The solar energetic balance and the dynamics of the radiative zone

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in collaboration with

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J. Marques, S. Mathis, S. Mathur, A. Palacios,
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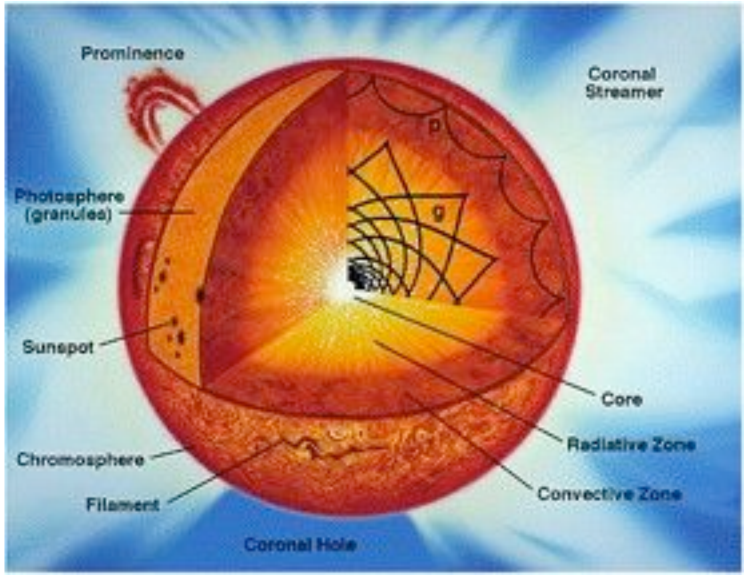
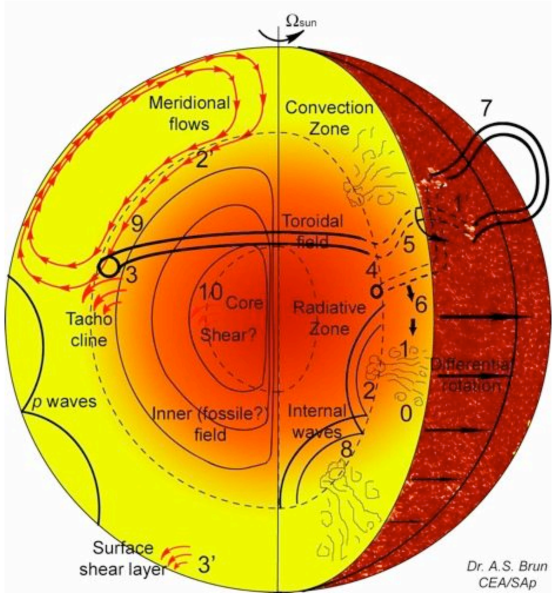
From a classical solar model to a dynamical solar model

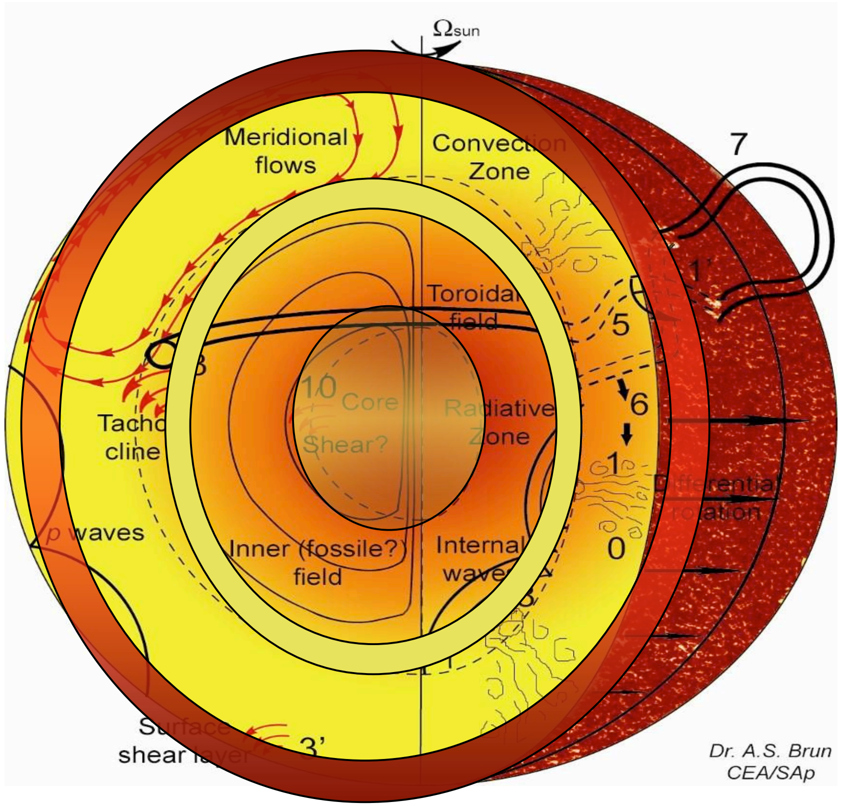


Brun and Jouve 2008



The understanding of the different sources of the solar activity can be studied in 3D but also in 1D because the dynamical effects on the structure are small but visible at the surface and the first stage (young Sun) can influence the present status

The missing bridges



- Detailed core rotation and order of magnitude of the fossil field

- Transition between the fossil field and the dynamo field

- Asphericity of the Sun, due to subsurface magnetic field and evolution of the radius with activity

-Emergence of the flow in X and UV and time dependence of the flow

- Heating of the corona, coronal waves, emerging flows

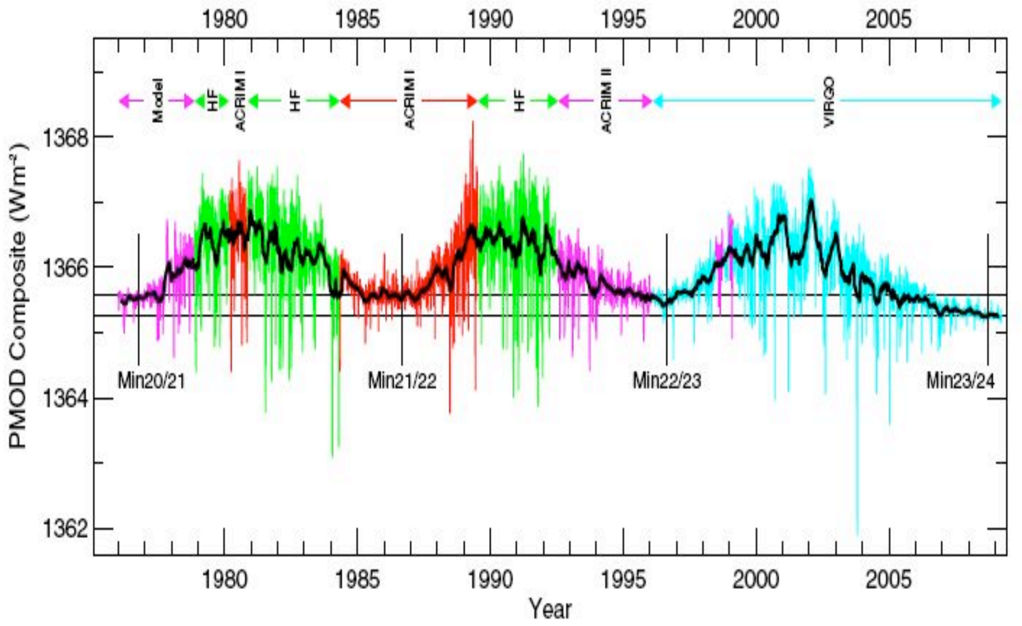
If we want to understand the origins of the solar activity

one cannot neglect the radiative zone which contains 98% of the total mass

Proposed items

- I- The total solar irradiance, the solar constant and the present minimum of activity
- II- The internal rotation and the young Sun
- III- The energetic balance and the sound speed

The total irradiance



SORCE: 1364 W/m^2 -1361 W/m^2

Absolute value under control ?

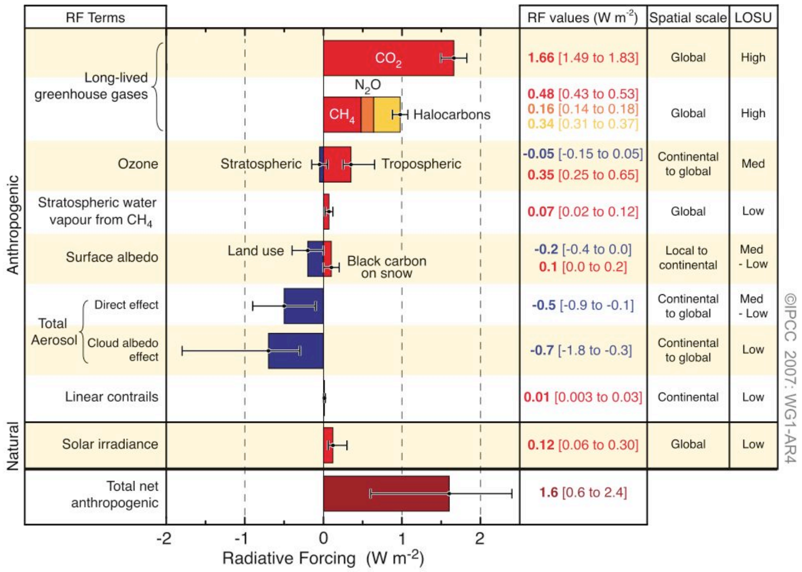
Temporal long term evolution ?

Variations up to a factor 3 or 4 greater than 0.1% during the maxima

C. Frohlich 2006, A&A 2009

For the GIEC, the total irradiance is the only source of variability on the earth climate and it is small,

Is it correct ?



The solar constant

Turck-Chièze & Lefebvre JASTP2010

- 4 structural equations: f (equation of state, opacity, nuclear reaction rates and composition) and $L = 4\pi R^2 \sigma T^4$

The energy produced by nuclear reactions equilibrates the energy lost at the surface

- L varies by 30% in 4.5 Gyr, 8% in 1Gyr, $8 10^{-9}$ in 100 years

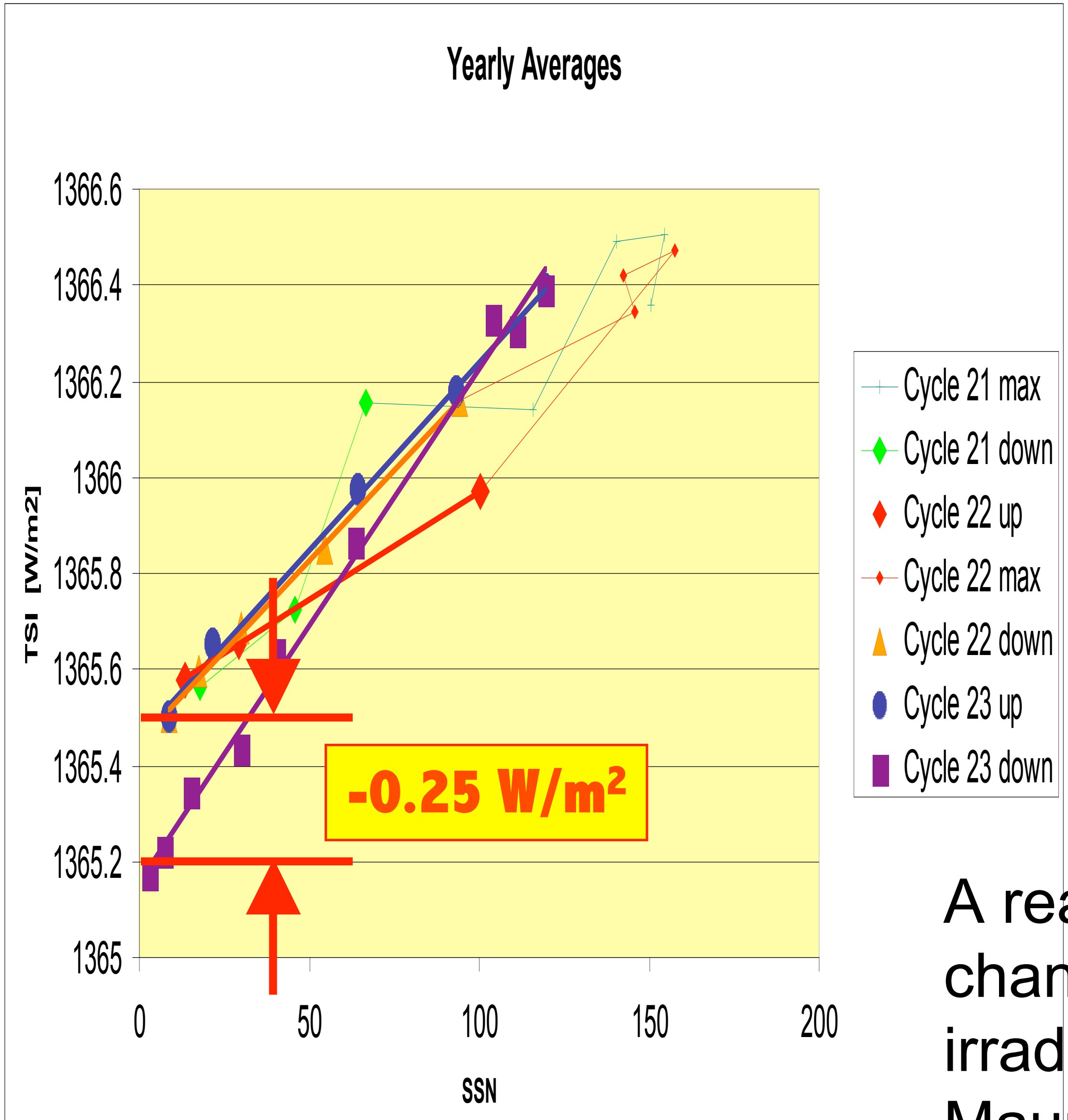
- Prediction of the solar neutrinos in agreement with detection for neutrinos associated to beryllium and boron if one considers the solar sound speed extracted by helioseismology:

