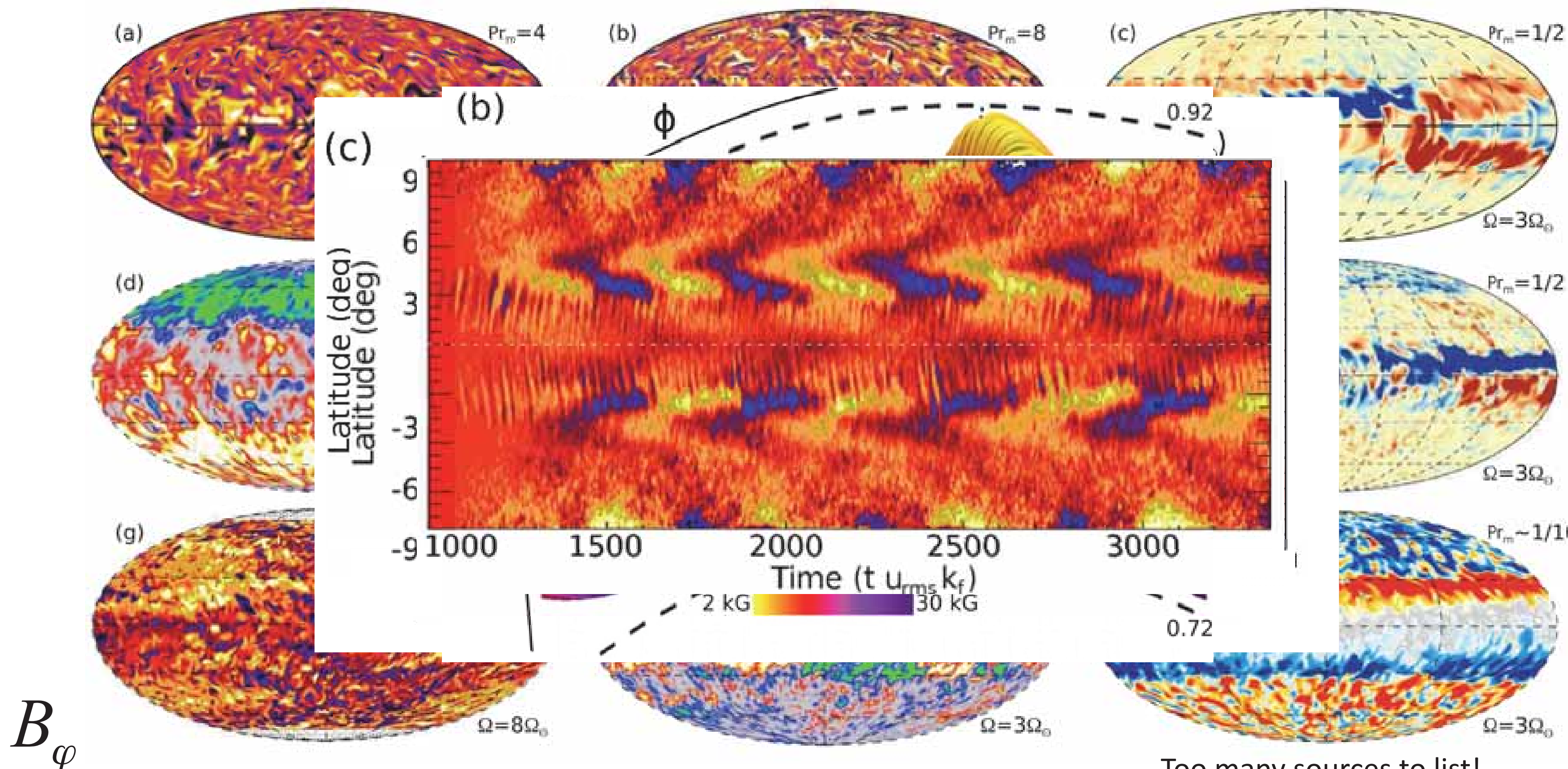
Stellar Cycles & Magnetism



X-Ray Emission

Convection Transition Regions

Progress in Stellar Dynamo Theory



Too many sources to list!

Essential Dynamo Processes

Evolution of Mean Magnetic Fields

$$\frac{\partial A}{\partial t} = \overbrace{\eta\left(\nabla^2 - \frac{1}{\lambda^2}\right)A}^{\text{magnetic diffusion}} - \overbrace{\frac{1}{\lambda}\mathbf{u}_m \cdot \nabla(\lambda A)}^{\text{meridional advection}} + \overbrace{\hat{\phi}\cdot\overline{\mathbf{u}'\times\mathbf{B}'}}^{\text{poloidal generation}}$$

$$\frac{\partial B}{\partial t} = \underbrace{\eta\left(\nabla^2 - \frac{1}{\lambda^2}\right)B}_{\text{magnetic diffusion}} + \underbrace{\frac{1}{\lambda}\frac{\partial\eta}{\partial r}\frac{\partial\lambda B}{\partial r}}_{\text{diffusive transport}} - \underbrace{\lambda\mathbf{u}_m\cdot\nabla\frac{B}{\lambda}}_{\text{meridional advection}}$$

$$- \underbrace{B\nabla\cdot\mathbf{u}_m}_{\text{compression}} + \underbrace{\lambda\nabla\Omega\cdot\nabla\times A\hat{\phi}}_{\text{stretching}} + \underbrace{\hat{\phi}\cdot\nabla\times\overline{\mathbf{u}'\times\mathbf{B}'}}_{\text{toroidal generation}}$$

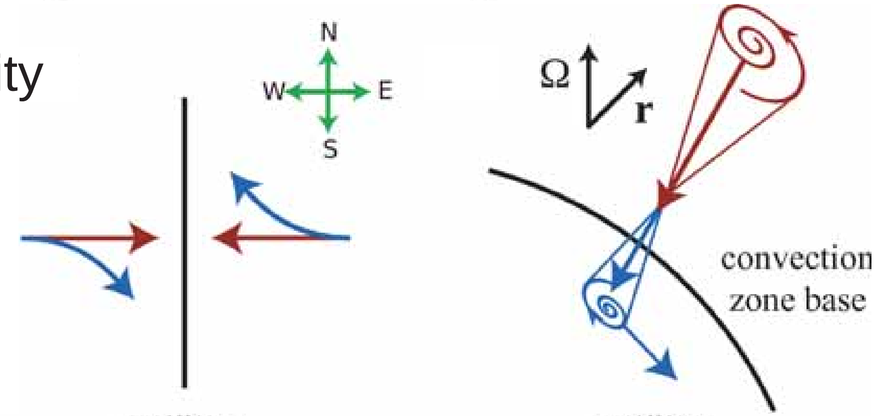
Turbulent Correlations

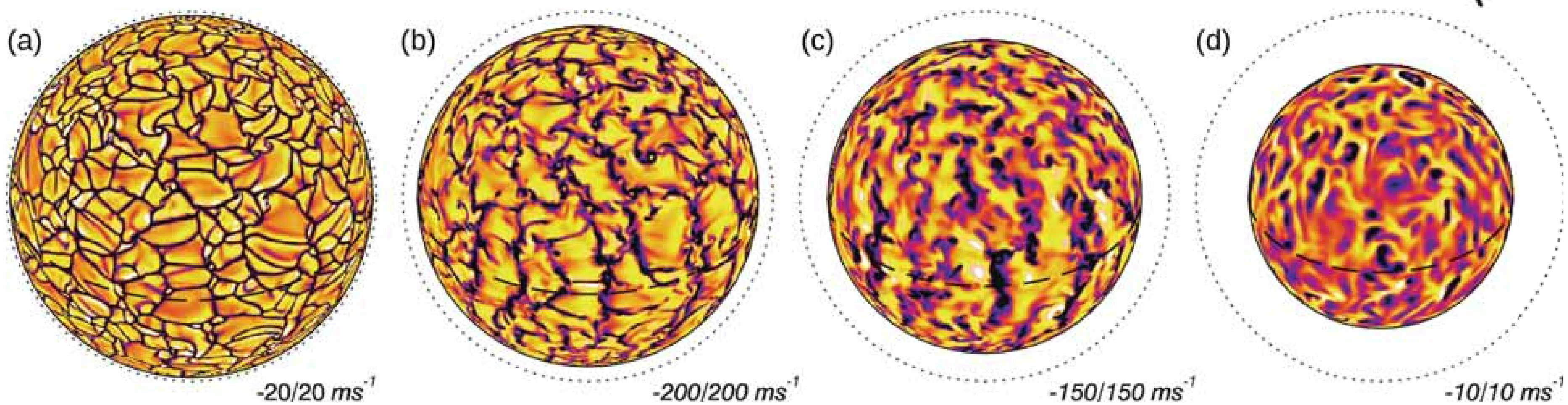
Rotation

- Fully resolved nonlocal 3D MHD
  Self-consistent flow and field
- Flux-transport dynamo (e.g., BL)
  Prescribed flows & model EMF
- Delta-correlated turbulence (MFT)
  Prescribed flows & model EMF

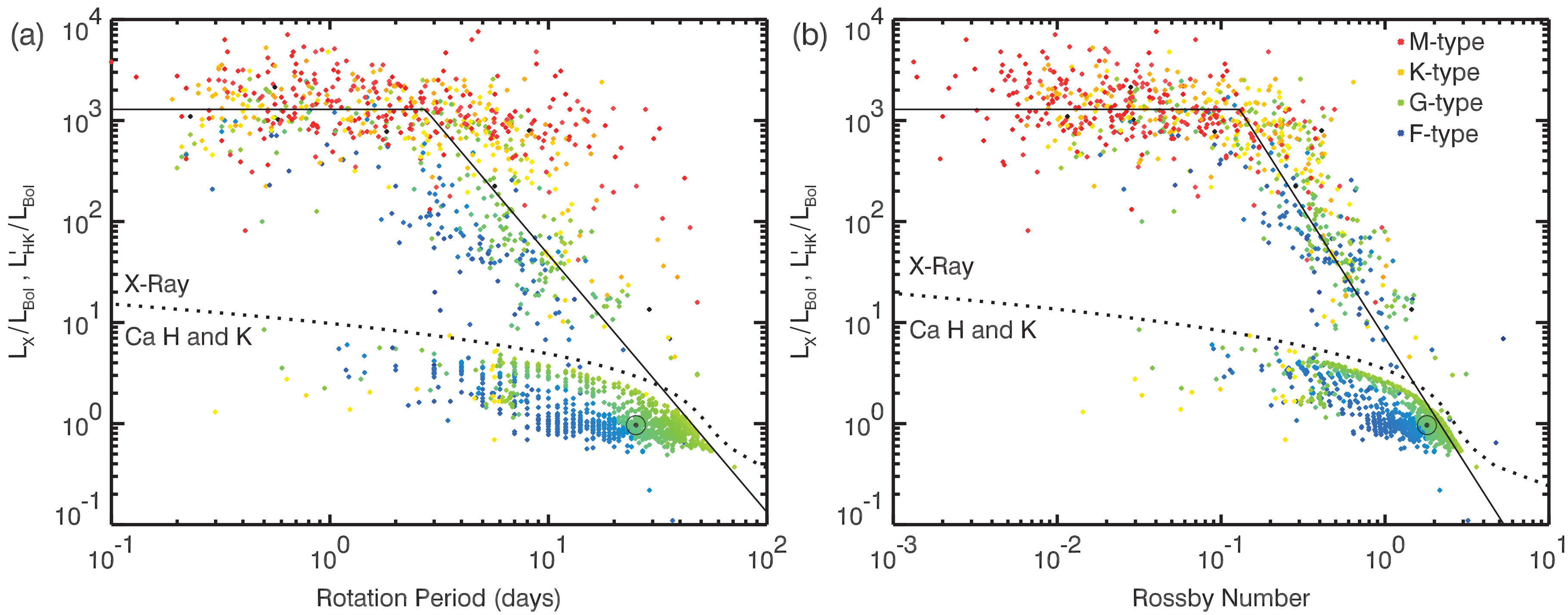
Elements of Stellar Magnetic Variability

- Observations of stellar magnetic variability
  - – Largely detects atmospheric phenomenon
- Basic building blocks of stellar dynamos
  - – Helical convection
  - – Rotation



