Simulations 3-D Hautes Performances de la MHD Stellaire

par Allan Sacha BRUN
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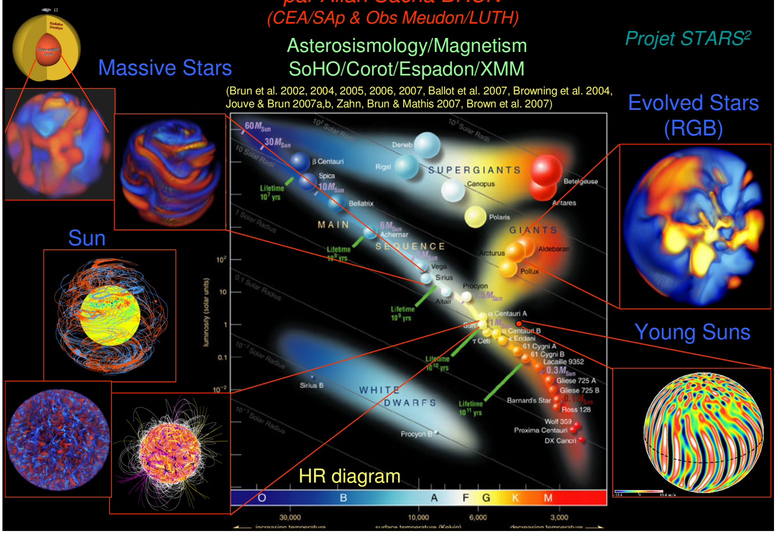
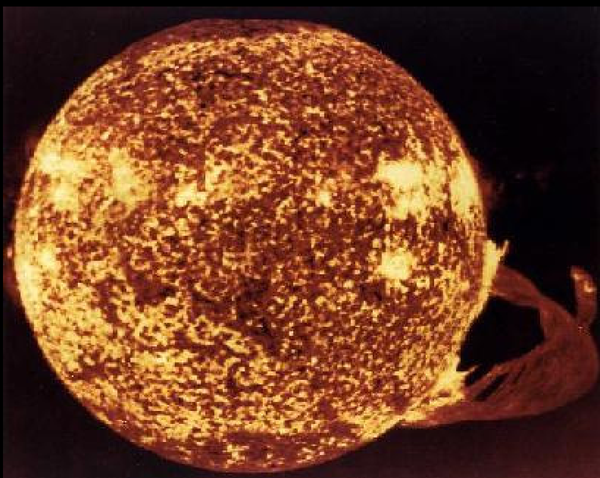
Asterosismology/Magnetism
SoHO/Corot/Espadon/XMM

Projet STARS²

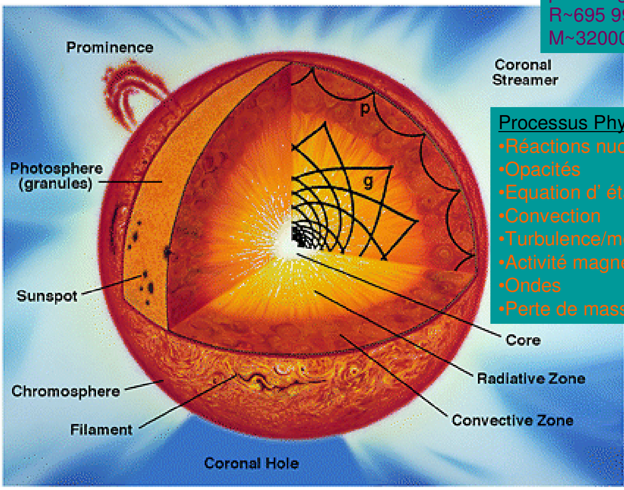
(Brun et al. 2002, 2004, 2005, 2006, 2007, Ballot et al. 2007, Browning et al. 2004, Jouve & Brun 2007a,b, Zahn, Brun & Mathis 2007, Brown et al. 2007)



Le Soleil



$T_c \sim 15.5\ 10^6$ K
$\rho_c \sim 155$ g/cm3
R~695 990km
$M \sim 320000\ M_{terre}$



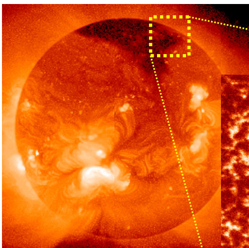
Processus Physiques:

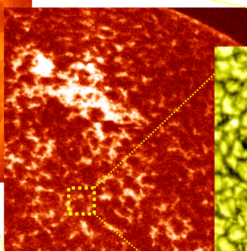
- Réactions nucléaires
- Opacités
- Equation d' état
- Convection
- Turbulence/mélange
- Activité magnétique
- Ondes
- Perte de masse

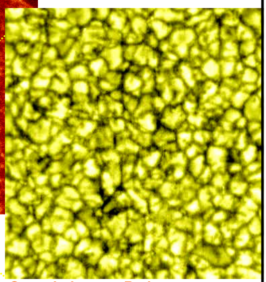
Échelles Spatio-Temporelles dans la Zone Convective Solaire

Plasma= gaz chaud (ionisé)
4^{eme} etat de la matière

L'Ordre dans le Chaos!







Grosses structures:
Eruptions,
Trous coronaux,
CMEs

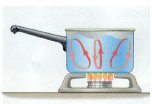
Cellules Géantes?
200+ Mm
10-20 jours

Supergranulation:
30-50 Mm
20 heures

Mesogranulation?
7-10 Mm
2 heures

Granulation:
1-2 Mm
5 mins

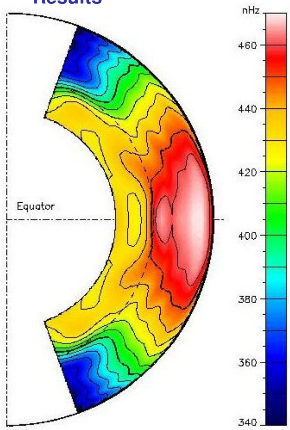
Petites structures:
Lignes Intergranulaires,
Points magnétiques
brillants, diffusion

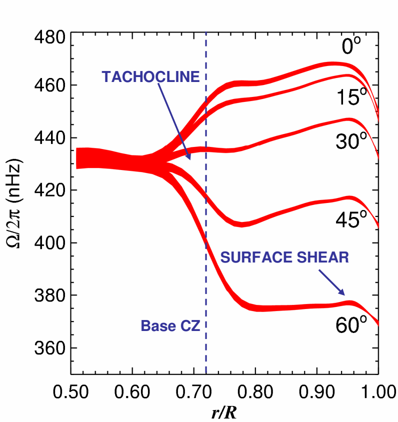


Solar Internal Rotation

(GONG, MDI data)

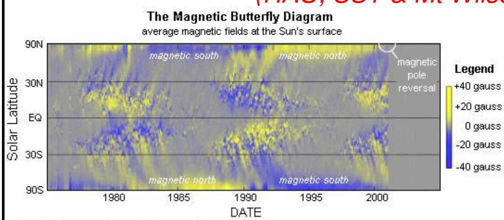
Helioseismology Results

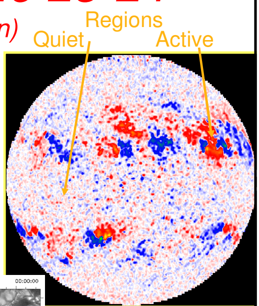




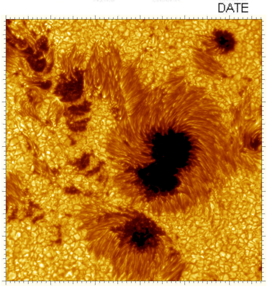
Solar Magnetic Cycle 23-24

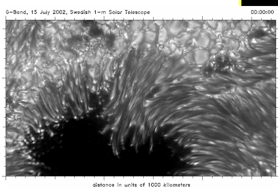
(HAO, SST & Mt Wilson)





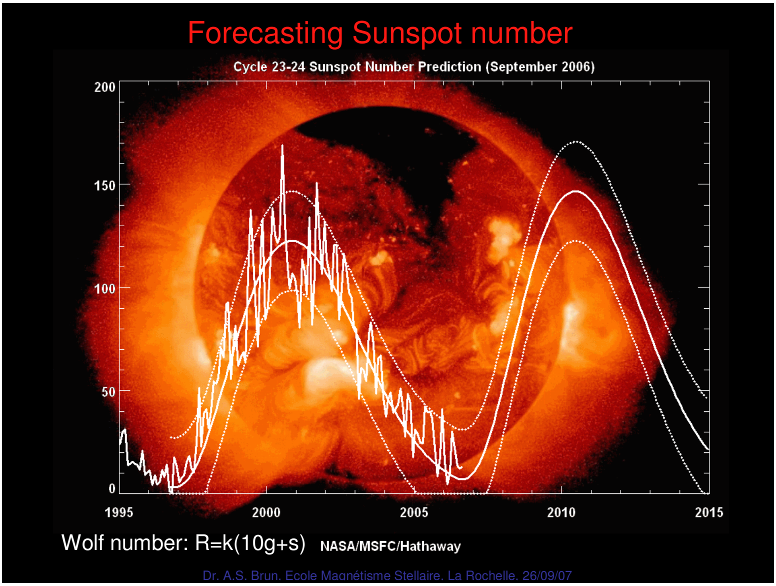
5895.9Å Na I
Magnétogramme

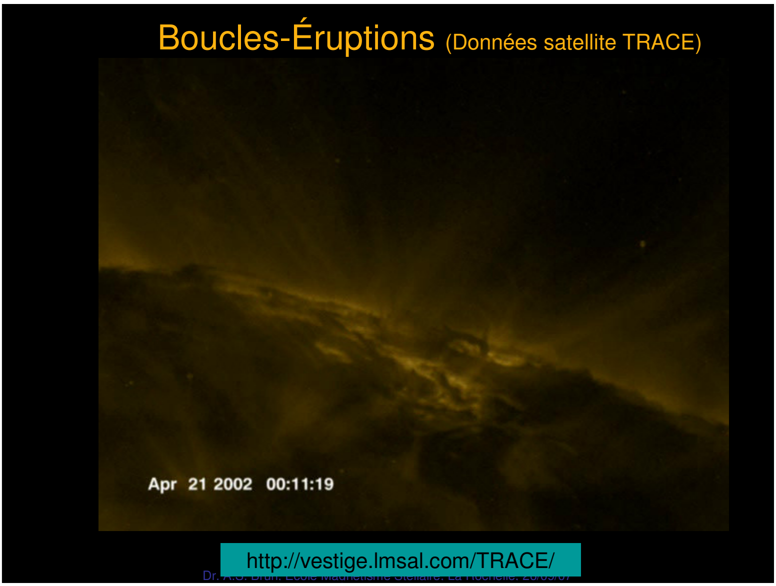




Small vs large scale dynamos

Large range of scales !

