From the Sun to young solar like stars

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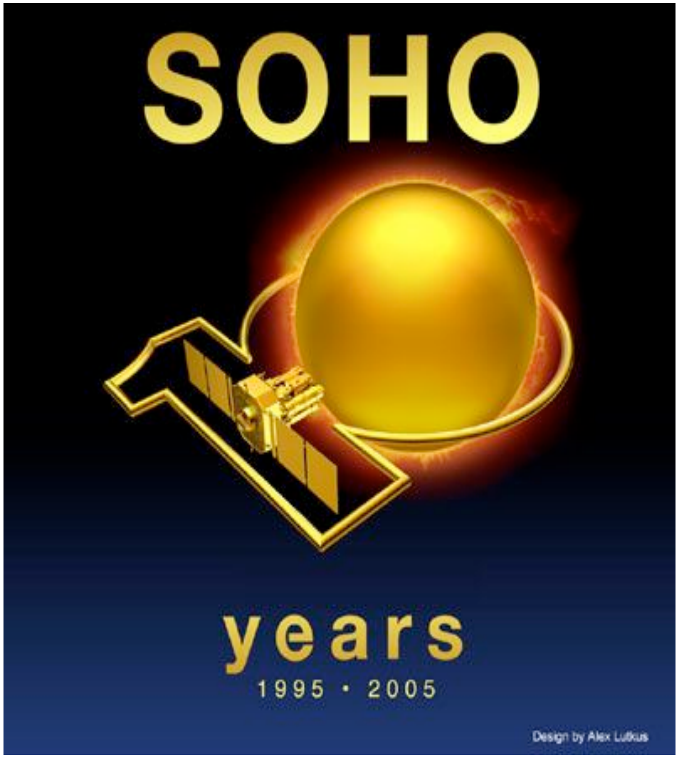
Internal rotation, Internal magnetic field,

Sound speed and activity of young Sun

SOHO, SDO and PICARD

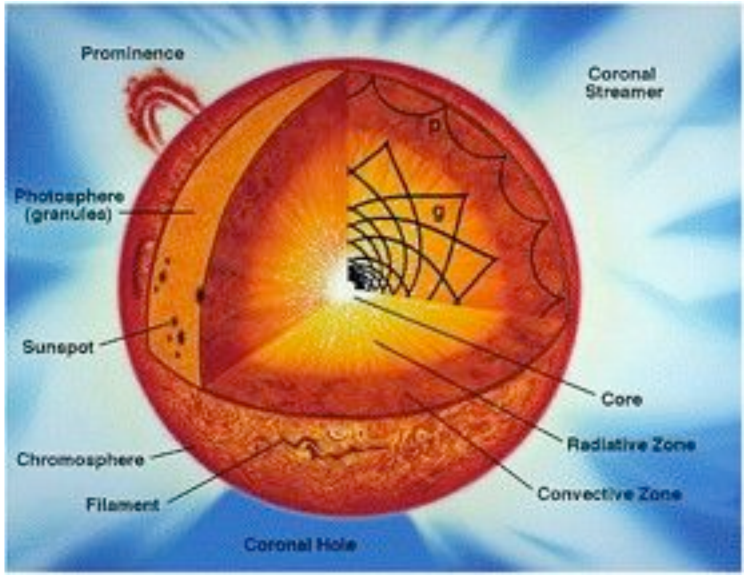
NASA: SDO 2010-2015



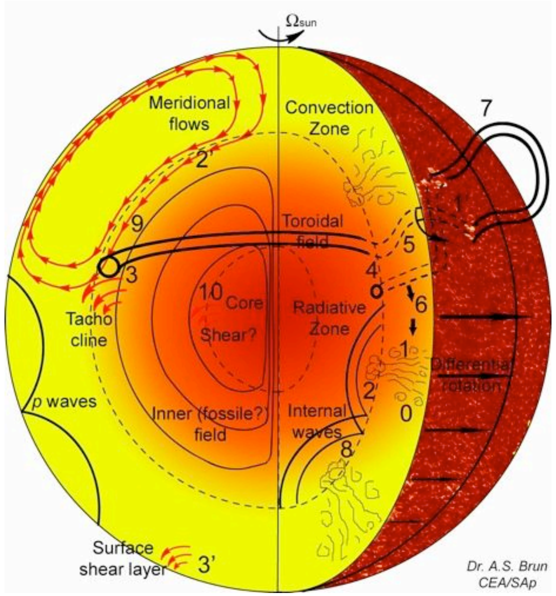
SOHO: 1995 - 2012

PICARD: Microsatellite CNES
Fr+Be+Ch 2010-2013

From a classical solar model to a dynamical solar model

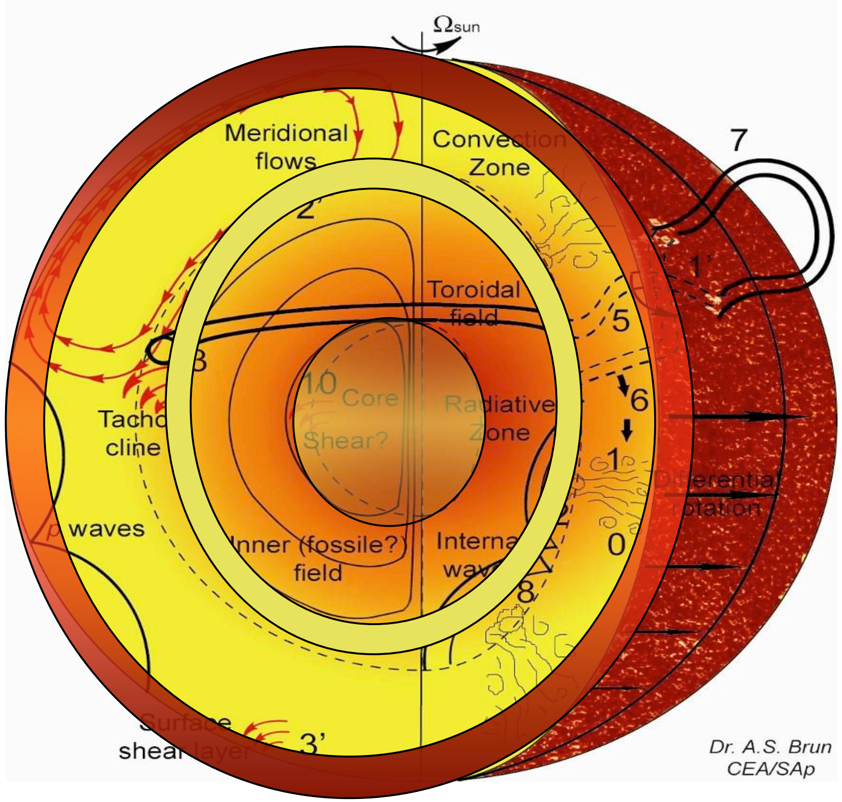


Brun and Jouve 2008



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 first stage can influence the present status