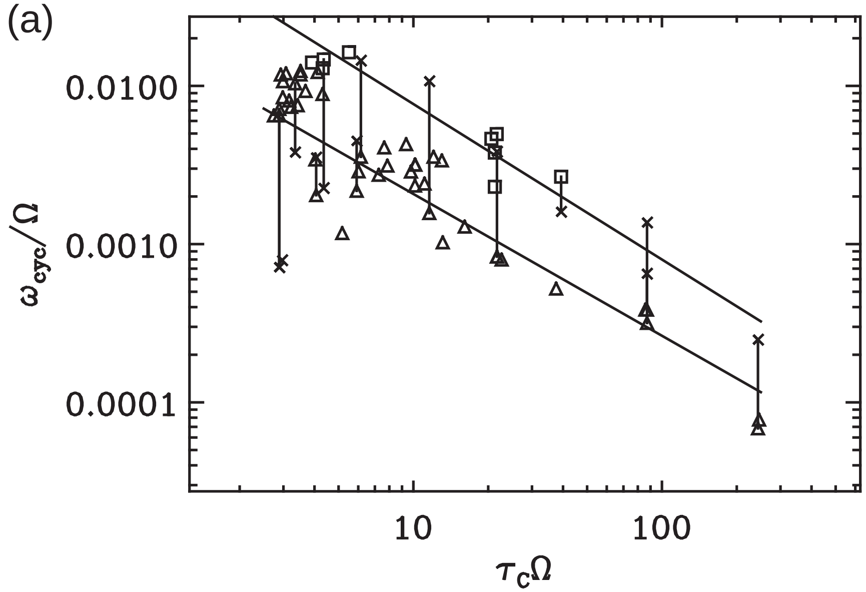


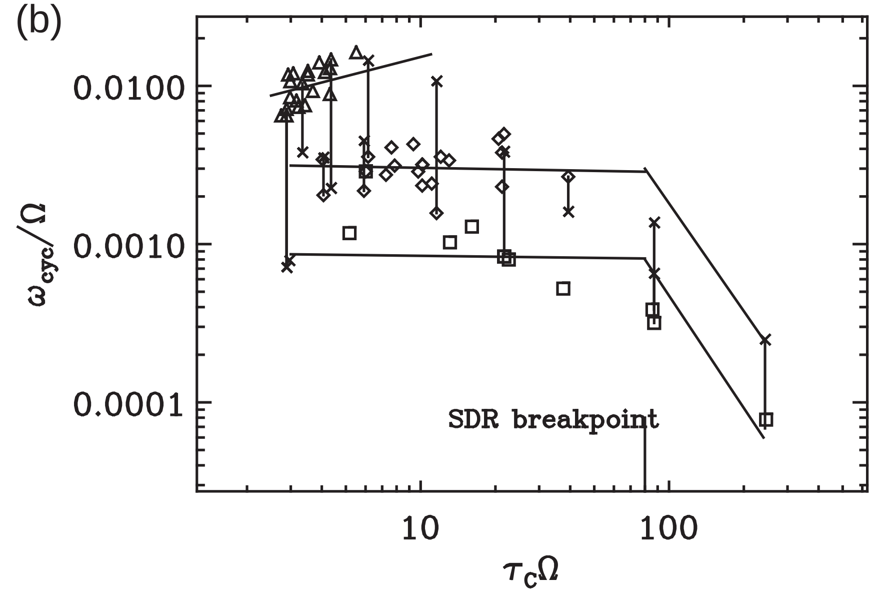
Rotation-Activity Correlation



Soderblum 1993, Wright 2004, Wright 2011

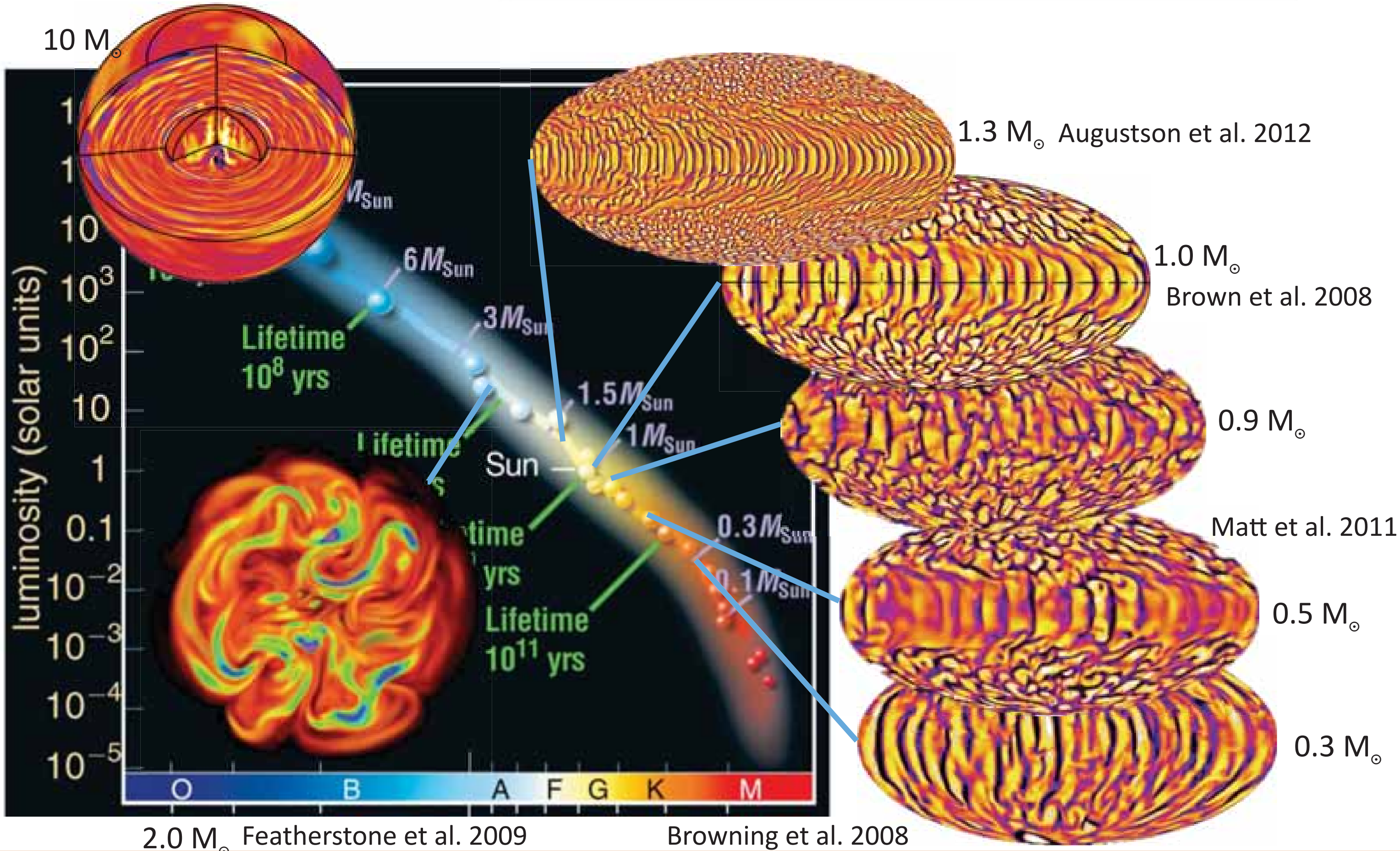
Rotation-Cycle Period Correlation





Saar 2009

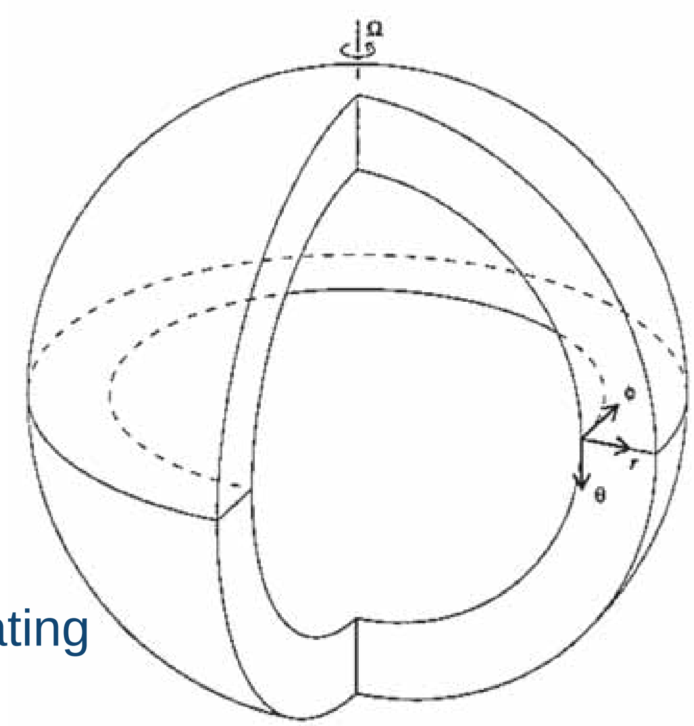
Simulating the Main-Sequence with ASH



Features of the ASH Code

The ASH (Anelastic Spherical Harmonic) code

- Parallel pseudospectral code
- Spherical harmonic & Chebyshev or Finite-difference decomposition
- Spherical shell geometry
- Semi-implicit time-stepping
- Realistic stratification
- Including a stiffly stratified stable layer
- Self-consistent evolution of mean and fluctuating flows and thermodynamics
- Magnetism

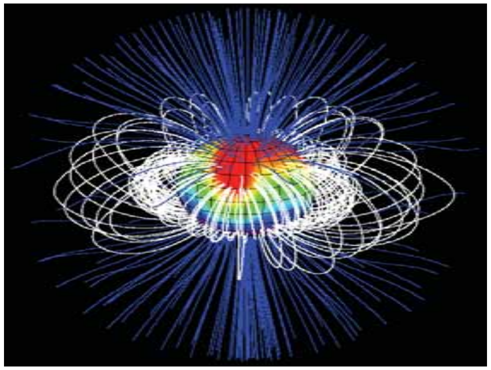


Clune et al. 1999; Miesch et al. 2000; Brun et al. 2004

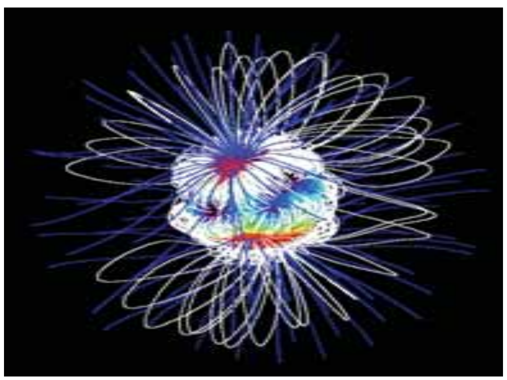
A Few Case Studies

- M dwarfs – Tiny Stars, Strong Fields
- A Young Sun – Faster Cycles & Intermittency
- Massive Stars – Core Convection & Hyper-equipartition

Tiny Stars and Strong Fields



ultra-cool star V374 Pegasi
(Donati et al.)



Young star V2129 Oph
(Donati et al.)

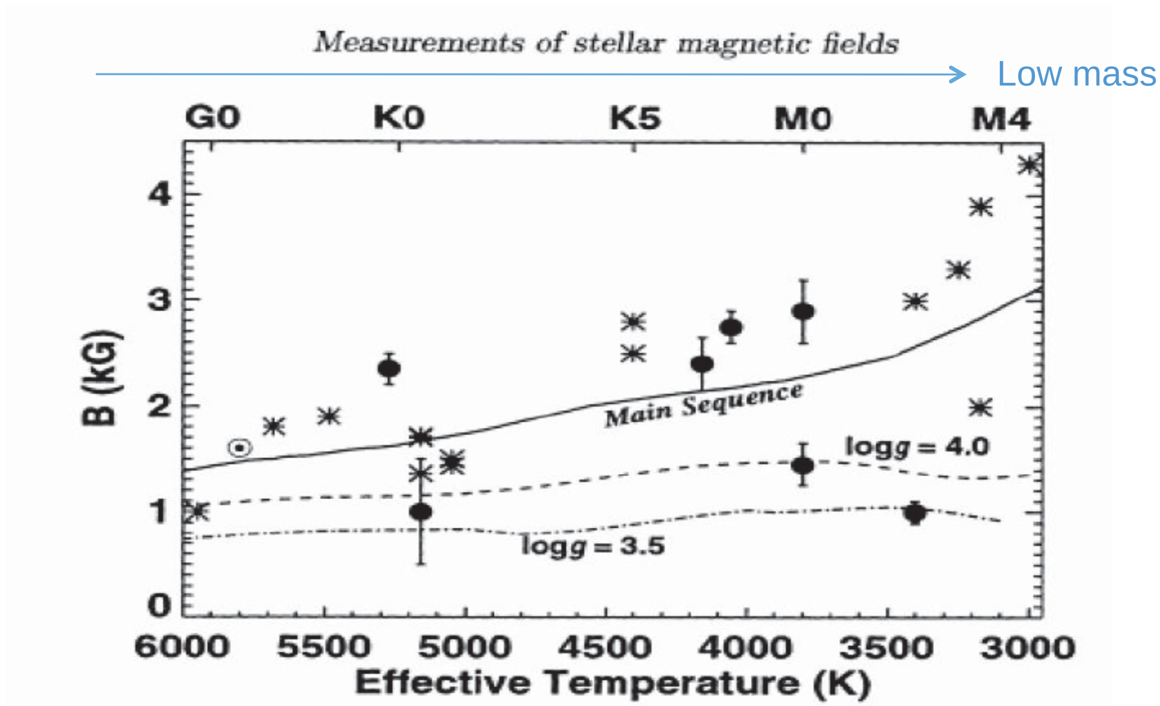
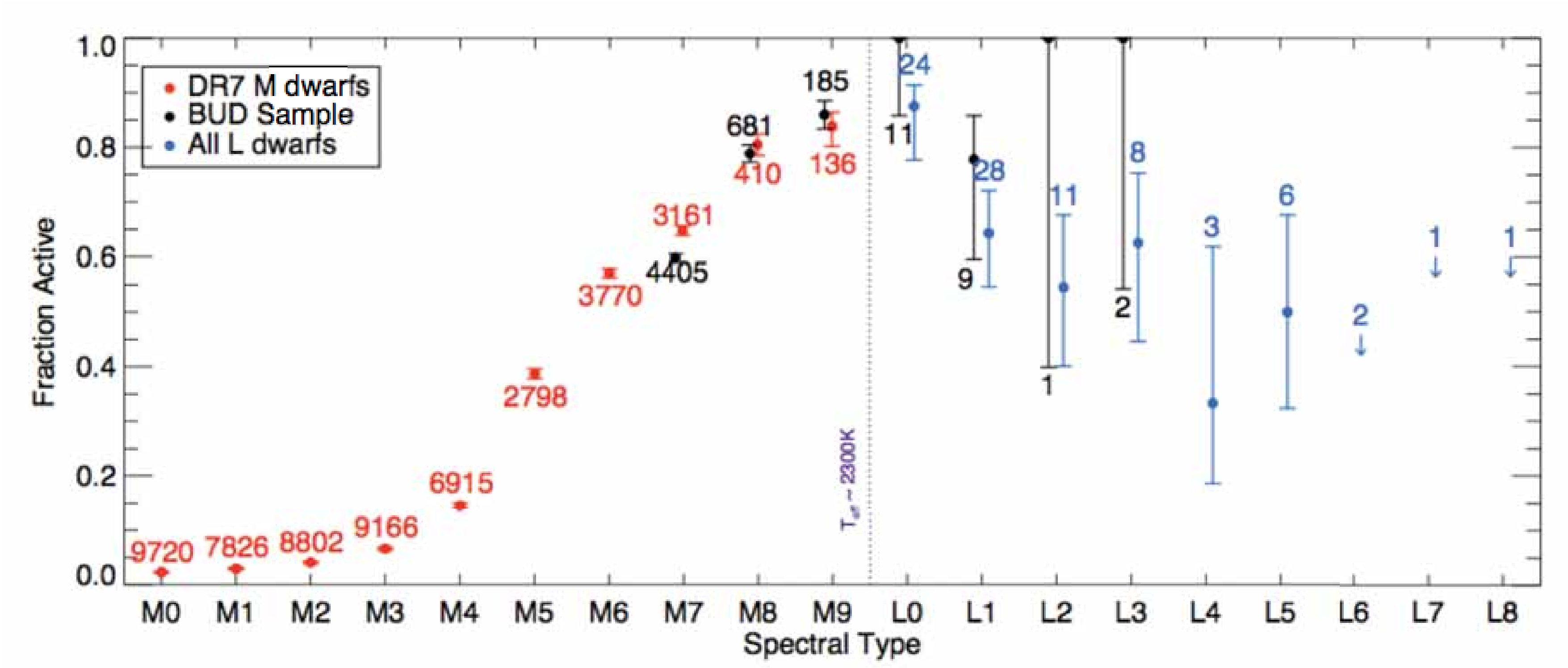


Figure 5. Predicted surface "equipartition" magnetic fields for cool stars. Also shown are measurements of main sequence stars (asterisks) and TTS (solid circles). The sun is shown by an encircled dot.

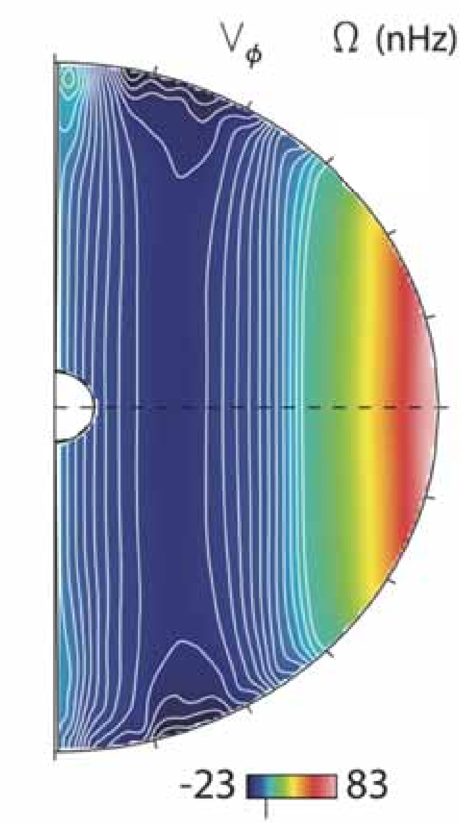
From Johns-Krull & Valenti

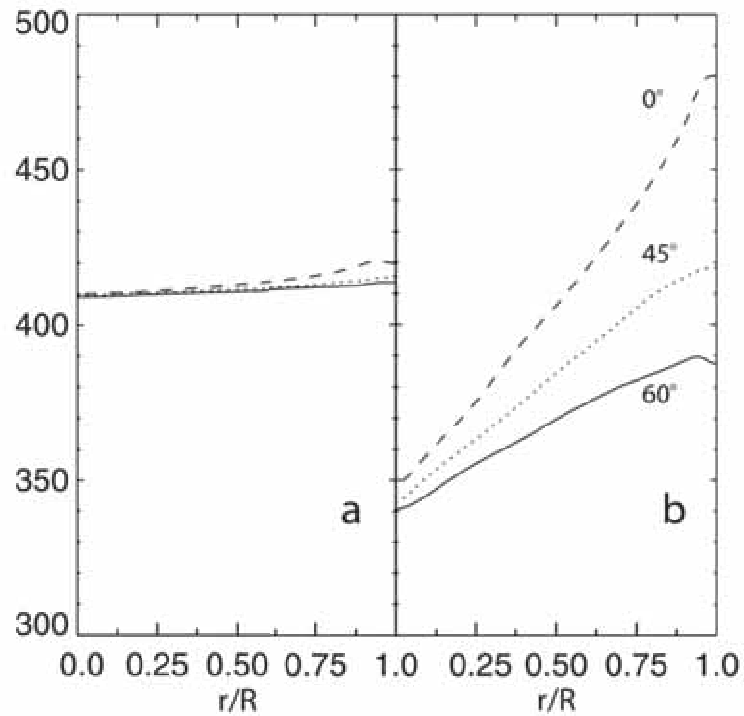
Interface Dynamo Transition?