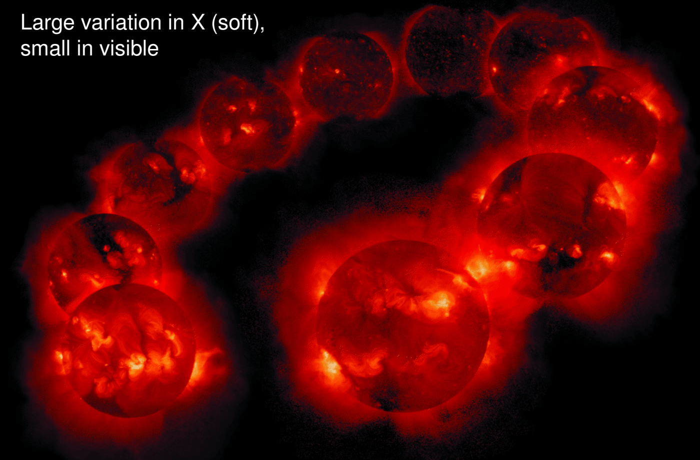

Forecasting Sunspot number
Cycle 23-24 Sunspot Number Prediction (September 2006)
200
150
100
50
0
1995
2000
2005
2010
2015
Wolf number: R=k(10g+s)
NASA/MSFC/Hathaway
Dr. A.S. Brun, Ecole Magnétisme Stellaire, La Rochelle, 26/09/07


Boucles-Éruptions (Données satellite TRACE)
Apr 21 2002 00:11:19
http://vestige.lmsal.com/TRACE/
Dr.

Solar Cycle 22 (Yohkoh)

http://www.lmsal.com/SXT/homepage.html

Large variation in X (soft),
small in visible

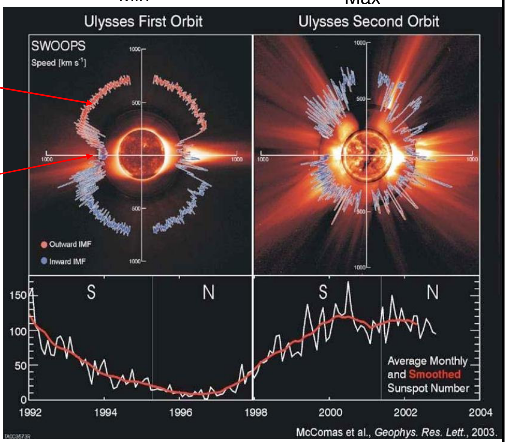


Vent solaire et Champ Coronal

Rapide là où les lignes de champ magnétiques sont ouvertes (troux coronaux)

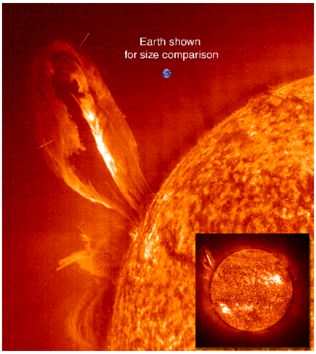
Lent là où les lignes de champ magnétiques sont fermées (streamers)

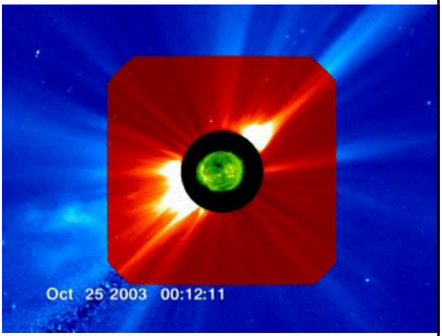
Min Max



Il faut 2.5 à 4.5 jours au vent solaire pour atteindre la Terre.
Il est composé surtout d'hydrogène ionisé (proton + électrons), de 8% d'hélium et de traces

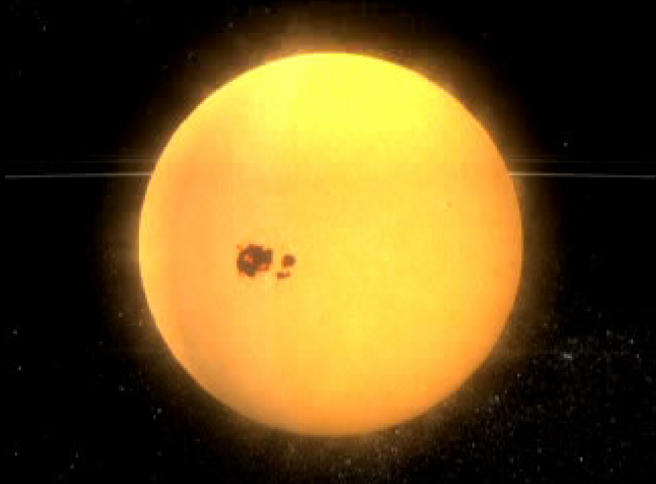
Éjections Solaires (CME's)





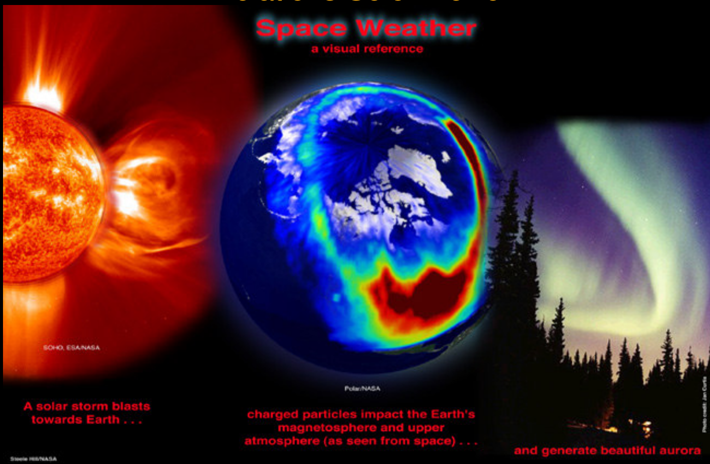
SoHO-EIT & Lasco

Ejection de Masse Coronale



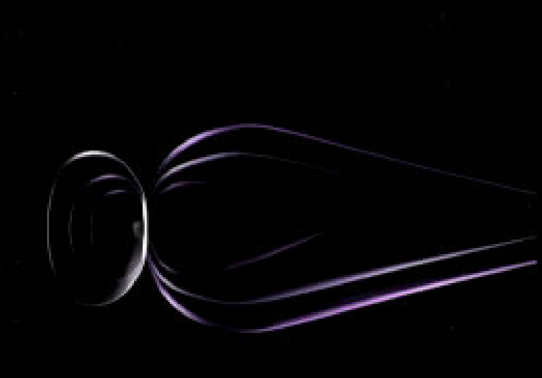
Nasa

Relations Soleil-Terre



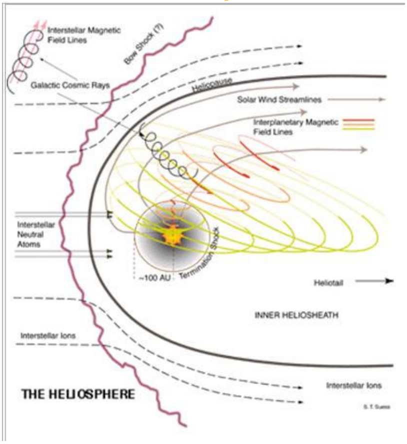
Aurores boréales

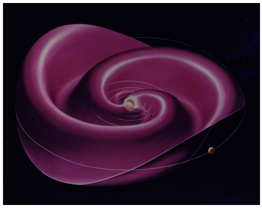
Relations Soleil-Terre (reconnection, sous orages)



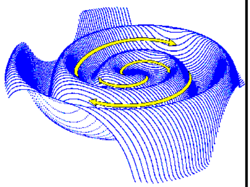
Nasa

Héliosphère

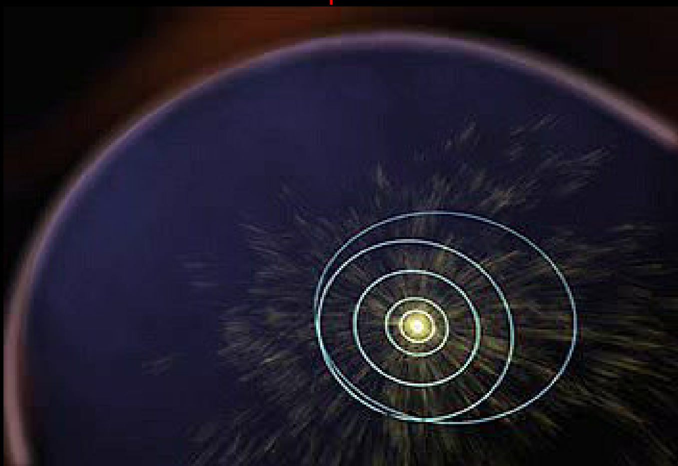




Spirale de Parker et Couche de Courant Neutre Héliosphérique



Héliosphère



Nasa

Equations MHD

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.(\rho \vec{v}) = 0$$

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v}.\vec{\nabla})\vec{v} = -\frac{\vec{\nabla} p}{\rho} - \frac{\vec{\nabla}.\vec{D}}{\rho} - g\hat{r} + 2\vec{v}\times\vec{\Omega} + \frac{1}{c}\vec{j}\times\vec{B}$$

$$\frac{\partial S}{\partial t} + \vec{v}.\vec{\nabla} S = \frac{1}{\rho T}\vec{\nabla}.(\kappa\rho T\vec{\nabla} S + \kappa_r \rho c_p \vec{\nabla} T) + \frac{2\nu}{T}[e_{ij}e_{ij} - \tfrac{1}{3}(\vec{\nabla}.\vec{v})^2] + Q_{ohm}$$

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

Cas d'un Fluide Stratifié Compressible
sous l'influence de la Rotation et du Champ Magnétique

3D MHD Code ASH (Anelastic Spherical Harmonics)
(Clune et al. 1999, Miesch et al. 2000, Brun et al. 2004)

Code ASH (Anelastic Spherical Harmonics)

(Clune et al. 1999, Miesch et al. 2000, Brun et al. 2004)

Approximation anélastique: filtre les ondes sonores mais garde la stratification

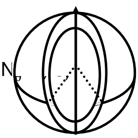
Décomposition Poloidal-Toroidal : conserve divergence ρu and B à la précision numérique

Approche LES-SGS: diffusivités effectives (turbulentes) ν, κ, η et flux d'énergie non résolu, F α kdS/dr

Méthode Pseudo-Spectrale:

Dimensions **Horizontales** : harmoniques sphériques $\mathbf{Y_l^m}$ (up to $l=l_{\mathbf{max}}$ =(2N

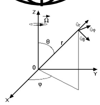
Dimension **Radiale** : polynômes de Chebyshev (N_r points collocation),



Evolution Temporelle:

