THE SEISMIC SOLAR CORE AFTER TWO YEARS OF SOHO MISSION

Sylvaine TURCK-CHIEZE
DAPNIA/Service d'Astrophysique, CEA Saclay
91191 Gif sur Yvette cedex, FRANCE
E-mail: cturck@Cea.Fr

and

Allan Sacha BRUN * and Rafaël Amos GARCIA
DAPNIA/Service d'Astrophysique, CEA Saclay, 91191 Gif sur Yvette cedex, FRANCE

ABSTRACT

After 30 years of investigation, the solar neutrino problem is still puzzling. We discuss here what the helioseismic investigation of the solar interior has already revealed on the quality of the standard solar model and present the perspectives.

1. The physical context

Since the first detection of solar neutrinos in 1968, different communities have contributed to understand the discrepancy between predictions and detections of solar neutrinos, showing the complexity of the interpretation of such measurements (Turck-Chièze et al., 1993). The problem is harder than thought at the beginning, due to the difficulty of detecting neutrinos on earth and to the fact that we have not yet been able to measure separately neutrinos of different sources as listed in table 1.

Table 1. Nuclear processes leading to neutrino emission.

$p + p \rightarrow D + e^+ + \nu_e$ (pp neutrinos)
$p + p + e^- \rightarrow D + \nu_e$ (pep neutrinos)
ppII chain: $^7Be + e^- \rightarrow ^7 Li + \nu_e$ (^7Be neutrinos)
ppIII chain: $^7Be + p \rightarrow ^8 B$ $^8B \rightarrow ^8 Be^* + e^+ + \nu_e$ $^8Be^* \rightarrow 2^4He$ (^8B neutrinos)
$p +^3 He \rightarrow \nu_e + e^+ +^4 He$ (hep neutrinos)
CNO I cycle: $^{13}N \rightarrow ^{13} C + e^+ + \nu_e$ (^{13}N neutrinos)
$^{15}O \rightarrow ^{15} N + e^+ + \nu_e$ (^{15}O neutrinos)
CNO II cycle: $^{17}F \rightarrow ^{17} O + e^+ + \nu_e$ (^{17}F neutrinos)

One could say that the aim of this research has shifted from a direct check of the central temperature and proton proton nuclear energy generation, to a double objective: a detailed verification of the solar nuclear plasma and a possible manifestation of neutrino oscillation, leading to an estimate of the electron neutrino mass.

*Presently, in JILA, University of Colorado, Boulder, CO 80309-0440

The Sun appears today as a natural laboratory of nuclear, plasma and atomic physics and gives access to a range of neutrino oscillation parameters which is not accessible to ground laboratories. Proving a very small mass oscillation of the neutrinos is difficult as we do not measure the neutrino emitted fluxes, so, all the different aspects of the problem must be examined with great care before reaching definitive conclusions. In these new perspectives, helioseismology is a useful tool to check the theoretical solar structure estimate, and consequently, to partly consolidate the estimated neutrino emission.

2. Standard solar model and neutrino emitted fluxes

The astrophysical community produces theoretical emitted fluxes for the different sources of neutrinos described above. Without any condition on the kinematics of the reactions (the energy dependence of the neutrino fluxes is deduced from the nuclear processes), these predictions are extracted from solar models which describe the temporal and radial evolution of the Sun in the classical framework of stellar evolution. By solving the four structure equations, one performs an ab initio complete calculation which requires a good description of the nuclear and atomic processes and *has no free parameter*.

The first equation assumes hydrostatic equilibrium (each gas shell is balanced by the competition between the downward gravitational force and the outward pressure force):

$$\frac{dP}{dr} = -\frac{M(r)\,G}{r^2}\rho \tag{1}$$

where P and ρ are the pressure and the density. *M(r)* represents the mass enclosed within a sphere of radius *r*:

$$\frac{dM}{dr} = 4\pi r^2 \rho \tag{2}$$

One further assumes thermal equilibrium. The energy $(4\pi r^2 \rho \epsilon)$ produced by nuclear reactions, balances the energy flux *L(r)* emerging from the sphere of radius *r*. Taking into account quasistatic gravitational readjustment and composition variation, one must incorporate a heat transfer term TdS where S is the total entropy per gram of the gas and the energy bookkeeping yields:

$$\frac{dL}{dr} = 4\pi r^2 \rho \left(\epsilon_{nucl} - T\frac{dS}{dt} \right) \tag{3}$$

Finally, the temperature gradient depends on the luminosity and the physical process of the energy transport. In a radiative region of a star, the diffusion approximation is appropriate, and the relation between temperature gradient and luminosity is:

$$\frac{dT}{dr} = \frac{-3}{4ac}\frac{\kappa\rho}{T^3}\frac{L(r)}{4\pi r^2} \tag{4a}$$

When the opacity coefficient κ increases too much, like in the external part of smaller stars with M $\leq 1.5 M\odot$ or when the luminosity is very high (in the internal part of stars with mass $> 1.5 M\odot$), the radiative gradient increases so much that matter becomes convectively unstable. The resulting temperature gradient is then nearly adiabatic:

$$\frac{dT}{dr} = \left(\frac{dT}{dr}\right)_{\rm ad} = \frac{\Gamma_2 - 1}{\Gamma_2}\frac{T}{P}\frac{dP}{dr} \text{ with } P^{1-\Gamma_2}T^{\Gamma_2} = const. \tag{4b}$$

From these structural equations, we extract temperature, density, pressure and composition for the different shells of the present Sun and consequently the neutrino emitted fluxes. One may notice that the energy sumrule which allows to extract without detailed calculations the pp neutrino flux from the present observed luminosity is explicitly contained in the third equation of stellar evolution.

So, if one supposes no magnetic interaction or change of flavour, $5.98\,10^{10}\nu_e$ reach the earth /s coming from this fundamental pp interaction which produces $1.68\,10^{38}\nu_e$/s. This is, of course, the main source of neutrinos coming from the Sun but unfortunately, the corresponding neutrino energy is small and this flux has never been measured totally and alone. The other sources are smaller: typically $1.32\ 10^{37}/s$ for ${}^7Be$ neutrinos $1.35\ 10^{34}/s$ for ${}^8B$, $1.31\ 10^{36}/s$ for ${}^{13}N$, $1.12\ 10^{36}/s$ for ${}^{15}O$. These sources are directly proportional to the density in the range of emission and are largely temperature dependent, typically $\mathbf{T}^8$-$\mathbf{T}^{10}$ for Be^7 neutrinos and $\mathbf{T}^{18}$-$\mathbf{T}^{24}$ for B^8 neutrinos, so they significantly depend on the solar structure. This representation of the Sun is the most economical way to describe a star and supposes that there is no effect of rotation, magnetic field and that the present photospheric abundance is used to determine the initial composition of the Sun. In this representation we introduce 3 observations: the luminosity of the Sun at an age of 4.55 Gyr from the beginning of the hydrogen burning, the solar radius and the detailed element composition for nuclei greater than helium coming from the photosphere determination and compared to meteoritic ones.