The missing bridges



Dr. A.S. Brun
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- 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

The young Sun and its analogs

In young stars, all the dynamical effects were amplified

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

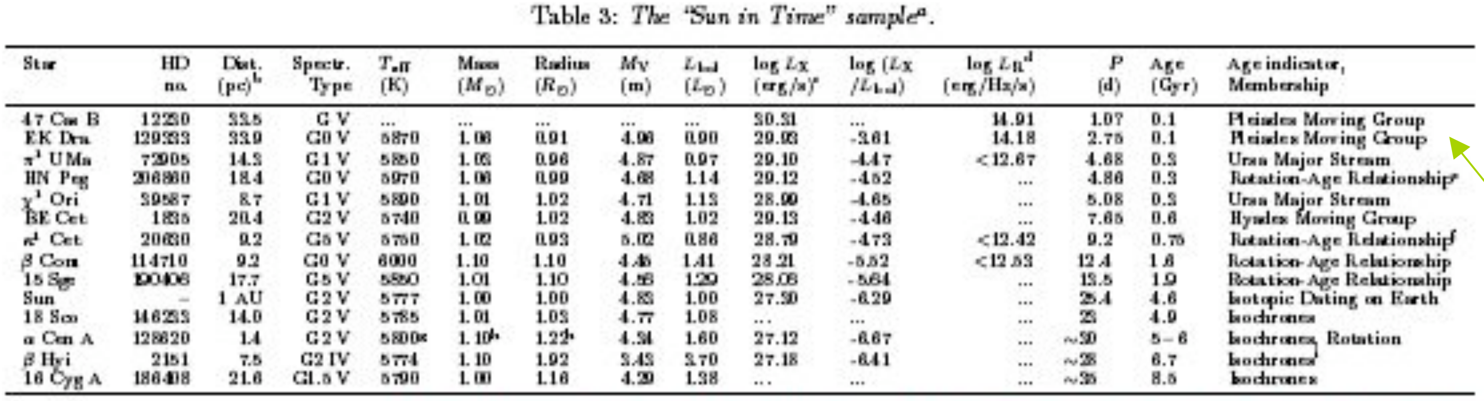


Table 3: *The "Sun in Time" sample*[a].

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).

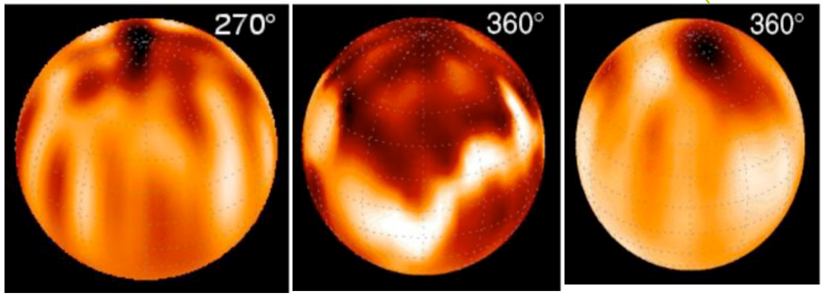
[e] Same rotation period as Ursa Major Stream G0V members.

[f] Possible member of the Hyades Moving Group.

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

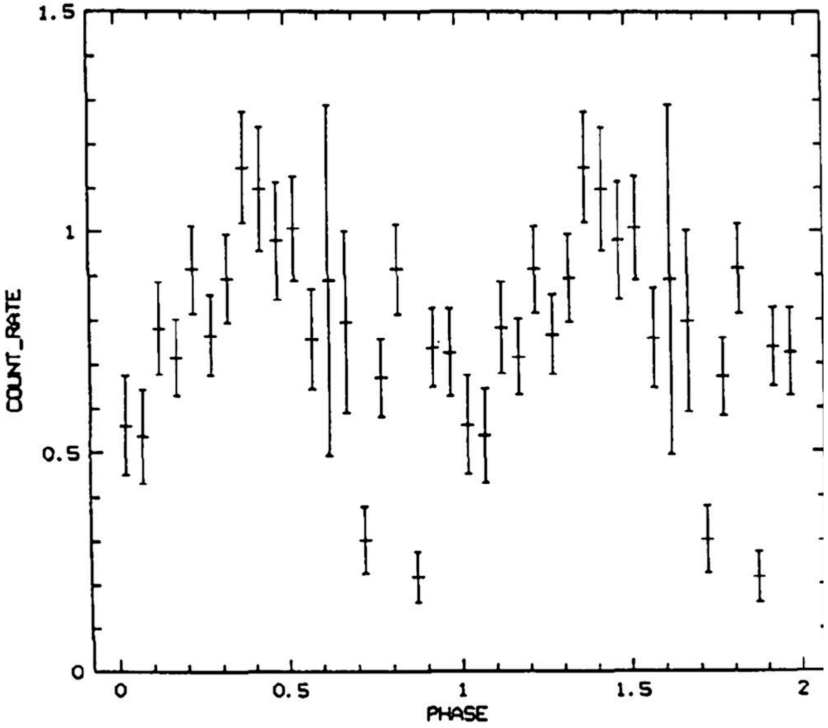
[h] From Kervella et al. (2003) based on interferometric observations.