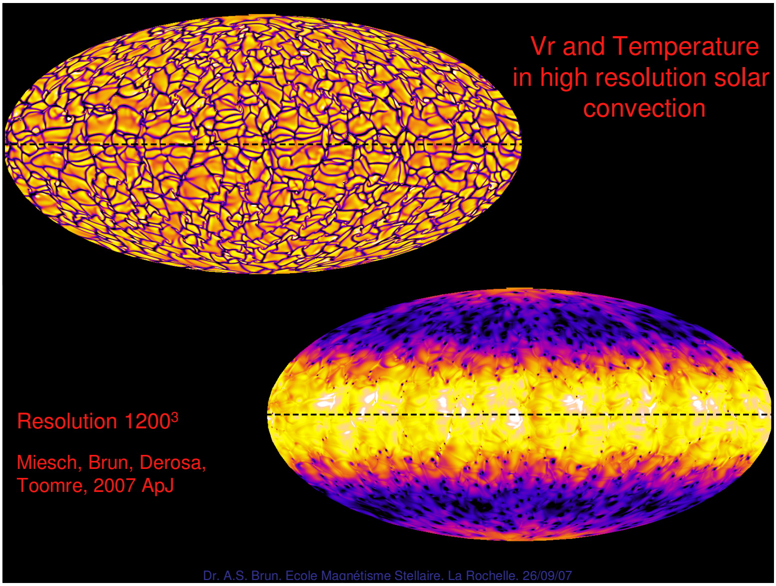
Termes Linéaires: Crank - Nicolson 2nd ordre (implicite),

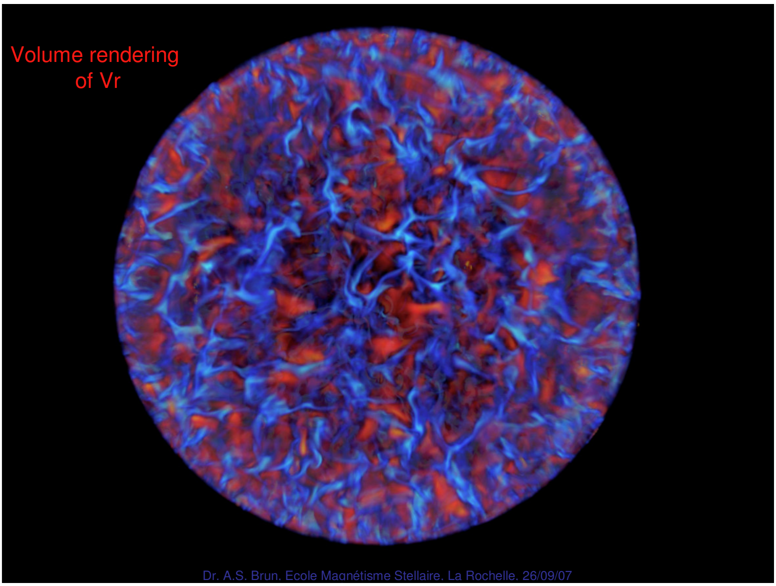
Termes NonLinéaires, Coriolis & Laplace: Adams-Bashforth 2nd ordre (expl



Parallélisme: *Langage de communication MPI*:

Derniers superordinateurs (HP TCS-1 (CCRT) & IBM SP4 (IDRIS, SDSC) atteignent 900 Mflops/pe. Plus grands nombres de cpus utilisés: 1072

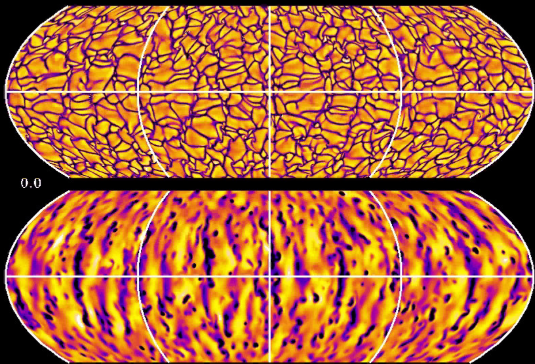

Vr and Temperature
in high resolution solar
convection
Resolution 1200³
Miesch, Brun, Derosa,
Toomre, 2007 ApJ
Dr. A.S. Brun. Ecole Magnétisme Stellaire. La Rochelle. 26/09/07


Volume rendering
of Vr
Dr. A.S. Brun. Ecole Magnétisme Stellaire. La Rochelle. 26/09/07

Convective Motions (Vr)

Resolution~ 1200^3
Re=VrmsD/ν~800
Pr=0.25

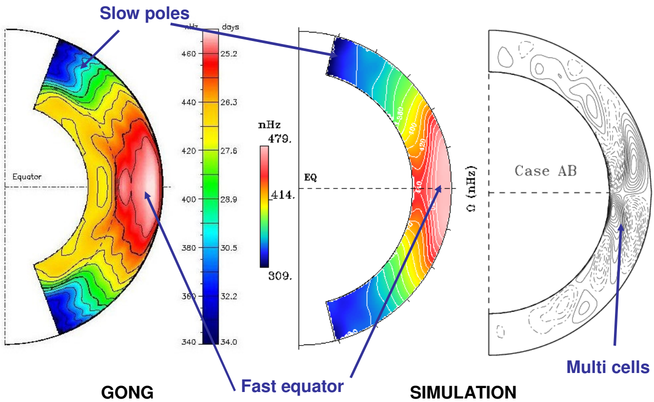
depth=0.96 R



(Brun & Toomre, 2002, ApJ, 570, 865)

Mean Angular Rotation Profile Ω

(Brun & Toomre 2002, ApJ 570, 865)



Taylor-Proudman Theorem & Thermal Wind

The curl of the momentum equation gives the equation for vorticity $\omega = \vec{\nabla} \times \vec{v}$:

$$\frac{\partial \vec{\omega}}{\partial t} + \vec{v}.\vec{\nabla}\vec{\omega} - \vec{\omega}.\vec{\nabla}\vec{v} = \nu \vec{\nabla}^2 \vec{\omega} + \frac{1}{\rho^2} \vec{\nabla}\rho \wedge \vec{\nabla} p \qquad \text{(a)}$$

Taylor-Proudman Theorem:

In a stationary state, the φ component of (a) can be simplified to:

$$2\Omega \frac{\partial \hat{v}_\varphi}{\partial z} = 0$$ => vφ is cst along z

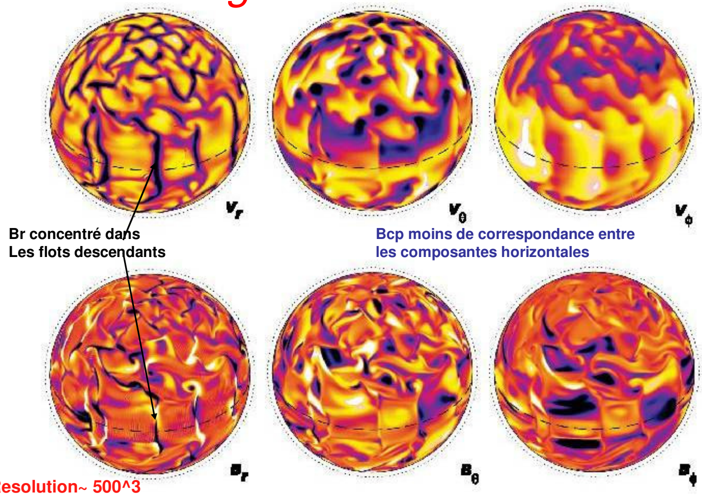
the differential rotation is cylindrical (Taylor columns) and the flows quasi 2-D.

Thermal Wind:

The presence of cross gradient between p and ρ (baroclinic effects) can break this constraint (as well as Reynolds & viscous stresses and magnetic field) :

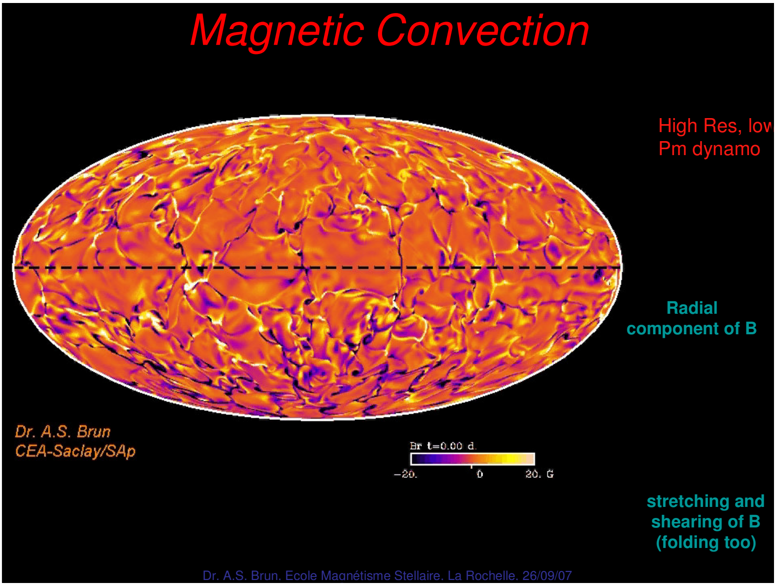
$$2\Omega \frac{\partial \hat{v}_\varphi}{\partial z} = -\frac{1}{\hat{\rho}^2} \vec{\nabla}\hat{\rho} \wedge \vec{\nabla}\hat{p}\Big|_\varphi = \frac{1}{\hat{\rho} C_p} \left[\vec{\nabla}\hat{S} \wedge -\hat{\rho}\vec{g}\right]\Big|_\varphi = \frac{g}{r C_p} \frac{\partial \hat{S}}{\partial \theta}$$

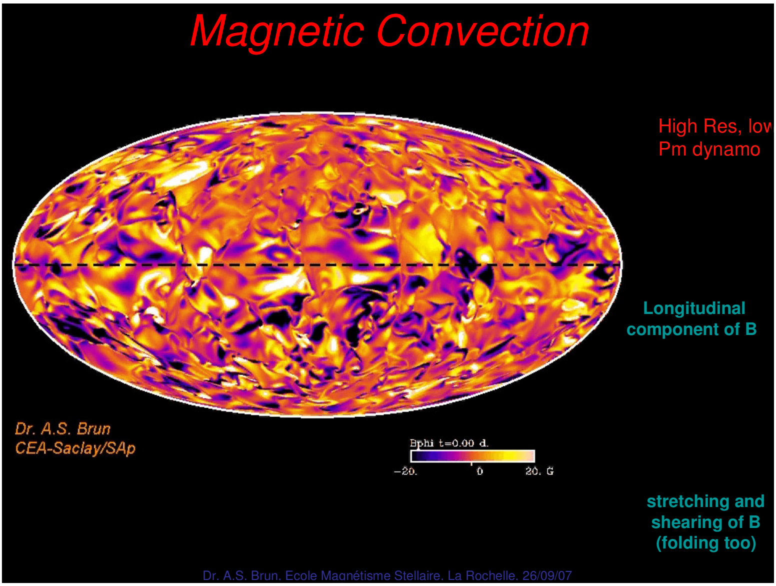
Magnetic Convection



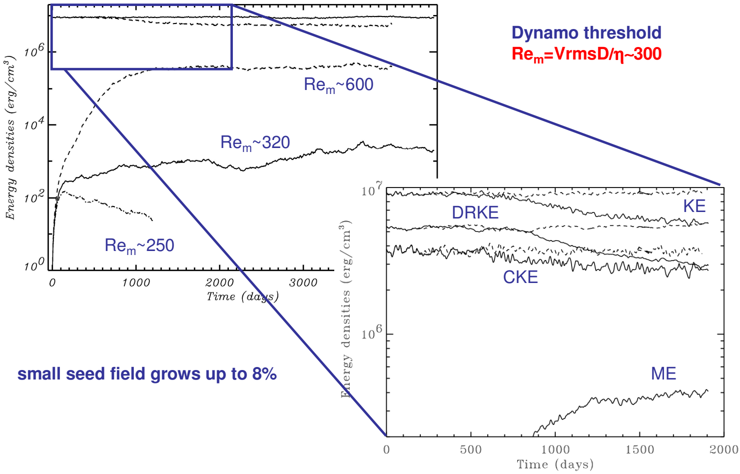
Resolution~ 500^3
Re=VrmsD/ν~150,P=0.25, Pm=4