$$T_c = 15.71\ 10^6\ \mathrm{K},\ \rho_c = 153,7\ \mathrm{g/cm^3}\quad X_c = 0.337$$

- Is there some contradiction between this assumption and the observation of the luminosity ??

Not really because the present luminosity is adjusted and the present role of rotation and magnetism on the solar structure is small but the Sun is not standard and is a magnetic star

Evolution of the subsurface layers along cycles



W. Schmutz 2009

No SSN these years

corresponds to

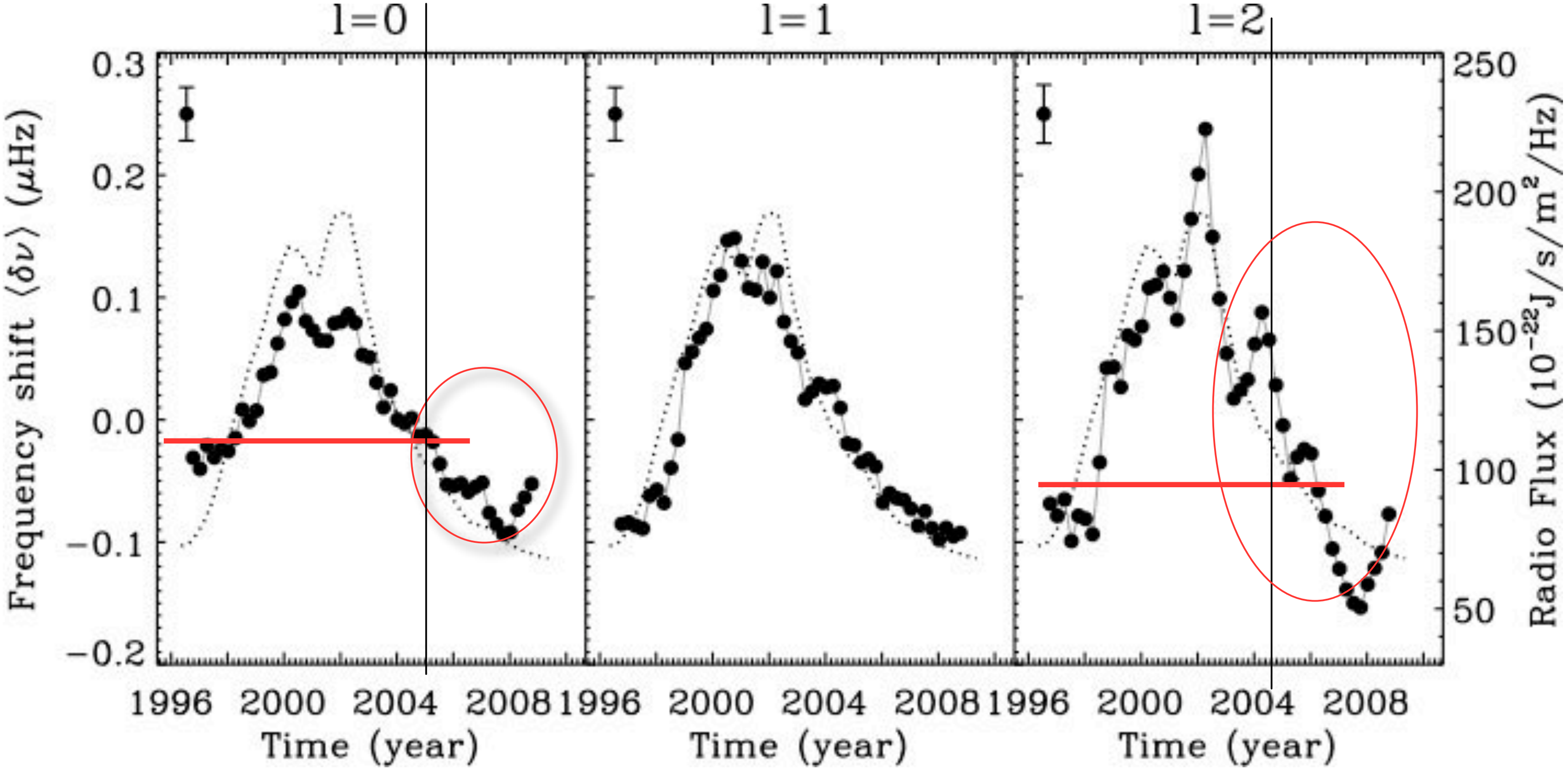
an interplanetary field of

B_{IMF}= 5.5 nT

A real minimum does not changed largely the solar irradiance=> minimum of Maunder SHAPIRO

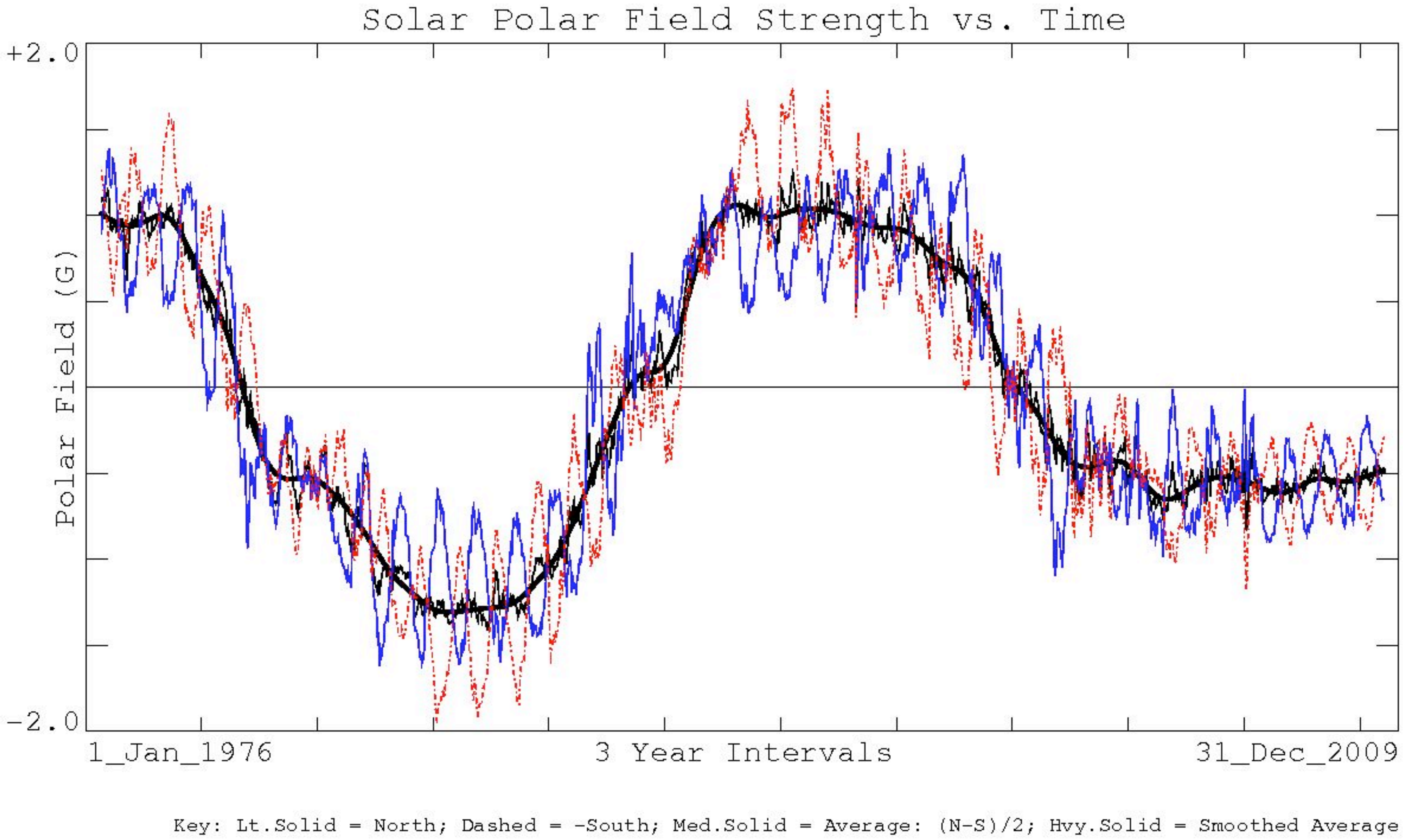
Acoustic modes with GOLF/SoHO

Minimum / Minimum Salabert et al. 2009



The minima can be characterized by a decrease of sub surface magnetic field. But the situation seems more complex. The comparison between1996 and 2004 partly confirms the remark of W. Schmutz for l=0 but the study shows an enriched information in the quadrupole mode l=2.

WSO (Scherrer)



-Impact of the rotation
on the subsurface layers DUEZ

- Impact of the fossil field
on the subsurface layers
DUEZ

- Evolution of the subsurface layers and
Role of the atmosphere in the
determination of the limb PIAU

Turck-Chièze IAU 264, Rio 2010

Turck-Chièze & Couvidat Rev Progress Physics 2010

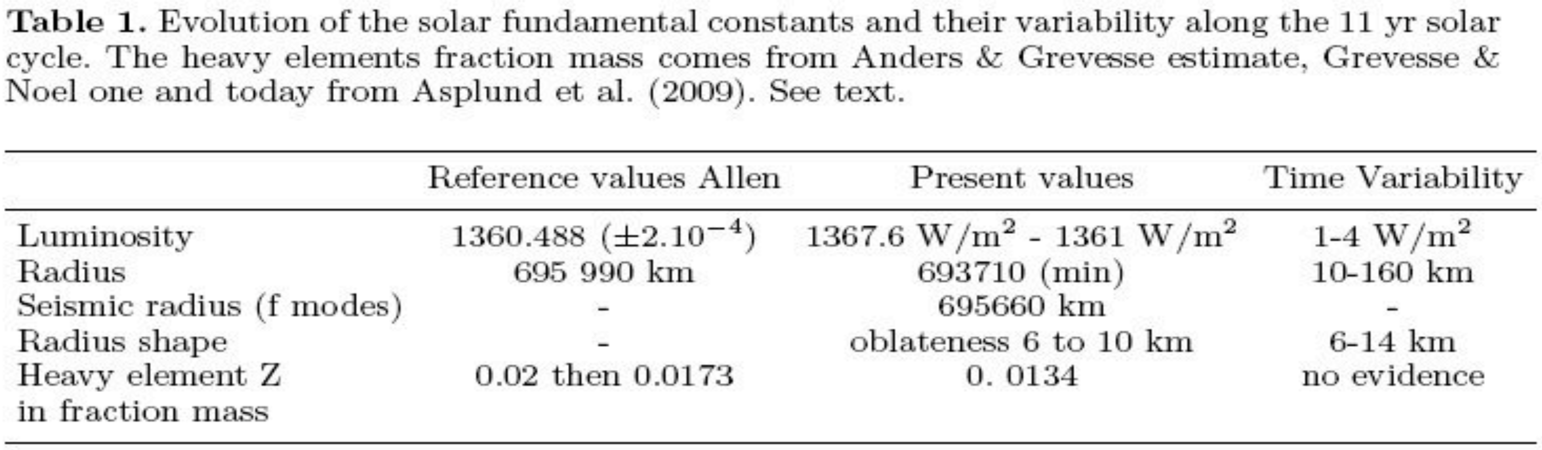


Table 1. Evolution of the solar fundamental constants and their variability along the 11 yr solar cycle. The heavy elements fraction mass comes from Anders & Grevesse estimate, Grevesse & Noel one and today from Asplund et al. (2009). See text.