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

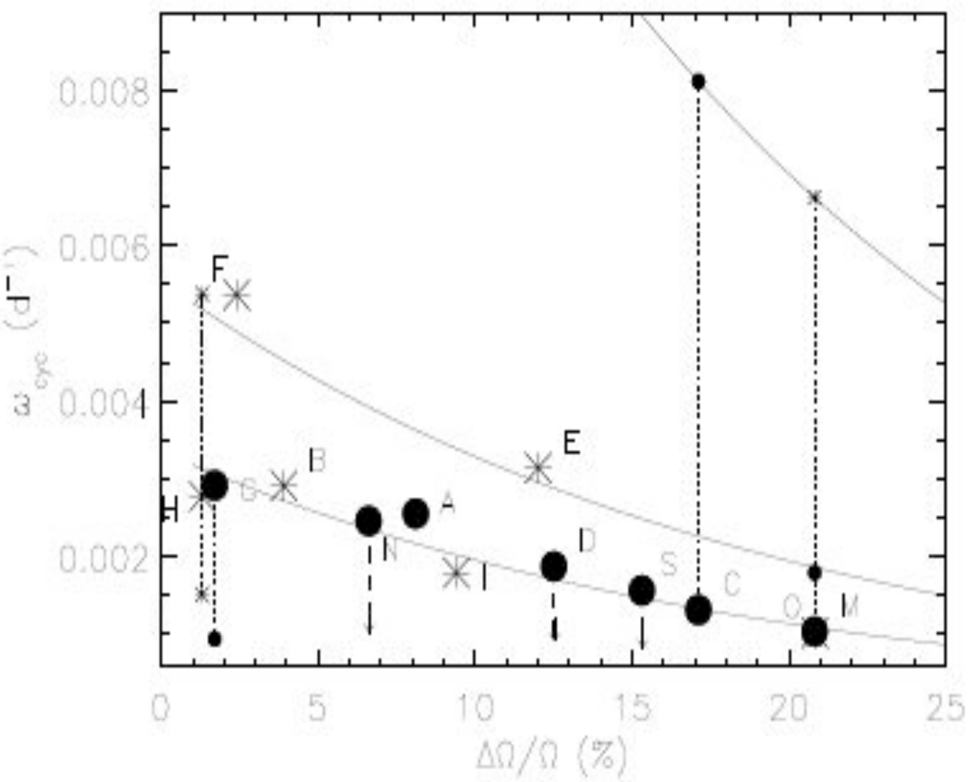


P= 1.47 days Strassmeier et al 2001, 2003 P= 2.75 days

Xray modulation and rotation rates



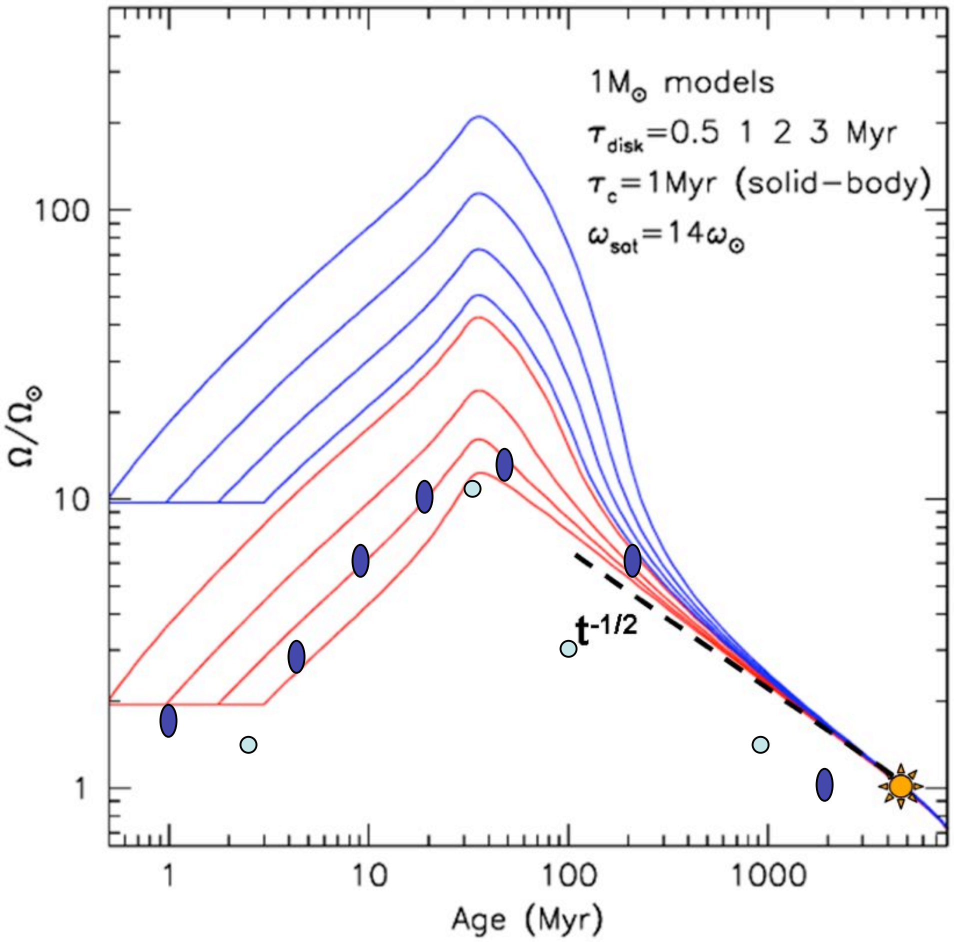
EK Dra (Gudel et al. 1995)



Messina and Guinan 2003

C: π1 Uma; D: EKDra

The magnetic field Influence on 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

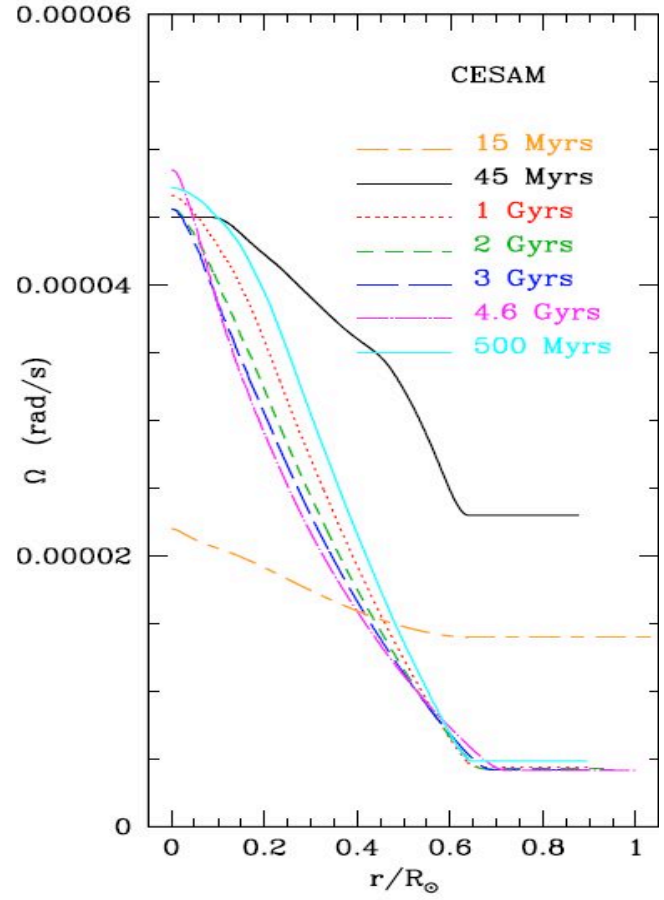
So depending on the disk lifetime, stars are rapid or low rotators.