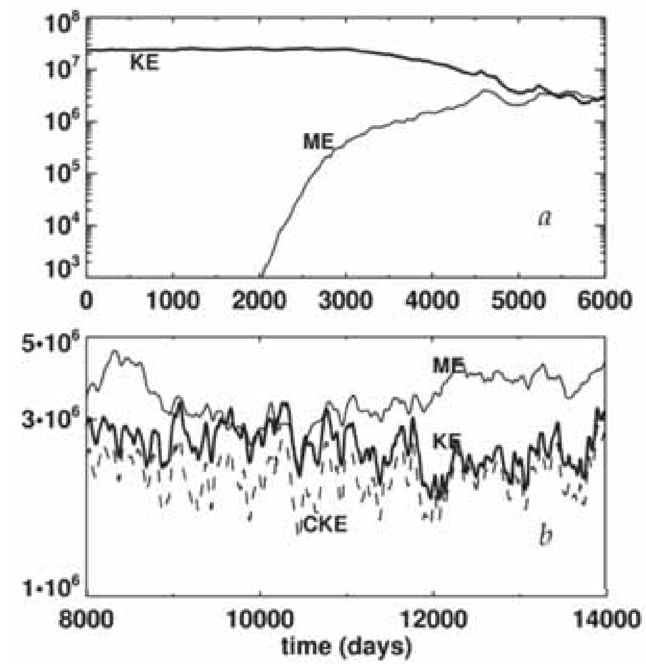


Schmidt 2014

Hydrodynamics versus MHD



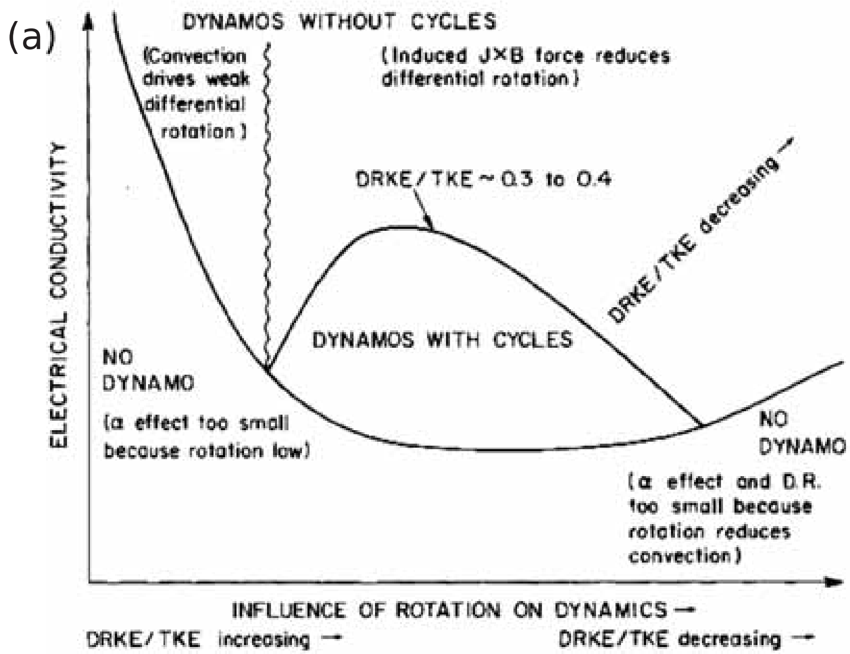




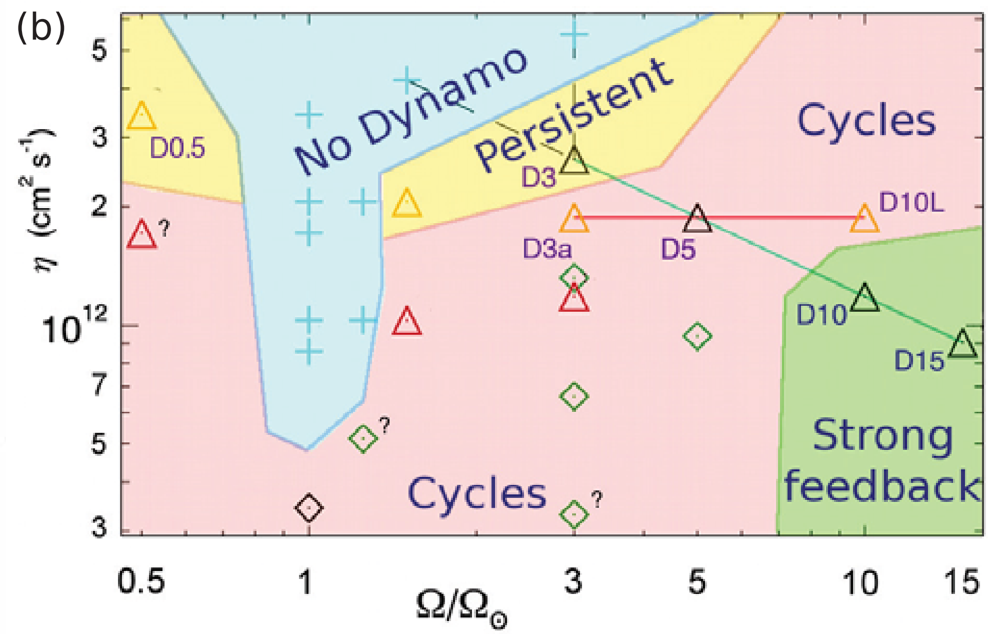
Browning 2008

A Young Sun

Dynamo Parameter Space
Rapidly Rotating Suns

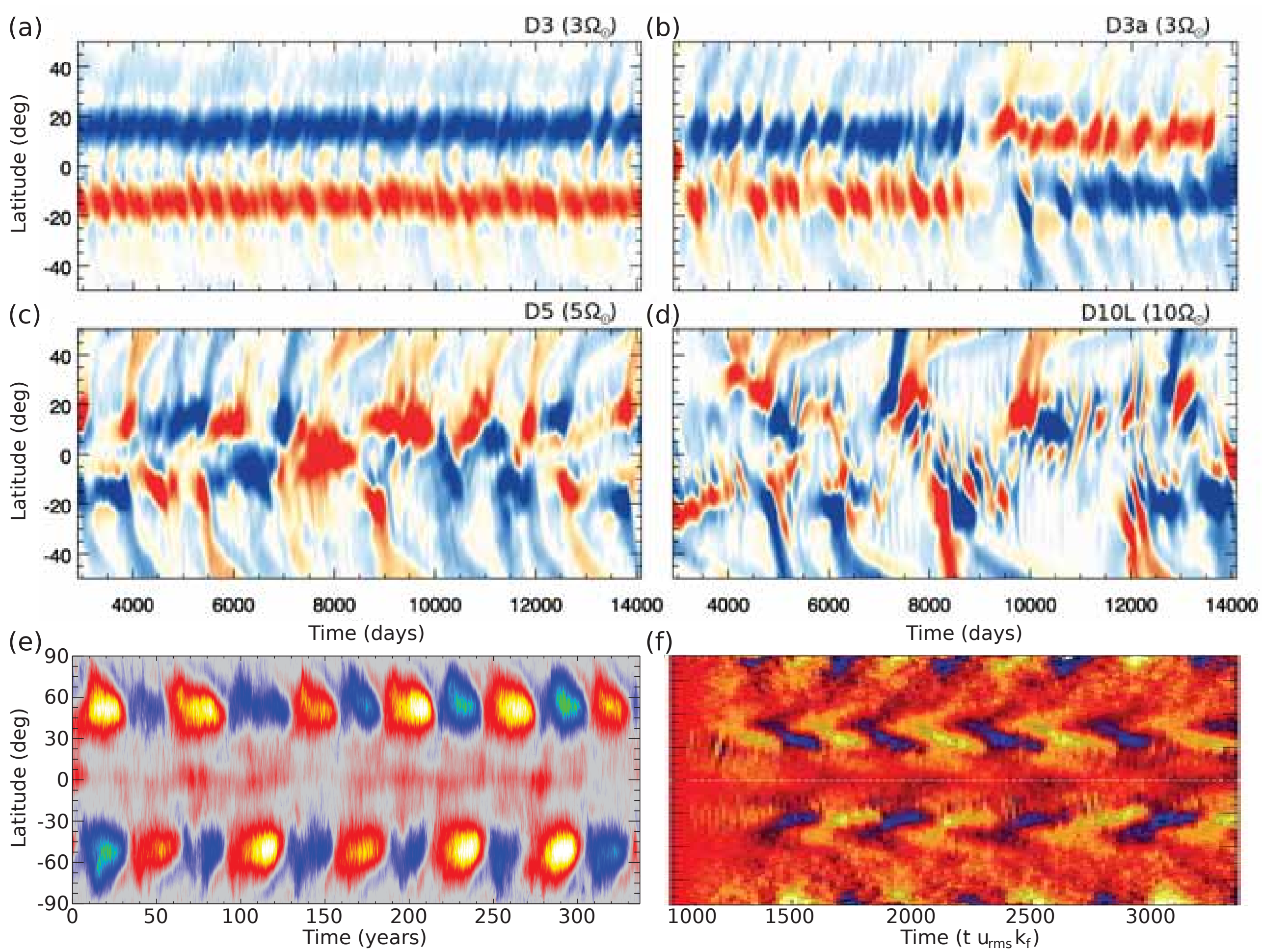


Gilman 1984

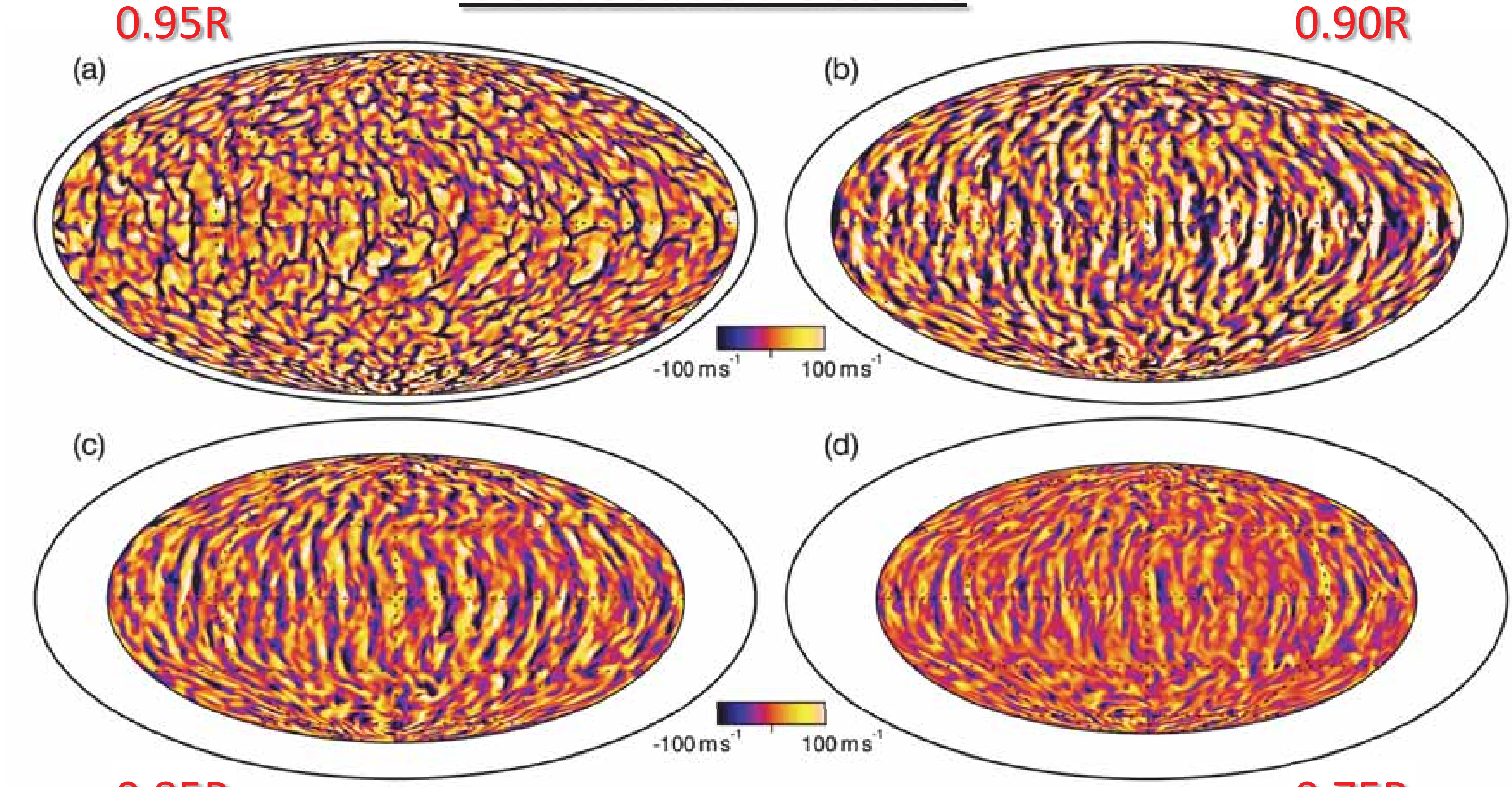


Brown 2011

Dynamo Parameter Space

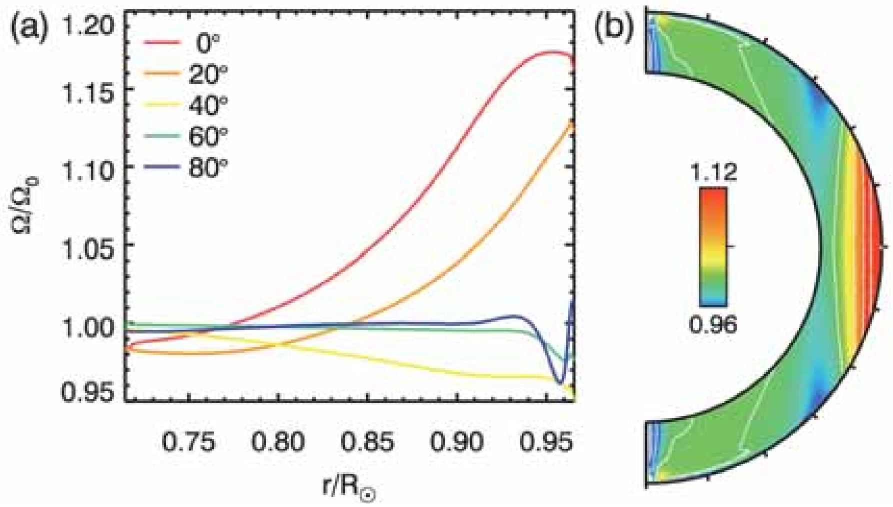


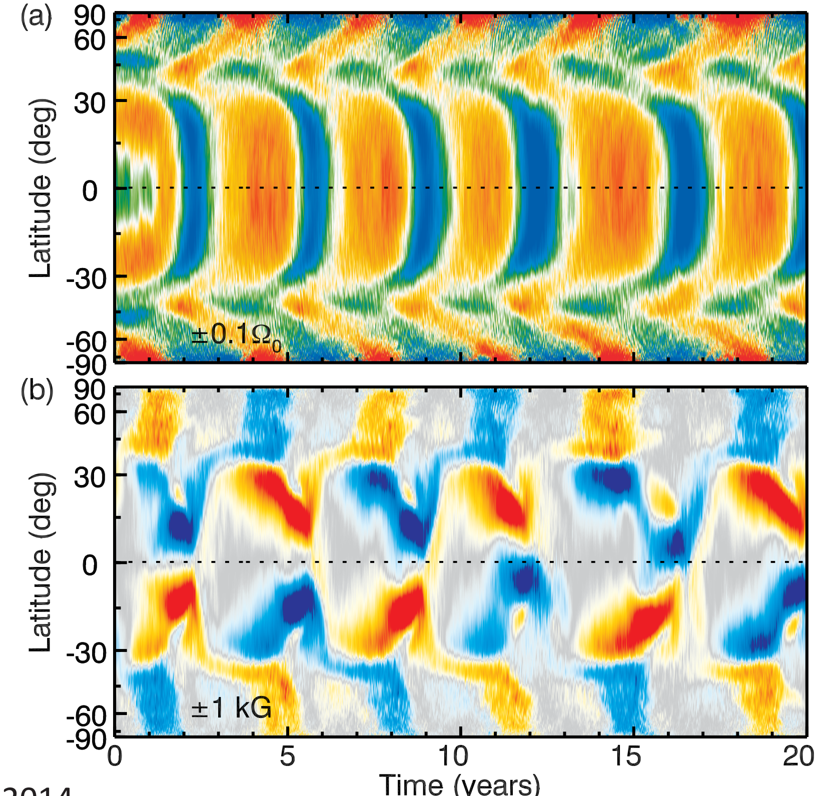
Convective Patterns



Augustson 2014

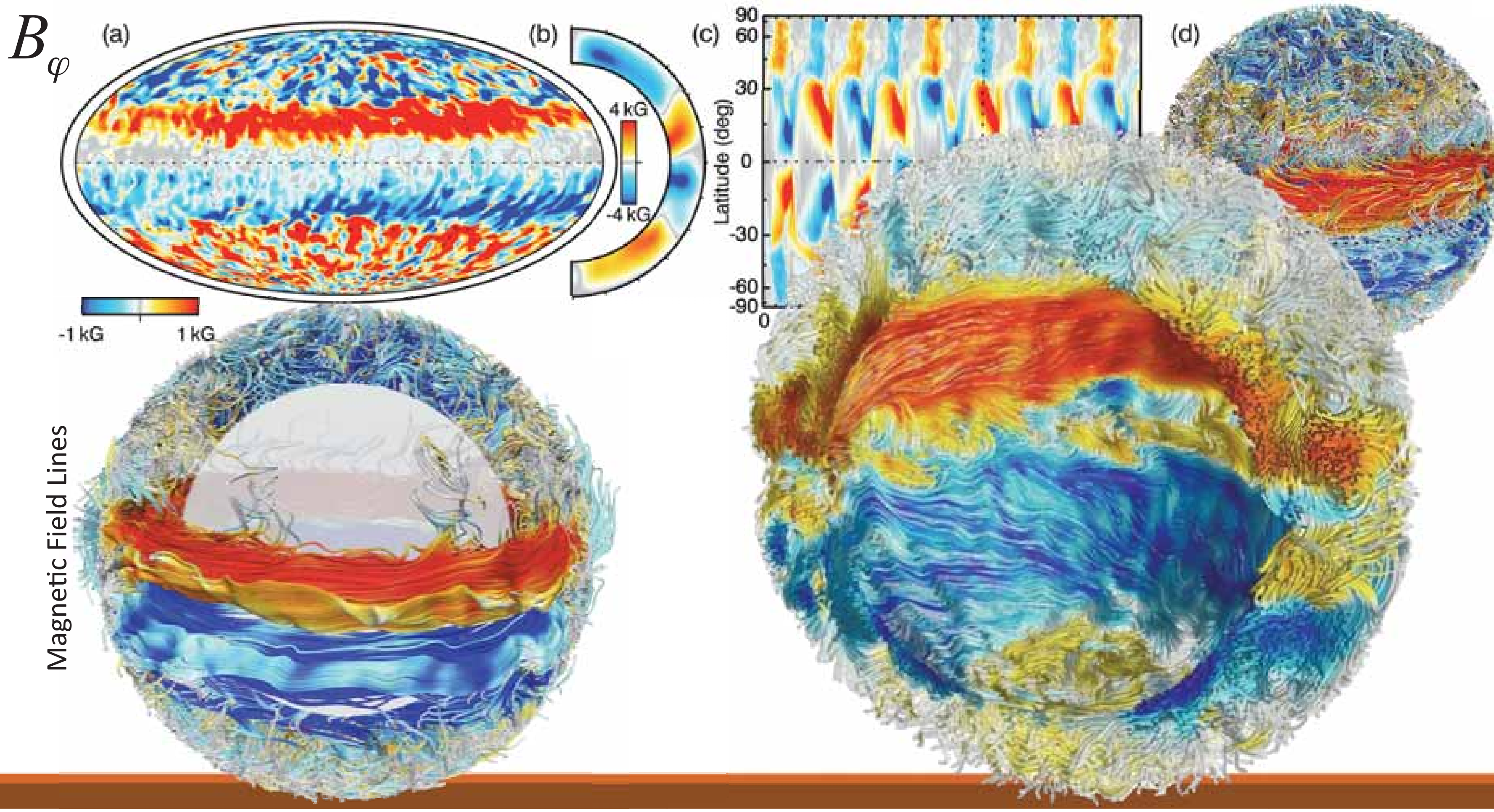
Differential rotation and its Evolution