	Reference values Allen	Present values	Time Variability
Luminosity	1360.488 ($\pm 2.10^{-4}$)	1367.6 W/m^2 - 1361 W/m^2	1-4 W/m^2
Radius	695 990 km	693710 (min)	10-160 km
Seismic radius (f modes)	-	695660 km	-
Radius shape	-	oblateness 6 to 10 km	6-14 km
Heavy element Z in fraction mass	0.02 then 0.0173	0. 0134	no evidence

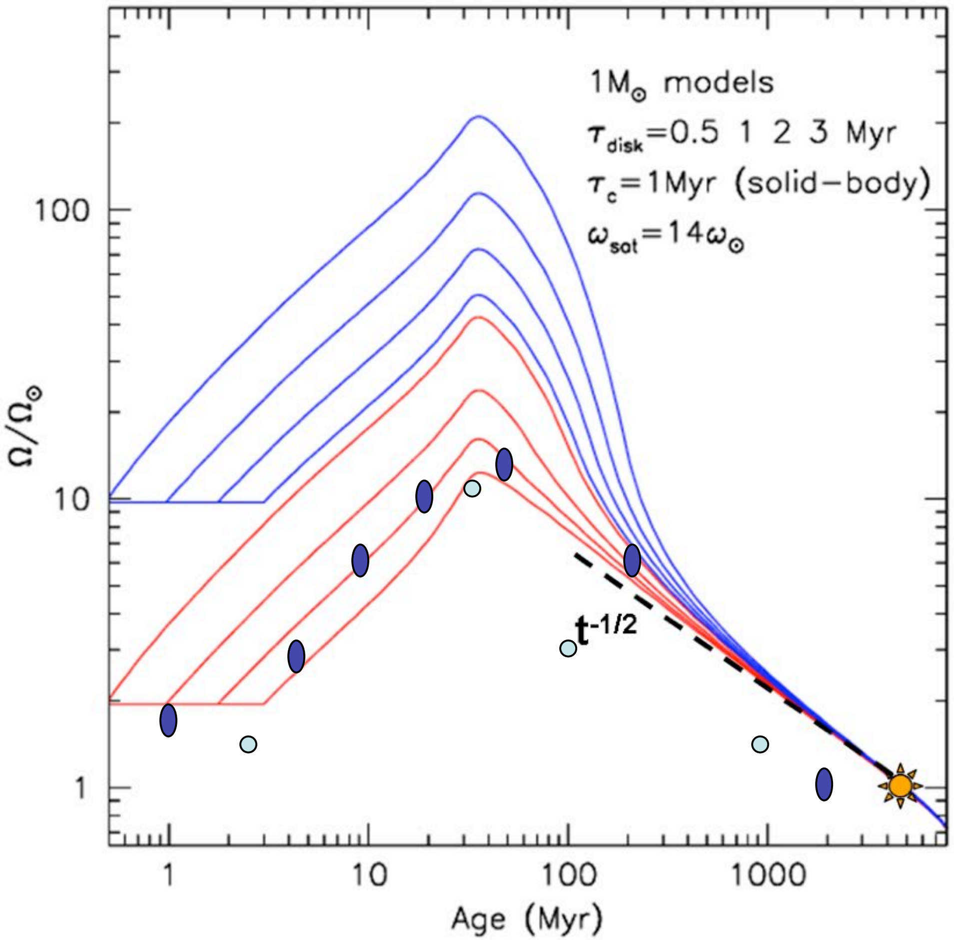
Standard model is calibrated in luminosity and radius at 10^{-5}

One needs to enrich this picture

II- The Sun is a magnetic star

Yes The Sun rotates, it implies the Sun life

The angular momentum evolution of young stars



Bouvier 2008, in Stellar Magnetism editors Neiner & Zahn

$dJ/dt \propto dM/dt\ \Omega\ R^2_A$

where R_A is the Alfven radius (Sun: $R_A = 30\ R_{sol}$).

Magnetized stellar winds are efficient to brake the magnetically active stars (a factor 1000 greater than any other phenomena). The Skumanich law on the main sequence is not universal

low rotators $dJ/dt \propto \Omega^3$

fast rotators $dJ/dt \propto \Omega$ for $\Omega > \Omega$ sat

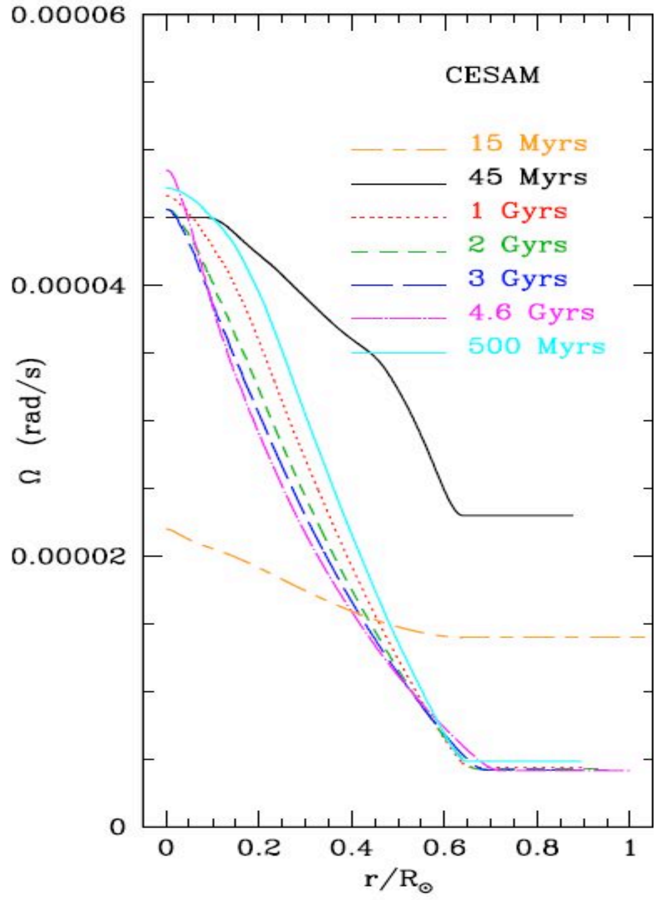
So depending on the disk lifetime, stars are rapid or low rotators.

Stellar magnetic field is the central ingredient which governs the rotational evolution of solar-like stars.

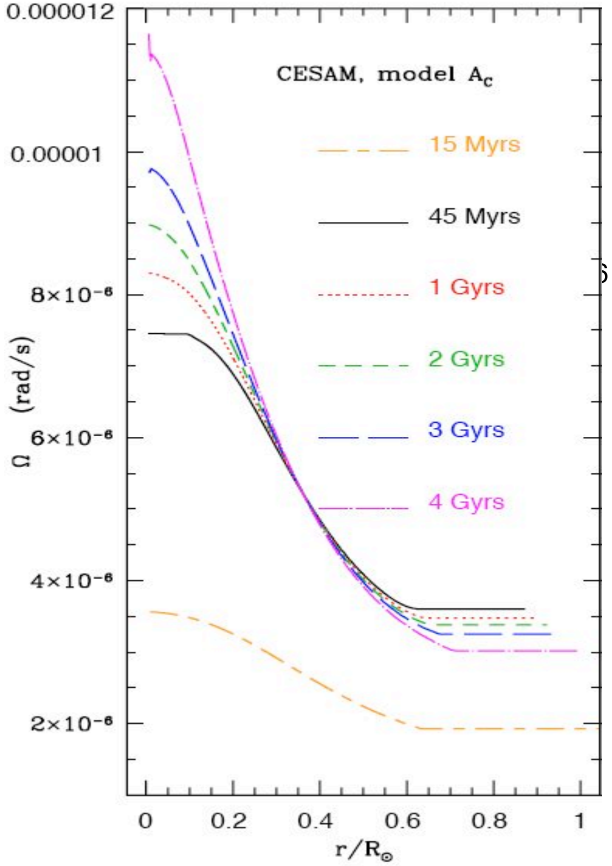
The theoretical evolution of the internal rotation

Turck-Chièze, Palacios, Marques, Nghiem ApJ 2010

$$\rho \frac{d}{dt}\left(r^2\overline{\Omega}\right) = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \overline{\Omega} U_2\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho \nu_v r^4 \frac{\partial \overline{\Omega}}{\partial r}\right)$$

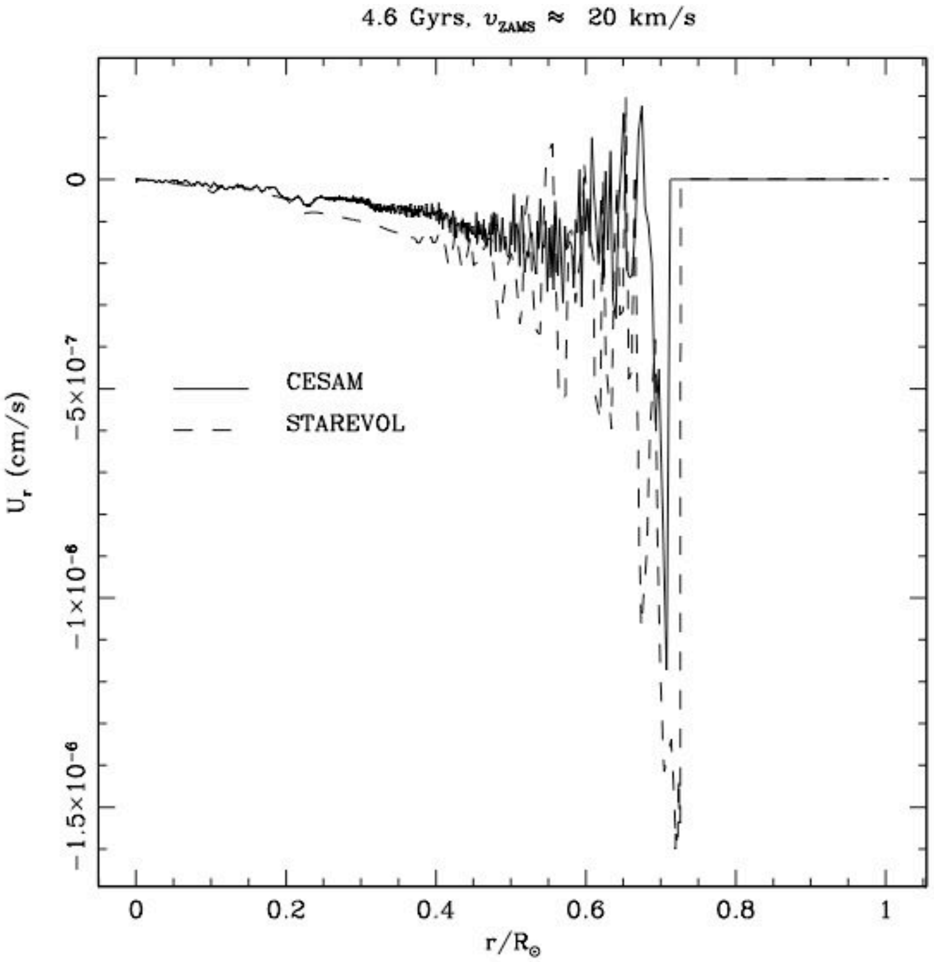


Initial strong rotation + braking



Low rotator without braking, increase of the solar core due to advection

The tachocline



The transport of momentum in radiative zone shows that there is a very different meridional circulation in radiative zone