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

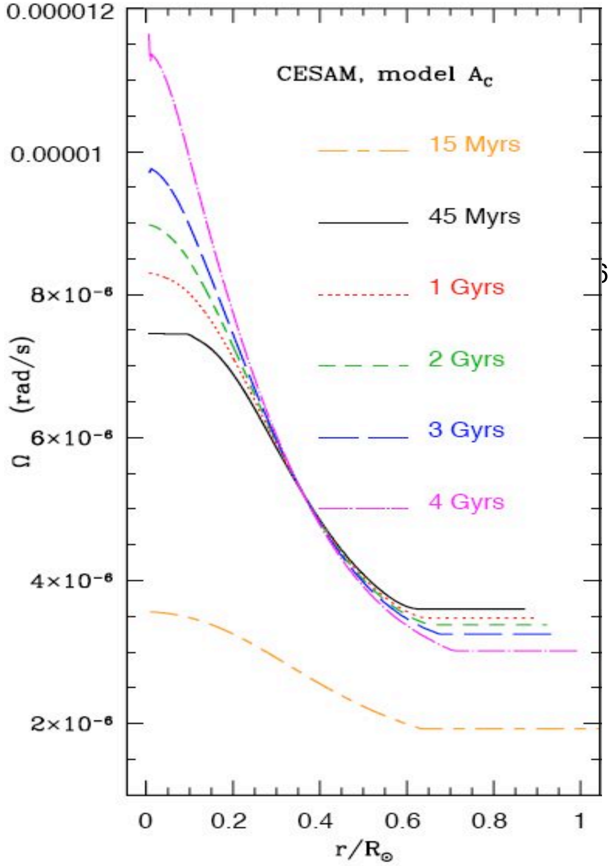
The theoretical evolution of the internal rotation