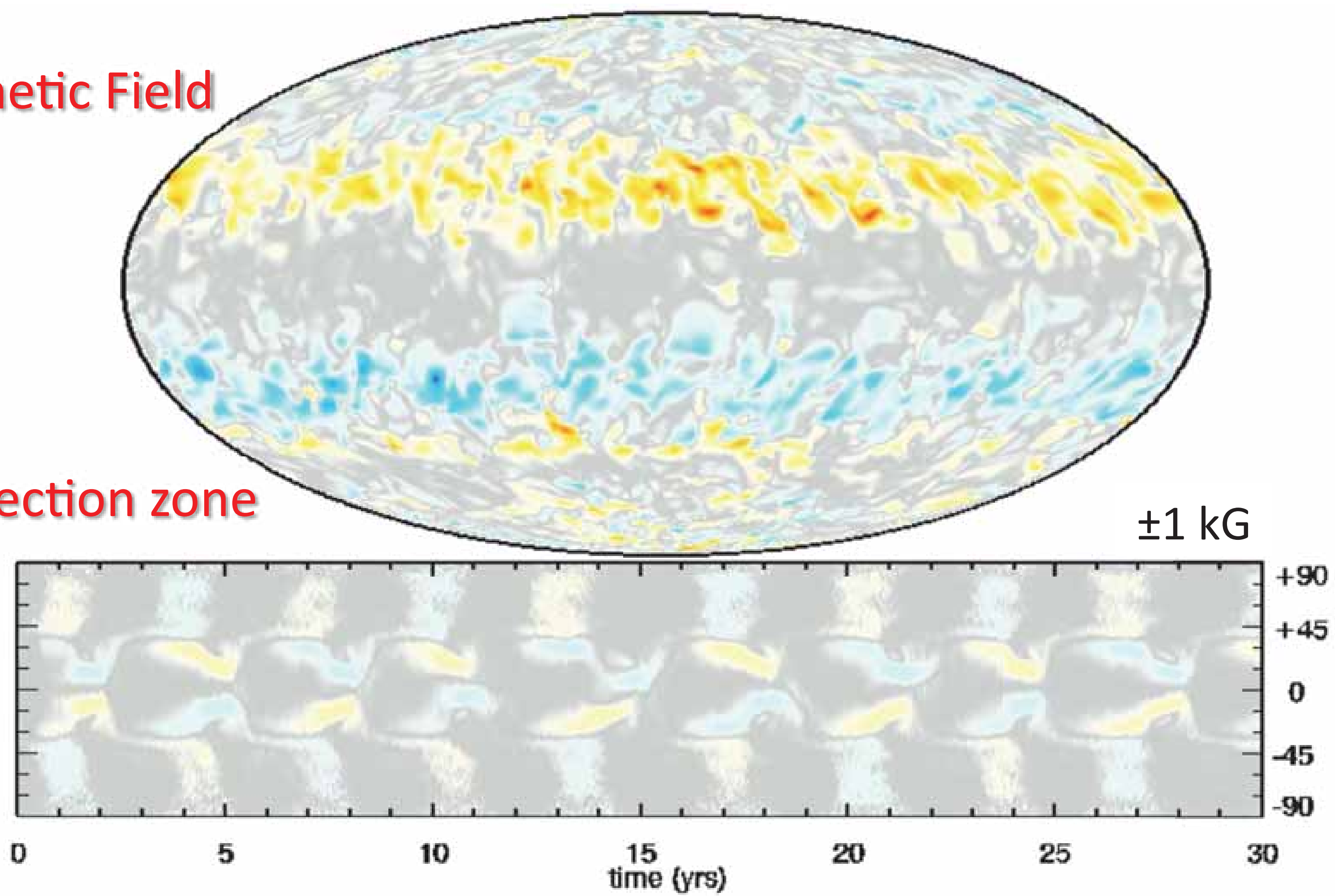
Augustson 2014

Wreaths and Magnetic Fields

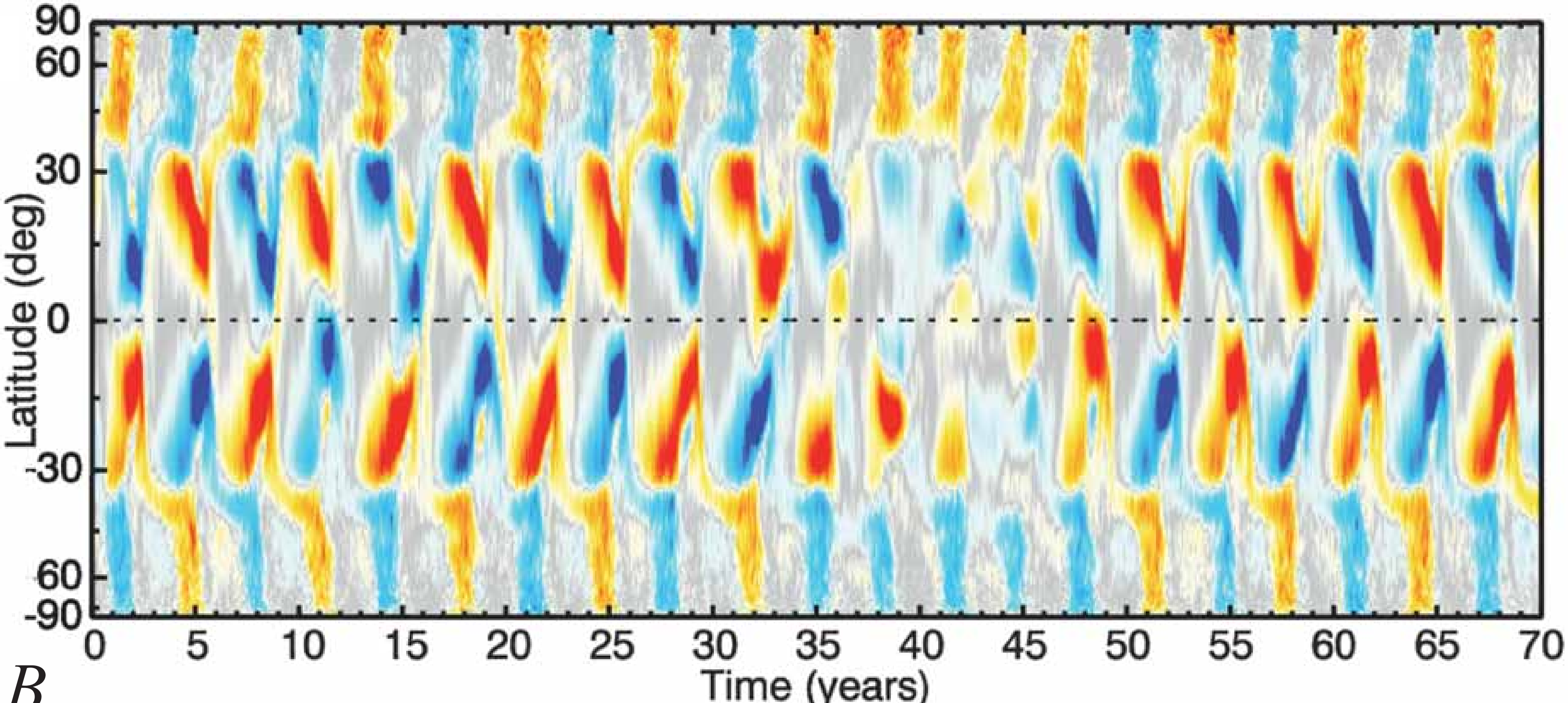


Toroidal Magnetic Field Evolution

In upper convection zone

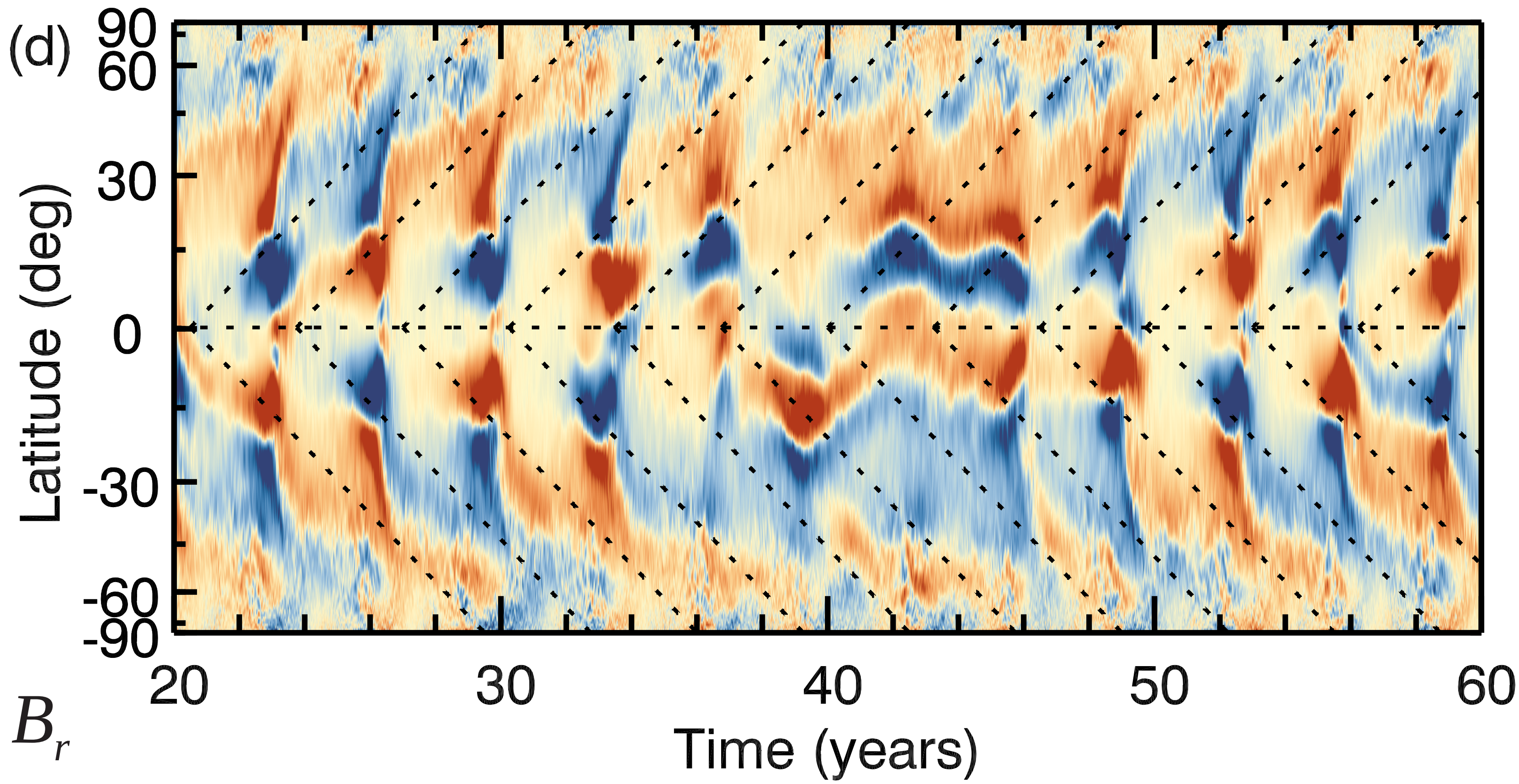


Long Running Cycles Punctuated with Grand Minimum

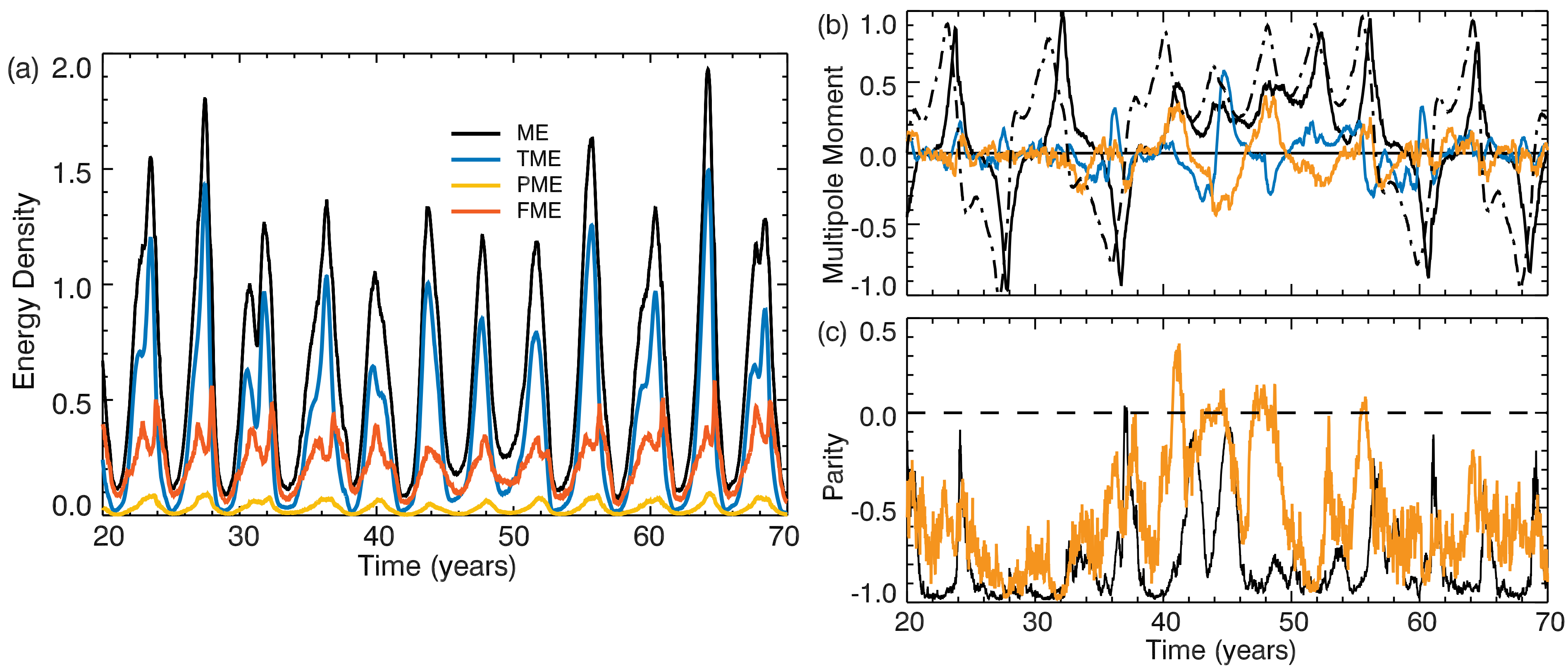


B_φ

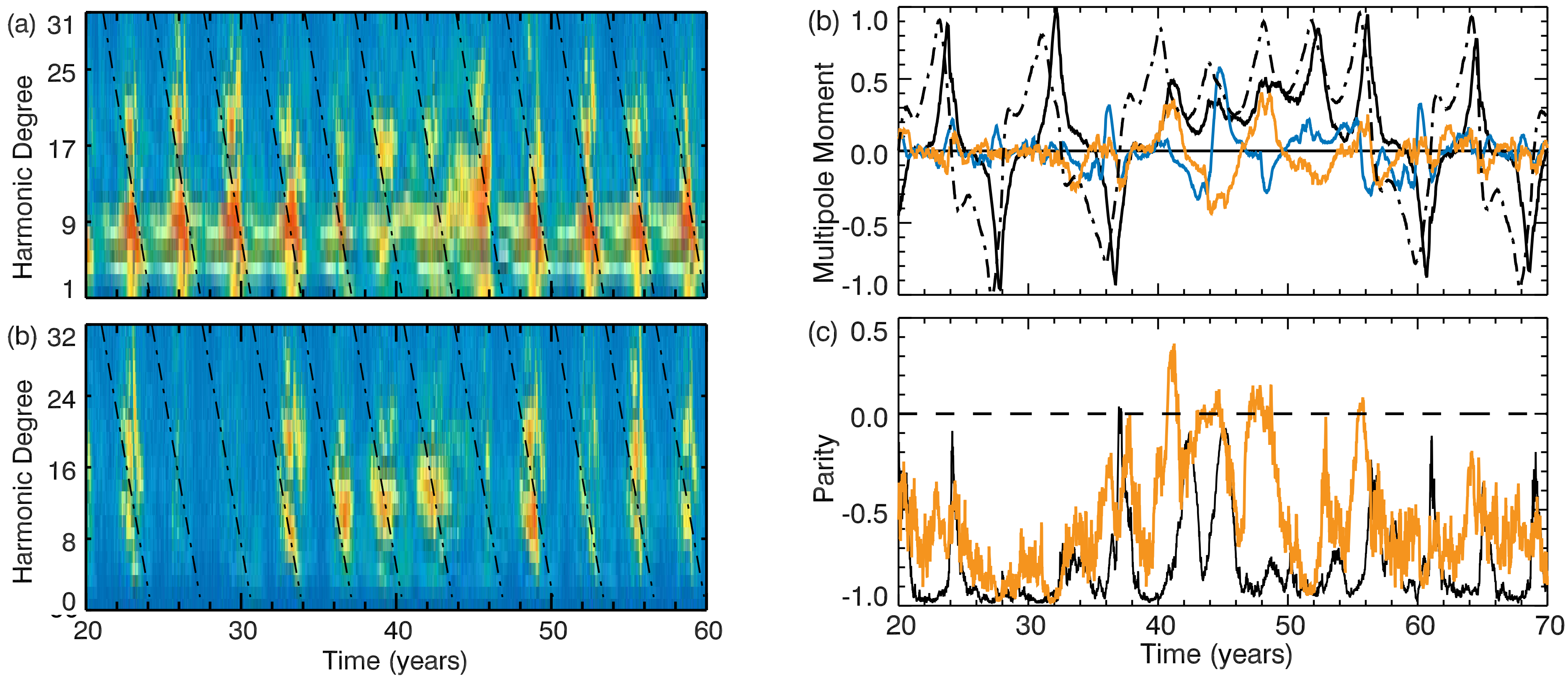
Long Running Cycles Punctuated with Grand Minimum



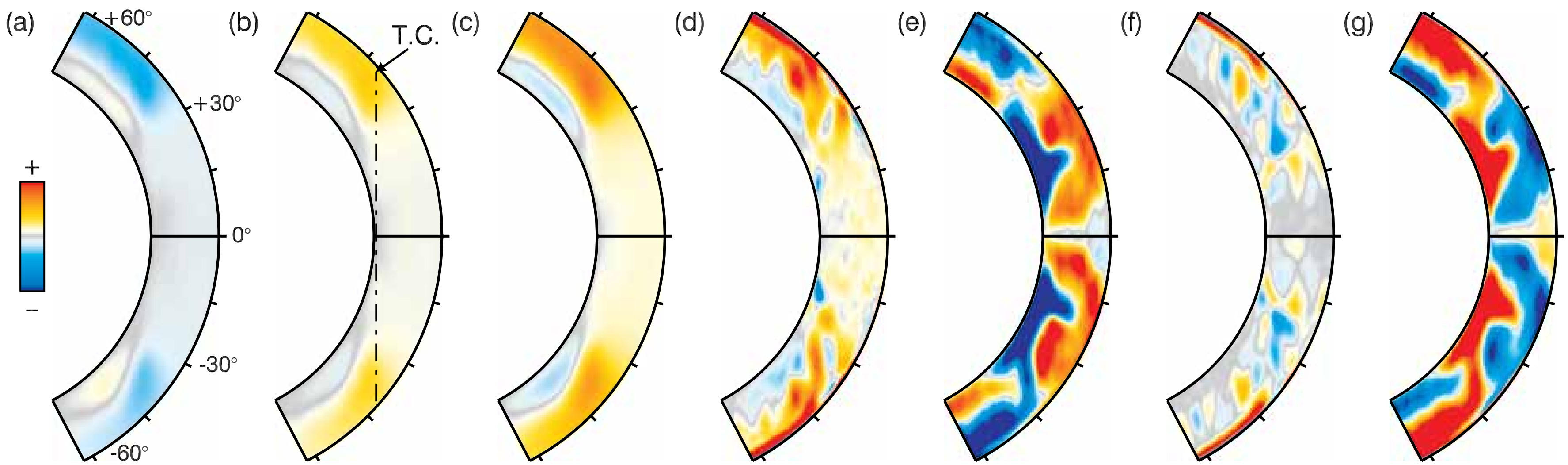
Long Running Cycles Punctuated with Grand Minimum



Long Running Cycles Punctuated with Grand Minimum