Case M3 (Brun, Miesch, Toomre 2004)


Magnetic Convection
High Res, low
Pm dynamo
Radial
component of B
Dr. A.S. Brun
CEA-Saclay/SAp
Br t=0.00 d
−20.
0
20. G
stretching and
shearing of B
(folding too)
Dr. A.S. Brun, Ecole Magnétisme Stellaire, La Rochelle, 26/09/07


Magnetic Convection
High Res, low
Pm dynamo
Longitudinal
component of B
Dr. A.S. Brun
CEA-Saclay/SAp
Bphi t=0.00 d.
−20.
0
20. G
stretching and
shearing of B
(folding too)
Dr. A.S. Brun, Ecole Magnétisme Stellaire, La Rochelle, 26/09/07

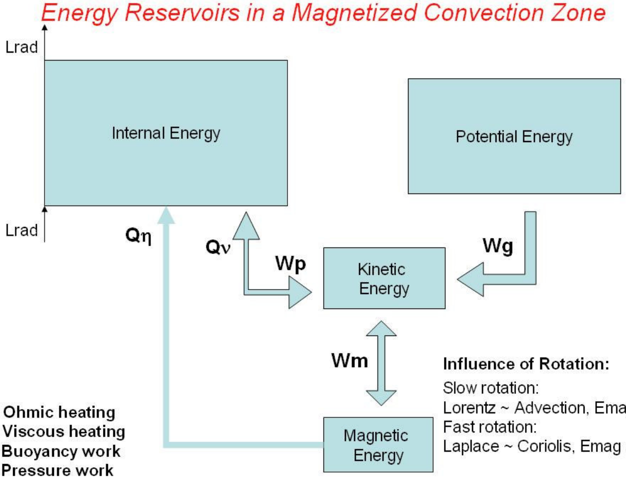
Dynamo Action – Magnetic Energy



Dynamo threshold
$Re_m = V_{rms} D/\eta \sim 300$

small seed field grows up to 8%

Energy Reservoirs in a Magnetized Convection Zone



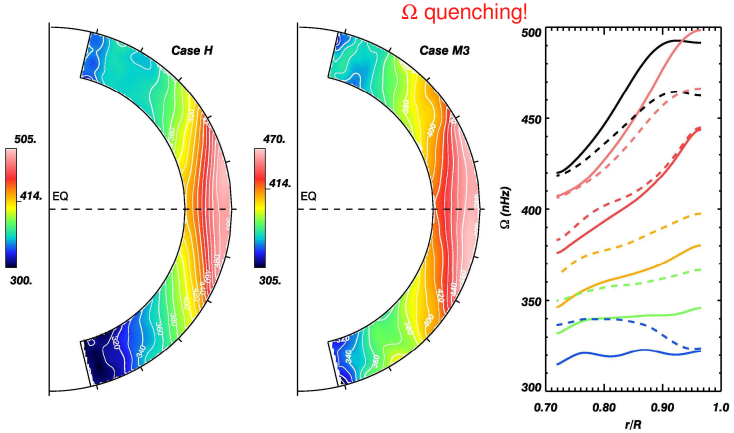
Influence of Rotation:
Slow rotation:
Lorentz ~ Advection, Emag ~ Eke
Fast rotation:
Laplace ~ Coriolis, Emag > Eke

Qη: Ohmic heating
Qv: Viscous heating
Wg: Buoyancy work
Wp: Pressure work
Wm: Lorentz force work

(Brandenburg et al. 1996, Brun et al. 2004)

Mean Angular Velocity Ω

Ω quenching!



Initial state of differential rotation

Evolved state of differential rotation under the influence of the Lorentz force

Angular Momentum Flux (MHD case)

Because of our choice of stress free and match to a Potential field boundary conditions, the total angular mometum L is conserved. Its transport can be expressed as the sum of 5 fluxes:

F_tot = F_Hydro + F_Maxwell + F_MeanB

with F_Hydro= F_viscous + F_Reynolds + F_meridional_circulation

In spherical coordinates:

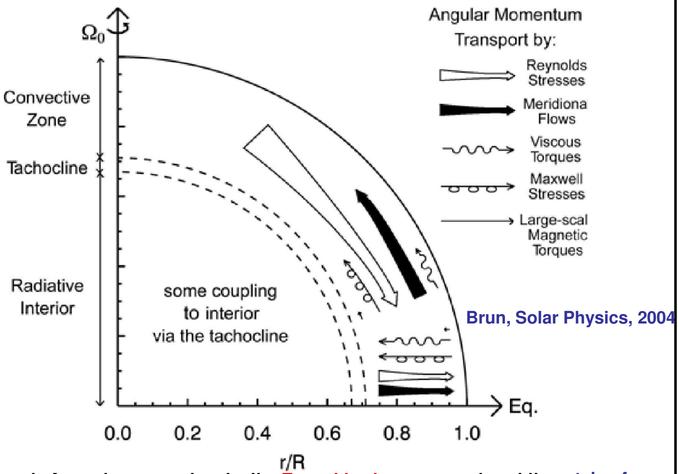
F_r and F_θ are the radial and latitudinal angular momentum fluxes:

$$F_r = \hat{\rho} r \sin\theta \left[-\nu r \frac{\partial}{\partial r}\left(\frac{\hat{v}_\varphi}{r}\right) + \widehat{v'_r v'_\varphi} + \hat{v}_r(\hat{v}_\varphi + \Omega_0 r \sin\theta) - \frac{1}{4\pi\hat{\rho}}(\widehat{B'_r B'_\varphi} + \hat{B}_r \hat{B}_\varphi) \right]$$

$$F_\theta = \hat{\rho} r \sin\theta \left[-\nu \frac{\sin\theta}{r} \frac{\partial}{\partial \theta}\left(\frac{\hat{v}_\varphi}{\sin\theta}\right) + \widehat{v'_\theta v'_\varphi} + \hat{v}_\theta(\hat{v}_\varphi + \Omega_0 r \sin\theta) - \frac{1}{4\pi\hat{\rho}}(\widehat{B'_r B'_\varphi} + \hat{B}_r \hat{B}_\varphi) \right]$$

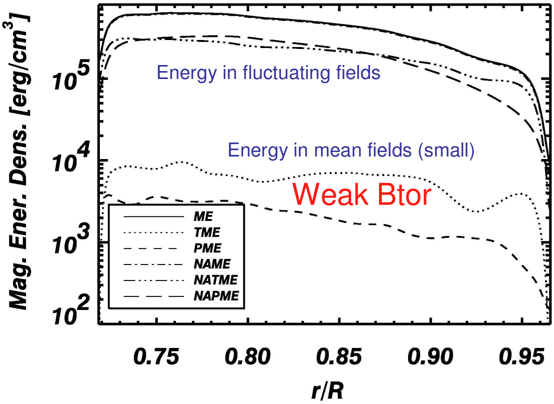
Transport of ang. mom. by diffusion, advection, merid. circ., Maxwell stresses & Mean B

Angular Momentum Balance in Presence of B



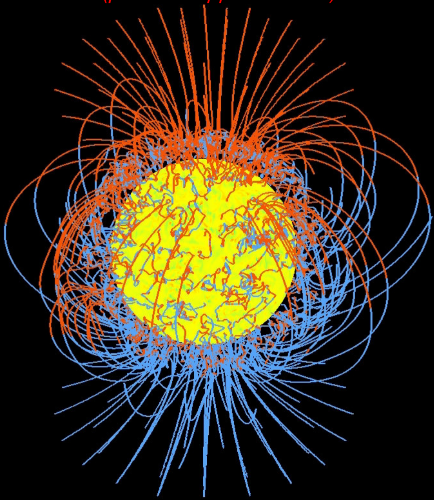
The transport of angular momentum by the Reynolds stresses remains at the origin of the equatorial acceleration. The Maxwell stresses seeks to speed up the poles.

Energy Decomposition vs r



Magnetic energy peaks at the bottom of the shell, due to pumping by convective plumes

3-D Reconstruction of the inner and Coronal Field
(potential approximation)



case G

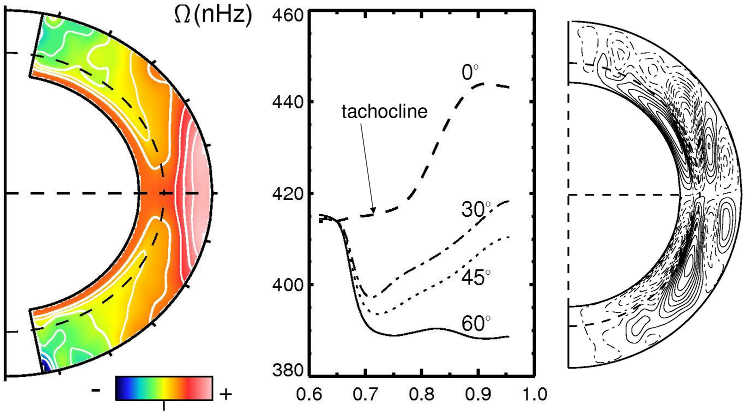
(Brun et al., ApJ, 2004, Brun 2007)

Some Pending Issues in Solar Dynamo

1. High Pm numbers of the simulation of turbulent dynamos (need specific LES-SGS closure, for exemple resolve fully B but « model » V for scales smaller than magnetic diffusivity scale, see Ponty et al. 2004)
2. What type of global dynamo in the Sun: Babcock-Leighton, α–Ω or a mix of both types? Role of Meridional Circulation flows?
3. Need to further improve solar differential models and explain the solar rotation profile down to the nuclear core
4. What processes stop the tachocline to becoming thicker (Maxwell stresses, g-waves, anisotropic turbulence….?)
5. Toroidal flux tube emergence, role of twist, field strength, interaction with surrounding turbulent convection
6. Interactions between « fossil » inner field and dynamo generated one?

Dr. A.S. Brun, Ecole Magnétisme Stellaire, La Rochelle, 26/09/07

Influence of a Tachocline



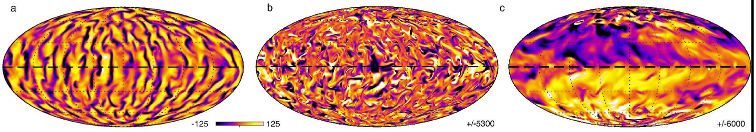
We impose a thermal wind in the stable lower zone compatible with a tachocline of shear maintained by a viscous drag.