Turck-Chièze, Palacios, Marques, Nghiem ApJ 2010

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

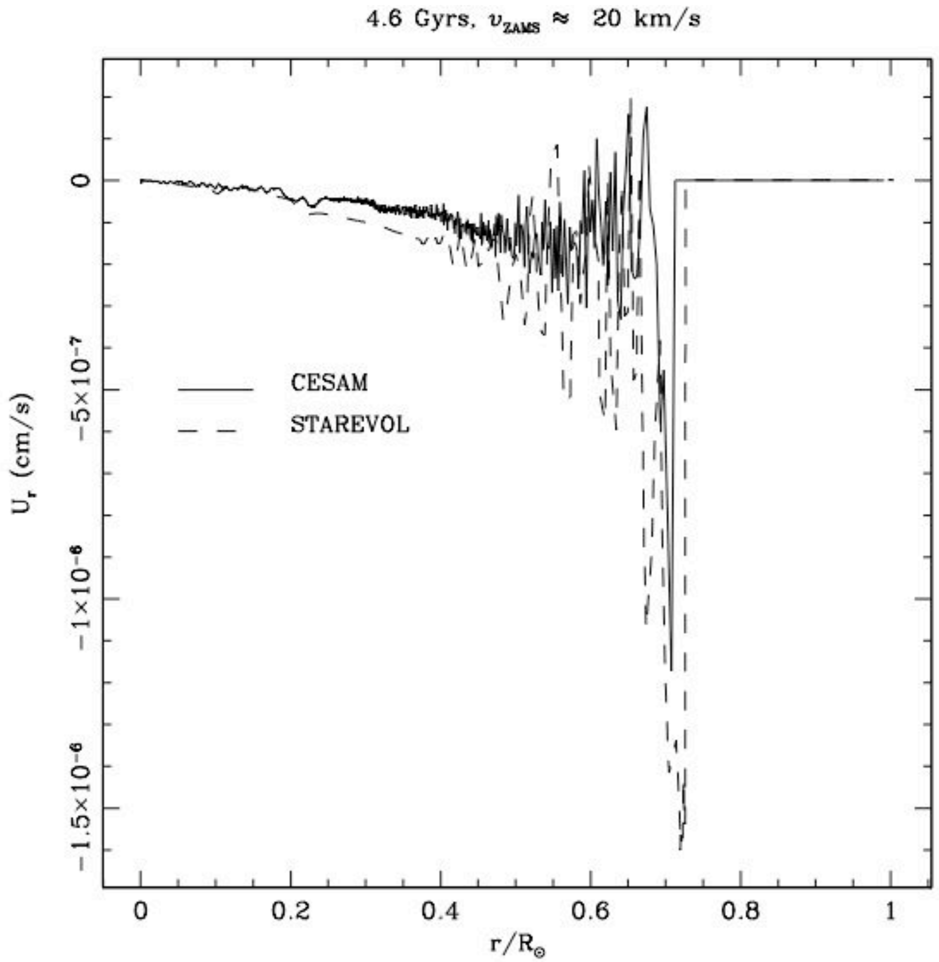


Initial strong rotation + braking



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

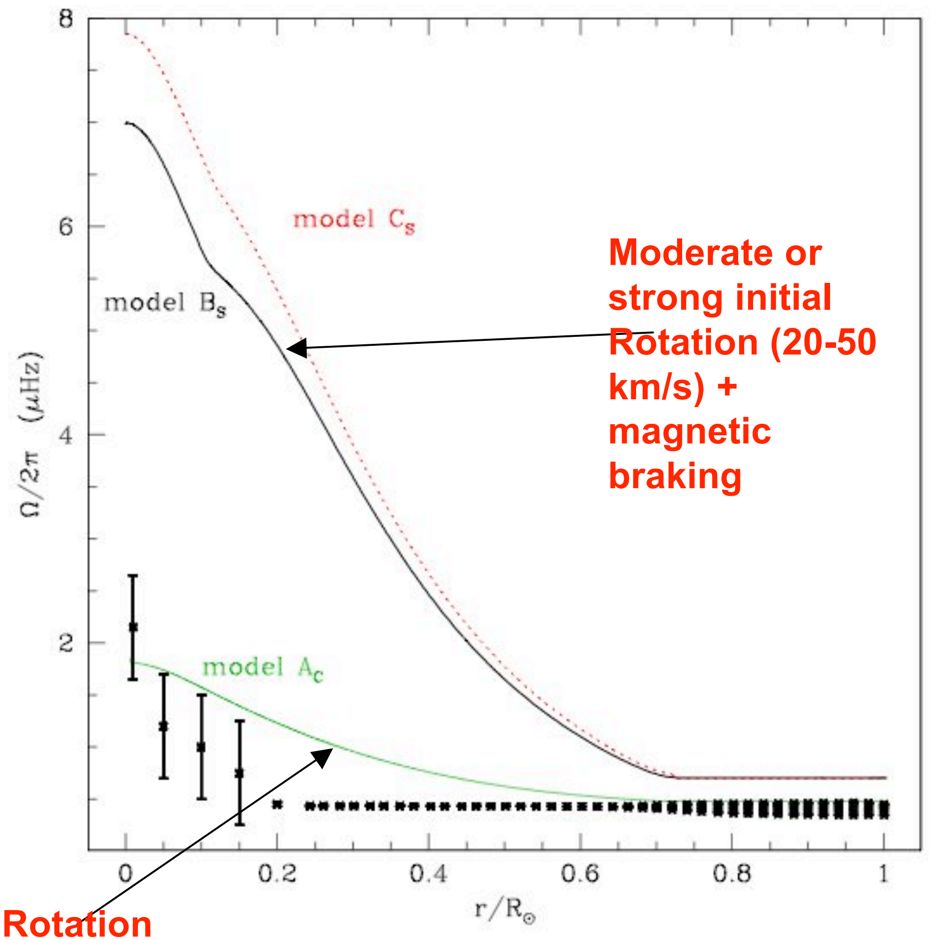
some m/s

So the tachocline is now well understood

They also play a crucial role in the stability of the solar dynamo

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
- One needs certainly magnetic field to flatten the profile outside of the core (Eggenberger et al. 2007)

Internal magnetic field

Observationally poorly known

deep fossil field (Duez, Mathis 2009; Duez et al. 2009, Mestel & Moss 2010)

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

Deep field in the radiative zone

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

$$\frac{\partial P}{\partial M} = -\frac{GM}{4\pi R^4} + < \mathcal{F}_T >_\theta$$

$$\frac{\partial T}{\partial M} = \frac{\partial P}{\partial M}\frac{T}{P}\nabla$$

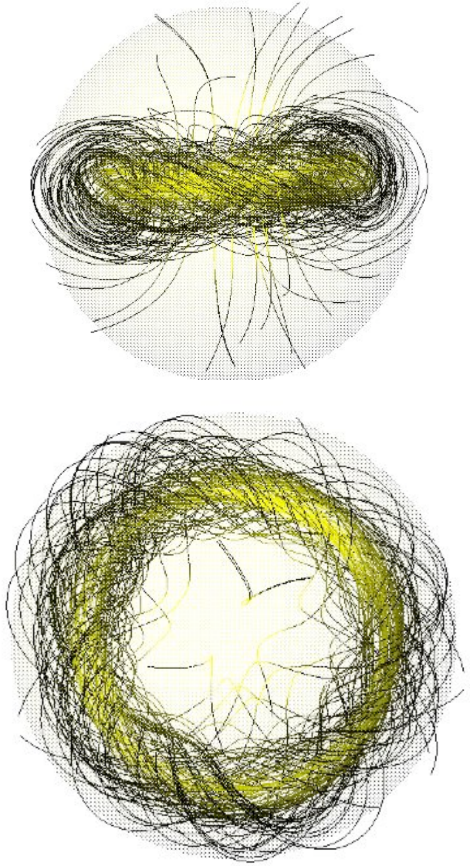
$$\frac{\partial R}{\partial M} = \frac{1}{4\pi R^2 \rho}$$

$$\frac{\partial L}{\partial M} = \epsilon - \epsilon_G = \epsilon - \frac{\partial U}{\partial t} + \frac{P}{\rho^2}\frac{\partial \rho}{\partial t} + \frac{Q}{\rho} + \frac{\nabla\cdot\Pi}{\rho}$$

$$\frac{\partial X_i}{\partial t} = -\frac{\partial F_i}{\partial M} + \Psi_i(P_{gaz}, T; \mathcal{X}) \qquad (1 \le i \le n_{elem})$$

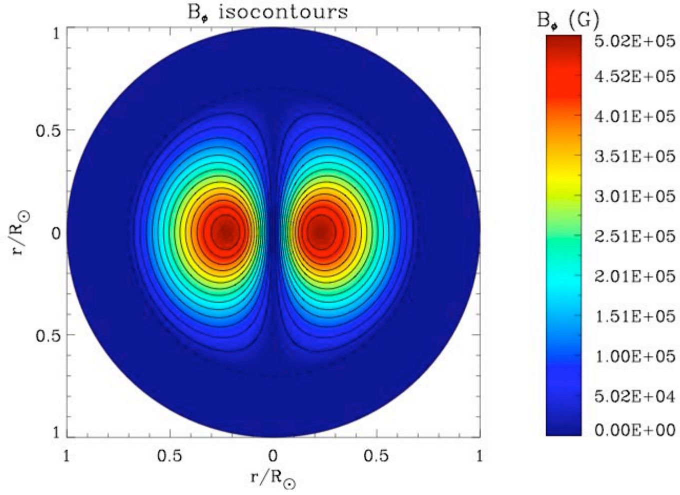
$$+ \qquad L = 4\pi R^2 F_{tot} = 4\pi R^2 \left(F_{rad} + F_{conv} + F_{\rm mag}\right)$$

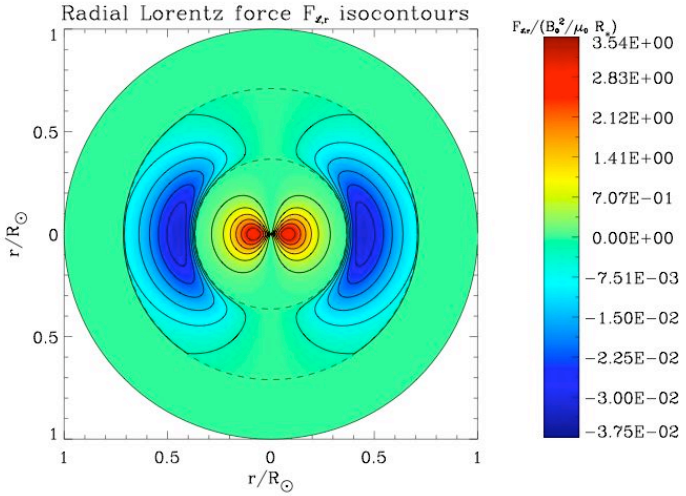
A stable configuration supposes a mixture of poloidal and toroidal fields