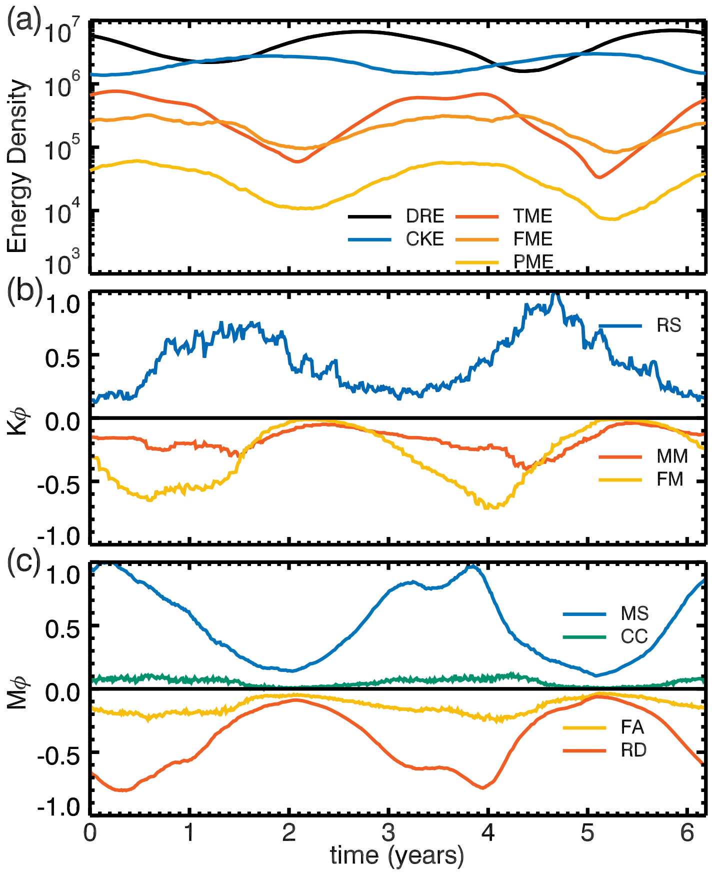
Time Evolution of Magnetic Energy Generation

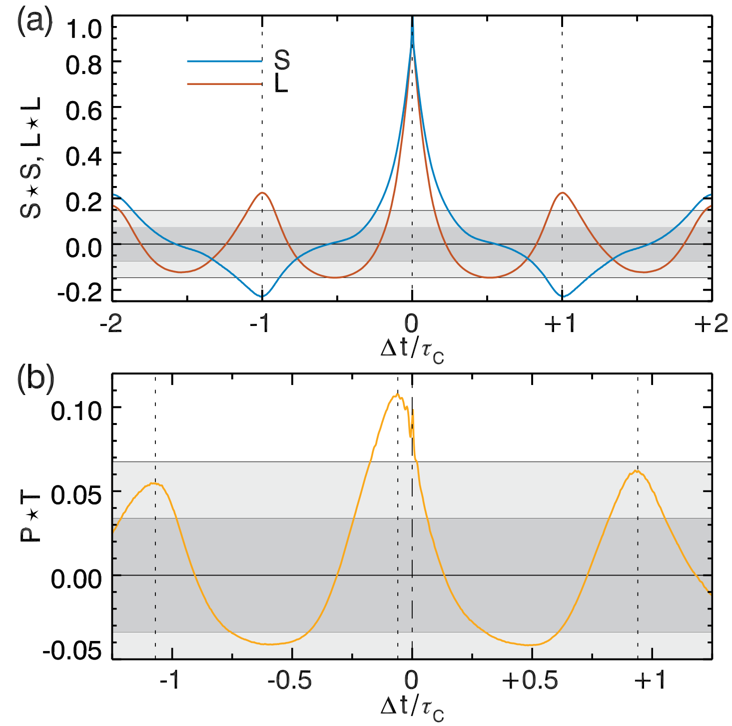


$$\Delta\langle A_\varphi\rangle = \langle A_\varphi\rangle_2 - \langle A_\varphi\rangle_1 = \int_{t_1}^{t_2} \hat{\varphi}\cdot\langle \mathbf{v}' \times \mathbf{B}'\rangle dt$$

$$+ \int_{t_1}^{t_2} \hat{\varphi}\cdot\left(\langle \mathbf{v}\rangle \times \langle \mathbf{B}\rangle\right) dt - \int_{t_1}^{t_2} \eta\langle J_\varphi\rangle dt.$$

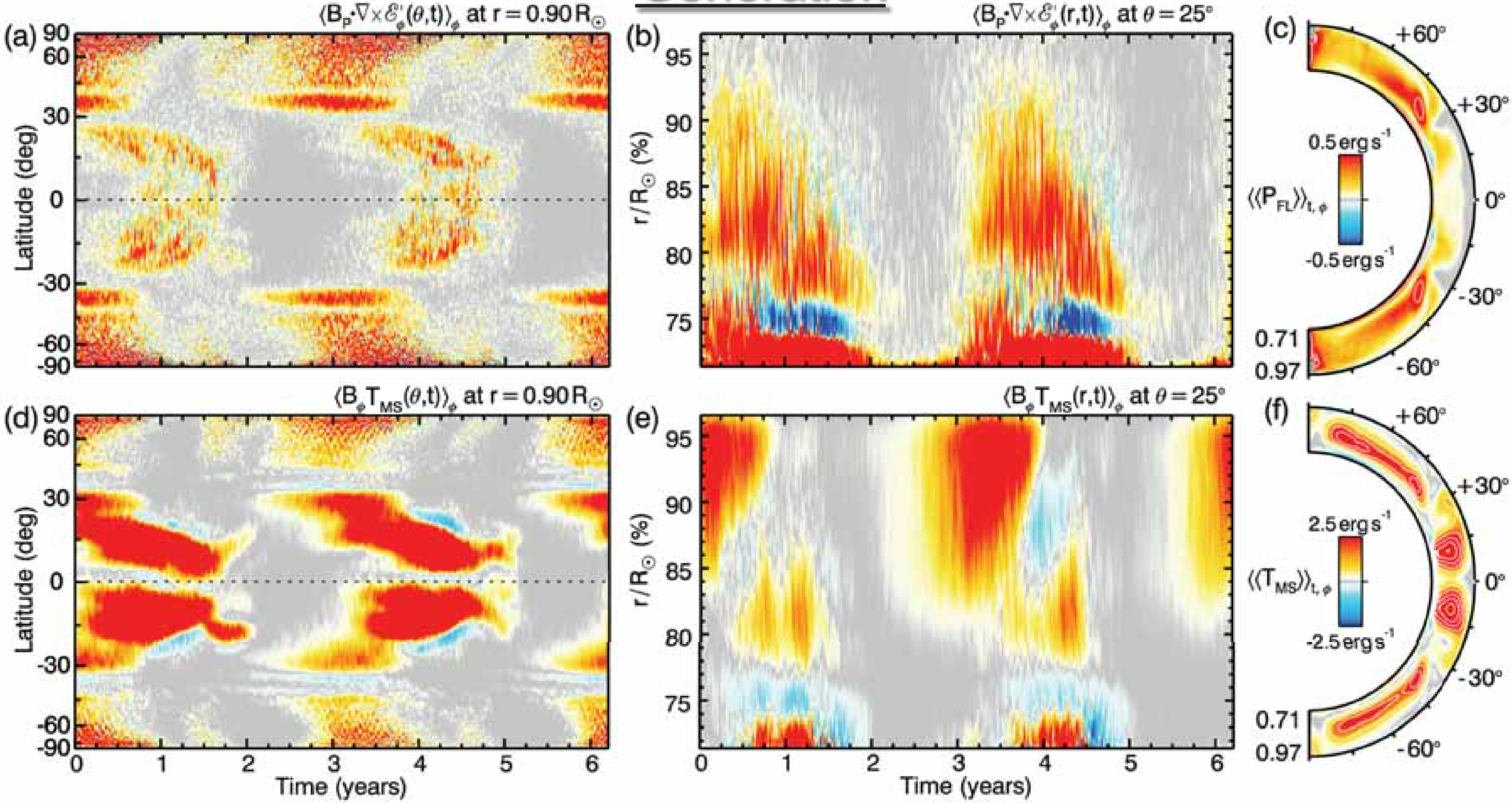
Time Evolution of Magnetic Energy Generation