Browning et al. 2006, ApJL

Convection pattern and magnetic field structure

Mid depth CZ

In Stable zone



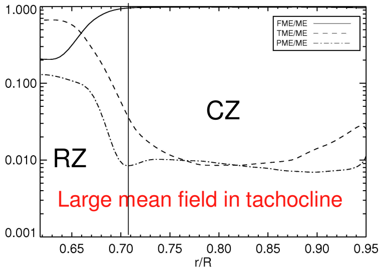
Vr

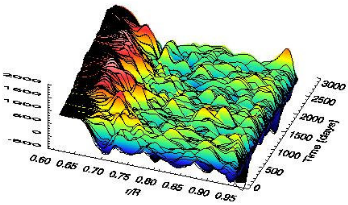
Bphi

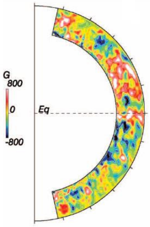
The B field is much more organized in tachocline (possessing an antisymmetric profile)

Browning et al. 2006, ApJL

Getting Strong Toroidal Field



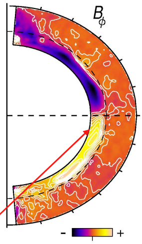


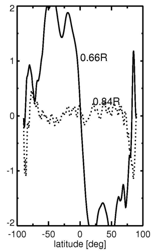


Brun et al. 2004

No tachocline:
mixed polarity
no symmetry

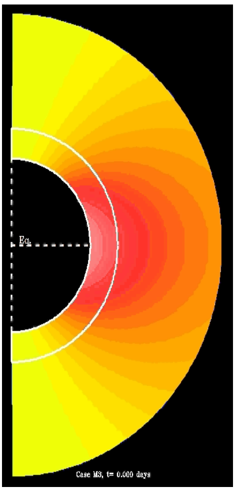
Browning et al. 2006

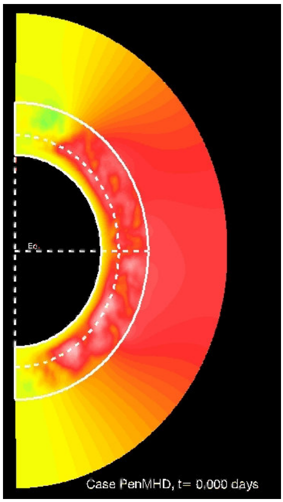




antisymmetric field

Getting Organized Field down below





More stable
Poloidal field

stable
layer

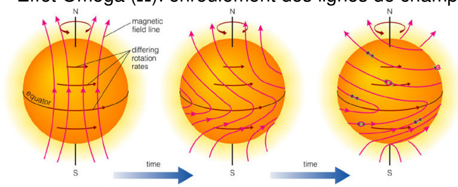
Browning et al. 2006

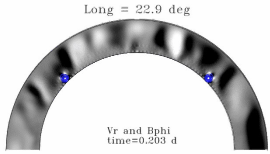
no stable layer

Transport et génération du champ toroidal Btor

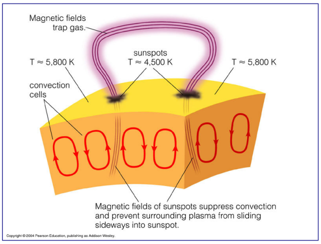
Effet Omega (Ω): enroulement des lignes de champ

Jouve & Brun 2007, AN, in press



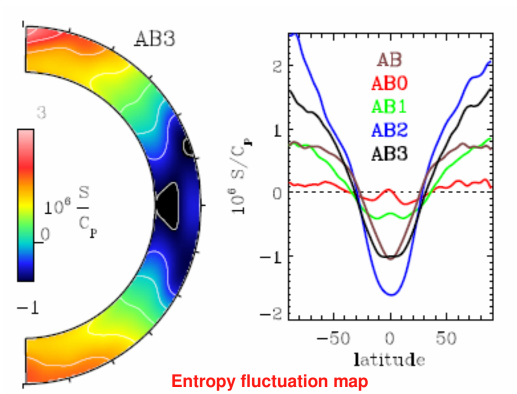


Simulations CEA projet STARS2



Thermal BC's Influence

Let's consider an entropy profile of the type: $S(r_{bot}, \theta) = a_2 Y_2^0 + a_4 Y_4^0$ to model the influence of the tachocline on convection.



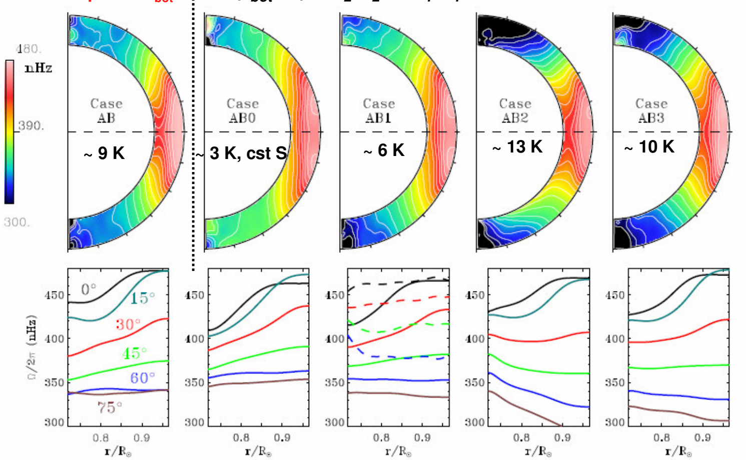
Latitudinal entropy variation in 5 cases

Entropy fluctuation map

Miesch, Brun & Toomre 2006 ApJ, accepted

Thermal BC's Influence on Differential Rotation Profile

No imposed S_{bot} $S(r_{bot}, \theta) = a_2 Y_2^0 + a_4 Y_4^0$ **Best Case**

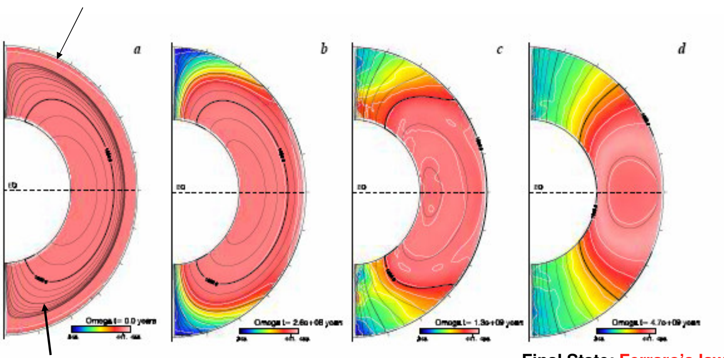


Miesch, Brun & Toomre 2006 ApJ

3-D MHD Models of Solar Radiative Interior

Brun & Zahn 2006, A&A, 457, 665

Top of radiative zone (shear imposed by convection zone on top of RZ)



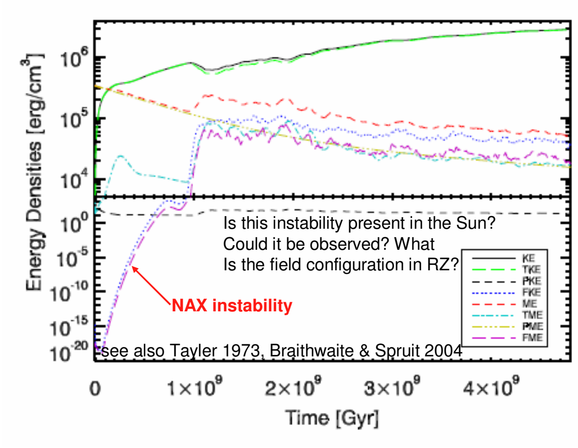
Fossil magnetic field

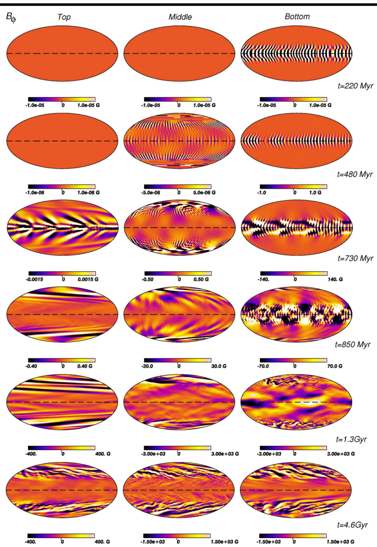
Final State: Ferraro's law of isorotation @ solar age

Interaction between a fossil field and the inward propagation of a latitudinal shear (e.g. the solar differential rotation)

Non-Axisymmetric Instabilities

Brun & Zahn 2006, A&A, Zahn, Brun, Mathis 2007, A&A



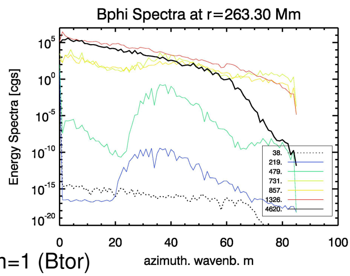


Hign m (Bpol)

Non-Axisymmetric Instabilities of Bpol and Btor

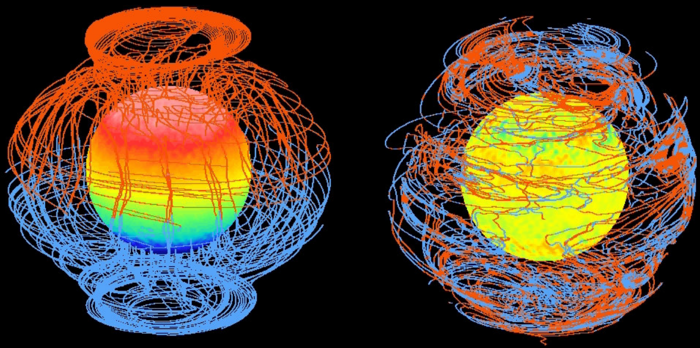
Brun & Zahn 2006, A&A, 457, 665
Zahn, Brun, Mathis, A&A in press

Is there a dynamo in the solar radiative Interior based on Tayler's instability?



m=1 (Btor)

3-D Field Lines Reconstruction



All m

m =/= 0

(Brun & Zahn 2006,
Zahn, Brun, Mathis 2007, A&A; Brun 2007, AN)

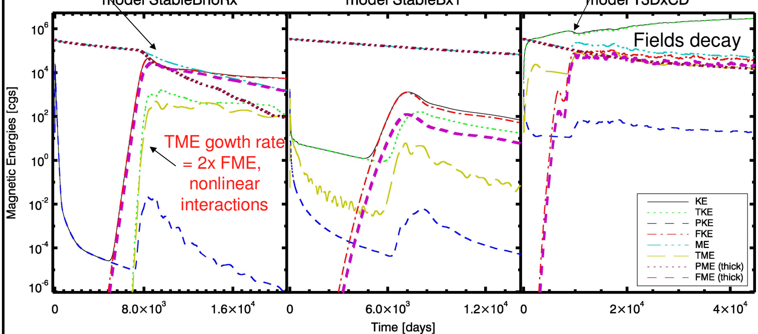
Dr. A.S. Brun, Ecole Magnétisme Stellaire, La Rochelle, 26/09/07

Energy Temporal Evolution in Non-Rotating vs Rotating and/or Sheared Radiative Zones

Saturation of high m linked to Bpol

Brun, A.S. 2007, AN, in press

Saturation of m=1 linked to Diff rot



Mean Poloidal Field always decays

TME initially much higher in sheared case ⇔ ω-effect

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Dynamo Action in Rotating and Sheared Radiative Zones

•Spruit in 1999 & 2002 and Braithwaite 2006, propose the existence of dynamo in stellar radiative zone possessing large scale (m=0) differential rotation :

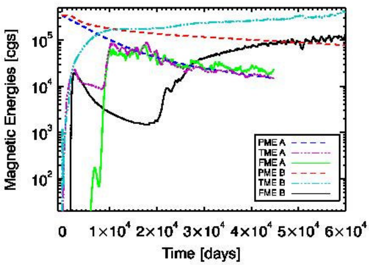
We (Zahn, Brun, Mathis 2007) disagree on their dynamo loop.