some 10^{-6} cm/s

or smaller

than

in convective zone

some m/s

So the tachocline is now well understood

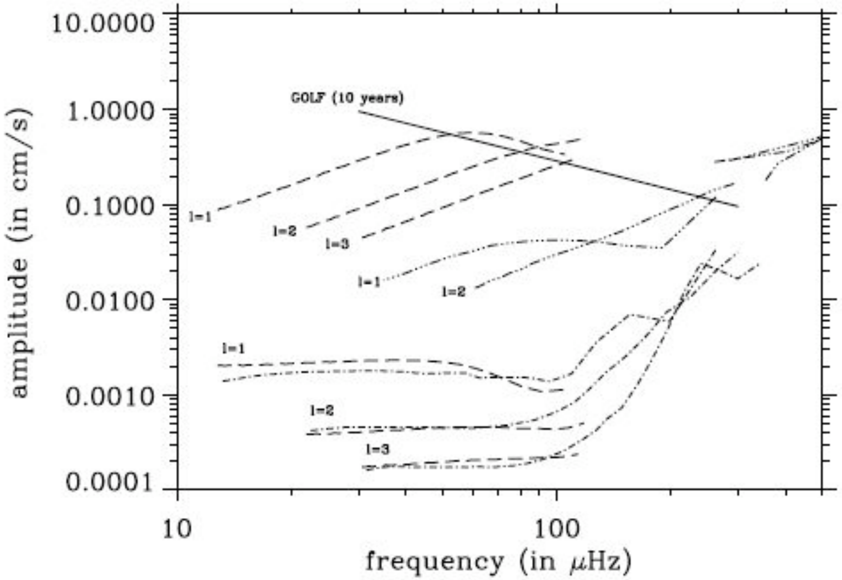
It also plays a crucial role in the stability of the solar dynamo

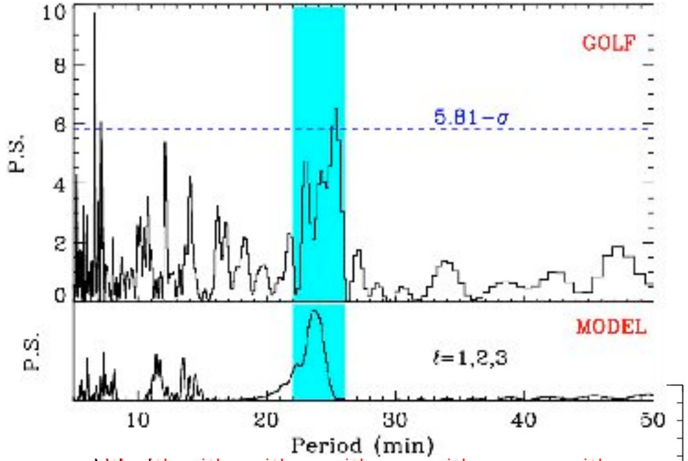
Present core rotation:

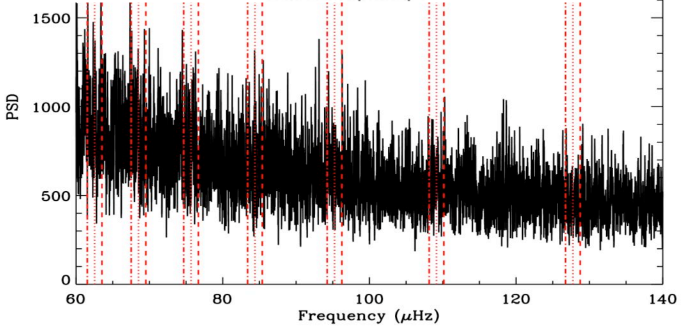
g mode detection GOLF/SOHO

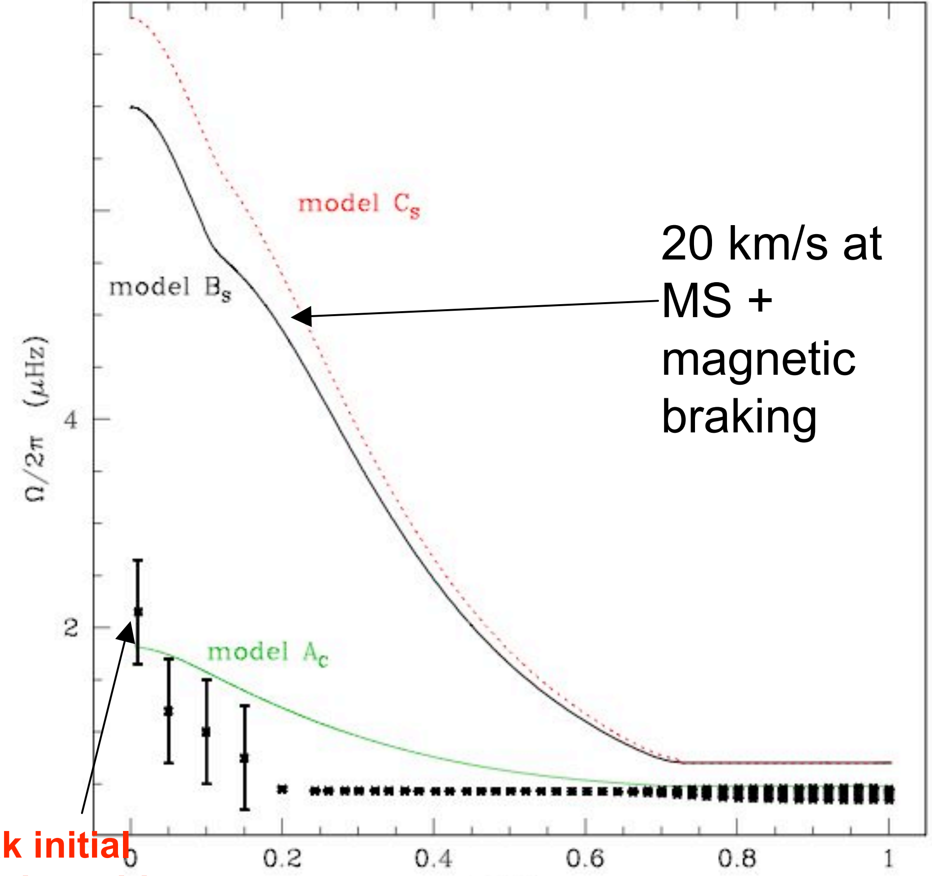
Turck-Chièze et al. 2004,

Garcia et al. 2007 Science dipole modes









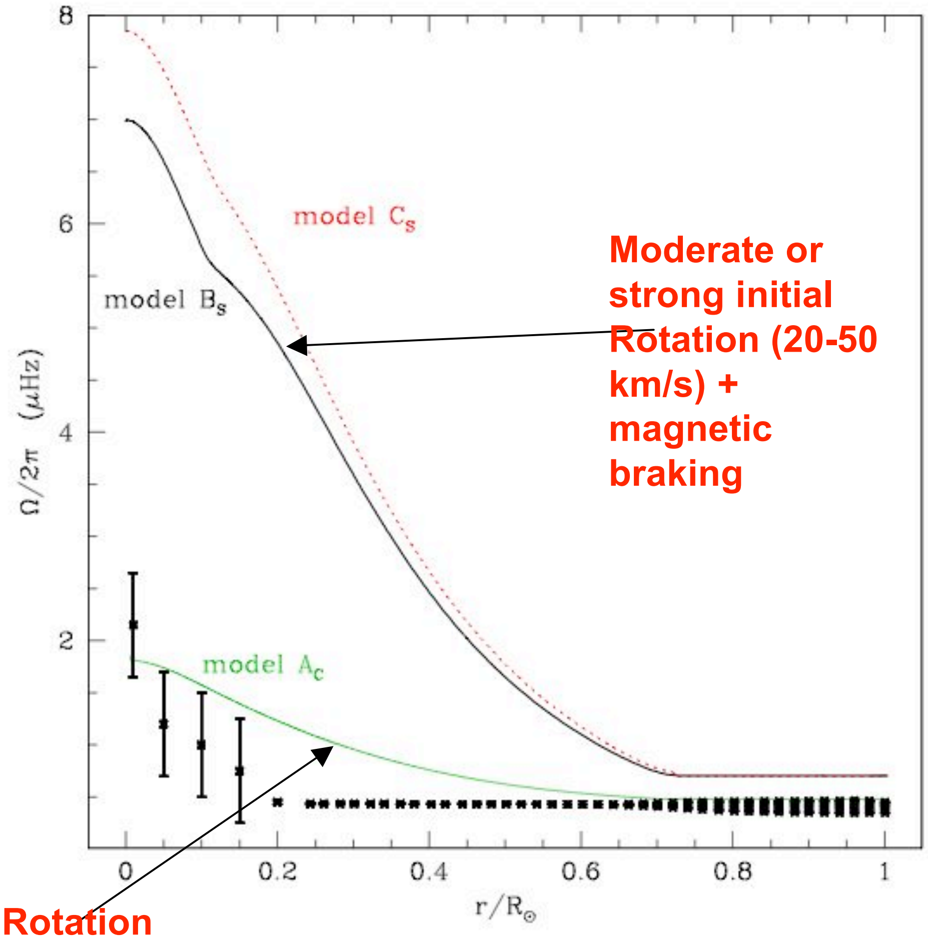
20 km/s at MS + magnetic braking

Weak initial Rotation without magnetic braking

New constraints from individual g modes in 2010

Dynamics of the solar core

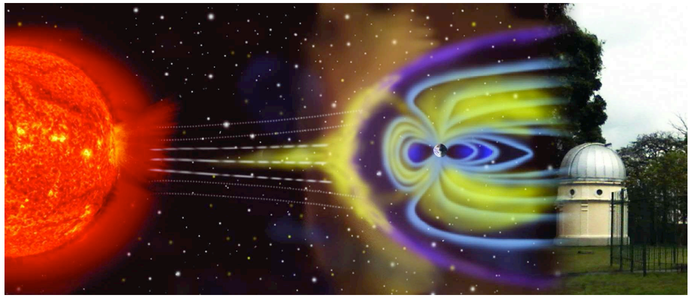
Turck-Chièze, Palacios, Marques, Nghiem, ApJ 2010 nearly accepted



Moderate or strong initial Rotation (20-50 km/s) + magnetic braking

Slow Rotation without magnetic breaking

- The radial differential rotation exists in all models and exists also in the Sun thanks to the detection of the asymptotic gravity modes.
- The increase in the core is built during the contraction phase and then slightly evolved
- The young Sun was a slow rotator
- One needs certainly magnetic field to flatten the profile outside of the core or gravity waves MATHIS

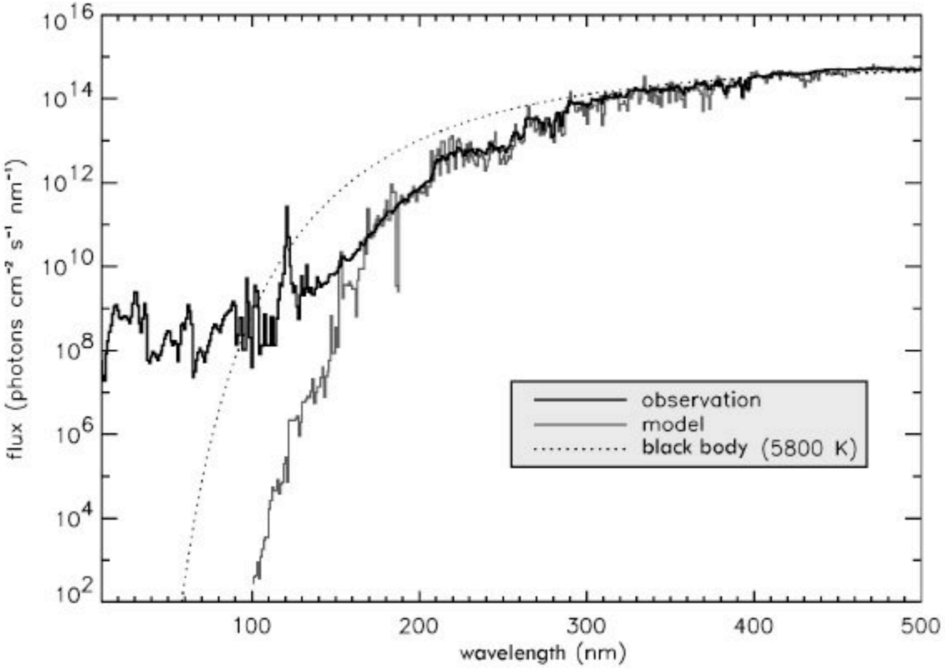


Thuillier, de Witt, Schmutz 2007

PICARD: Main objectives

Understand the solar variability

Estimate its impact on Earth atmosphere



The Sun is a magnetic star, what can we say about its internal magnetic field story ?

