Stellar Rotation
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Dynamical Processes Induced by the Internal Solar Rotation

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Abstract. Helioseismology has been developed to extract internal sound speed, rotation and magnetic field. Such informations will put strong constraints on the present missing dynamical phenomena. Starting from the present observations on the rotation, I discuss quantitatively two important regions, the transition region between radiation and convection, called tachocline and the radiative region. In the tachocline, lithium indicator shows that a turbulent mixing is certainly present in main sequence solar like stars. On the other end, a detailed study of pre-main sequence stars encourages also the introduction of magnetic effects in addition to such a term below 10 Myr. For the solar radiative zone, the difficulty to determine the rotation profile is first noticed and discussed showing the great advantage of the gravity modes or mixed modes in addition to the acoustic modes. A possible profile, decreasing from 0.4 to 0.2 $R_\odot$ and then increasing in the very central region is suggested by the present observations. The consequences in terms of dynamical processes are discussed.

1. Introduction

Stellar seismology is a very powerful tool to improve stellar evolution, but it is also a very subtle one. At the present time, most of the results comes from helioseismology thanks to ground networks and spatial experiments aboard SoHO. The sound speed profile is now known from the surface to the core (down to 6% $R_\odot$) with an accuracy better than 10^{-4}. Nowadays, it puts constraints on the solar core and excludes strong mixing and spurious effects on the nuclear processes (Turck-Chièze et al. 2001a). This leads to a convergence on the emitted neutrino fluxes constrained by seismic models (Figure 1) (Watanabe & Shibahashi, 2001; Turck-Chièze et al. 2001b). The agreement of these numbers with recent neutrino detections put unambiguous origin to the neutrino puzzle, pointing out the evidence of oscillations between the different flavours of neutrinos. These models do not represent yet the real Sun, and the evidence of dynamical processes represent the secund step. In helioseismology, their manifestation appears through the splitting of the modes (their symmetry puts constraints on the internal rotation, their asymmetry on the magnetic field). Interesting results have been obtained for the convective zone through imaging helioseismology (Christensen-Dalsgaard, these proceedings; Brun & Toomre, 2002).

In this review, I shall comment on the mixing induced in the tachocline region which corresponds to the transition between the radiative and convective regimes. The lithium burning is a good indicator for looking for dominant magnetohydrodynamical processes acting in pre-main sequence and main sequence solar type stars. Then I shall present the status of the rotation in the radiative zone down to the core.

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2. Mixing in the Tachocline Region

Spiegel & Zahn (1992) analyzed theoretically the role of shear layers due to the rather sudden change between differential rotation in the convective zone and solid rotation in the radiative one. They describe the horizontal motions of the flow in this region. Chaboyer & Zahn (1992) have then deduced an approximate 1D mixing turbulent term in this transition region. The time dependent of the diffusive transport in the vertical direction has the following dependence:

$$D_T(t) \propto \Omega(t)\nu_H^{1/2}\left[\Omega'(t)/\Omega(t)\right]^2 \; ; \; d_\odot = 2l_{\rm tacho} \propto \Omega(t)^{1/2}/\nu_H^{1/4}$$

where $\Omega(t)$ is the time evolution law of the rotation at the basis of the convective zone. The differential rotation Ω'(t) is connected to the rotation by the law $\Omega' \propto \Omega^{0.7\pm0.1}$ (Donahue, Saar & Baliunas, 1996). The horizontal viscosity ν_H depends on the width $l_{\rm tacho}$ of the tachocline. The helioseismic results (Kosovishev 1997, Corbard et al., 1999) constrain the present solar values, $\Omega_{\rm BCZ}$ = 430 nHz and $l_{\rm tacho}$= 0.025 $R_\odot$. We have examined the impact of such a term on the sound speed profile and on the photospheric composition mainly for helium and lithium. Lithium is a crucial indicator for the complete understanding of this zone due to its temperature burning. The introduction of this term in the diffusivity equation improves the profile of the sound speed in smoothing the composition gradient just below the limit of the convective zone and creates partial destruction of lithium in main sequence evolution contrary to classical models (Figures 1, 2).

In a first study (Brun, Turck-Chièze & Zahn, 1999), we have shown that a Skumanich rotation law (1972) $\Omega(t) \approx t^{-1/2}$ may reasonably explain the profile of the lithium destruction during the main sequence for Hyades, M61 and the Sun and can in parallel improve the general solar photospheric observations in limiting the microscopic diffusion by 10% with an improved estimate of the photospheric helium. In a second step, Piau & Turck-Chièze (2001) have examined the lithium destruction during pre-main sequence period in including a rotation law from Bouvier et al. (1997) which supposes an increase of the stellar rotation up to the disconnection from the disk. With the introduction of such process we marginally describe the Hyades lithium depletion. We note nevertheless a too strong destruction of lithium before 10 Myr (Figure 2) due to a large extension of the convective envelope at this age. This fact is not directly related to the induced tachocline but prevents to understand the young clusters as α Per, Pleiades and Blanco I observations. During this stage of evolution, magnetic activity of the star is important and could impact on the extension of the convective zone (Ventura et al. 1998, Feigelson et al. 2003).