The helioseismic probes are today used to check if these hypotheses are correct or if extra processes are also visible, this is the reason why the solar model has received a lot of attention these last 10 years to avoid misleading interpretation of the observations. The including physics has been improved by:

- a reanalysis, including remeasurement of some of them, of all the nuclear cross sections participating in the hydrogen burning (Adelberger et al., 1998 and references therein). The estimated ${}^7Be(p,\gamma)$ cross section has been reduced by 15 % (Adelberger et al., 1998; Hammache 1998) but stays the most badly determined (20 %).

- The improvement of the equation of state and opacity calculations in quality (checked by experimental laser measurements) and completness (Rogers, Swenson and Iglesias, 1996; Iglesias and Rogers, 1996).

- an improvement of the accuracy in numerical simulations (better than 10^{-4}).

3. The transparency of the Sun to acoustic and gravity waves

During the last thirty years, in parallel to the progress on neutrino detections, major efforts have been carried out by the observers to improve the quality and the accuracy of the seismic data and by theoreticians to develop and increase the efficiency of this diagnostic. Now, with the availability of more than 2 years of SOHO data and long time series ground based observations, the helioseismic constraints allow us to go one step further in our understanding of the internal structure of the Sun. In this section, we will briefly review the basis of the helioseismic tool.

The Sun, as a self-graviting sphere of compressible gas, oscillates around its equilibrium state with a period of about 5-min. These oscillations are interpreted as a superposition of waves propagating inside the star (acting as a resonant cavity), and forming standing waves: the eigenmodes of vibration. By projecting these modes onto spherical harmonics Y_l^m, we write any scalar perturbations as (in the case of the pressure $p^{'}$) (Christensen-Dalsgaard and Berthomieu 1991)

$$p^{'}(r,\theta,\varphi,t) = p^{'}(r) Y_l^m(\theta,\varphi) \exp i\omega_{n,l,m} t \quad ,$$

and the vector displacement $\vec{\xi}$ as

$$\vec{\xi}(r,\theta,\varphi,t) = \left(\xi_r(r), \xi_h(r)\frac{\partial}{\partial\theta}, \xi_h(r)\frac{\partial}{\sin\theta\partial\varphi}\right) Y_l^m(\theta,\varphi) \exp i\omega_{n,l,m} t \tag{5}$$

where $\xi_h = 1/(\omega^2 r)[p^{'}/\rho + \Phi^{'}]$ is the horizontal displacement, $\Phi^{'}$ the gravitational potential perturbation, $\omega_{n,l,m}$ the eigenfrequency and ρ the gas density. The quantum numbers n, l, m are respectively the radial order (number of nodes along the radius), the degree (measures the total horizontal waves number on the surface by $k_h \sim L/R_\odot$, with $L = \sqrt{l(l+1)}$) and the azimuthal order (number of nodes along the equator). Restricting ourself to adiabatic oscillations within the Cowling approximation ($\Phi^{'}$ neglected) and considering only small radial wavelength compared to $R_\odot$, we reduce the 4th-order system of equations to a second-order wave equation, with the following dispersion relation (Christensen-Dalsgaard and Berthomieu 1991)

$$k_r^2 = \frac{1}{c_s^2}\left[F_l^2\left(\frac{N^2}{\omega_{n,l,m}^2} - 1\right) + \omega_{n,l,m}^2 - \omega_c^2\right] \tag{6}$$

where the squared length of the wave vector is written as the sum of a radial and a horizontal component $|\vec{k}| = k_r^2 + k_h^2$, $k_h^2 = F_l^2/c_s^2$ is the horizontal wave number, $F_l^2 = L^2 c_s^2/r^2$ the Lamb frequency, $N^2 = g[1/\Gamma_1 d\ln p/dr - d\ln\rho/dr]$ the Brunt-Väisälä frequency, $\omega_c^2 = c_s^2(1 - 2dH_\rho/dr)/4H_\rho^2$ the acoustic cut-off frequency (~ 5.8 mHz), $H_\rho^{-1} = -d\ln\rho/dr$ the density scale height, Γ_1 the adiabatic exponent and $c_s^2 = \Gamma_1 p/\rho$ the sound speed.

The oscillatory solutions of the wave equation define two types of waves, i.e acoustic ones (with $\omega_{n,l,m} > N, F_l$) and gravity ones (with $\omega_{n,l,m} < N, F_l$). Figure 1 shows the properties of these modes, the acoustic modes have their maximum amplitude at the surface (left side), the gravity modes are excellent probes of the solar core and are evanescent at the surface with rather small amplitude (right side).

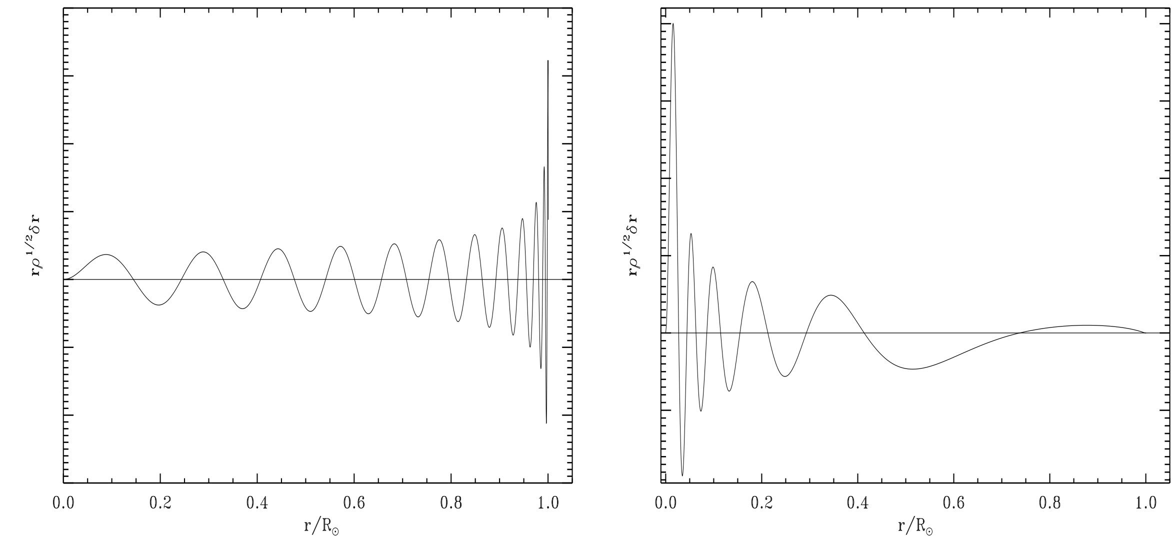

Fig. 1. Eigenfunctions of an acoustic mode (ℓ =0 radial mode, n=23), and of a gravity mode (ℓ =2, n=10).