The young Sun and its analogs

In young stars, all the dynamical effects were amplified

Often by a factor 1000

Güdel Living Review Solar Phys 4 (2007) 3 and Bouvier (2008) in Stellar Magnetism

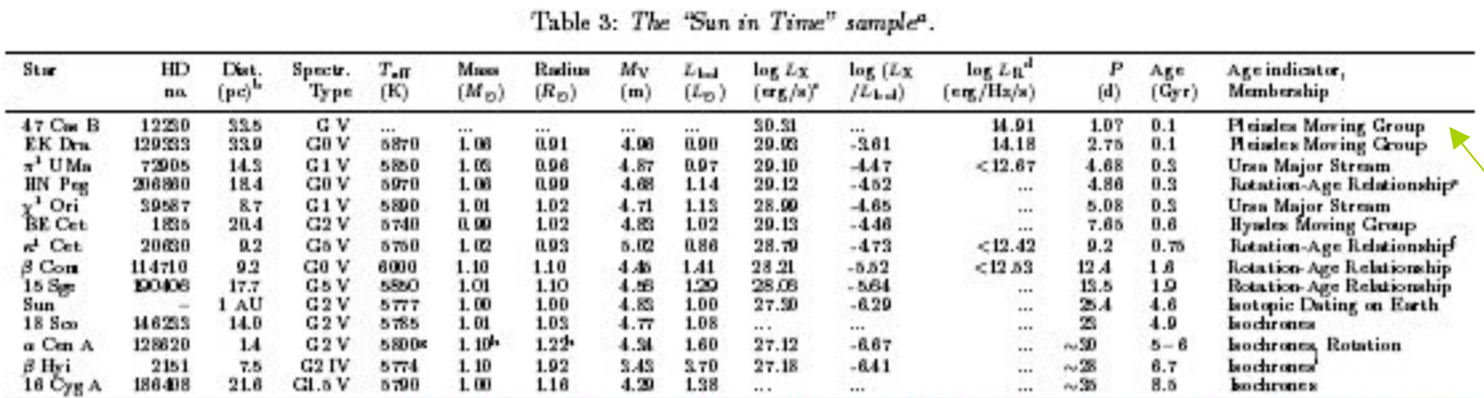


Table 3: *The "Sun in Time" sample*[a].

Star	HD no.	Dist. (pc)[b]	Spectr. Type	$T_{\rm eff}$ (K)	Mass ($M_\odot$)	Radius ($R_\odot$)	M_V (m)	$L_{\rm bol}$ ($L_\odot$)	log L_X (erg/s)[c]	log (L_X /$L_{\rm bol}$)	log L_R[d] (erg/Hz/s)	P (d)	Age (Gyr)	Age indicator, Membership
47 Cas B	12230	33.5	G V	...	...	...	...	...	30.31	...	14.91	1.07	0.1	Pleiades Moving Group
EK Dra	129333	33.9	G0 V	5870	1.06	0.91	4.96	0.90	29.93	-3.61	14.18	2.75	0.1	Pleiades Moving Group
π^1 UMa	72905	14.3	G1 V	5850	1.03	0.96	4.87	0.97	29.10	-4.47	<12.67	4.68	0.3	Ursa Major Stream
HN Peg	206860	18.4	G0 V	5970	1.06	0.99	4.68	1.14	29.12	-4.52	...	4.86	0.3	Rotation-Age Relationship[e]
χ^1 Ori	39587	8.7	G1 V	5890	1.01	1.02	4.71	1.13	28.99	-4.65	...	5.08	0.3	Ursa Major Stream
BE Cet	1835	20.4	G2 V	5740	0.99	1.02	4.83	1.02	29.13	-4.46	...	7.65	0.6	Hyades Moving Group
κ^1 Cet	20630	9.2	G5 V	5750	1.02	0.93	5.02	0.86	28.79	-4.73	<12.42	9.2	0.75	Rotation-Age Relationship[f]
β Com	114710	9.2	G0 V	6000	1.10	1.10	4.46	1.41	28.21	-5.52	<12.53	12.4	1.6	Rotation-Age Relationship
15 Sge	190406	17.7	G5 V	5850	1.01	1.10	4.58	1.29	28.08	-5.64	...	13.5	1.9	Rotation-Age Relationship
Sun	–	1 AU	G2 V	5777	1.00	1.00	4.83	1.00	27.30	-6.29	...	25.4	4.6	Isotopic Dating on Earth
18 Sco	146233	14.0	G2 V	5785	1.01	1.03	4.77	1.08	...	...	...	23	4.9	Isochrones
α Cen A	128620	1.4	G2 V	5800[g]	1.10[h]	1.22[h]	4.34	1.60	27.12	-6.67	...	~30	5 – 6	Isochrones, Rotation
β Hyi	2151	7.5	G2 IV	5774	1.10	1.92	3.45	3.70	27.18	-6.41	...	~28	6.7	Isochrones[i]
16 Cyg A	186408	21.6	G1.5 V	5790	1.00	1.16	4.29	1.38	...	...	...	~35	8.5	Isochrones

[a] Parameters mostly collected from Dorren and Guinan (1994a), Güdel et al. (1997b), Güdel et al. (1998b), Güdel and Gaidos (2001), Guinan and Ribas (2002), Ribas et al. (2005), and Telleschi et al. (2005).

[b] Stellar distances are from the Hipparcos Catalogue (Perryman et al., 1997)

[c] L_X refers to the 0.1 – 2.4 keV band as measured by ROSAT.

[d] For radio observations of further solar analogs, see Güdel et al. (1994) and Güdel and Gaidos (2001).

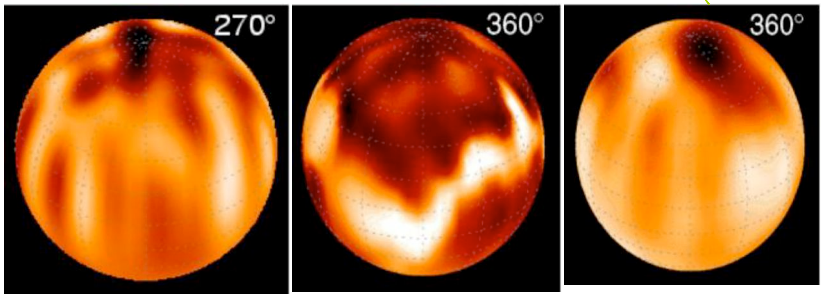
[e] Same rotation period as Ursa Major Stream G0V members.

[f] Possible member of the Hyades Moving Group.

[g] From Chmielewski et al. (1992).

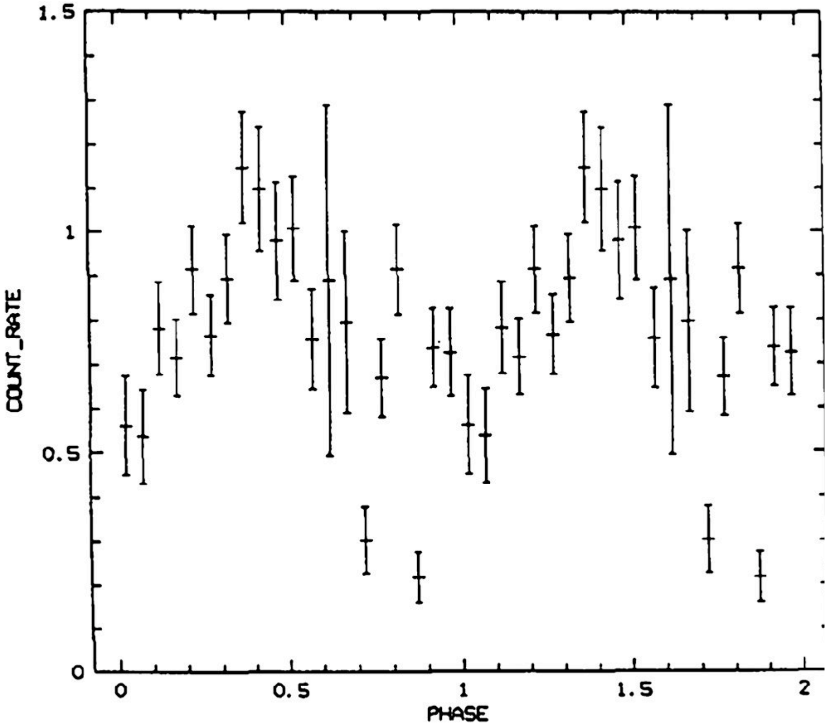
[h] From Kervella et al. (2003) based on interferometric observations.

[i] Isochrone age from Dravins et al. (1998); L_X normalized to 1 $R_\odot$.

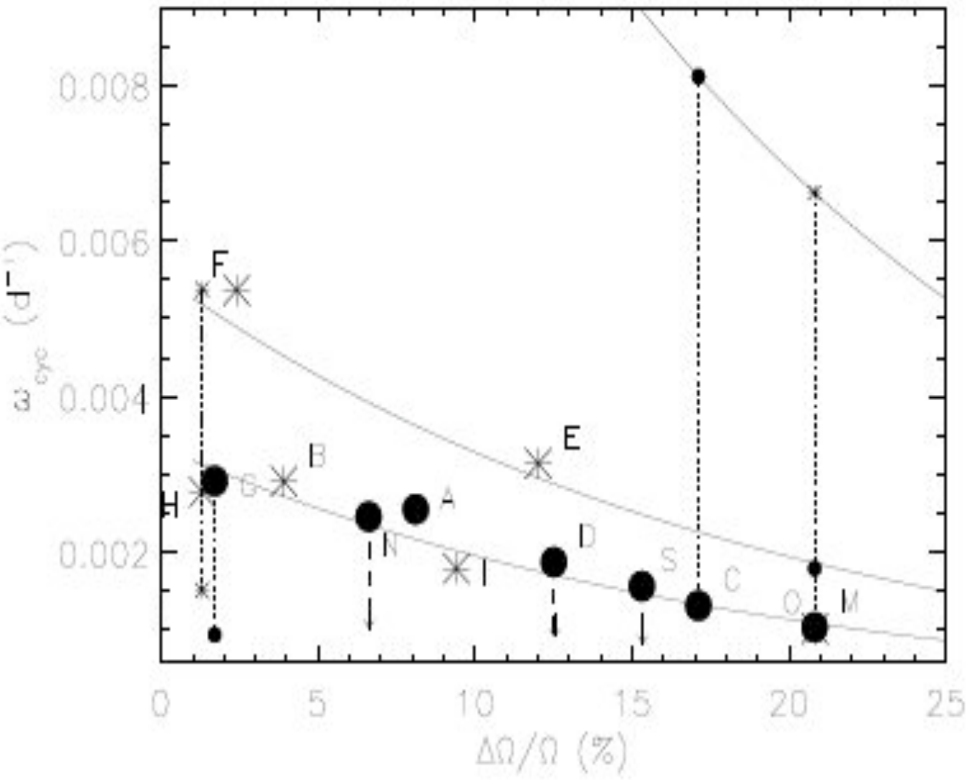


P= 1.47 days Strassmeier et al 2001, 2003 P= 2.75 days

Xray modulation and rotation rates



EK Dra (Gudel et al. 1995)