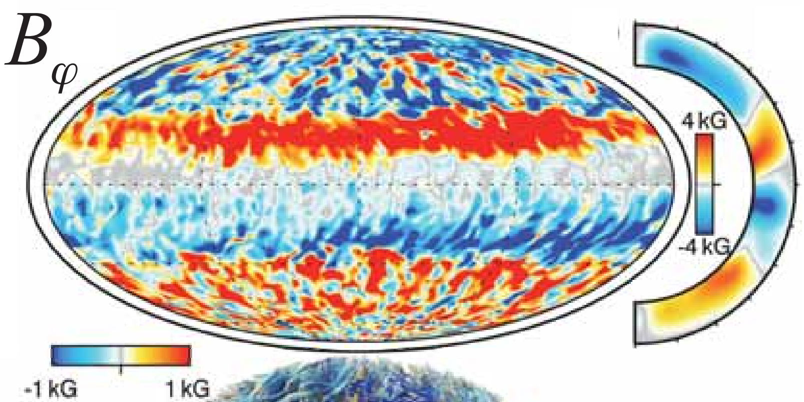


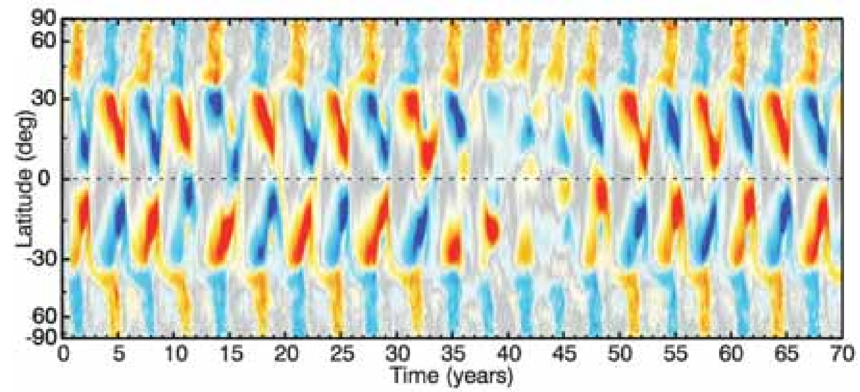
Time evolution of volume averaged kinetic and magnetic energy generation

Time Evolution of Magnetic Energy Generation

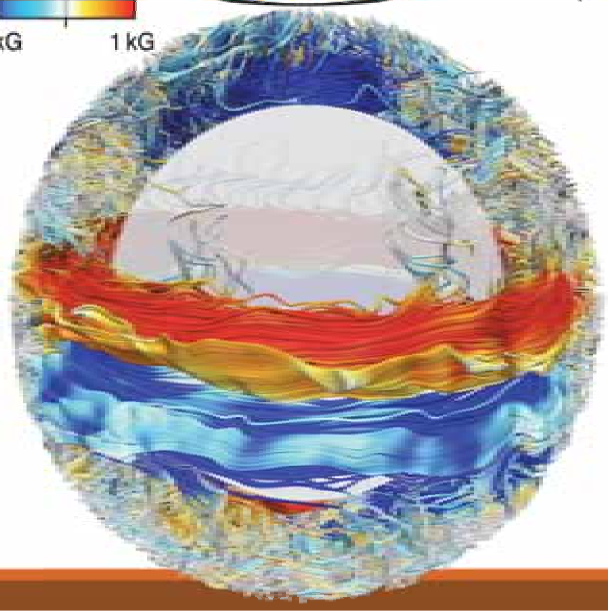


Cycling Wreaths of Magnetism in a Stellar Dynamo Simulation





Magnetic Field Lines



Features similar to the observed solar dynamo:

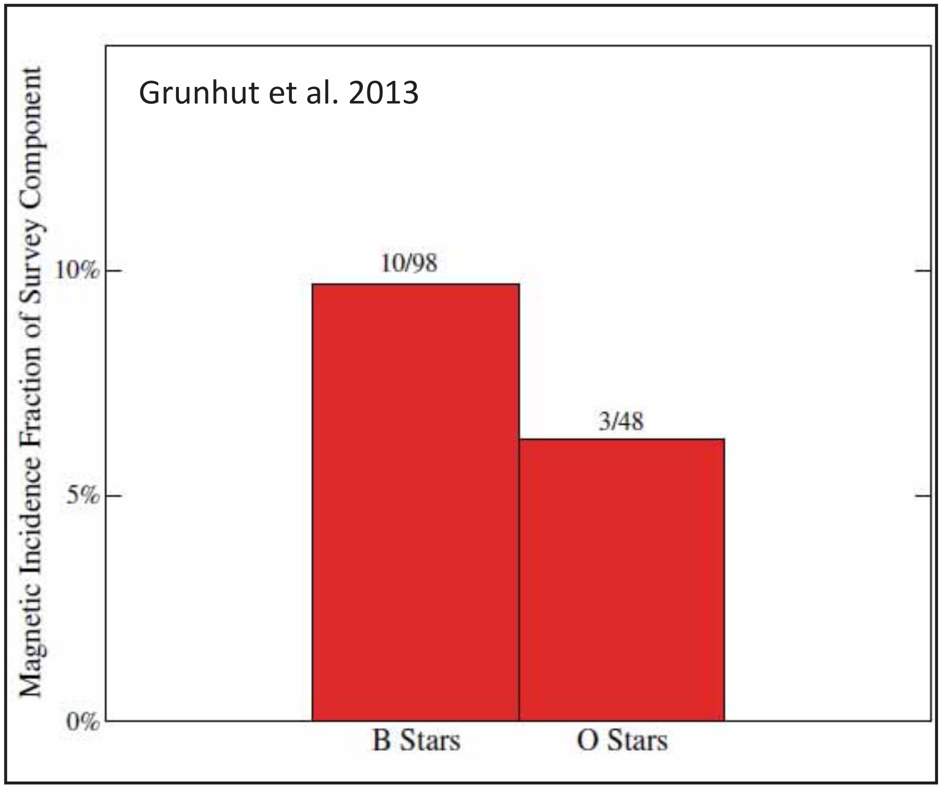
- Magnetic energy (activity) cycles
- Regular polarity reversals
- Equatorward propagation of magnetic structures
- Grand minimum

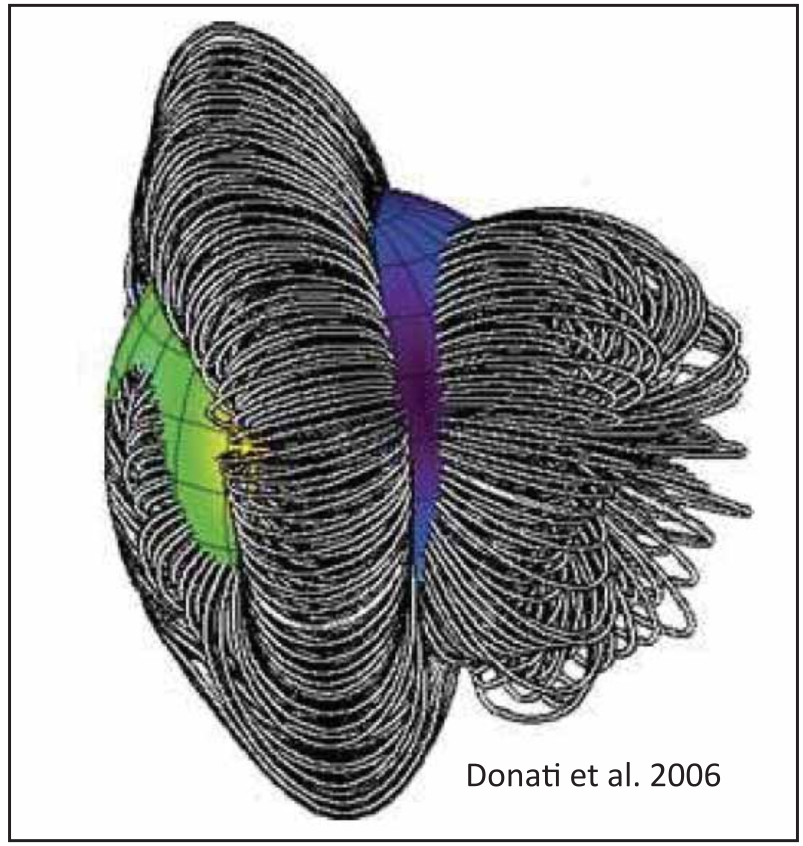
Physical processes at work (Augustson et al., ApJ, 2014):

- Polarity cycle arising from
  - Strong Lorentz-force feedback
  - Low-latitude poloidal field generation
  - Resistive collapse
- Equatorward propagation through a nonlinear dynamo wave
- Grand minimum arising from loss of phase correlation

Massive Stars and Core Convection

Massive Star Magnetism

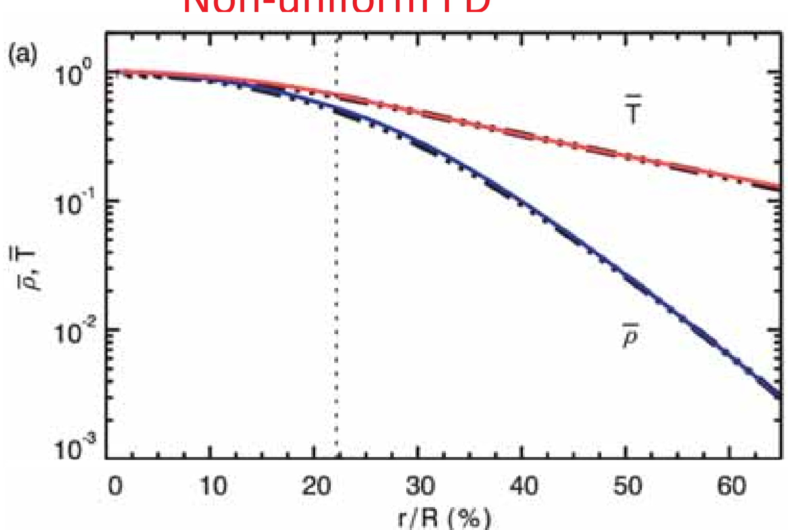




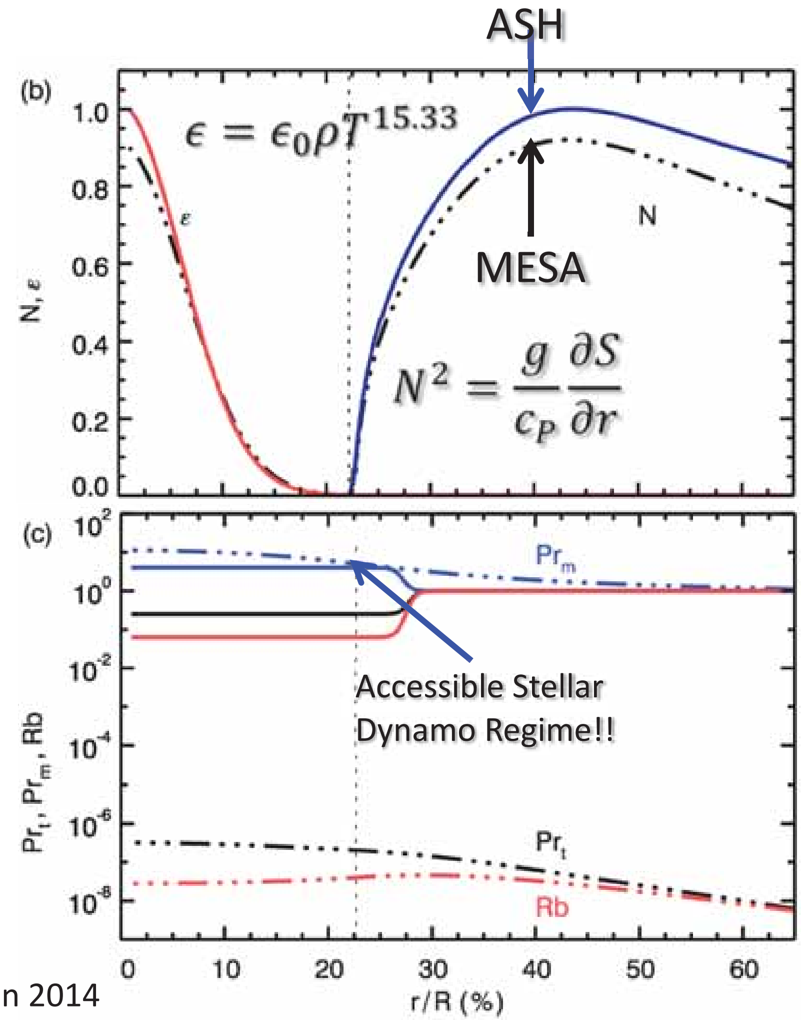
Problem Setup

MS B-type Star Simulations

- 10 Solar Masses (MESA)
- Rotation:
  30 – 480 km/s (v_{eq})
  0.1 – 50% of breakup
- Non-uniform FD