Our third study leads to seismic models (Turck-Chièze et al. 2001b). These models have been built to mimic the thermodynamical conditions of the nuclear core observed by the seismic probe for the emitted neutrino fluxes. In modifying the physical ingredients (cross section pp +1%, Z/X +3-4 %), we get a core sound speed profile in agreement with helioseismic observations but we deteriorate the region of the tachocline. One exploring possibility is to interpret the residual bump of the model including turbulence (continuous line) in Figure 1 as the residual manifestation of other processes acting in the radiative zone with some influence on the radial composition: meridional circulation (Theado & Vauclair 2002), gravity modes...

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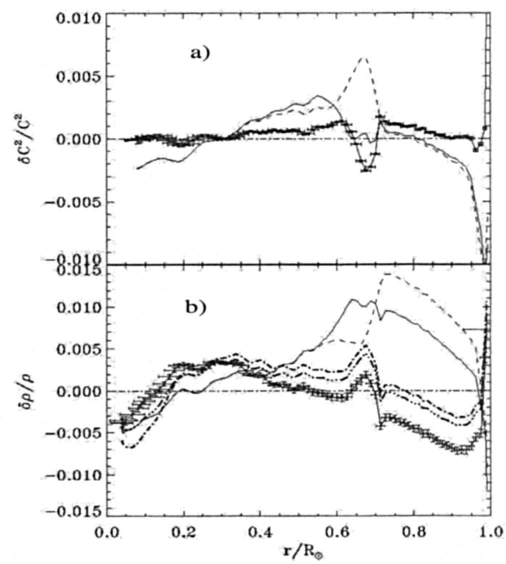

Figure 1. Squared sound speed and density differences between helioseismic results and models: classical model (dashed line), classical model with turbulent term (continuous line), seismic model (line with error bar). For the density the other curves correspond to modifications of nuclear reaction rates. From Turck-Chièze et al. (2001).

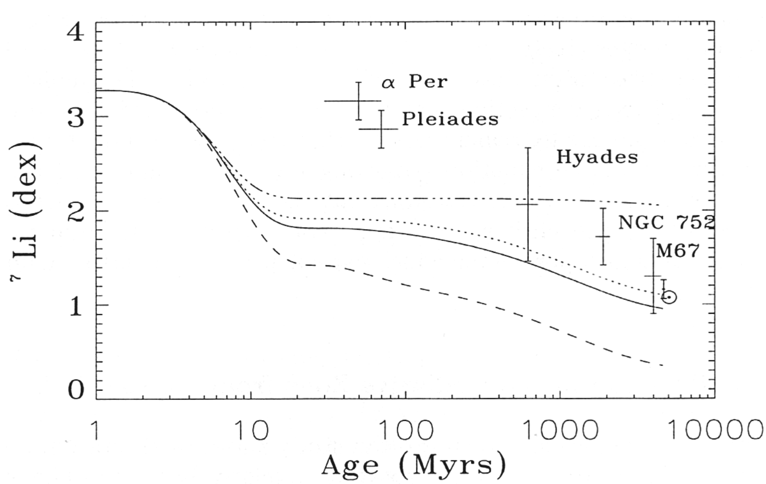

Figure 2. Time dependence lithium depletion for three models taking into account the lifetime of stellar disks for a star of 1 $M_\odot$ and a solar composition (— 0.5 Myr, continuous line: 3 Myr, ... 10 Myr) The model with only microscopic diffusion and no turbulent term (-...-) is also compared to different observations. From Piau (2001); see also Piau & Turck-Chièze (2001).

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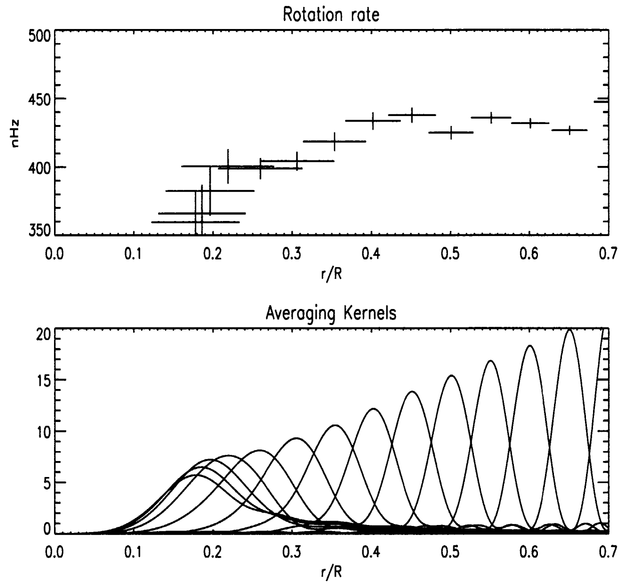

Figure 3. Solar radiative rotation profile deduced from GOLF+LOWL and the relative resolution kernels. From Turck-Chièze et al. 2002.

The profile of the density shows us that we have not yet a complete description of all the phenomena acting in the solar interior.