Messina and Guinan 2003

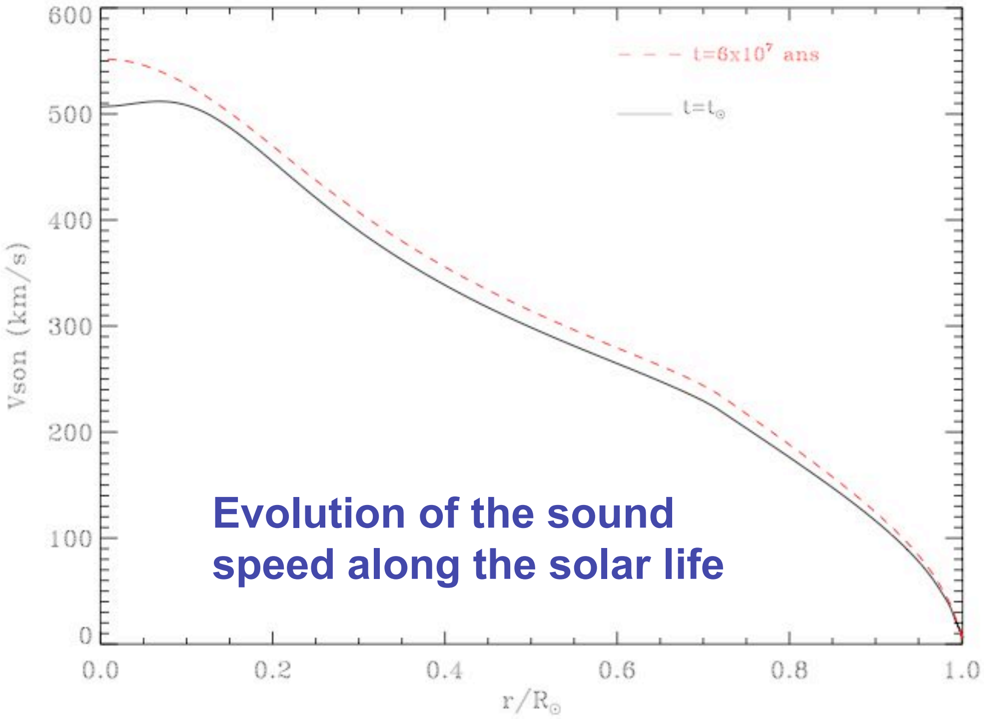
C: π1 Uma; D: EKDra

Energetic balance including magnetic loss

Turck-Chièze, Piau, Couvidat 2010 ApJ lett

$$dL/dr = 4\pi\, r^2\, \rho\, (\varepsilon_{nucl} - T\, dS/dt)$$

$$\frac{\partial L}{\partial M_r} = \left\langle \varepsilon - \frac{\partial U}{\partial t} + \frac{P_{\rm gas}}{\rho^2}\frac{\partial \rho}{\partial t} + \frac{1}{\rho}Q_{\rm Ohm} + \frac{1}{\rho}F_{\rm Poynt} \right\rangle_{\theta,\varphi} ;$$



Evolution of the sound speed along the solar life

Does the central luminosity equilibrates the present solar luminosity ?

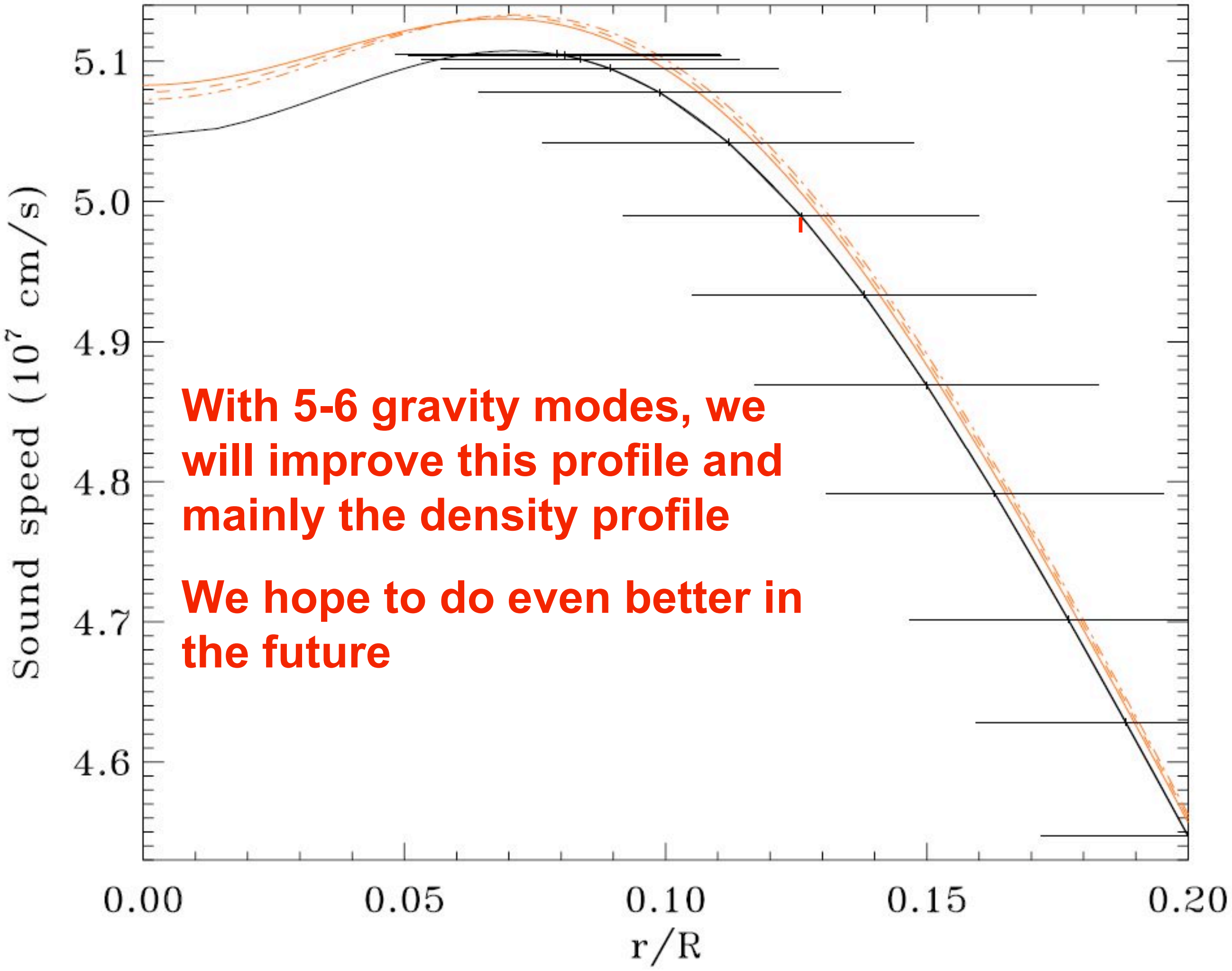
What have been lost during the solar life from magnetic energy???

Zoom on the solar core

Asplund SSM (T= 15.5 10^6K) and

Seismic model (T= 15.75 10^6K) T-C et al. 2001, Basu et al. 2009

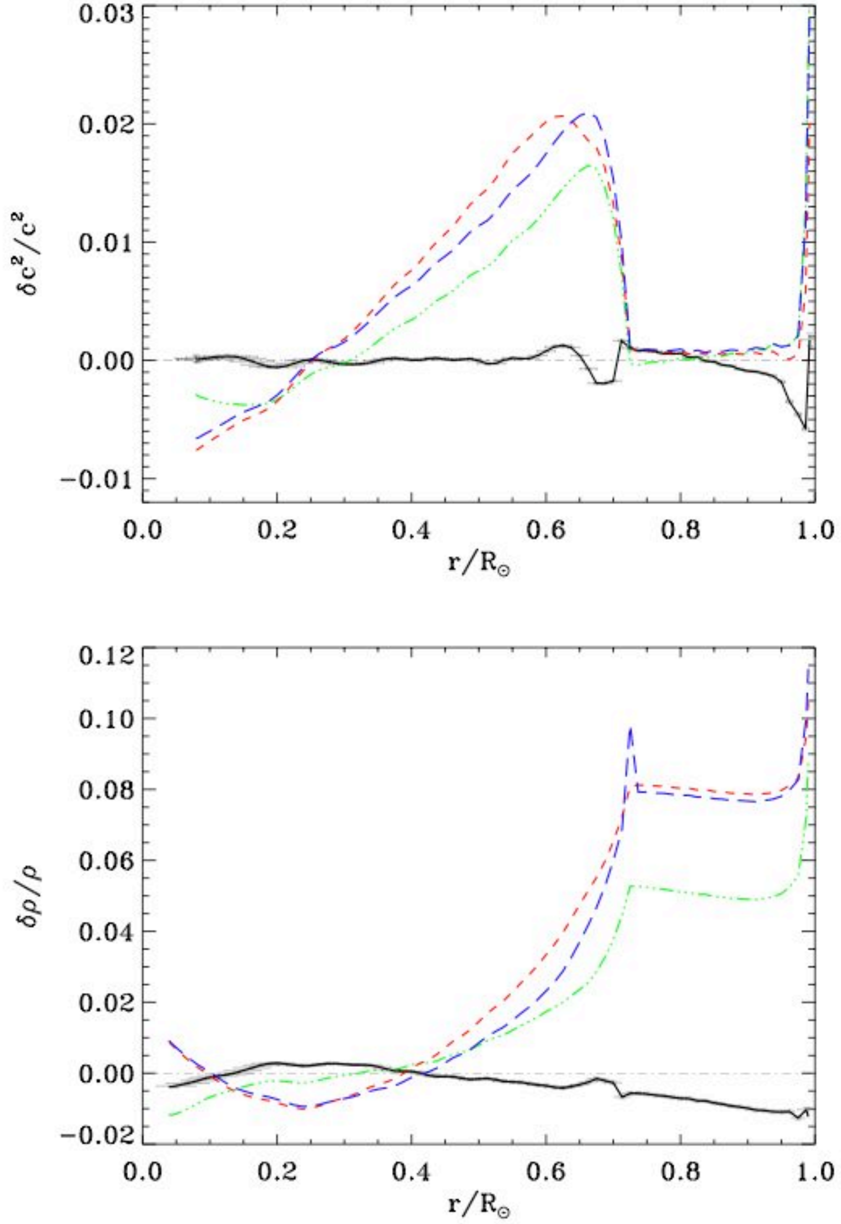
Asplund SSM and L increased by 2.5% or 5% in the core



With 5-6 gravity modes, we will improve this profile and mainly the density profile

We hope to do even better in the future

Mass loss Guzik, Mussack 2010, T-C, Piau, 2010



$$\dot{M}_W = 9\ 10^{-12}\tau(Gyrs)^{-2.23}$$

M initial 1.33 M_{sol} ??