About 3500 acoustic modes (the so-called 5-min oscillations) have been already observed and give us stratified information about the solar internal structure. Today, the research of gravity modes remains one of the big challenge of modern helioseismology to properly describe the solar core.

There are two ways to use the seismic data to probe the internal structure of stars:
a) The direct method: comparison of predicted and observed acoustic frequencies
b) The indirect method using inversion procedures to deduce radial profile of crucial variables as the squared sound speed c_s^2, the density ρ or the adiabatic exponent Γ_1, the rotation and compare them to computed model.

Up to now, we consider two variables extracted from GOLF and MDI data (Lazrek et al., 1997, Kosovishev et al. 1997), namely the internal rotation profile and the sound speed profile deduced from observations and compared to uptodate solar models (Turck-Chièze et al. 1997).

4. The sound speed: a very useful but surprising quantity

We can extract more and more properly the solar sound speed profile from the helioseismic data, consequently, if we may demonstrate that there is a significant deviation between the Sun and the theoretical model, this could be the opportunity to go beyond this theoretical model and deduces neutrino fluxes directly from our observation of the Sun. Before that, it is interesting to compare the sensitivity of the two present probes: neutrinos and sound speed for the neutrino puzzle. We have recalled the ^8B neutrino flux dependence on the central temperature of the star. One can remark that if the Sun was exactly at the beginning of hydrogen burning the chlorine prediction would be 0.57 SNU (instead of the present 7 SNU prediction) and the gallium one 67 SNU (instead of 127 SNU) that means a factor 15 and 2 smaller respectively. On the other side, as it is shown on figure 2, one may notice that the central sound speed has only varied by 9 % during the same period of time. Effectively, as

$$\Delta c^2/c^2 = \Delta T/T - \Delta\mu/\mu \tag{7}$$

and $\Delta T/T$ = 13.5% (T_{init}= 13.5 $10^6 K$), $\Delta\mu/\mu$ = 32 % (the mean molecular weight passes from 0.31 to 0.41), so $\Delta c/c$= -9%. So we conclude that we need to know the sound speed profile with an extremely good accuracy (better than 10^{-3}) if we would like to observe some deviation of this quantity at the level of 1%, which is exactly what is required for questionning the present solar structure with a doubt of less than 2 % on the central temperature (see below). This is the demanding challenge of the SuperKamiokande result. By chance, it is approximatively what we can wait from the helioseismic results as the acoustic frequency determination depends on the integration time (at least 1 year) and the knowledge of the excitation of the modes.

It is also important to note that there is no direct determination of the temperature through acoustic modes and that $\Delta c^2/c^2$ could be different from $\Delta T/T$ as it is shown on the above example.

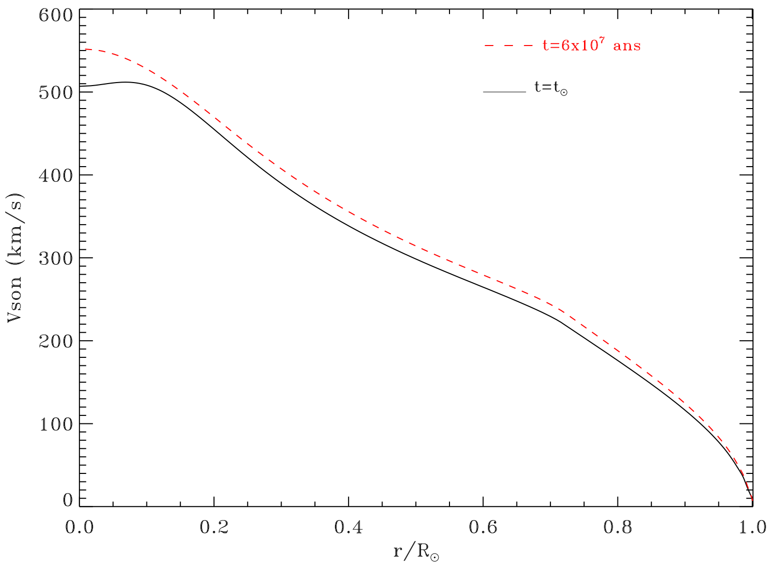

Fig. 2. Evolution of the sound speed along the hydrogen burning

5. The solar internal rotation

In addition to the sound speed and the density, we can extract a very useful quantity which is the rotational splitting between the different m components of a specific degree l. As is shown on figure 3, this quantity is of the order of 450 nHz. As one can imagine from the photospheric observation of the Sun, this quantity is not constant in latitude as the equator turns quicker than the pole. The quality of the acoustic mode data allows to follow this variation along the radius, and one can remark that this rotation rate varies rather quickly just near the surface (effect of magnetic field ?) and then stays rather constant in radius down to the transition region between radiative and convective transport of energy. This is not a very sharp transition as we introduce in classical models and one may imagine shear flows which induce mixing of elements (see below). Then we observe a rather rigid rotation of the whole Sun.

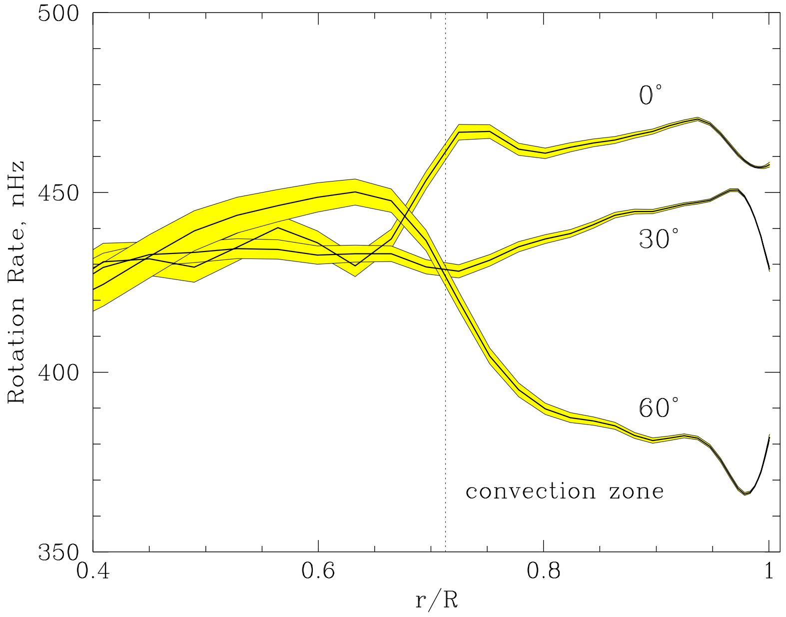

Fig. 3. Radial rotation frequency obtained by MDI instrument aboard SOHO for 3 latitudinal angles, 0 corresponds to the equator (Kosovishev et al. 1997).