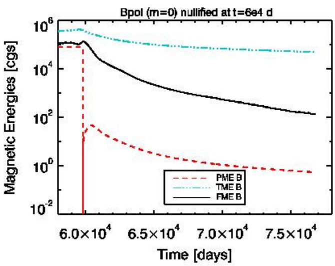
•Further do not see such Dynamo action in our ZR (i.e the initial poloidal field Bpol is not regenerated): either the dynamo threshold has not been reached in our simulation or the simulation by Braithwaite was not run long enough (run for ~1 Ohmic decay time), or its mag BC's and the way he is maintaining its differential rotation leads to different results.

•We did reduce η by a factor of 10 so effective Rm 10 times higher (Rm ~10^5), but we still do not see dynamo……

Dynamo Action in Rotating and Sheared Radiative Zones

We do see transient magnetic energy growth but no overall building up and sustaining of all components of field over severall Ohmic decay time



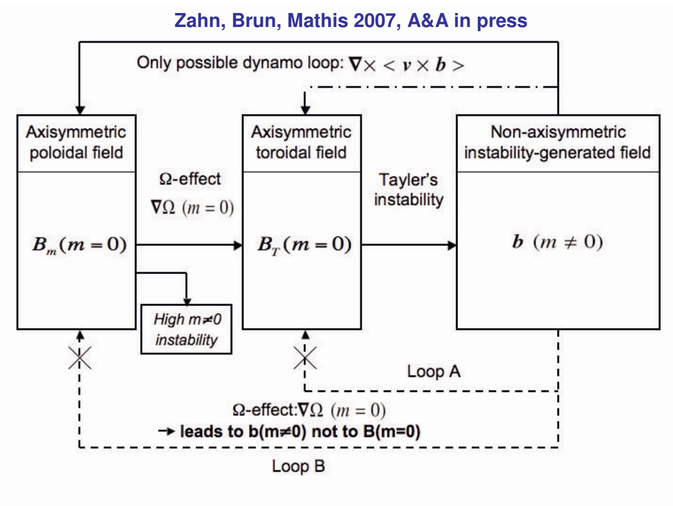


Case A: Rm=10^4
Case B: Rm=10^5

Switching off the mean poloidal field leads to a decaying state of all mag

Zahn, Brun, Mathis 2007, A&A in press

Dynamo Loop in Radiative Zone



A Theoretical View of the Sun's Interior Dynamics

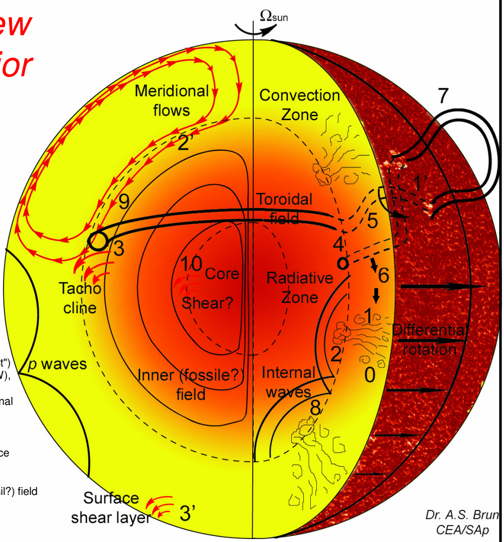
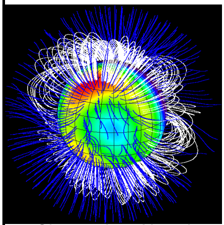


Figure Caption:
0: Turbulent convection (plumes)
1: Generation/self-induction of B field ("alpha-effect")
or 1': Tilt of active region, source of poloidal field
2: Turbulent pumping of B field in tachocline
or 2': Transport of B field by meridional flows
in CZ into the tachocline
3: Field ordering in toroidal structures by large scale
(radial and latitudinal) shear in tachocline ("omega-effect")
3': Surface shear layer, Solar sub surface weather (SSW),
surface dynamics of sun spot?
4: Toroidal field becomes unstable to m=1 or 2 longitudinal
instability (Parker's)
5: Rise (lift) + rotation (tilt) of twisted toroidal structures
6: Recycling of weak field in CZ
or 7: Emergence of bipolar structures at the Sun's surface
8: Internal waves propagating in RZ and possibly
extracting angular momentum
9: Interaction between dynamo induced field, inner (fossil?) field
in the tachocline (with shear, turbulence, waves, etc...)
10: Instability of inner field (stable configuration?)
+ shearing via "omega-effect" at nuclear core edge?
Is there a dynamo loop realized in RZ?

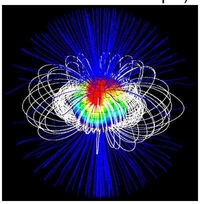
Dr. A.S. Brun, Ecole Magnétisme Stellaire, La Rochelle, 26/09/07

Stellar Magnetism: X Luminosity

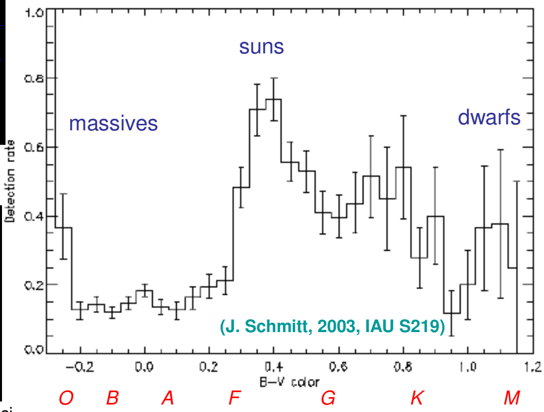
(ROSAT All Sky Survey, EspaDONS)



Observations Narval
(J.F. Donati,
massive star tau Scorpii)

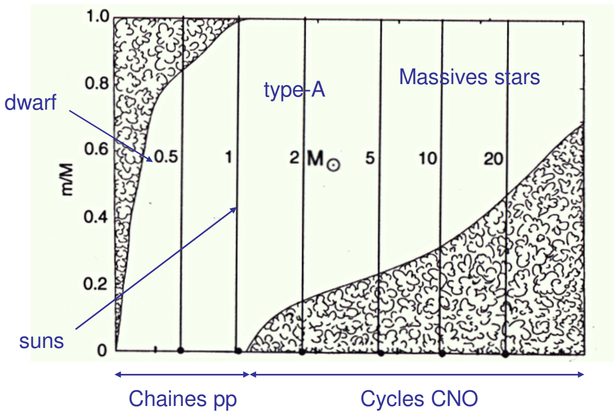


ultra-cool star V374 Pegasi



Co,nvection in Stellar Interior

Transition between envelope and core convection: M ~1.3 Msol



Solar Type Stars (late F, G and early K-type)

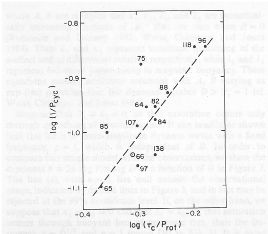
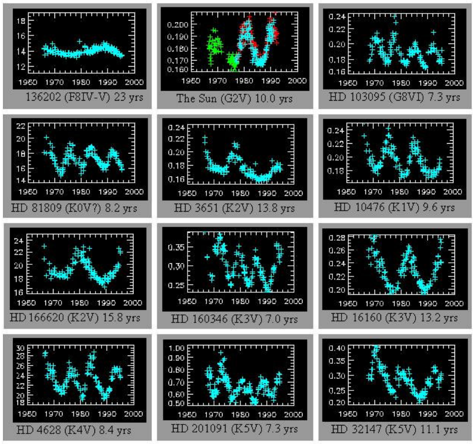


FIG. 2.—Log $(1/P_{cyc})$ vs. log (τ_c/P_{rot}) for the stars of Table 1. The dashed line is a linear least squares fit to the data.



Dans ces étoiles l'activité dépend de la rotation et du temps convectif via le nbre de Rossby $Ro=P_{rot}/\tau$

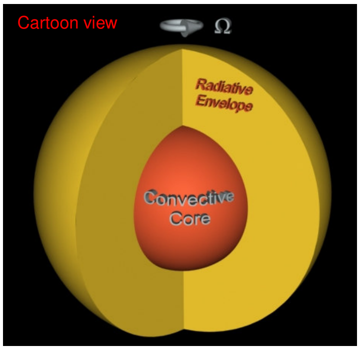
$\langle R'_{HK}\rangle = Ro^{-1}$

Sur 111 étoiles du projet HK (F2-M2):
31 signal plat ou linéaire
29 variables irrégulières
51 + Soleil cycles magnétiques

Wilson 1978
Baliunas et al. 1995

CaII H & K lines , $\langle R'_{HK}\rangle$

Core Convection in $2M_{sol}$ Star



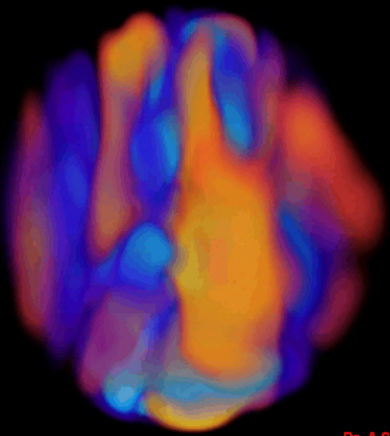
Star Caracteristic

$M=2M_{sol}$, T_{eff}=8570 K
$R=1.9\ R_{sol}$, $L=19\ L_{sol}$
$\Phi=\Phi_{sol}$ or P=28 days

Eq d'Etat = Loi des Gaz Parfait
Source énergie nucléaire ~ ❒ $\mathfrak{M}_0 T^8$
Pas de gradient μ
Coeur central r~0.02R omis