L_{init} = 1.5 Lsol

Improvement of the prediction of the sound speed

CONCLUSION

- **One needs to better describe the young Sun to understand the internal structure of the present Sun and the arrival of life on Earth**
- **First hints:**
    - **the rotation of the young Sun was not so high probably,**
    - **Mass loss has played a crucial role in the history of the luminosity at the first stage**

- **Future works:**
    - **The history of the magnetic field**
    - **How has it been amplified, what amplitude does it get? 3D simulations, more observations of mass loss,**
    - **Better describe the interaction of the fossil field with the tachocline and the interaction of the fossil field with the dynamo field: variabilities**
    - **Building a complete dynamical solar model (1D-2D-3D)**

Internal magnetic field

Observationally poorly known

deep fossil field (Duez, Mathis 2009; Duez et al. 2009)

sub surface field (Nghiem et al. 2006; Lefebvre & Kosovichev 2007; Lefebvre, Nghiem, T-C 2009)

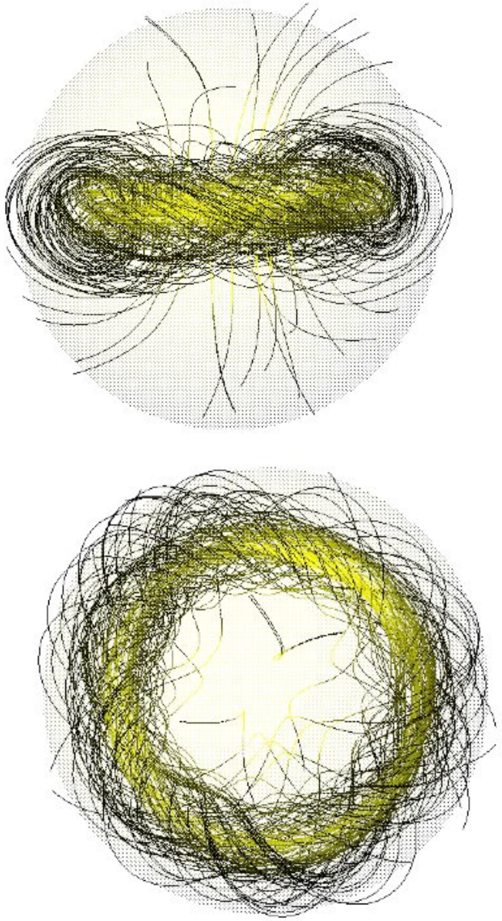
- Deep field in the radiative zone

$$P = P_{\mathrm{gas}} + P_{\mathrm{mag}}$$

$$\begin{aligned}
\frac{\partial P}{\partial M} &= -\frac{GM}{4\pi R^4} + < \mathcal{F}_T >_\theta \\
\frac{\partial T}{\partial M} &= \frac{\partial P}{\partial M}\frac{T}{P}\nabla \\
\frac{\partial R}{\partial M} &= \frac{1}{4\pi R^2 \rho} \\
\frac{\partial L}{\partial M} &= \epsilon - \epsilon_G = \epsilon - \frac{\partial U}{\partial t} + \frac{P}{\rho^2}\frac{\partial \rho}{\partial t} + \frac{Q}{\rho} + \frac{\nabla \cdot \Pi}{\rho} \\
\frac{\partial X_i}{\partial t} &= -\frac{\partial F_i}{\partial M} + \Psi_i(P_{gas}, T; \mathcal{X}) \qquad (1 \leq i \leq n_{\mathrm{elem}})
\end{aligned}$$

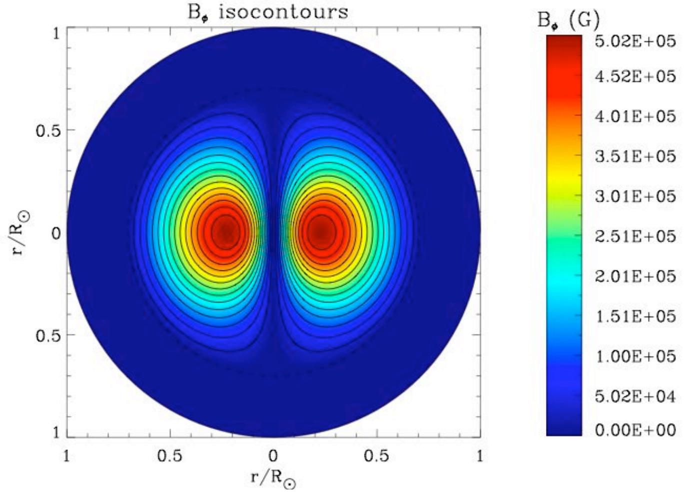
$$+ \qquad L = 4\pi R^2 F_{\mathrm{tot}} = 4\pi R^2 \left(F_{\mathrm{rad}} + F_{\mathrm{conv}} \; + F_{\mathrm{mag}} \right)$$

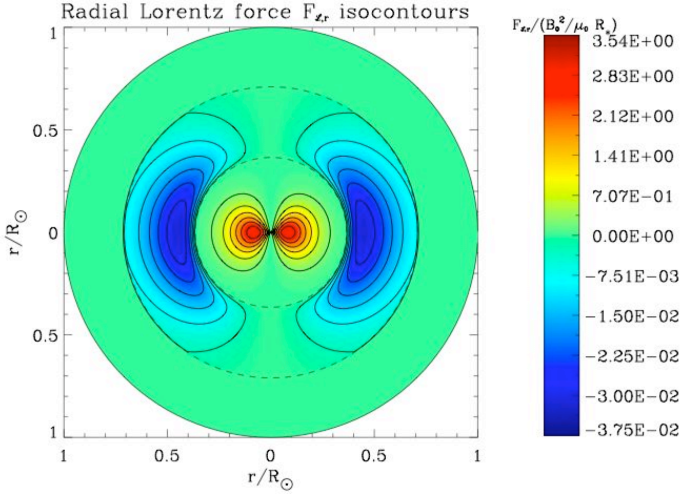
A stable configuration supposes a mixture of poloidal and toroidal fields



Braithwaite ApJ 2008

First MHD calculations in 1D stellar models with an initial non force free configuration of a mixed field





Duez and Mathis 2009; Duez et al. 2009

Effect of a RZ confined fossil field of 2.1 MG analytical results

- $J_0 = 7.74\ 10^{-6}$; $J_2 = -7.66\ 10^{-8}$
- $c_0 = -1.6010^{-6}$; $c_2 = 1.58\ 10^{-8}$

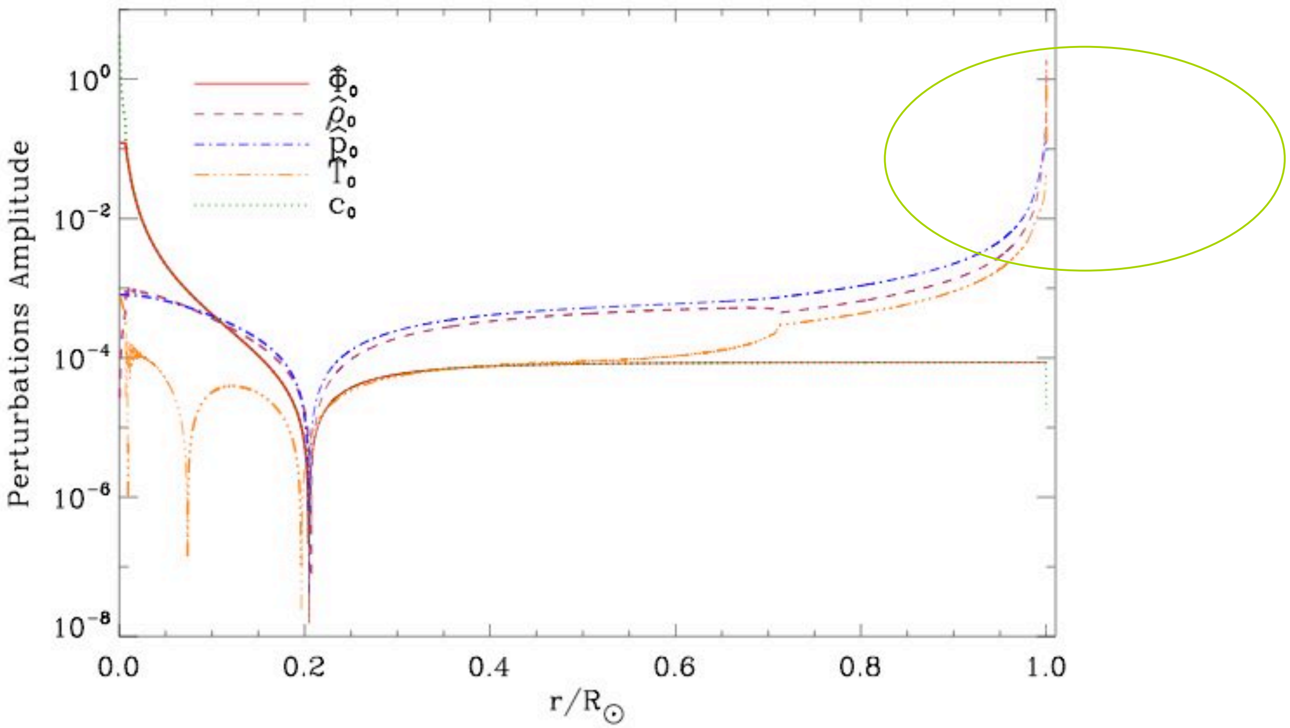
$$J_l = \left(\frac{R_*}{GM_*}\right)\widehat{\phi}_l\left(r = R_*\right)$$

$$\begin{aligned}\phi(r,\theta) &= \phi_0(r) + \phi^{(1)}(r,\theta)\\ &= \phi_0(r) + \sum_{l\geqslant 0}\widehat{\phi}_l(r)\,P_l(\cos\theta)\end{aligned}$$

$$r_P(r,\theta) = r\left[1 + \sum_{l\geqslant 0} c_l(r) P_l(\cos\theta)\right]$$

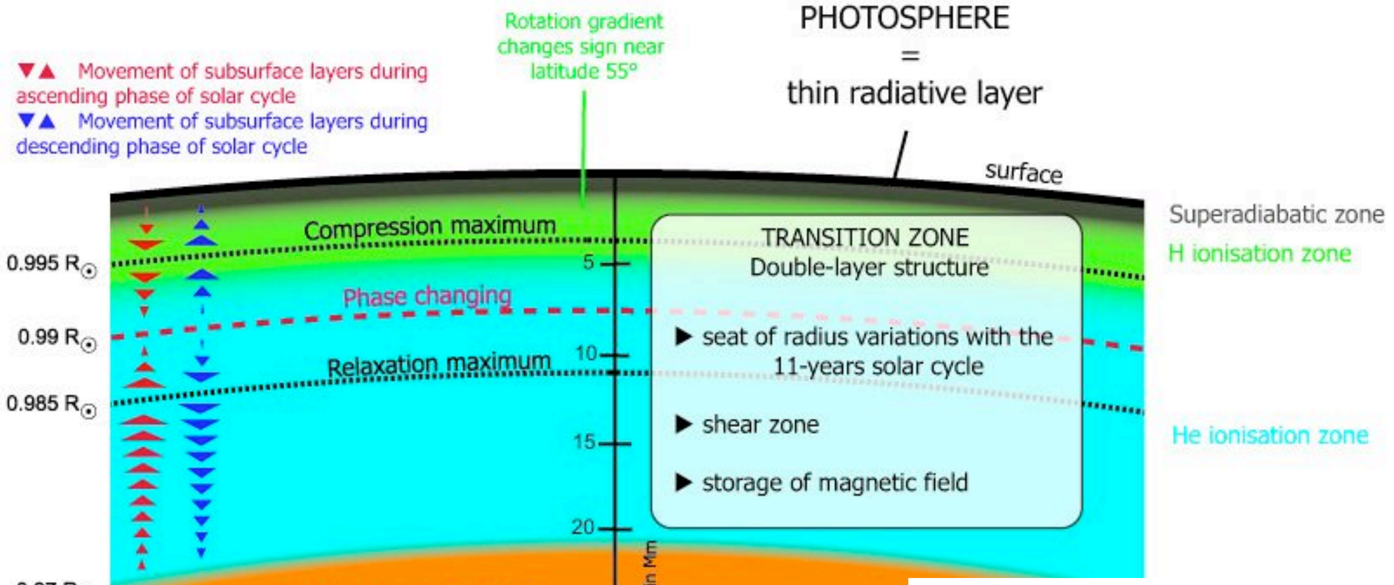
$$c_l = -\frac{1}{r}\frac{\widehat{P}_l}{\mathrm{d}P_0/\mathrm{d}r} = \frac{\rho_0}{\mathrm{d}P_0/\mathrm{d}r}\left(\frac{1}{r}\widehat{\phi}_l + \frac{\mathcal{Y}_{\boldsymbol{F}_{\mathcal{L}};l}}{\rho_0}\right)$$