Braithwaite ApJ 2008

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





Duez, Mathis & Turck-Chieze, 2009

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

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

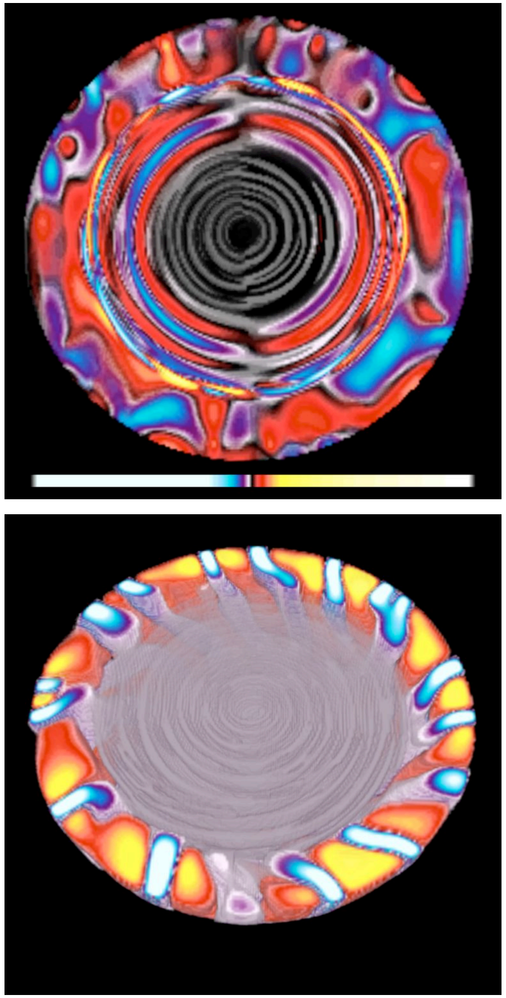
$$J_l = \left(\frac{R_*}{GM_*}\right)\widehat{\phi}_l\left(r = R_*\right)$$

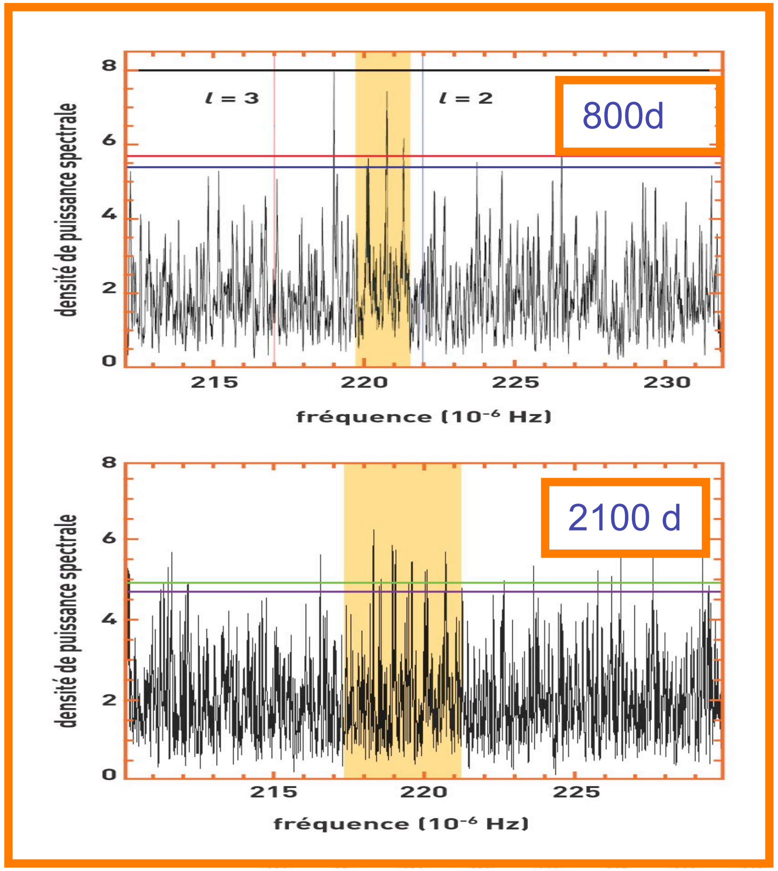
$$\begin{aligned}\phi\left(r,\theta\right) &= \phi_0\left(r\right) + \phi^{(1)}\left(r,\theta\right)\\ &= \phi_0\left(r\right) + \sum_{l\geqslant 0}\widehat{\phi}_l\left(r\right)P_l\left(\cos\theta\right)\end{aligned}$$

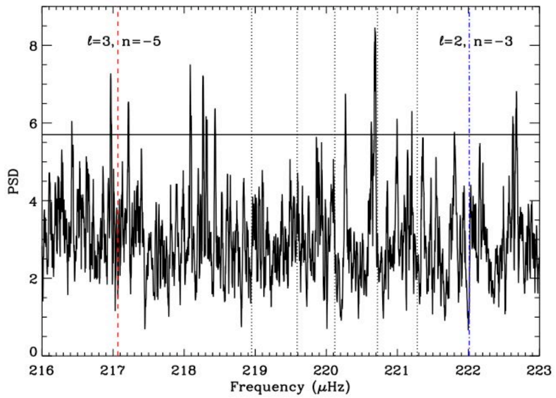
$$r_P(r,\theta) = r\left[1 + \sum_{l\geqslant 0} c_l(r)P_l(\cos\theta)\right]$$