Browning, Brun & Toomre 2004, ApJ; Brun, Browning, & Toomre 2005, ApJ

Collaboration avec M. Browning & J. Toomre



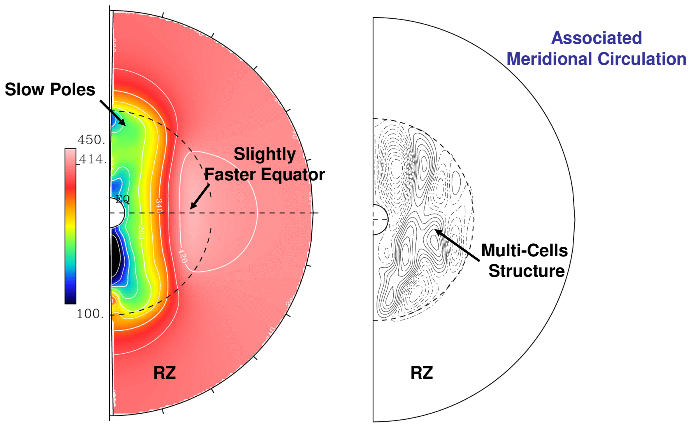
Rendu 3D de la Vitesse radiale

Re~140, P=0.25

(Browning, Brun & Toomre 2004, ApJ, 601, 512)

Dr. A.S. Brun
CEA-Saclay, SAp

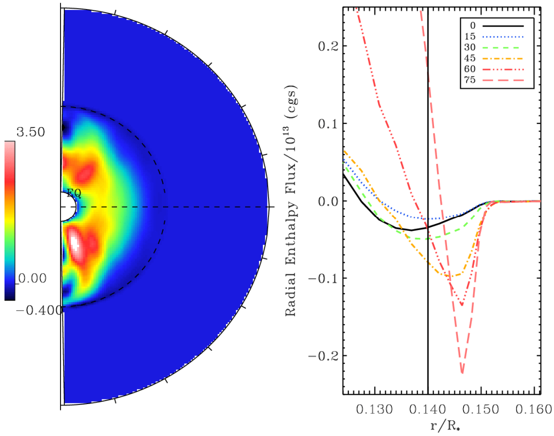
Rotation Profile



Browning, Brun & Toomre 2004, ApJ; Brun, Browning, & Toomre 2005, ApJ

The core rotates differentially, with a pole to equator contrast $\Delta\Omega/\Omega o \sim 40\%$

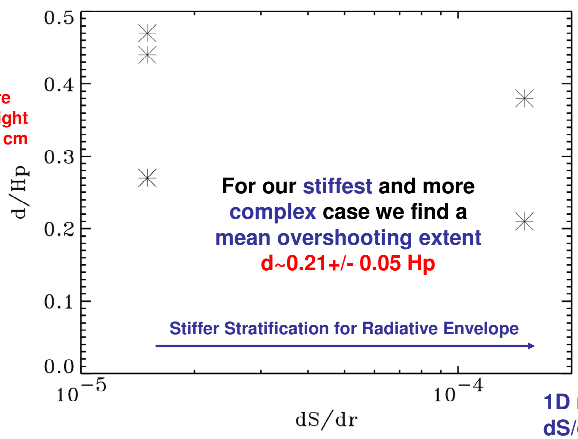
Radial Convective Flux



The convective energy transport varies with latitude and so does the overshooting in amplitude and extent.

Mean Overshooting Extent in $2M_{sol}$ Star

Pressure Scale Height Hp~8 10^9 cm



For our stiffest and more complex case we find a mean overshooting extent d~0.21+/- 0.05 Hp

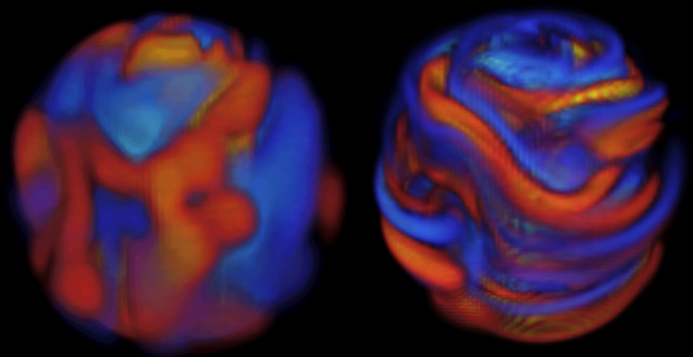
Stiffer Stratification for Radiative Envelope

More Complex flows

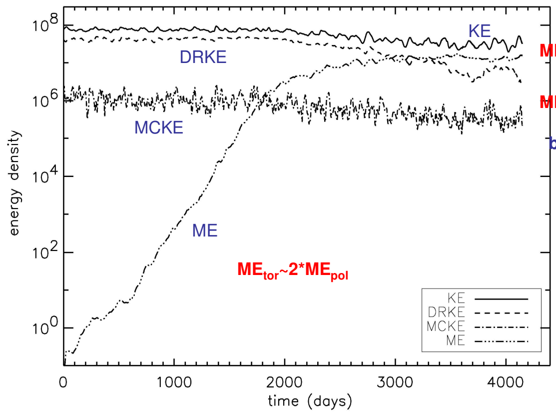
1D model dS/dr~10^{-2}

Core Dynamo

(Brun, Browning, Toomre 2005, ApJ, 629, 461)



Dynamo Effect –Magnetic Energy



ME~40%KE

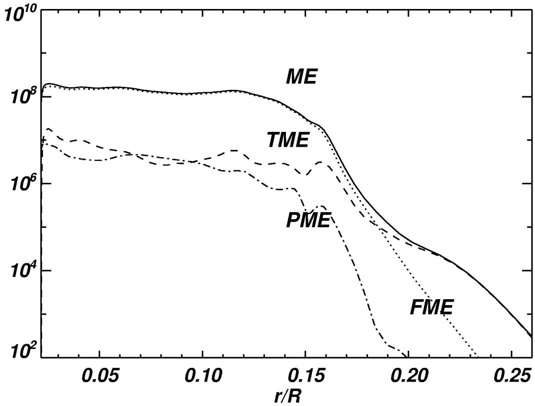
ME>DRKE & MCKE but < CKE

Browning, Brun & Toomre 2004, ApJ;
Brun, Browning, & Toomre 2005, ApJ

The Lorentz force jxB feeds back nonlinearly on the motions and seems to slow them down

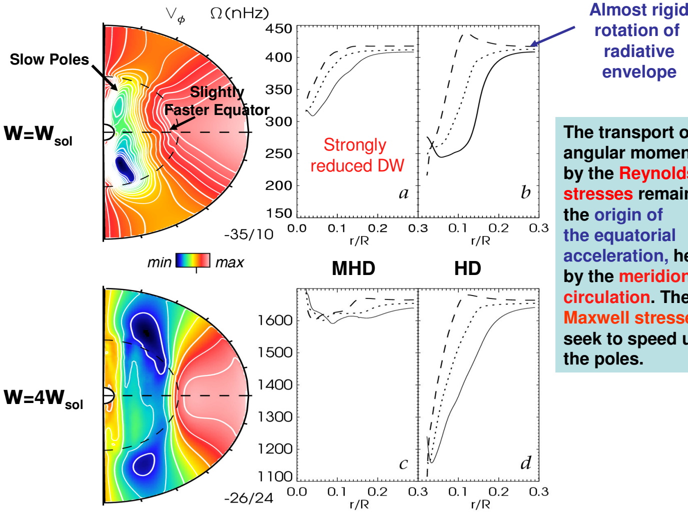
Dr. A.S. Brun, Ecole Magnétisme Stellaire, La Rochelle, 26/09/07

Magnetic Energy Distribution vs r



ME peaks slightly deep in the core, FME dominates except in overshooting region where TME does

Rotation Profile

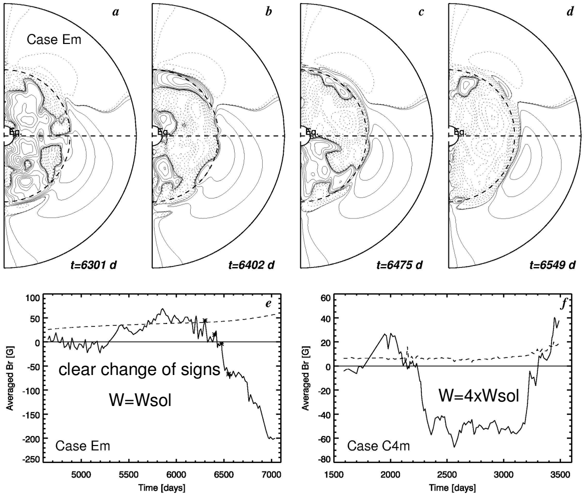


The transport of angular momentum by the Reynolds stresses remain at the origin of the equatorial acceleration, helped by the meridional circulation. The Maxwell stresses seek to speed up the poles.

Core Dynamo: Polarity Reversal

solid contours= clockwise circulation

Integral of Br over northern hemisphere



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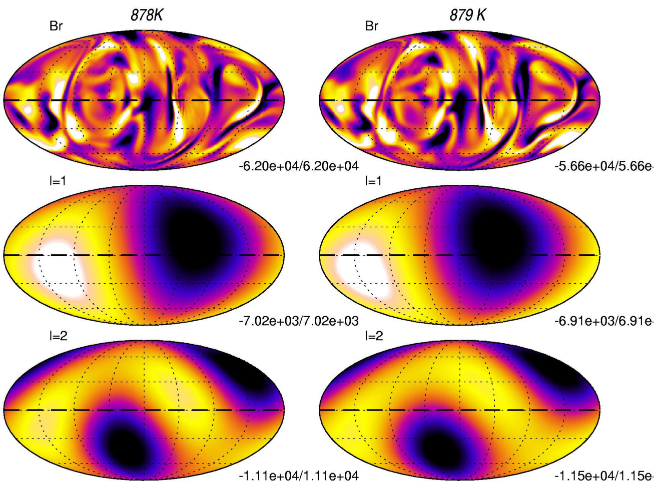
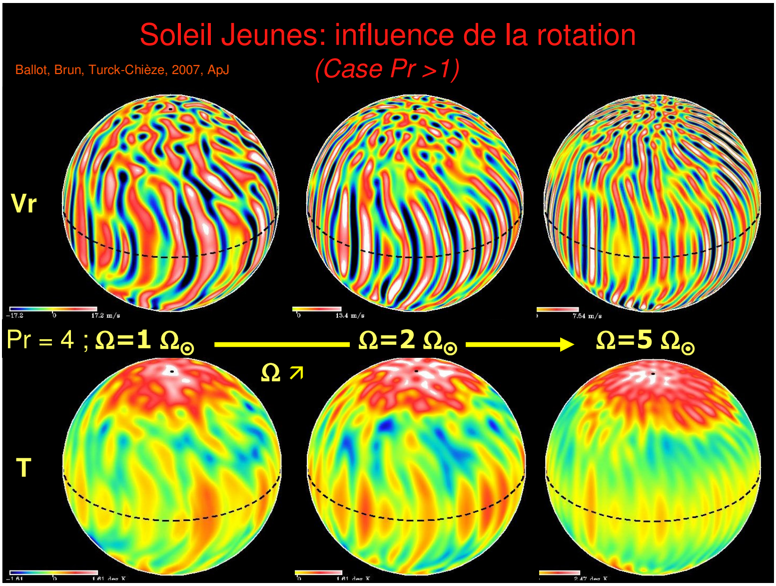
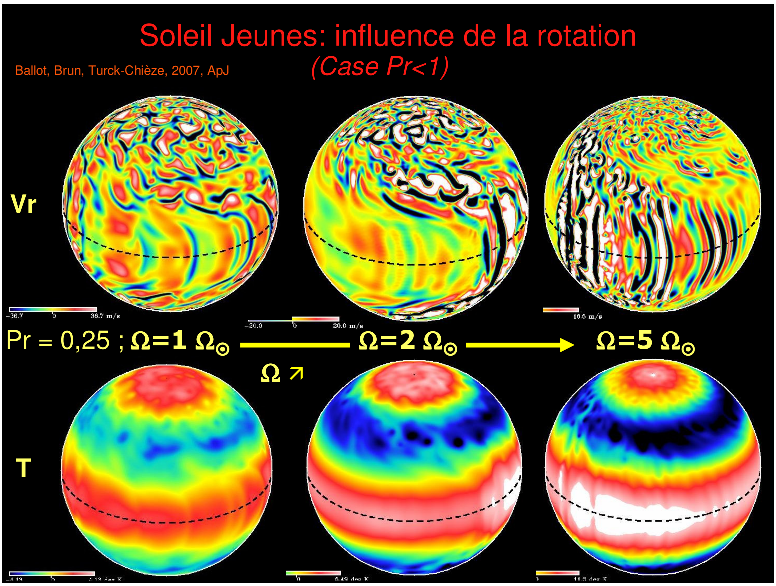
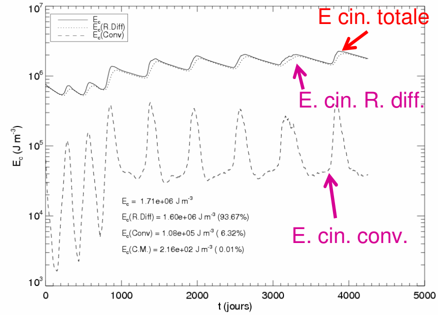
Dynamo Centrale: Dipole drift