In the central region, the determination of the rotation profile is not totally established. This is due to the intrinsic difficulty to extract this information from acoustic modes. No more than 5% of the absolute value of the rotation splitting comes from this region, that means 20-25 nHz. Today it is practically the uncertainty of the determination of such quantity (Lazrek et al 1996, 1997; Thiery et al. 1999), due to the fact that for dipolar and quadrupolar modes, they are only few m components and a long integration is required to reduce the uncertainty. So depending on the experiments, the results encourage an increase (IRIS, GOLF) or a decrease (GONG) of the rotation in the solar core (Corbard et al. 1999). Nevertheless it is reasonable to think today that the very central part of the Sun does not rotate at a rate greater than 4 km/s (2 km/s at the surface). This reduction of the rotation from about 50-100 km/s at the beginning of hydrogen burning down to this low value is not presently explained, so the consequences on the internal structure of the Sun are not yet introduced in the stellar structure equations.

6. A need for macroscopic motions in the description of the Sun

After a proper extraction of the sound speed from the acoustic mode frequency determination, we can compare the difference of the sound speed given by the Sun and the one deduced from the model (figures 4). As the difference is small for the reason explained previously, we generally express the square of this quantity to enhance the local deviations which are signatures of some missing processes or some badly determined phenomena in the models. The interpretation is only straight forward if we can associate some deviation to some specific signature, it has been the case for the determination of the photospheric helium which modifies the sound speed through the adiabatic exponent in a specific manner in the outer layers at 0.98 $R\odot$ (Vorontsov et al.,1991; Basu and Antia, 1997).

The results of these experimental and theoretical efforts are summarized in figures 4a) and 4b) (Brun, Turck-Chièze and Morel (1998); Brun, Turck-Chièze and Zahn (1999)). One notes a significant deviation (up to 80 σ) between the standard model and the real sun which must be understood. In these papers, we show that the solar structure has been substantially improved by the introduction of some extra processes not included in classical stellar evolution 10 years ago and prescribed by the helioseismic constraints.

These progresses concern the evolution of the elemental composition with time. Three terms are added in the equation describing the time evolution of the nuclear species X_i:

$$\frac{\partial X_i}{\partial t} = \frac{\partial X_i}{\partial t}_{nucl} - \frac{\partial\left[(4\pi\rho r^2(D_i + D_T)\frac{\partial X_i}{\partial m} - v_i X_i)\right]}{\partial m} \tag{8}$$

In the Sun, the very slow microscopic diffusion of the elements (Proffitt and Michaud 1991), dominated by the gravitational settling, modifies the composition along the radius and the progress done by the introduction of the first and third term is clearly visible on figure 4a. It has some impact on the hydrogen burning duration (reduction by about 0.6-1 Gyr). The presence of this process is the only way to interpret a rather cosmological photospheric helium determined by helioseismology (0.249 ± 0.003). Contrary to what was assumed in the classical stellar evolution, the

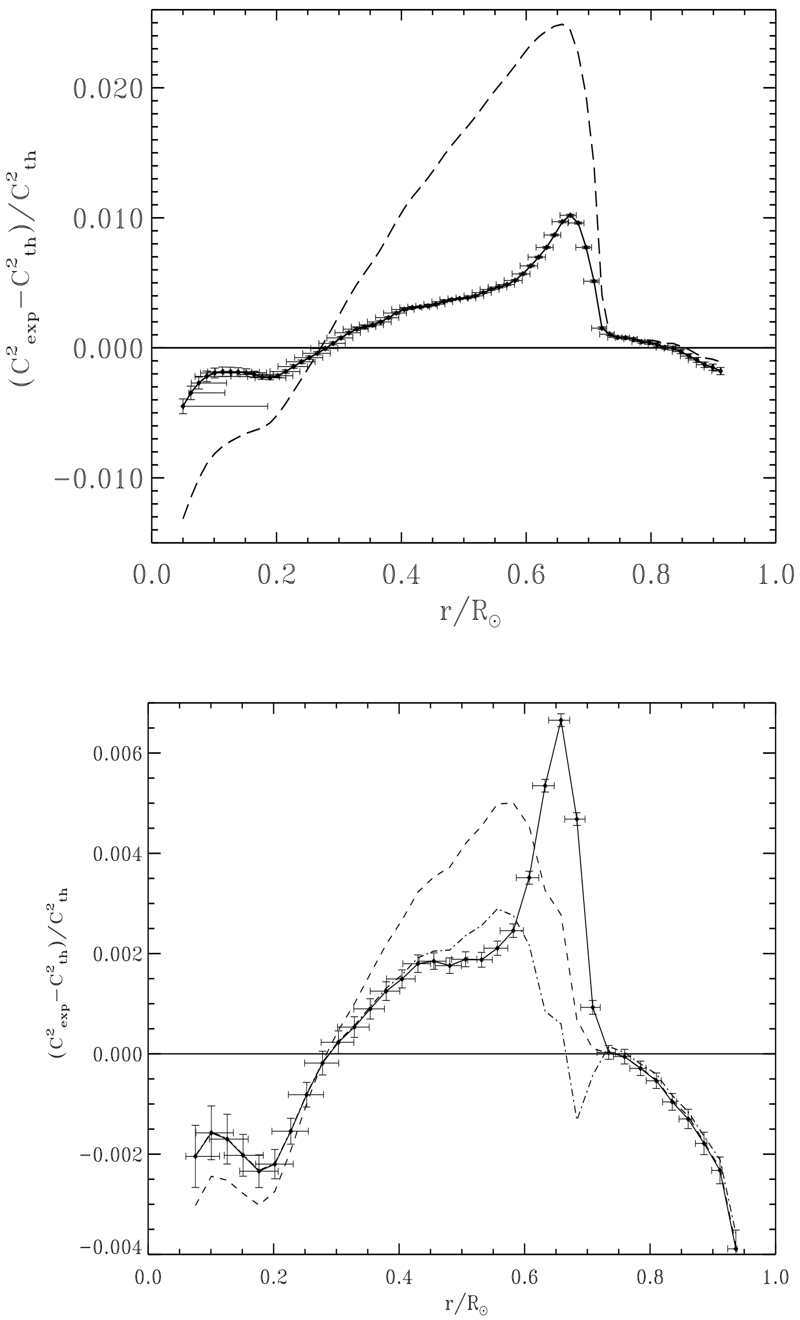

Fig. 4. Sound speed square difference between the Sun seen by GOLF (Gabriel 1995, 1997) + MDI (Scherrer 1995, Kosovishev et al., 1997) instruments aboard SOHO (Turck-Chièze et al. 1997,1998 a)) and solar models. The full line corresponds to a reference model where the microscopic diffusion is included. In the first figure, the model without this process is represented in dashed line (Brun, Turck-Chièze, Morel 1998). In the second figure, models include also turbulent terms, the dashed line corresponds to a model where the photospheric Z/X=0.0245 constraint of the reference model is kept, in the model with dot-dashed line, this constraint is relaxed, the photospheric Z/X stays in the error bars of the observations (Brun, Turck-Chièze, Zahn 1999) .

initial abundance is not strictly equal to the present photospheric one. The photospheric composition (relative to hydrogen) is reduced by about 10 % during the solar lifetime.