Structural effects



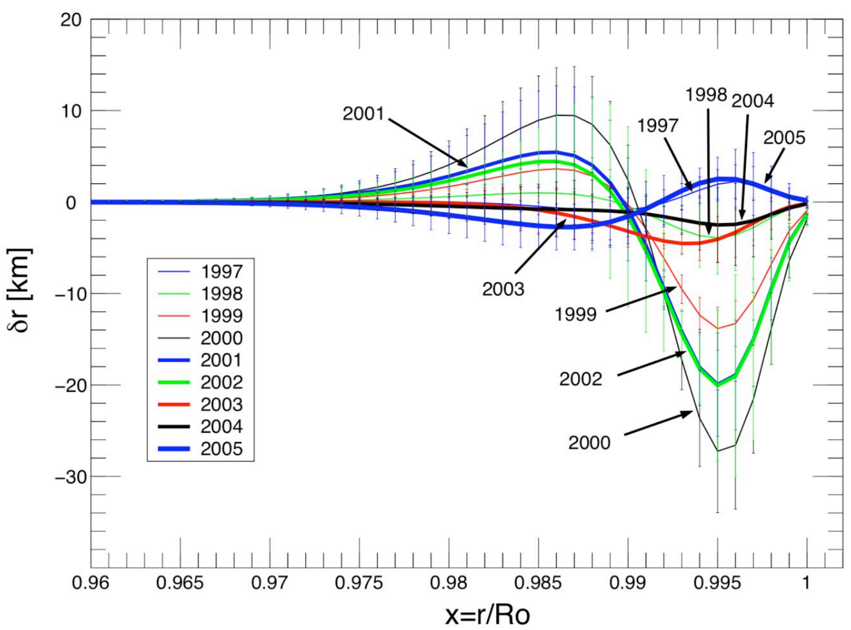
. Then we will consider the diffusive field to calculate the transport of angular momentum by the deep magnetic field

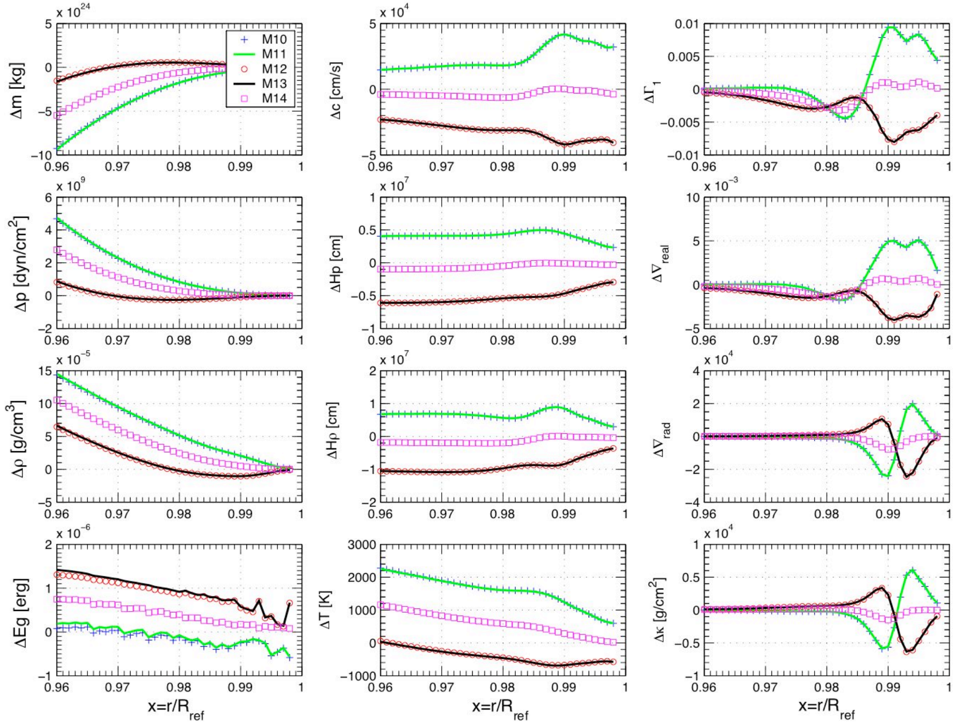
The subsurface variability: structural effects



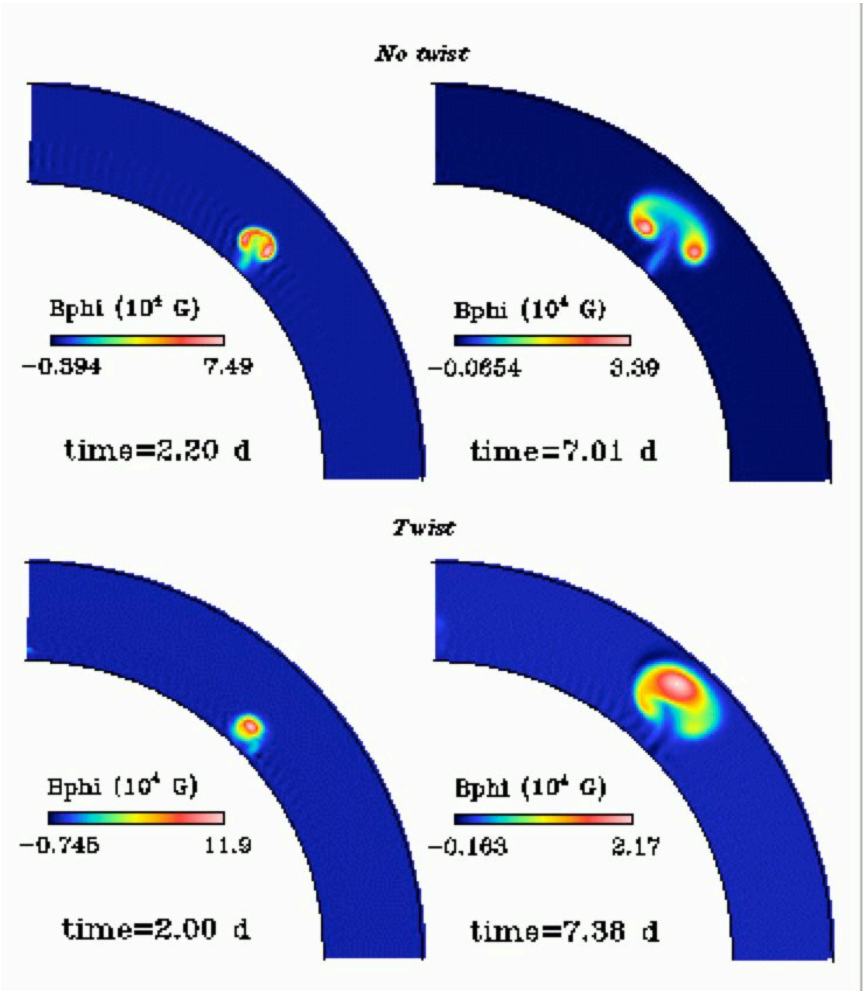
Lefebvre, Nghiem, Turck-Chièze ApJ, 690, 1272,2009

Radius variation along the solar cycle of about 10 km





The subsurface variability: dynamical effects



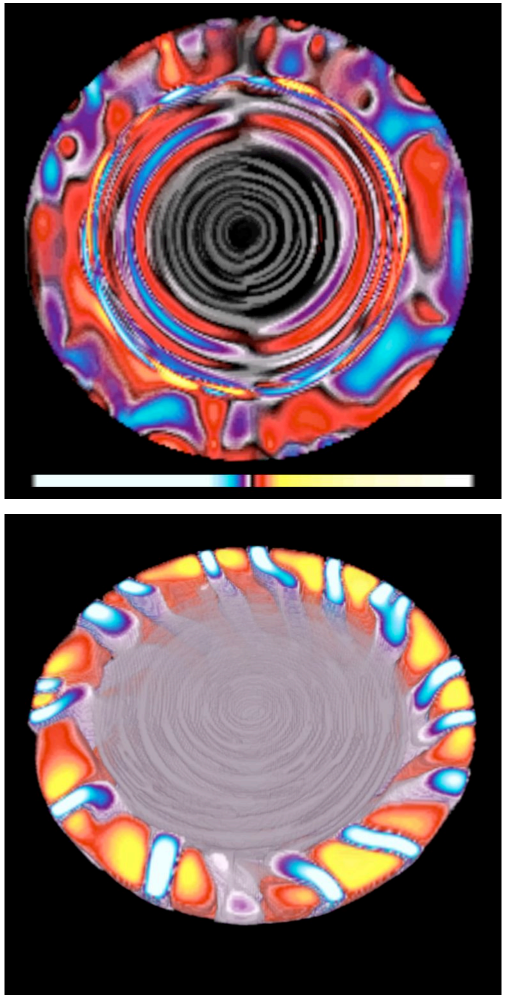
Jouve and Brun 2007

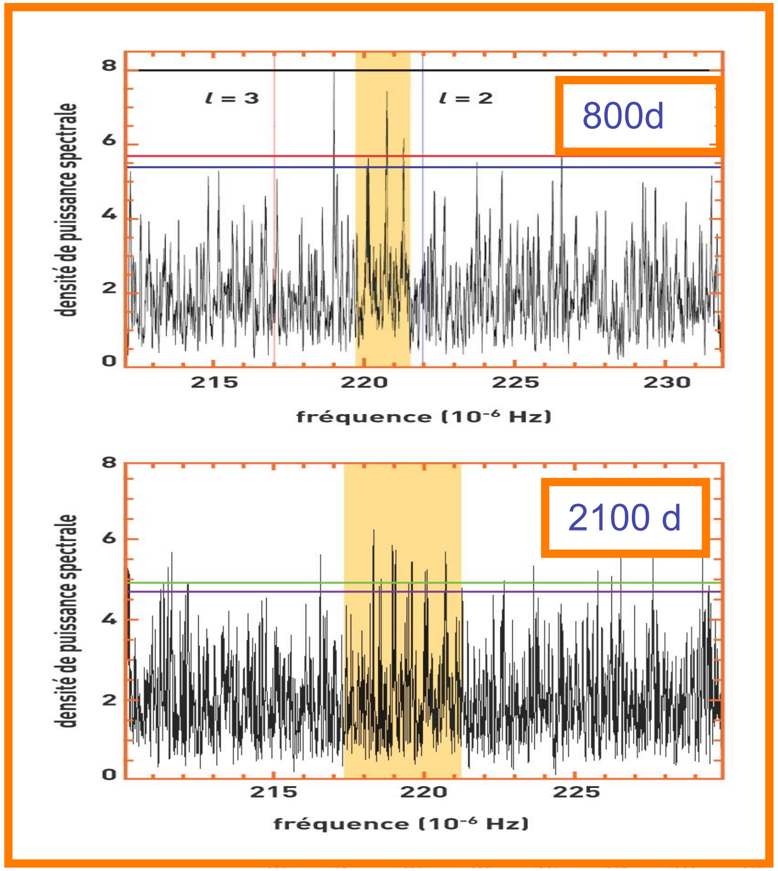
2D simulations of meridonal circulation and prediction of the coming solar cycles must be pursued (Dikpati, Kosovichev, Charbonneau …)

3D simulations of ascendent twisted flux tubes must be also pursue to understand why the magnetic field do not emerge at the surface of the Sun presently

f modes and variability of low degree p-modes may help to put constraints on the sub surface magnetic field + local seismology: SDO +PICARD

Gravity waves and the motions of the tachocline

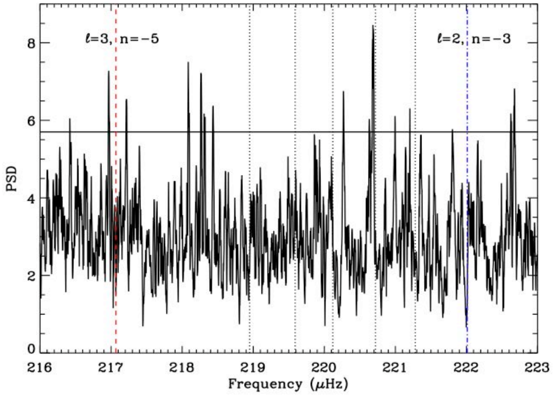




Gravity modes detection

GOLF/ VIRGO

Individual detection is important to see if the modes are influenced by the variability of the tachocline



Turck-Chièze et al. 2004;

Garcia et al. 2008

Summary and perspectives

- Introduction of all the dynamical phenomena in the 1D solar models, also 2-3D simulations
- Very small effect on the solar structure

except near the surface

- Then we will examine the interplay between phenomena and estimate the potential for other cycles or variabilities than the 11 year in order to better predict the variability of the solar activity

- Which observables do we need to support this study ?

Final objectives

- Build a new seismic model with new abundances and first g- modes included

- Improve the Dynamical Solar model with transport of momentum and chemicals by rotation (T-C, Palacios, Nghiem, Marques), magnetic field and gravity waves

- Improve the subsurface layers in adding the dynamo field and the magnetic field above the photosphere