A complete description of the frontier between the two class of energy transfer needs probably a magnetohydrodynamical picture of the different phenomena acting at this frontier. A complementary seismic view of some clusters as Pleiades or younger clusters will help to build a general picture (see EDDINGTON project, Roxburgh, these proceedings). In parallel 2D simulations of the interaction between convection-rotation and magnetic field (Toomre & Brun, these proceedings) are extremely useful. Presently, the introduction of a turbulent diffusivity in the equation governing the time evolution of the chemical processes is a good way to reproduce all the present solar observations. In this sense, this approach is a progress in comparison with the introduction of a constant overshoot parameter which cannot properly describe main sequence lithium burning.

3. The Rotation in the Radiative Zone from 0.4 to 0.2 $R_\odot$

The Sun is the unique case where we can study an internal rotation profile. The radial extraction of the convective rotation is relatively easy as one measures a lot of m components (high ℓ, $-\ell < m < +\ell$). Below 0.4 $R_\odot$, the extraction of the rotation profile is more difficult due to the properties of the acoustic modes. We measure few components of each mode penetrating this region (ℓ below 10), so the error bars increase due to stochastic excitation and the contribution coming from the internal part is only a small fraction of the measured value (typically less than 6% for $R < 0.2$ $R_\odot$ for most of the acoustic modes). In consequence,

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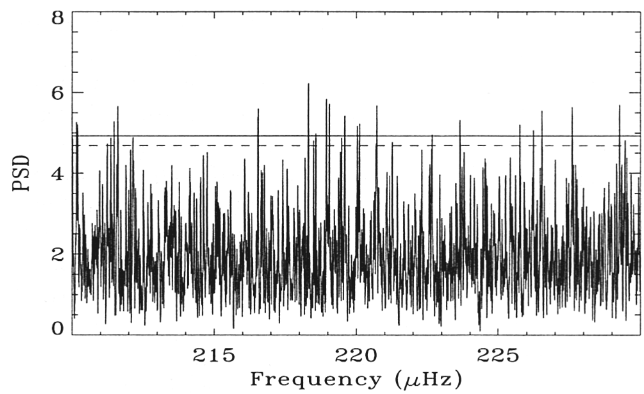

Figure 4. Detection of a quintuplet (full line) or sextuplet (dashed line) with more than 90% probability to contain signal after 2035 days of GOLF observation.

we need to integrate during a longer duration to improve the accuracy (today typically 5 yr with spatial experiments and about 10 yr in networks). We get now low order acoustic modes (necessity of good signal/noise) which have higher lifetime (Turck-Chiéze et al. 2002) and represent for the future a real chance to measure quicker and proper to follow the time variability of this internal rotation. We need also to properly remove the differential rotation of the convective zone and the slight variation of the rotation at the surface. The analysis of GOLF and LOWL data shows a slight decrease of the equatorial rotation profile between 0.4 and 0.2 $R_\odot$ (Figure 3). There is now a consensus for this tendency with all the existing instruments (BiSON, IRIS (Fossat et al. 2003), GOLF and MDI). Nevertheless, we need to be cautious because only a 2D inversion profile may avoid any contamination coming from the latitudinal dependence of the external rotation. If this profile is finally confirmed, it puts strong constraints on the physical process which leads to this fact. The impact of internal magnetic field would mainly lead to a flat solid rotation along the radiative zone. Recent works show that gravity modes may induce such a decrease (Talon these proceedings).

4. The Rotation Profile in the Nuclear Core

Acoustic modes do not reveal sufficient information on the nuclear rotation core because the $\ell = 1$ modes penetrate only down to 0.05 $R_\odot$ and their kernels are quite large (Figure 3). The best way to investigate this region is to detect mixed modes (typically ℓ=1, 2, n=1, 2, 3) or some gravity modes. These modes have a predicted very low amplitudes in a region of high level granulation noise, so we have developed a technique which allows to look for multiplets in the range 150-400 nHz. Such method has been applied to GOLF/SoHO observations which has been designed especially for this search. Using a statistical analysis dedicated to this study, we have followed some gravity mode candidates since the launch

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of SoHO. One specific case, presented in Figure 4 shows a structure with an amplitude of about 2 ± 1 mm/s. It has appeared first as a triplet with 90% confidence level (1290 days) then as a quintuplet. If this candidate is a gravity mode ℓ=2, n=-3, the spacing between the five components suggests an increase up to at least 600 nHz of the rotation in the very central part of the Sun with a different rotational axis than the rest of the radiative zone (Turck-Chièze et al. 2002). The potential interest of such case is large. A confirmation or not will be looked for in the SoHO observations up to 2007. The period of low activity will be the best for this search if the instruments are still performant. A way to reduce the solar granulation noise is also under study through the GOLF NG project. The objectives of this project is to extract Doppler velocities at different altitudes of the sodium line (Turck-Chièze et al. 2001c). This must allow to reduce the duration of observations (typically 1 year instead 5) to follow variability of the phenomena with time and progress on the understanding of the solar cycle and its impact in the Solar-Earth relationship.

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