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

Gravity waves and the motions of the tachocline





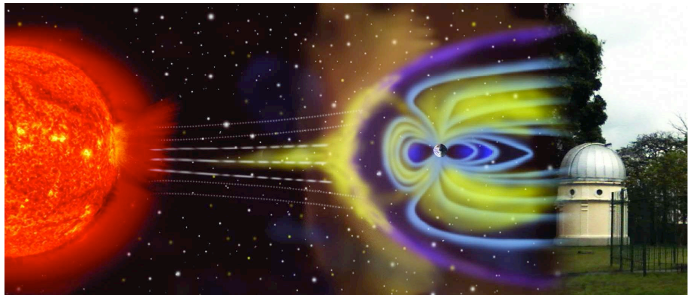


Gravity modes detection GOLF/ VIRGO

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

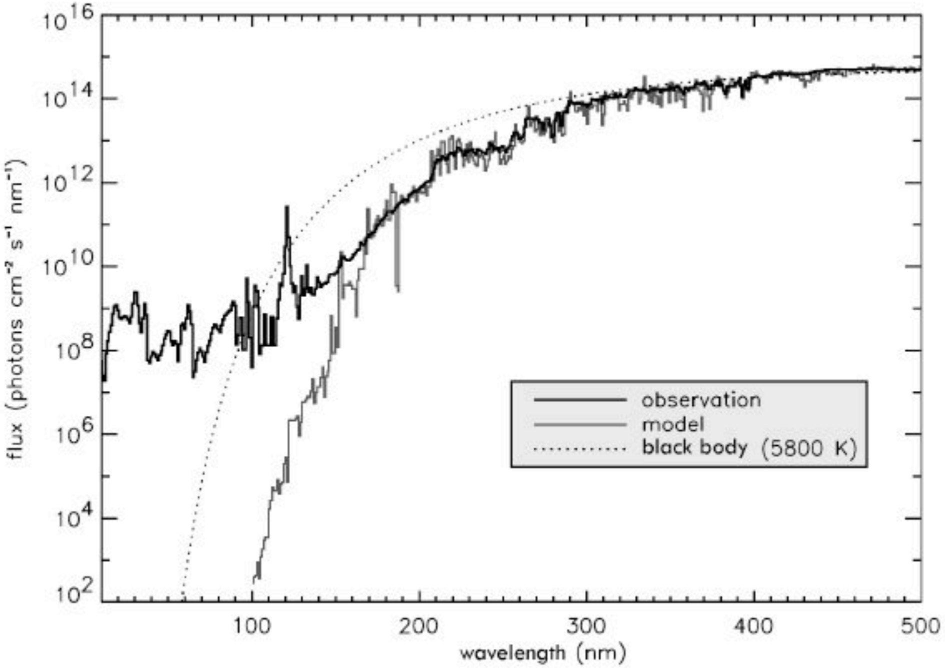


Thuillier, de Witt, Schmutz 2007

PICARD: Main objectives

Understand the solar variability

Estimate its impact on Earth atmosphere



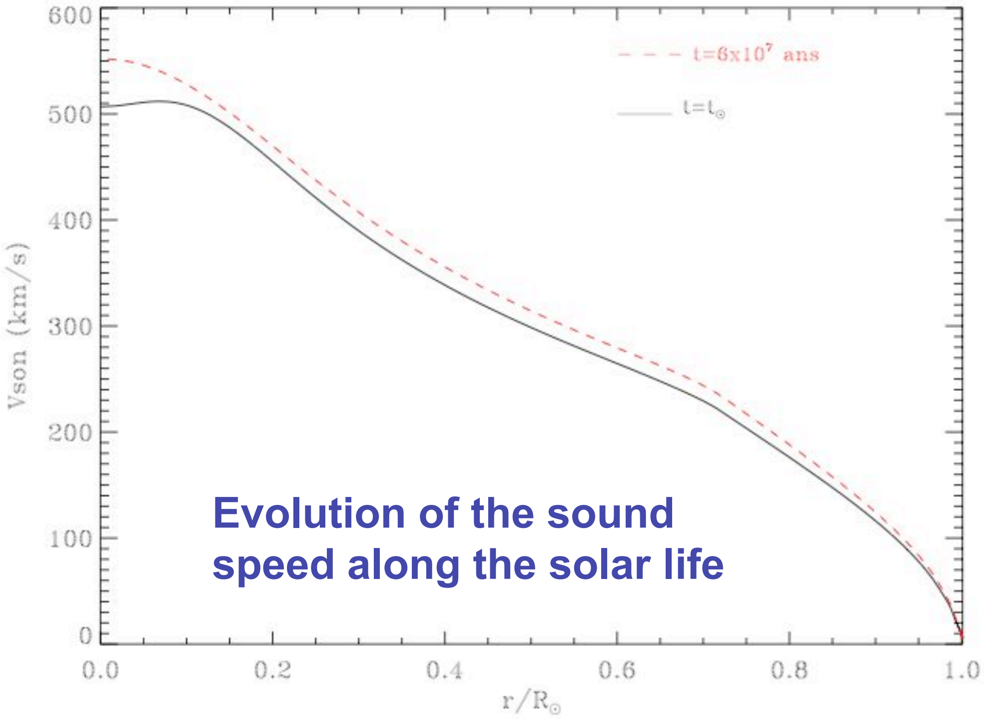
The Sun is a magnetic star, what can we say about its internal magnetic field ?

Energetic balance including magnetic loss

Turck-Chièze, Piau, Couvidat 2010 ApJ lett
Duez, Mathis & Turck-Chièze, MNRAS 2010,
Duez, Turck-Chièze, Mathis, ApJ 2010

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

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



Evolution of the sound speed along the solar life

Does the central luminosity equilibrates the present solar luminosity ?