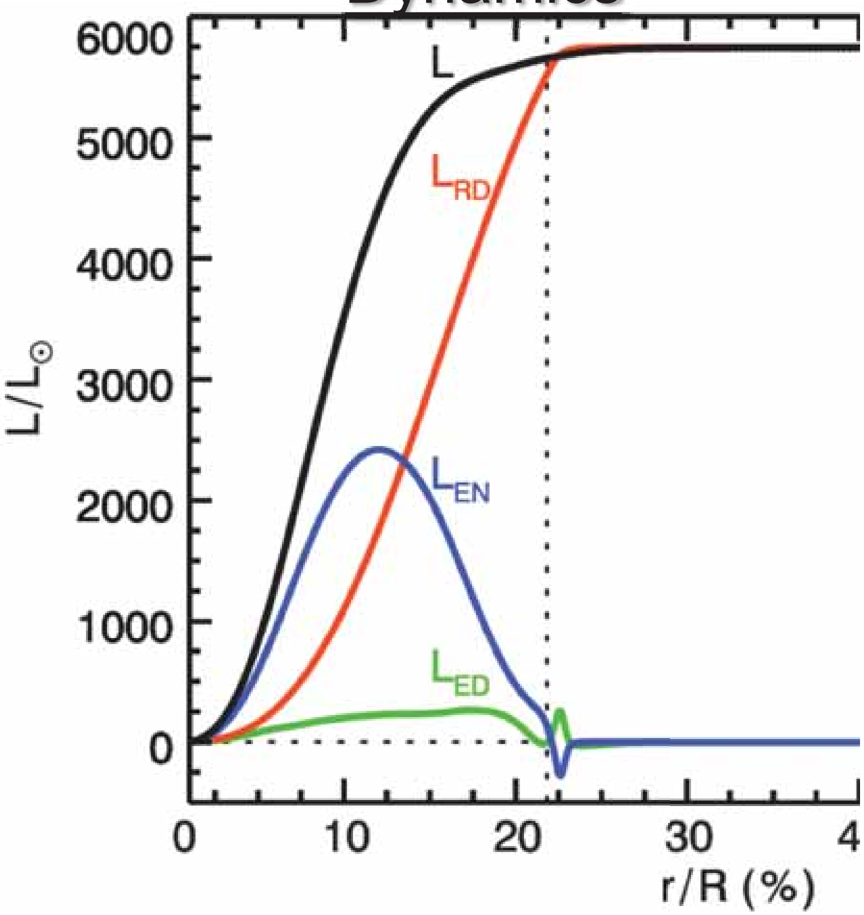


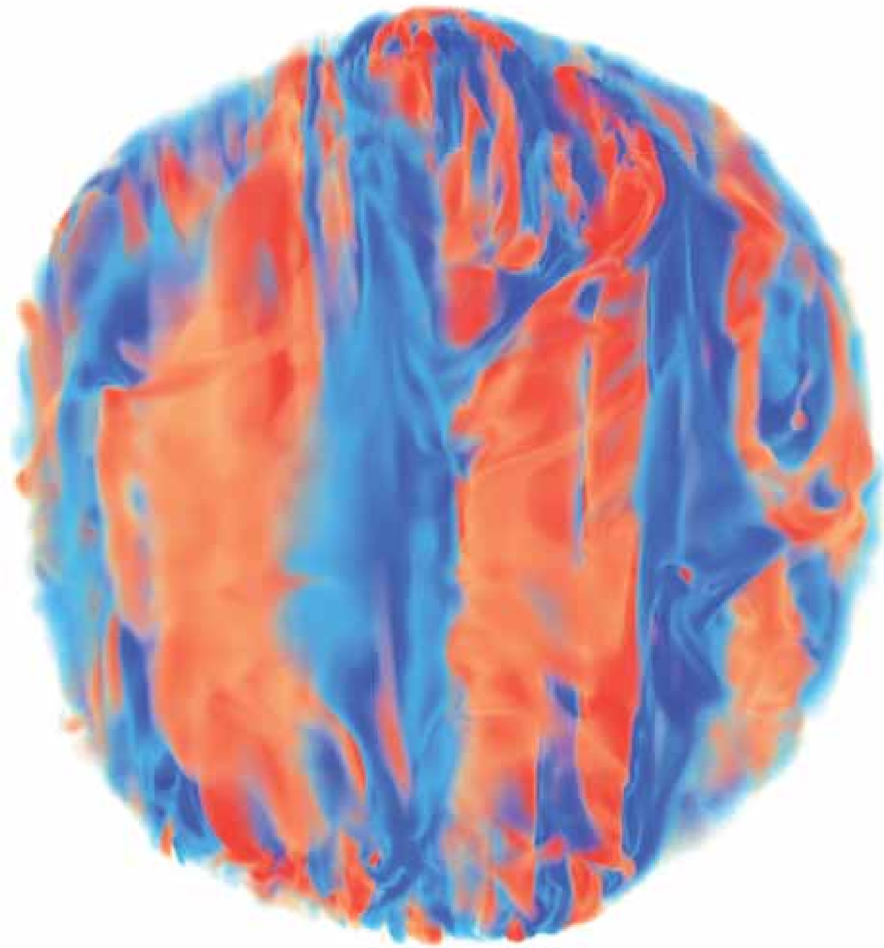
65% of the star



Augustson 2014

Energy Flux and Convective Dynamics



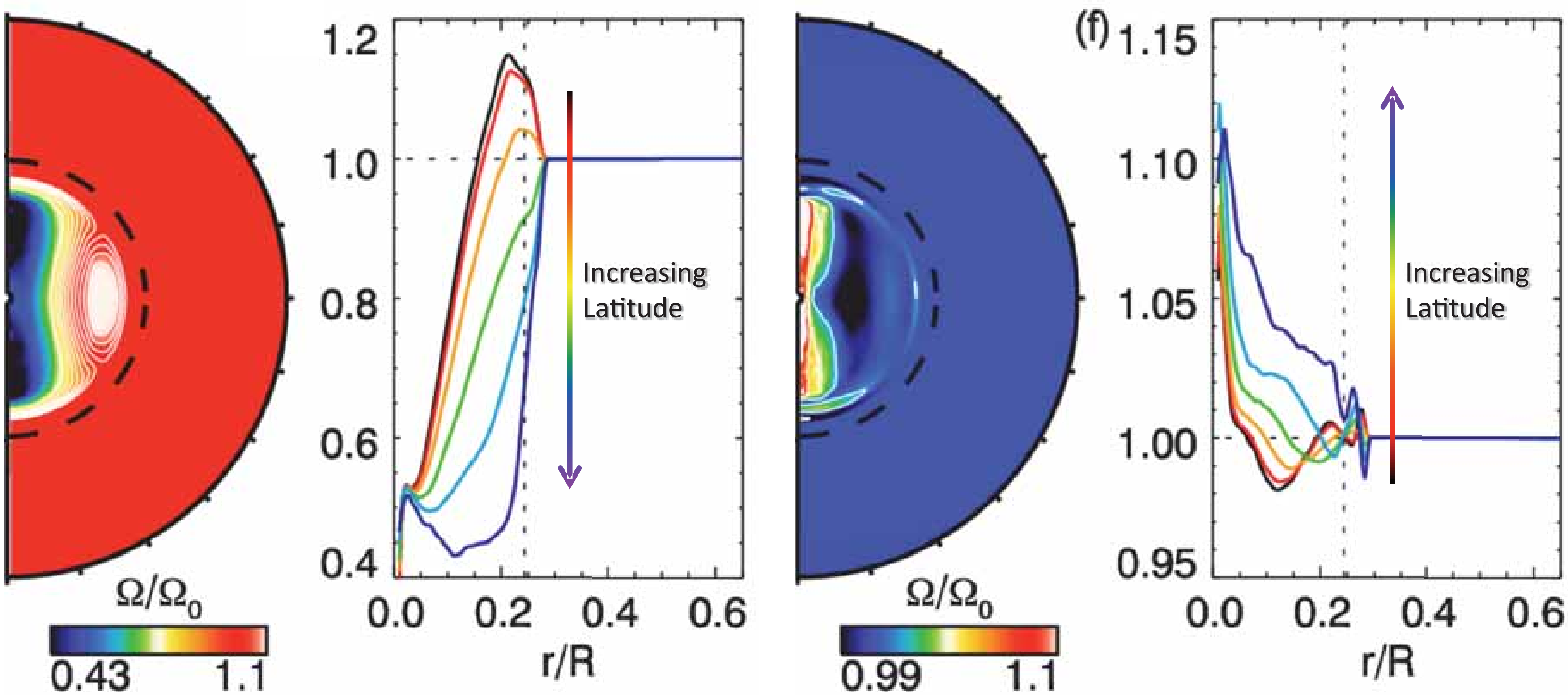


Augustson 2014

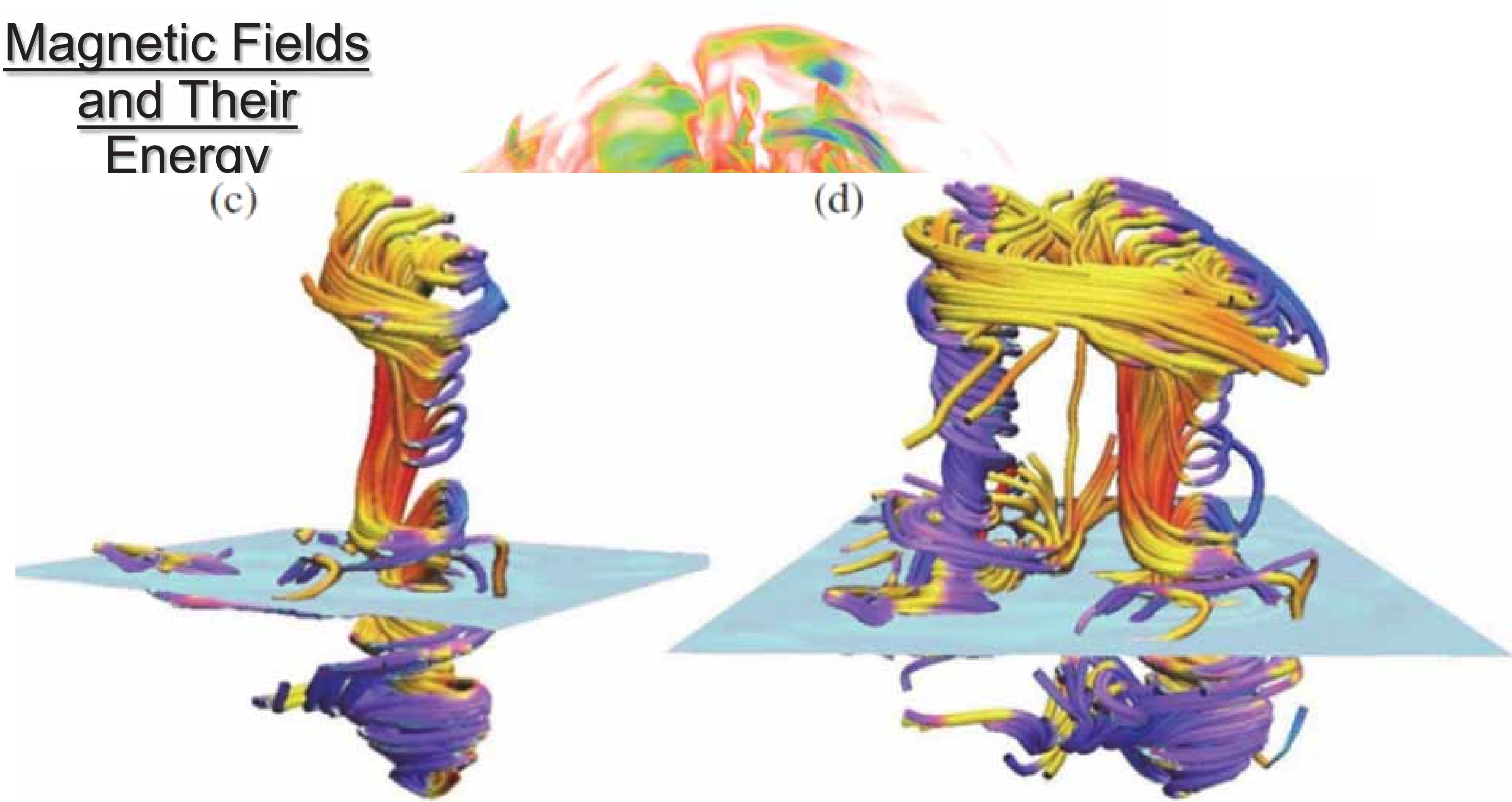
Hydrodynamics versus MHD

Marked difference in differential rotation

Augustson 2014



Magnetic Fields and Their Energy



Augustson 2014

Properties of B-type Star Convection and Magnetism

Case	KE	KE_{DR}	ME	FME	TME	ME/KE	B_{max}	$\Delta\Omega_r / \Omega_0$
H4	73.1	66.4 (91.%)	–	–	–	–	–	0.495
M4	3.91	0.17 (4.5%)	4.08	3.71 (91.%)	0.30 (7.4%)	1.06	0.76	-0.078
M8	2.20	0.14 (6.2%)	4.52	4.19 (93.%)	0.20 (4.5%)	2.07	1.06	-0.017
M16	1.42	0.09 (6.5%)	5.42	5.17 (95.%)	0.15 (2.8%)	3.86	1.17	-0.012
M64	1.22	0.06 (5.9%)	7.33	6.95 (95.%)	0.12 (1.6%)	6.01	1.53	-0.013

KE = Kinetic Energy
10^7 erg cm^{-3}

ME = Magnetic Energy
10^7 erg cm^{-3}

B_{max} in MG

Augustson 2014

Magnetostrophic Balance

Cases	Λ	Rm'	Λ_D	Ro	$Ro^{-1}\Lambda_D$	ME/KE
M4	330	2080	0.15	0.35	0.42	1.06
M8	493	1960	0.25	0.16	1.5	2.07
M16	383	1640	0.23	0.06	3.83	3.86

$$\Lambda_D = \frac{(1/4\pi)\boldsymbol{\nabla} \times \boldsymbol{B} \times B}{\rho 2\boldsymbol{\Omega} \times \boldsymbol{u}} = \frac{(1/8\pi)B^2}{\rho\Omega u L}$$

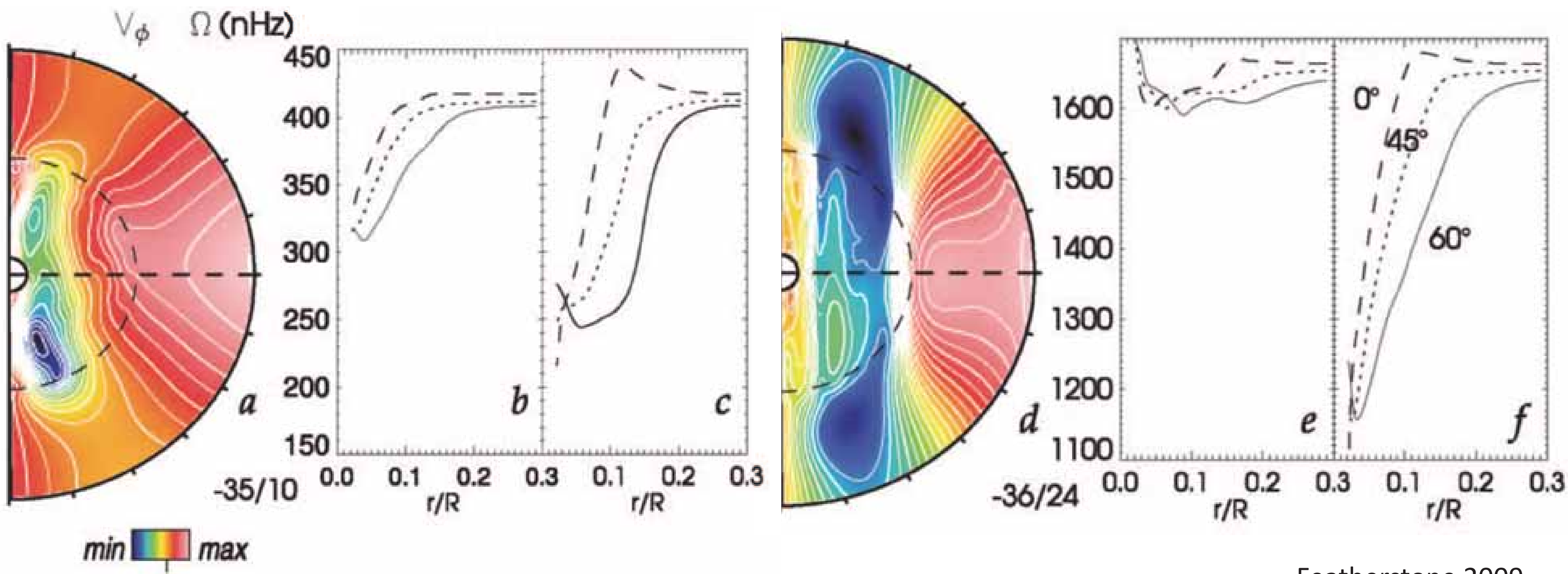
$$\Lambda = \frac{(1/8\pi)B^2}{\rho\Omega\eta} = \Lambda_D Rm$$

$$\Lambda_D = \frac{(1/8\pi)B^2}{\rho\Omega u L} = \frac{(1/8\pi)B^2}{(1/2)\rho(u^2)} Ro \qquad \Longrightarrow \qquad \frac{ME}{KE} = \Lambda_D Ro^{-1}$$