The model including the microscopic diffusion is considered today as our standard model, it is obtained with a constraint on the luminosity, radius and photospheric heavy element composition. The introduction of such a process increases the sum of the neutrino predictions for the chlorine and water detectors by about 20%. But one knows for a long time that such a process cannot act freely in stars as predicted anomalies on more evolved star than the Sun are not observed (Vauclair, Vauclair, Michaud 1978). It is the reason for the introduction of the D_T term (T for turbulent) in eq. (8) which must partly inhibit the previous process.

Up to recently, astrophysicists had treated this term in an ad hoc manner. But the internal rotation measured by helioseismology has demonstrated a clear transition between differential rotation in the external convective zone and a rather rigid rotation in the radiative zone (Kosovishev et al. 1997, and figure 3). The thickness of such a transition (Corbard et al., 1998) corresponds to the observed peak in the sound speed profile, clearly visible in figure 4b. This suggests that the inhibition of the microscopic diffusion at the radiative-convective transition could be due to some instability induced by the differential rotation of the Sun (Spiegel and Zahn 1992). Taking into account this dynamical process leads to a better understanding of the lithium deficit problem in solar-like stars, and improves the photospheric helium determination (Brun, Turck-Chièze and Zahn 1999). In limiting the microscopic diffusion, the net effect is a slight relative reduction of the neutrino fluxes but we have noticed that if we relax the imposed constraint of Z/X=0.0245 (Z is here the heavy element mass fraction, X, hydrogen mass fraction) at the surface and accept a slight increase of 5%, always compatible with the present observation of the heavy element composition, one gets a very good agreement with the solar sound speed profile (dot-dashed line in figure 4b) with practically the same neutrino predictions than the standard model as the solar core is not modified by the introduction of such a process.

Despite these progresses, the SuperKamiokande (SK) ^8B neutrino flux is 50 % of the flux obtained by the best solar model including the processes mentionned previously, the chlorine result is 0.37 of the predicted value, and the gallium one about 60 % (see table 1). We recall that there is no free parameter in the neutrino estimates. **Following the initial objective of these measurements, we can guarantee from the confrontation of the SK result with the theoretical prediction that the central temperature of the Sun is under control within 2%.** This success confirms the basis of stellar evolution and the major hydrogen burning stage. But this is certainly not sufficient to solve the neutrino puzzle.

7. The solar core and the neutrino predictions

If we believe the figures 4, we may consider that we have reached a quantitative check of the theoretical solar structure which gives confidence in the present solar neutrino estimates and that we can exclude any astrophysical problem. Effectively, the residual present discrepancy in the core, seems small to put in evidence some astrophysical new phenomenon. But we note the high sensitivity of the sound speed to fundamental ingredients: 2% variation on pp reaction is visible: effect of $2\ 10^{-3}$ on the sound speed, 2% variation of the opacity coefficients locally is also measurable (same effect). Paradoxically, acoustic modes are indirectly sensitive to the solar core and cannot check the absolute value of the opacities. It is why the slight deviation observed in figure 4b) in the central sound speed let place for some nuclear modification inside the present uncertainties (nuclear model) and to some ^7Be abundance variation (^7Be model) which leads to a significant reduction of the emitted neutrino fluxes (table 2 and Turck-Chièze 1999).

Table 2. Confrontation of observed neutrino detections and respective neutrino predictions for the chlorine, gallium and water detectors in the case of the reference model and two other models which suppose variation of the cross sections in the present error bars or a reduction of the ^7Be abundance in the Sun to respect the SuperKamiokande result.

		Observations		
Experiments	Chlorine exp.	SuperK exp. $(10^6/\mathrm{cm}^2/\mathrm{s})$	Gallium GALLEX	experiments SAGE
	2.55 ± 0.25 SNU	2.44 ± 0.26	76 ± 8 SNU	70 ± 8 SNU
calibration			0.91 ± 0.08	0.95 ± 0.12
		Predictions		
Ref. model	7 ± 1.7 SNU	5 ± 1.25	127 ± 8 SNU	127 ± 8 SNU
Nuclear model	5.2 SNU	3.21	119 SNU	119 SNU
^7Be model	3.87 SNU	2.4	105 SNU	105 SNU

1 SNU is the solar neutrino unit which is equal to 10^{-36} capture/atom s.

Extensive studies between experimental seismic results and between experiments and models show that the present accuracy of the sound speed determination in the solar core is probably underestimated. We have observed first different results with different experiments at the level of some 10^{-3}. This is partly due to the nature of the acoustic modes and the method used to extract the sound speed. Indeed, the acoustic modes are extremely adapted to check the thermodynamical quantities of the low density outer layers. But, on the 3500 detected acoustic modes, only about 100 penetrate the nuclear region and less than 30 reach the center. Figures 5 show the power spectrum of these modes (ℓ =0,1,2,3) for the GOLF experiment. We may calculate the acoustic radius (or travelling time) of a radial mode penetrating down to the core (Turck-Chièze and Brun 1997):

$$\tau(r) = \int_r^R dr/c(r) \tag{9}$$

This mode passes about 70 % of its time in the region above 0.6 $R_\odot$ (this is a priori even better for high degree modes) this region is now very well described and has largely questionned the simple representation of the standard model which does not consider effect of rotation and complex convective flows, ignoring also the role of the magnetic field which produces the well observed solar cycle. But the same mode passes only 3 % of its time between 0.2 and 0.1 $R_\odot$ and less than that below. If we suspect a phenomenon which may modify the central temperature by 1 or 2 %, we are looking for effect smaller than 3 10^{-4} of the frequency observed (less than 1 μHz at 3000 μHz, 0.5 at 1500 μHz). This is largely the kind of accuracy we reach today with the ground based networks (BiSON, IRIS, GONG) and the SOHO satellite (GOLF, MDI) but we are still looking for inacceptable effects or bias due to the bad knowledge of the surface. It is why extensive studies (Basu et al. 1999) are connected to the way we extract the sound speed which may summarize as follows:

$$\frac{\delta\omega_i}{\omega_i} = \int K^i_{c^2,\rho}(r)\frac{\delta c^2}{c^2}(r)dr + \int K^i_{\rho,c^2}(r)\frac{\delta\rho}{\rho}(r)dr + \frac{F_{\mathrm{surf}}(\omega_i)}{E_i} \tag{10}$$

In this equation $\delta\omega_i$ is the difference between the observed and theoretical frequency of the mode i (see figure 5b) and the kernels $K^i_{c^2,\rho}$ and K^i_{ρ,c^2} are known functions of the reference model which relate the changes in frequency to the change in c^2 and ρ. The last term comes from the difficulty to describe the solar near surface layers. Effectively, one notes a systematic bias between absolute predicted values and observed ones illustrated by figure 6 for different solar models (Turck-Chièze et al. 1997).