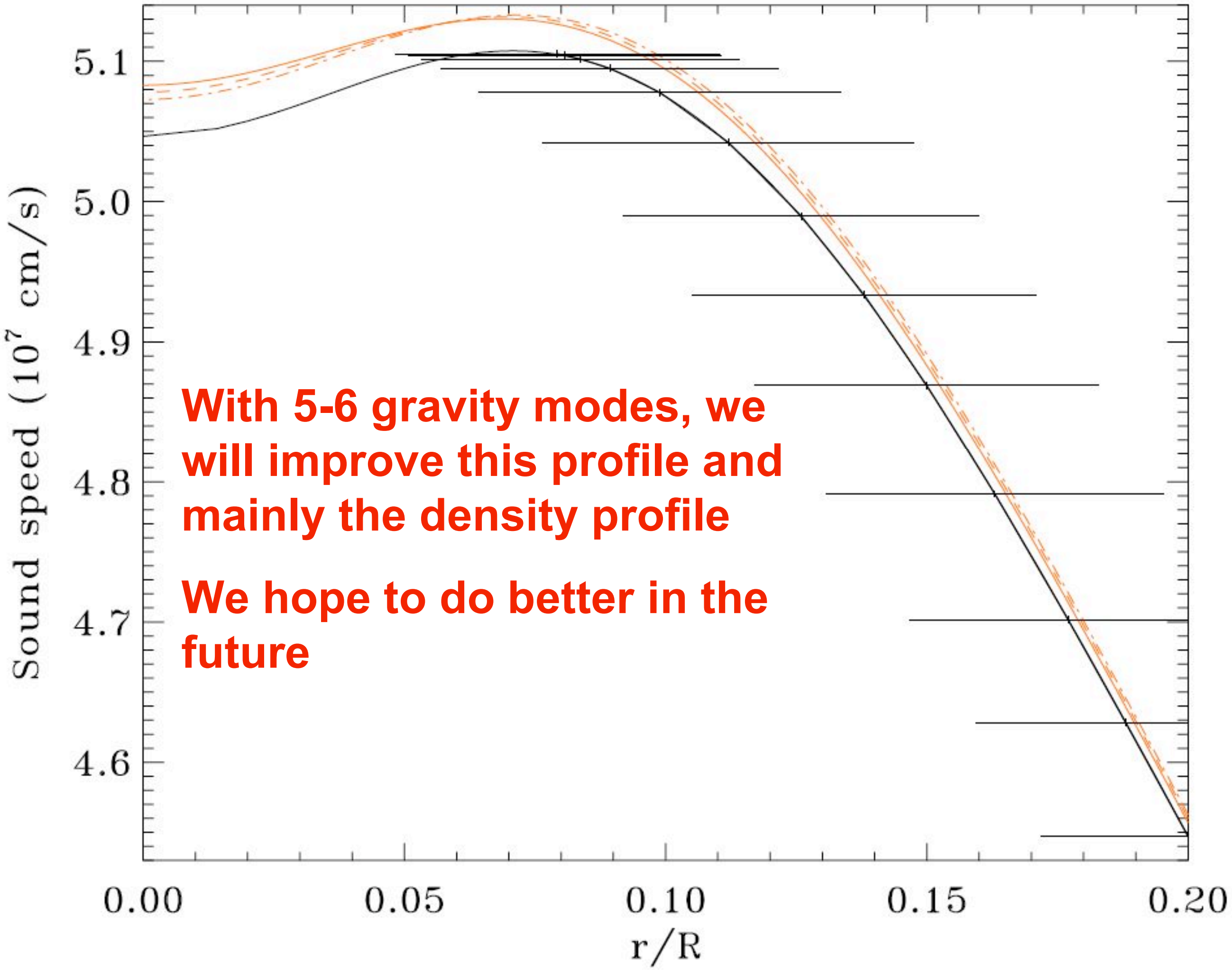
What have been lost during the solar life from magnetic energy???

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

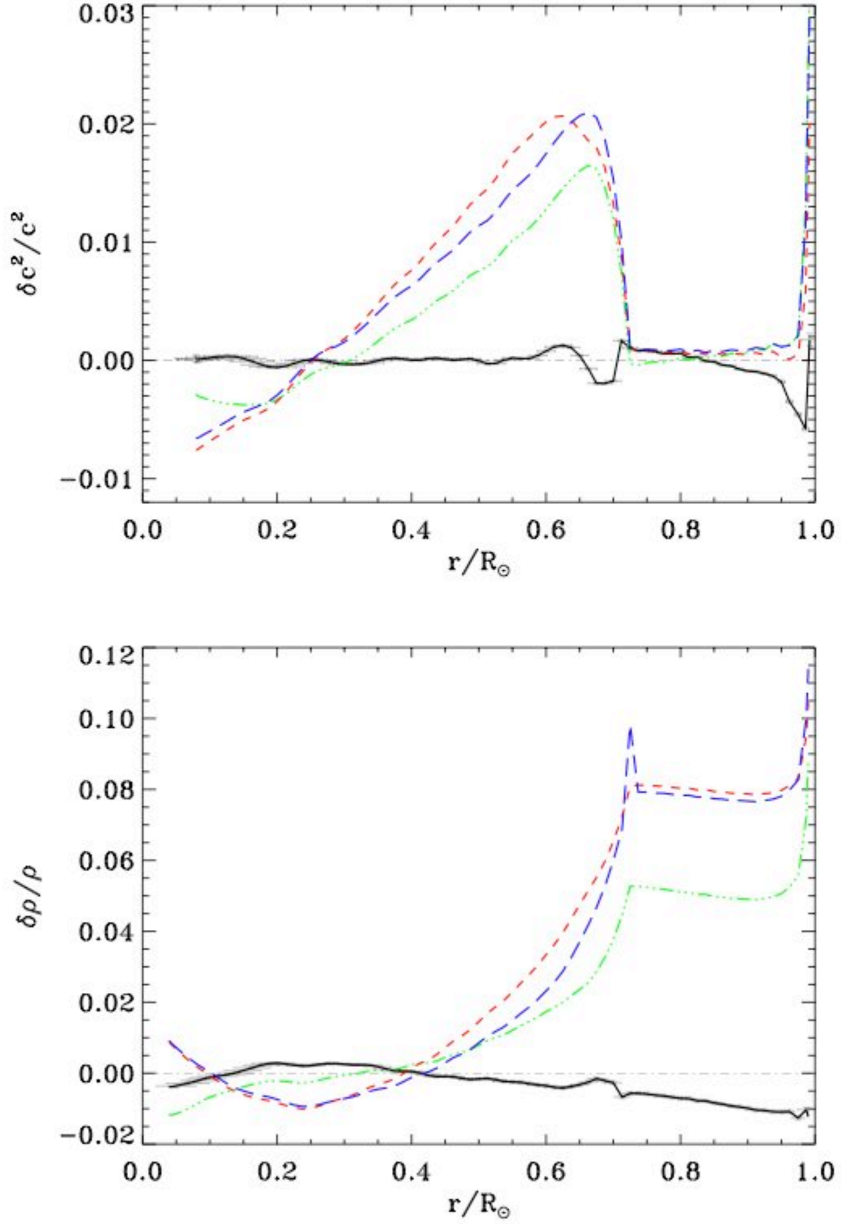


With 5-6 gravity modes, we will improve this profile and mainly the density profile

We hope to do better in the future

Mass loss

Guzik, Mussack 2010, T-C, Piau, 010



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

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,**
  - **Building of a dynamical solar model (1D-2D-3D)**