Augustson 2014

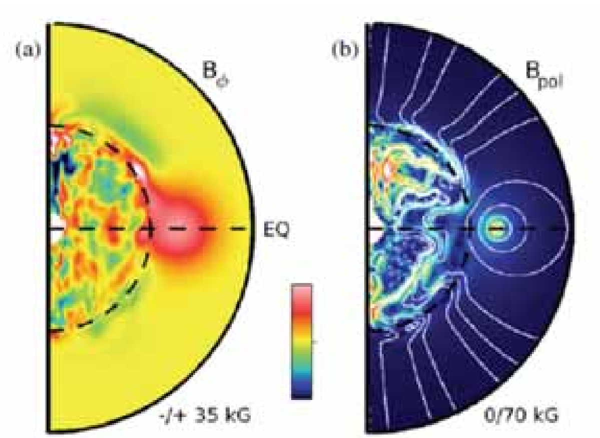
Hydrodynamics versus MHD

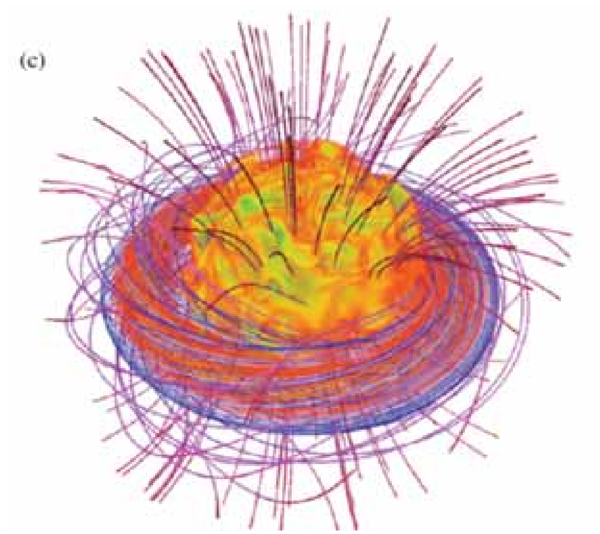
Marked difference in differential rotation

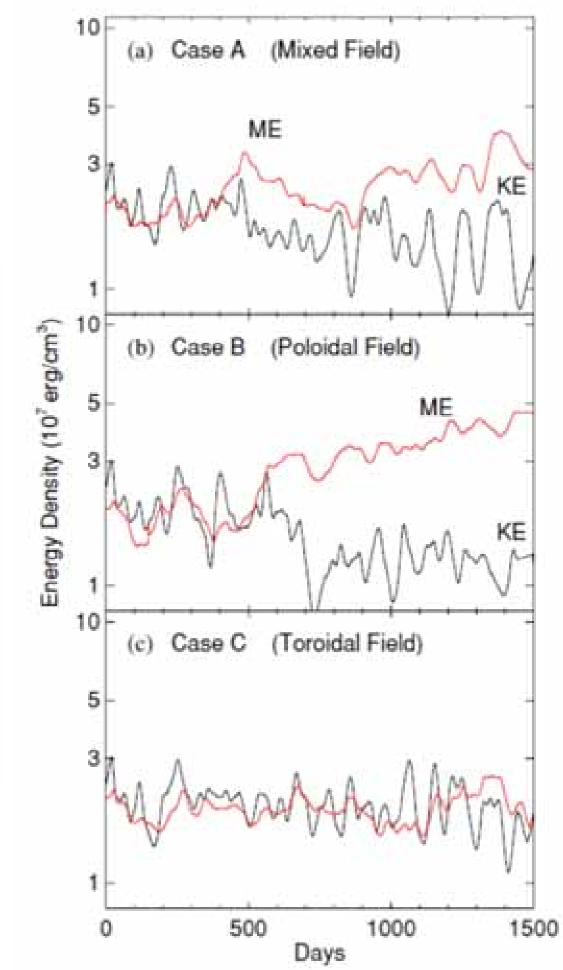


Featherstone 2009

Impact of Fossil Field Geometry

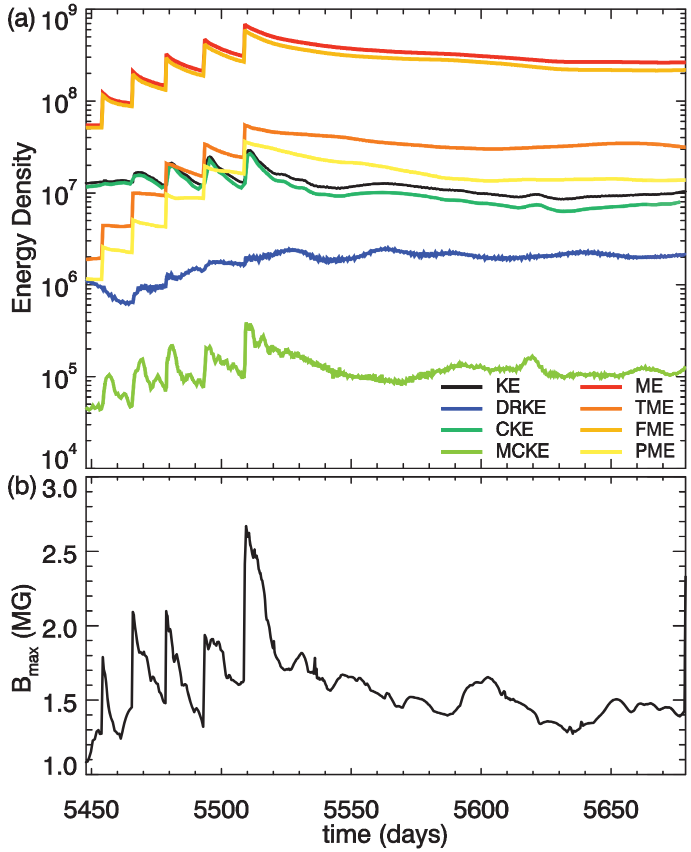




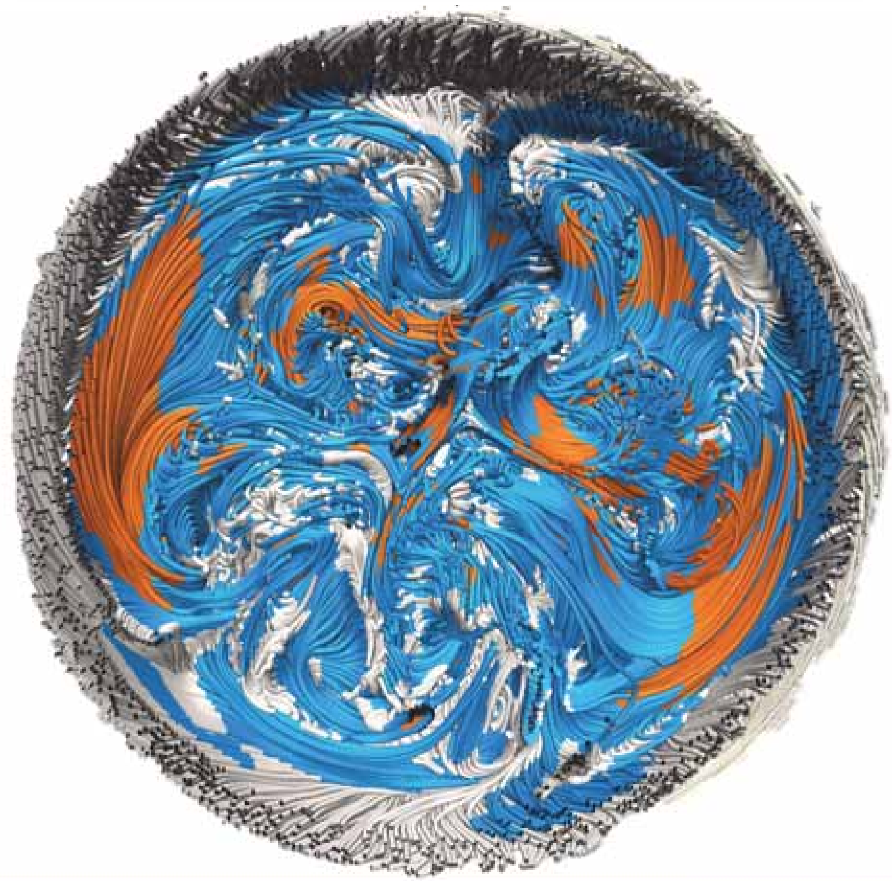


Featherstone 2009

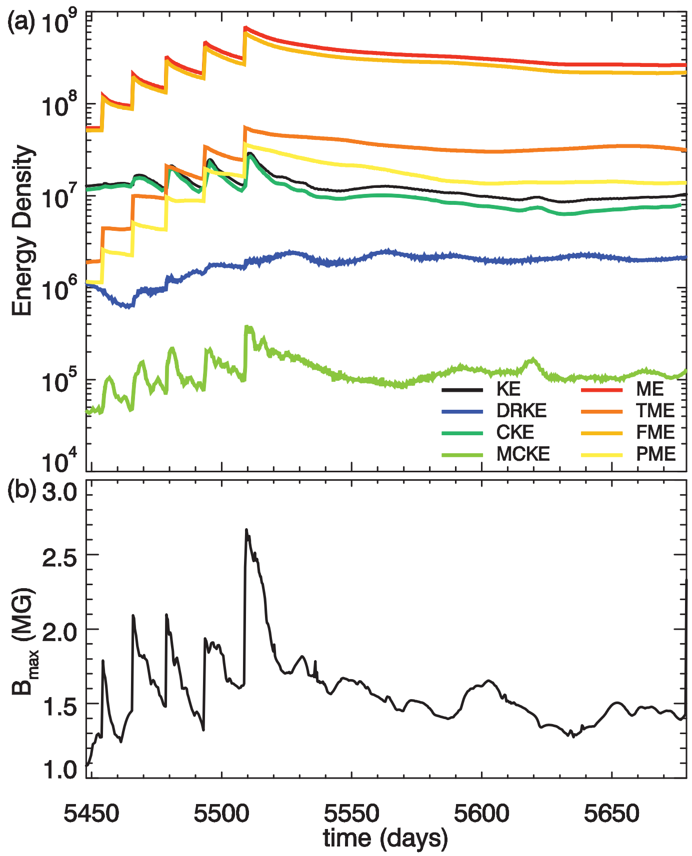
Impact of Initial Conditions



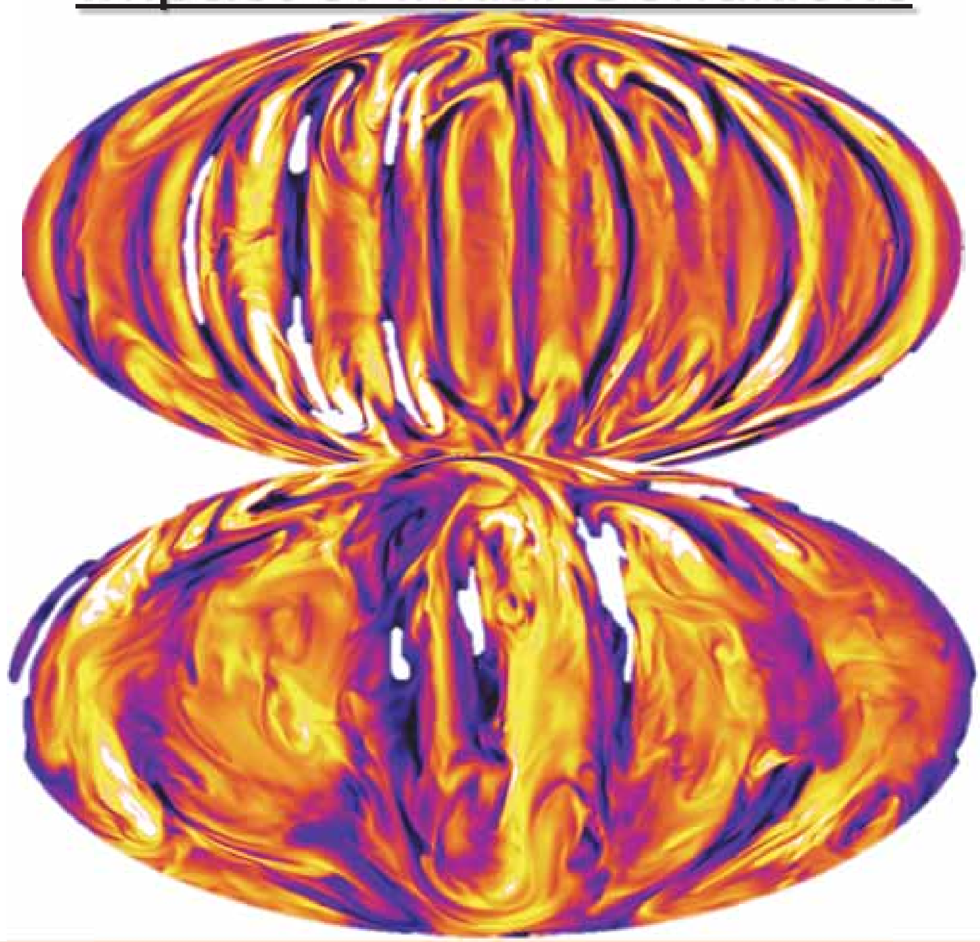
Augustson 2014



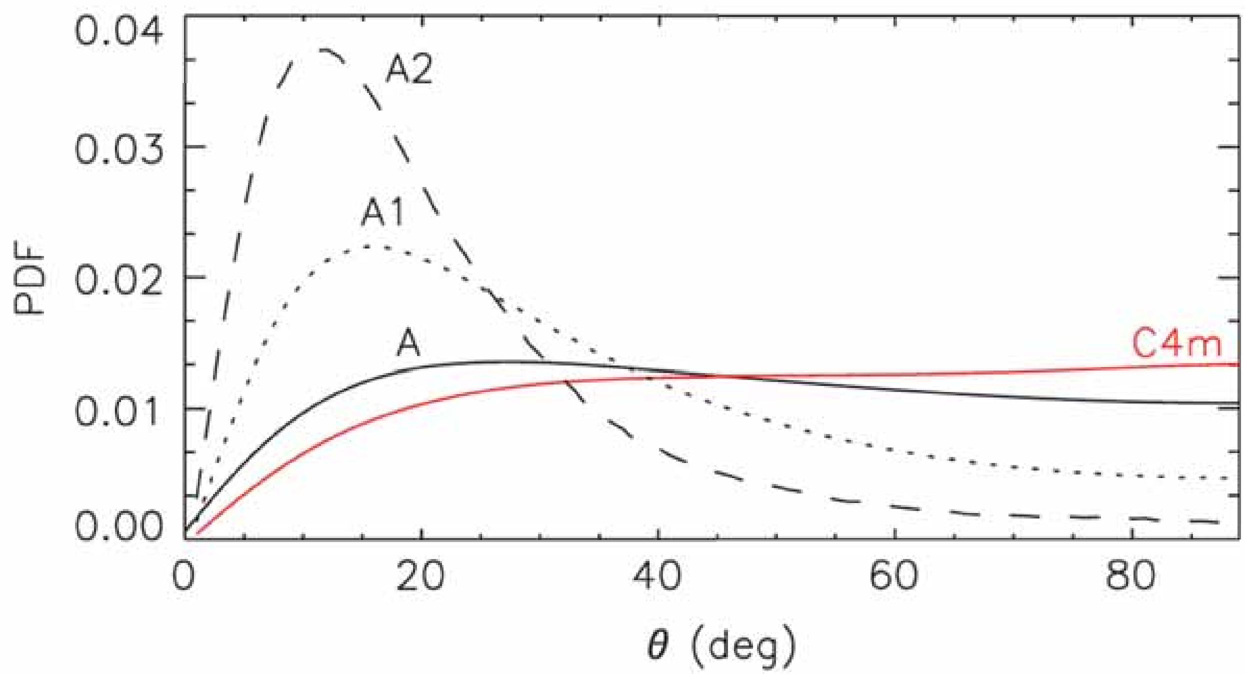
Impact of Initial Conditions



Augustson 2014



How can such states exist?



$\theta = \cos^{-1}(v \cdot B / |v||B|)$

Increasing superequipartition levels lead to increasing alignment

Featherstone 2009

Summary and Outlook

– Rossby number

  Rotational scaling of: cycle period and activity

  What are appropriate Rossby numbers?

  Stellar convective amplitudes & energy transport?

– Strong internal magnetic states

  Impacts upon transport & field morphology

  How far can super-equipartion be pushed?

– Influence of a stable radiative interior?

– Is there such a thing as a nonmagnetic star?