This problem is reasonably well taken into account in eq (10) but may perturb the extraction of the information of the solar core as a very small amount of the total frequency is concerned by the solar core (Brun et al., 1997). Impressive progresses have been realised these last years to understand the excitation of the modes and some spurious effect as the asymmetry of the line (Toutain et al., 1998, Thiery et al., 1999), to develop more and more sophisticated techniques of inversion... but the conclusion on the real difference between the Sun and the model in the core supposes a proper understanding of this surface effect and of the solar cycle effect which is also of the same order than any modification of the core (about 0.5 μHz). In fact, the low part of the frequency spectrum is interesting because the modes of low order reflect lower at the surface and are less sensitive to all these perturbations (typically below 2000 μHz, figure 6). It is why we are confident that we shall progress on the accuracy of the sound speed in the solar core with longer observations and good instruments,

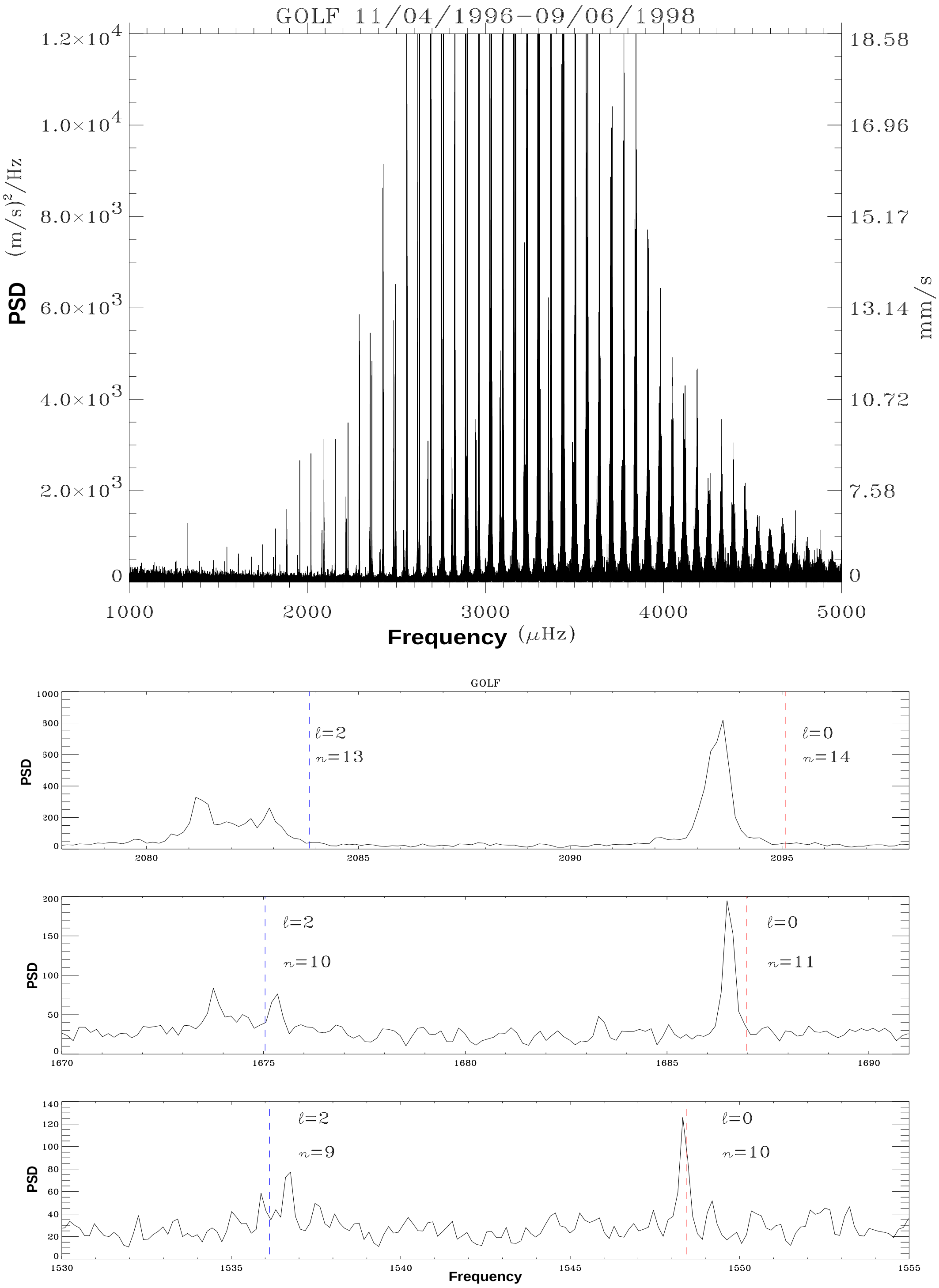

Fig. 5. The first figure shows the acoustic mode power spectrum of the GOLF experiment (Gabriel et al. 1995,1997). Each frequency is perfectly identified through theoretical acoustic predictions coming from solar models and oscillation codes. The fact that the width of the mode is larger at high frequency indicates that their lifetime is shorter due to the large influence of the surface turbulent motions. Then several zooms of the previous spectrum in the low frequency range show the identification and the comparison between observed modes and theoretical predictions (Brun, Turck-Chièze and Morel 1998).

despite the fact that the inner turning point generally increases with frequency. In this context, the excellent signal/noise ratio obtained aboard the satellite SOHO helps a lot.