Soleil Jeunes: influence de la rotation
Ballot, Brun, Turck-Chièze, 2007, ApJ
(Case Pr >1)
Vr
Pr = 4 ; Ω=1 Ω⊙
Ω=2 Ω⊙
Ω=5 Ω⊙
Ω ↗
T


Soleil Jeunes: influence de la rotation
Ballot, Brun, Turck-Chièze, 2007, ApJ
(Case Pr<1)
Vr
Pr = 0,25 ; Ω=1 Ω⊙
Ω=2 Ω⊙
Ω=5 Ω⊙
Ω ↗
T

Spatial and Temporal Intermittency



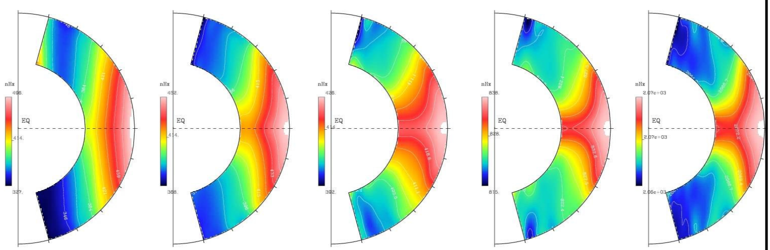
Pr ↘ et Ω↗
Forte intermittence spatiale
➔ convection turbulente « localisée »

➔ Régime « oscillant » : « localisé » dans l'espace des paramètres.
Probablement dépassable vers un état chaotique.
[Gröte & Busse 2001]
Rmq : cependant ΔΩ/Ω peu variable…

Cas Pr=0.25 & **Ω=5 Ω⊙**

Ballot, Brun, Turck-Chièze, 2007, ApJ

Differential Rotation vs Ω

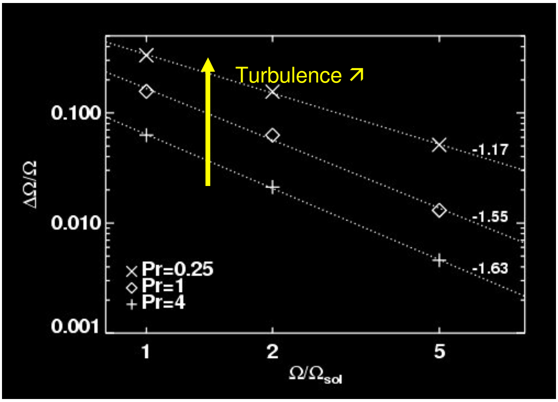


Pr = 0,25 ← **Pr = 4 ; W=1 W⊙** → **W=5 W⊙**

DW↗ **DW↘**

Ballot, Brun & Turck-Chieze 2007, ApJ

Differential Rotation vs Ω



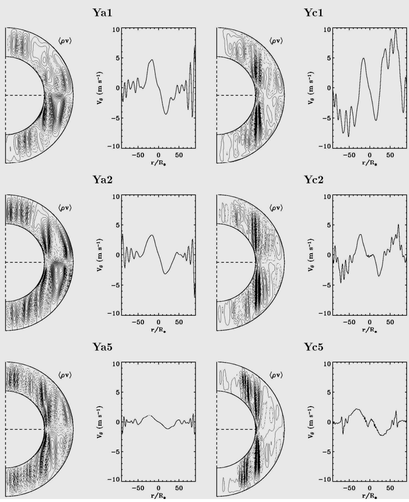
Decrease of ΔΩ/Ω and ΔΩ with Ω
(However with Pr=0.25, ΔΩ ~ cste)

Ballot, Brun & Turck-Chieze 2007, ApJ

Meridional Circulation vs Ω

Prandtl nb

Pr=4



Prandtl nb

Pr=1/4

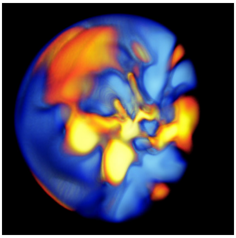
Ballot, Brun & Turck-Chieze 2007, ApJ

Decrease of V_θ with Ω

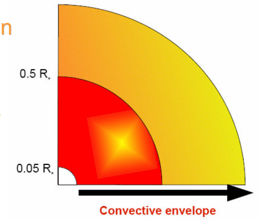
RGB Stars

Palacios & Brun 2007

Pop II RGB star @ the "*bump*"
$M_* = 0.8\ M_\odot$ $L_* = 425\ L_\odot$ $R_* = 39\ R_{sol}$



computational domain



- ¤ $L \approx$ constant
- ¤ $\rho \sim [10^{-5}; 10^{-3}]$ g/cm^3
- ¤ $\Omega = \Omega_{sol}/10 = 2.6\ 10^{-7}$ rad s^{-1}

Rigid stress free boundaries

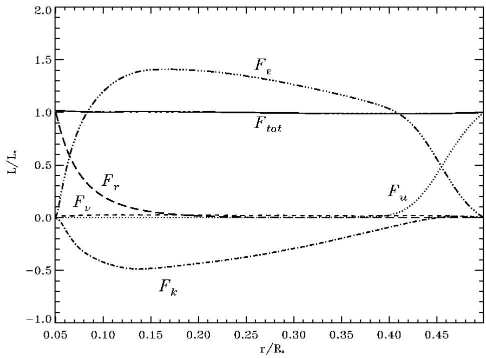
Prandtl number $\frac{\kappa}{\nu} = 1$

Longer run over 4200 days, e.g. more than 12 rotations

Energy Budget

Palacios & Brun 2007

Convective luminosity > L_* to compensate the negative kinetic luminosity
→ differs from MLT predictions
Negative kinetic energy represents up to 50% of the flux in the inner part of the domain



Convection in RGB Stars

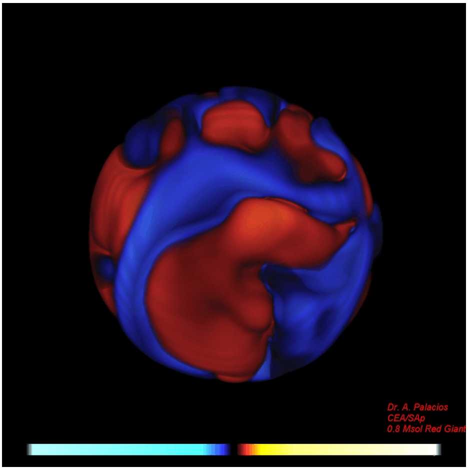
3D rendering of the radial velocity in the Mod1 Simulation.

Resolution : 400^3

Prandlt number : 1

Reynolds number : 368

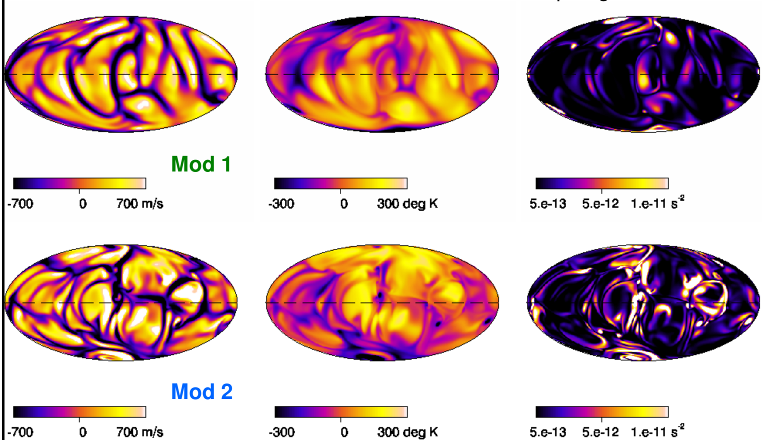
Palacios & Brun 2007



Dr. A.S. Brun, Ecole Magnétisme Stellaire, La Rochelle, 26/09/07

Convection

V_r @ domain top edge | T @ domain top edge | Enstrophy @ domain top edge



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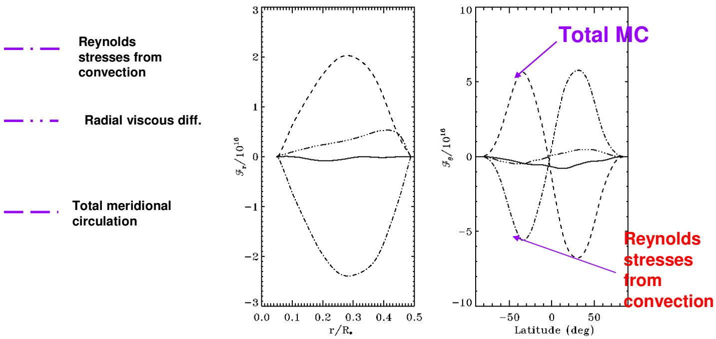
Flows

Outward radial transport of AM by MC
In lat., MC and Reynolds stresses are opposite and compensate each other

Radial Flux | Latitudinal Flux



Rotation

Palacios & Brun 2007

Large differential rotation in the radial and latitudinal directions

Cylindrical rotation : less marked for Mod 2.

Rotation law for the 2 models close to $\Omega \propto r^{-0.4}$