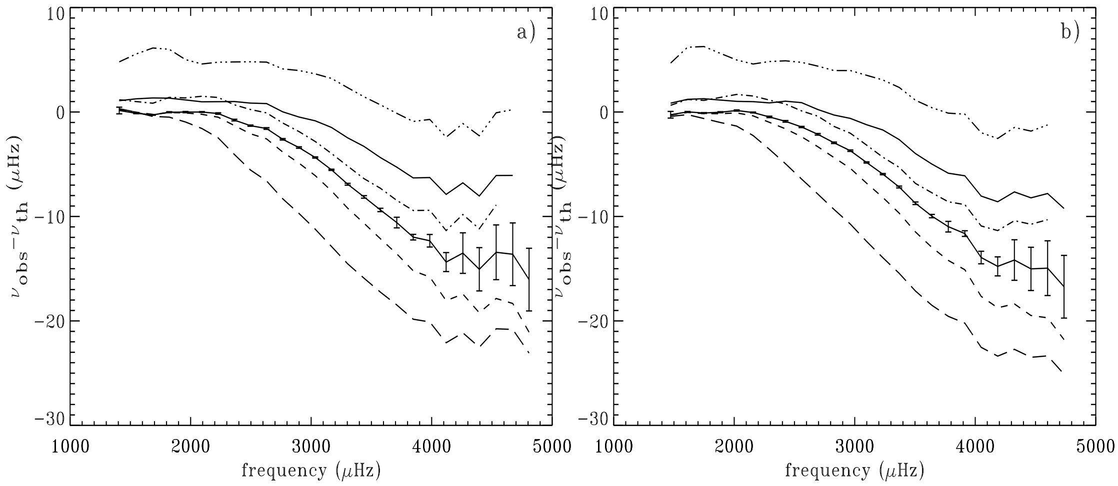

Fig. 6. Frequency differences between GOLF observations and different solar models for radial modes (a) and modes with $l = 1$ (b), in the sense (sun) - (theory): $- \cdots -$(no microscopic diffusion): Turck-Chièze and Lopes (1993); full line: Gabriel and Carlier (1997); $- \cdot -$: Guzik et al. (1996); full and experimental error bars: Christensen-Dalsgaard et al. (1996); $- - -$: Morel, Provost and Berthomieu (1997); large $- - -$: Brun et al. (1997). From Turck-Chièze et al., 1997.

Considering all these points which limit the present accuracy in the description of the core, we believe that we cannot conclude today on predicted neutrino emitted fluxes from helioseismology without an extensive study of radial modes of low frequency and a proper rotation and density radial profiles. Efforts are in progress with this perspective.

8. The gravity modes

The measurement of the gravity modes would be of course very useful to be sure of what we extract and to discriminate different physical effects (Brun, Turck-Chièze and Morel, 1998).

The frequency of these modes is proportional to:

$$\int_0^r N(r)/r dr \tag{11}$$

where N is the Brunt Väisälä frequency:

$$\mathrm{N}^2 = \mathrm{g}\left(\frac{1}{\Gamma_1}\frac{\mathrm{dlnP}}{\mathrm{dr}} - \frac{\mathrm{dln}\rho}{\mathrm{dr}}\right)$$

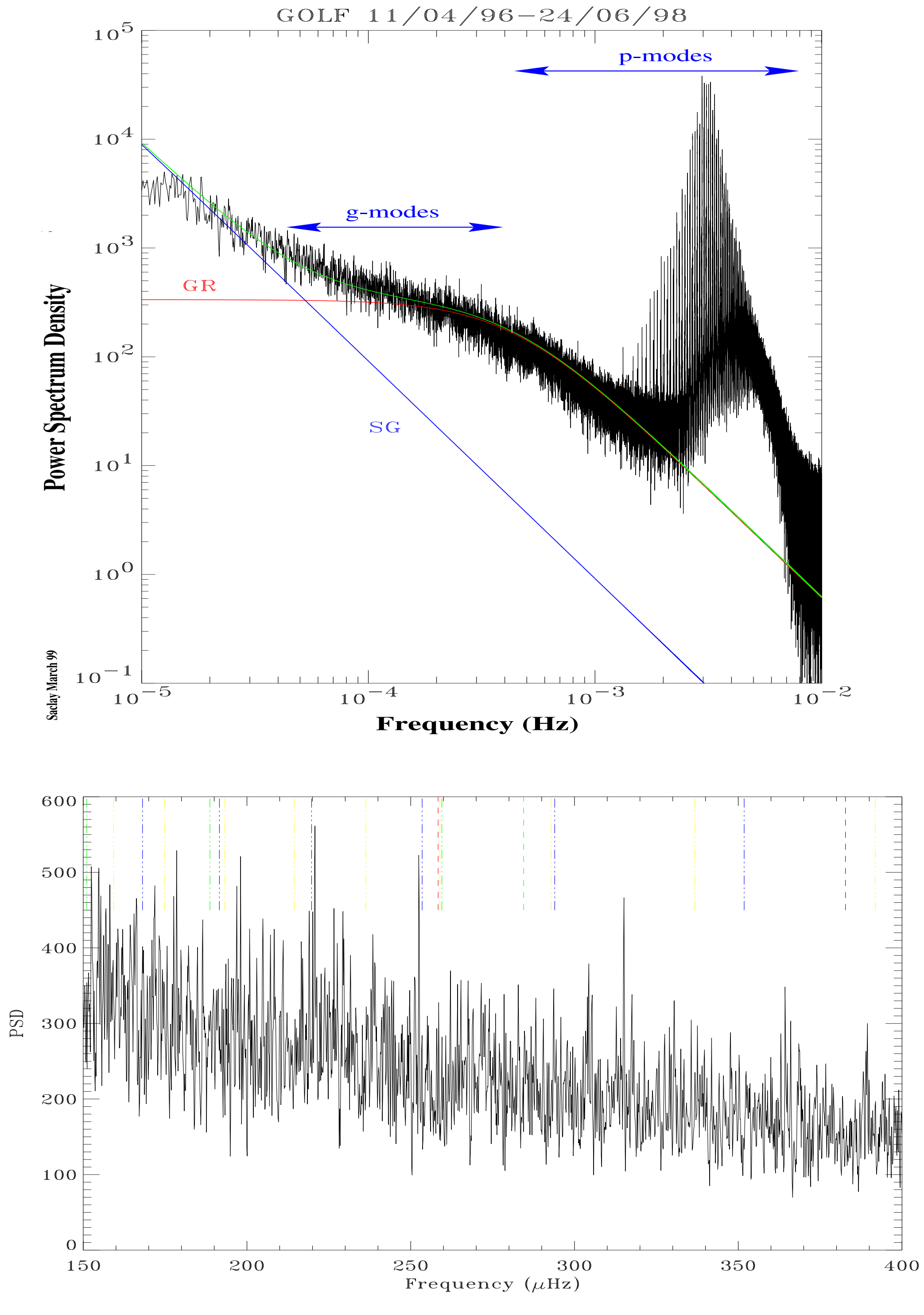

Fig. 7. Power spectrum density of the GOLF instrument. a) the whole range of frequency covering g and p modes with superimposed the suggested origin of the noise: GR granulation noise, SG supergranulation noise. b) a zoom on the most promising region to detect gravity modes, with on the top of the figure the standard model predicted frequencies for $\ell = 1,2,3$.

and enhances the information of the core (60 % from the inner 0.2 $R_\odot$) contrary to the acoustic mode frequency (5%). It is the reason why the gravity mode frequencies are 6 to 10 times more sensitive to any perturbation of the core (Brun, Turck-Chièze and Morel, 1998; Provost, Morel and Berthomieu, 1999). This is an important objective of the helioseismic experiments aboard SOHO. Figure 7a) shows the frequency spectrum obtained with the GOLF instrument including the range of gravity and acoustic modes, figure 7b) is a zoom on the gravity range spectrum. The difficulty to detect these modes comes from their estimated small velocity amplitude (of the order of some mm/s or less) coupled with a large statistical fluctuation of the solar noise in the corresponding range of frequency. Some possible candidates are under investigation on the SOHO satellite (Gabriel et al. 1998), following a strategy using all the characteristics of the g-modes (Turck-Chièze et al. 1998b).

Larger effort is in preparation to reduce the inherent granulation noise seating in the range of frequencies where they are waiting. This may justify a new experimental effort in order to better determine the Döppler velocity by following the time deformation of the observed solar line (sodium or nickel).

9. Conclusion

After 20 years of efforts, the acoustic modes have revealed interesting motions in the solar interior which were not present in the classical solar model. Presently, keeping a monodimensional description of the Sun, governed by the usual structural equations, we are able to improve our understanding of the astrophysical observations of the photospheric abundances. It is the first time that we can demonstrate and quantify that macroscopic motions in the Sun introduce extra mixing below the classical transition between transport of energy by radiation and convection. In this simplified picture, we cannot yet reproduce horizontal currents clearly visible in the convective zone nor generating the magnetic field which is at the origin of the solar cycle. These improvements do not modify significantly the neutrino fluxes as the modifications appear in the outer part of the Sun. But these successes show the power of such probes to look inside the Sun and enrich our simplified picture of a star. With the SOHO mission, we progress on the accuracy useful to probe the solar core, rejecting slowly the surface effect perturbation which may limit the accuracy we are able to reach today, in reality we reach today some 10^{-3} on $\Delta c/c$ in this range and we are looking for effect smaller than 1%. So the analysis continue, and we can already say that no evident deviation has been observed which may explained the three neutrino experimental results and that several ideas as important mixing at the frontier of the solar core have been rejected but subtle effects (including nuclear ones), influencing or not the sound speed profile may lead to reduction in neutrino predictions. The gravity modes would be the best probes to disentangle different physical processes which may be missing in this region of the Sun and they are actively researched.

One knows already that we need to understand the angular momentum story of the stars which probably implies a good estimate of the time dependence of rotation and magnetic fields before being able to predict a correct emitted neutrino fluxes with the challenge to contribute to better investigate the central region of the stars or to demonstrate the neutrino oscillations.

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11. Bibliography

Adelberger, E. et al., *Rev. Mod. Phys.* **70** (4) (1998) 1265.
Basu, S. and Antia, H.M. *MNRAS* **287** (1997) 189.
Basu, S., Turck-Chièze, S., Berthomieu, G. and the GOLF team, *ApJ* (1999) in preparation
Brun, S. et al., 1997, *in Sounding solar and stellar interiors*, **Symposium IAU 181**, ed J. Provost and F.X. Schmider, poster volume, p 69.
Brun, S., Turck-Chièze, S., Morel, P., 1998, *Astroph. J.* **506** (1998) 913.
Brun, S., Turck-Chièze, S., Zahn, J.P., *Astroph. J.* (1999) to appear.
Christensen-Dalsgaard, J. & Berthomieu, G., *in Solar interior and atmosphere* (1991) eds Cox, A. N., Livingston, W. C. & Matthews, M., **Space Science Series** University of Arizona Press, p 401.
Christensen-Dalsgaard, J. et al. *Science* **272** (1996) 1286.
Corbard, T., Berthomieu, J., Provost, J., & Morel, P. *Astron. Astroph.* **330** (1998) 1149.
Corbard, T. et al., *Proceedings of the SOHO6/GONG 98 Worshop, 'Structure and dynamics of the Interior of the Sun and Sun-like Stars'* ed. S. Korzennik & A. Wilson, **ESA SP-418** (1999) 741.
Gabriel, M. and Carlier, F., *Astron. Astrophys.* **317** (1997) 580.
Gabriel, A. H., and the GOLF team, *Sol. Phys.* **162** (1995) 39.
Gabriel, A. H., and the GOLF team, *Sol. Phys.* 175 (1997) 207.
Gabriel, A., Turck-Chièze, S., Garcia, R., et al., *in Structure and Dynamics of the Interior of the Sun and sun-like stars* (eds. S.G. Korzennik & A. Wilson), **ESA SP-418** (1998) 61.
Guzik, J., Cox, A. N. and Swenson, F. J., *Bull. Astron. Soc. India* **24** (1996) 161.
Hammache, F. et al. Phys. Rev. Lett. **80** (1998) 928.
Iglesias, C. & Rogers, F. J. *ApJ* **464** (1996) 943.
Kosovichev, A. G., Schou, J., Scherrer, P. H., et al. *Sol. Phys.* **170** (1997) 43.
Lazrek, M., Pantel, A., Fossat,et al. *Sol. Phys.* **166** (1996) 1.
Lazrek, M., Baudin, F., Bertello,et al. *Sol. Phys.* **175** (1997) vol 2.
Morel, P., Provost, J., and Berthomieu, G., *Astron. Astroph.* **327** (1997) 349.
Provost, J., Berthomieu, G., Morel, P., *in Solar composition and its evolution, from core to corona*, ed. S. Steiger, **Space Science Review**, p 117.

Proffitt, C. R. & Michaud, G., *Astroph. J..*, **380** (1991) 238.
Rogers, F. J., Swenson, J. & Iglesias, C. *Astroph. J.* **456** (1996) 902.
Scherrer, P. H. and the MDI team, *Sol. Phys.* **162** (1995) 129.
Spiegel, E.A., & Zahn, J.P. *Astron. Astroph.* **265** (1992) 106.
Thiery et al., *Astron. Astroph.* (1999) submitted.
Toutain, T., Appourchaux, T., Fröhlich, C., Kosovichev, A. G., Nigam, R., & Scherrer, P. H. *Astroph. J.* **506** (1998) L147.
Turck-Chièze, S. & Lopes, I. *Astroph. J.* **408** (1993) 347.
Turck-Chièze, S., Däppen, W., Fossat, E., Provost, J., Schatzman, E. & Vignaud, D., *Physics Rep.* **230** (2-4) (1993)57-235.
Turck-Chièze, S., Basu, S., Brun, A. S., et al., *Sol. Phys.* **175** (1997) 247-265.
Turck-Chièze, S., Basu, S., Berthomieu, et al., *in Structure and Dynamics of the Interior of the Sun and sun-like stars* (eds. S.G. Korzennik & A. Wilson), **ESA SP-418** (1998a) 555.
Turck-Chièze, S., Brun, S., Chièze, J.P., Garcia, R., *in Structure and Dynamics of the Interior of the Sun and sun-like stars* (eds. S.G. Korzennik & A. Wilson), **ESA SP-418** (1998b) 549.
Vauclair, G., Vauclair, S., Michaud, G., *ApJ* **223** (1978), 920.
Vorontsov, S. V., Baturin, V. A., Pamyatnykh, A. A., *Nature* **349** (1991) 49.