MeV Neutrinos: What is seismology telling us?

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Abstract: The Sun and the Supernovae are very interesting MeV neutrino sources and remarkable examples of symbiose between astrophysics and particle physics researches. Helioseismology has allowed a clear characterization of the solar central plasma. Neutrino detections have also solved challenging questions. Today, we converge on a proper, but yet classical, description of the solar core and deduce a prediction of the most energetic neutrino fluxes with a high degree of confidence. The present impressive agreement between prediction and SNO detection leads to an unambiguous evidence for a solution of the neutrino puzzle and a clear demonstration of the presence of solar neutrino oscillations.

Nevertheless, it is worth to notice that the main role of seismology is to contribute to determine a dynamical view of the stellar interiors. The description of the magneto-hydrodynamical processes is nowadays the present objective for a renewal of the stellar discipline. This year, important results on the Sun constitute a real breakthrough towards a dynamical vision of the Sun from which we may hope to extract complementary solar neutrino properties. More and more, it seems that there is interest to look for correlations between neutrino detections and magnetic activity of the Sun. Next, dynamical processes will be studied in a large number of stars, including those for which they play a dominant role, with an evident impact on supernova description. Astrophysicists and particle Physicists, once more, will join their effort to better understand these objects. Interesting cosmological consequences will be deduced.

1. The MeV neutrino sources

The two natural neutrino MeV sources, the Sun and the Supernovae, are studied with more and more interest as the richness of their plasma properties is inaccessible in laboratories. Nevertheless, the level of knowledge of these sources is extremely different. The solar internal structure is scrutinized for more than thirty years with two independent probes: neutrinos and acoustic modes. In the case of supernovae, the emitted neutrinos have been detected only once, for the Supernova 1987A.

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It is evident also that these two sources are extremely different. If the Sun has a continuous emission of neutrinos, the emission coming from a supernova explosion is quasi instantaneous, with a peak of 0.025 s. Less than 1 % of the total produced solar energy is emitted by the neutrinos, whereas the main part of the released energy in a supernova explosion is contained in the neutrino emission.

If the Sun emits neutrinos up to 14 MeV and has a well determined energy spectrum (see figure 1), the range of emission for the supernovae is large from 5 MeV to about 100 MeV. The impact of the different neutrino oscillation solutions on the supernova energy spectrum is high, mainly for the SNO detector, even the waiting statistics in Superkamiokande is higher, so there is extremely large interest to detect supernova neutrinos in the present observatories to put more constraints on the neutrino properties or on the explosion mechanism. The diversity of the supernovae [1] and consequently of the supernova explosions encourages also the study of the different supernova precursors. Supernovae Ia have initial mass below 8 $M_\odot$, and final mass probably below 1.5 $M_\odot$, Supernovae II have initial mass between 8 to 30 $M_\odot$, final mass below 10 $M_\odot$, Supernovae Ib and c have initial mass above 30 $M_\odot$ and final mass always below 10 $M_\odot$. With such a range in mass, questions on geometry, asphericity, rotation, metallicity have not a clear answer today.

The progenitors of supernovae appear as deformed stars with asymetric mass loss (at least for the massive ones) which encourage a 3D description. The direct and indirect role of the rotation on the oblatness of massive stars is now proven. So their representation will largely benefit from seimic observations, capabilities of parallel computers and the introduction of macroscopic motions. The impact on the geometry of the explosion is something extremely exciting to study. Moreover, the role of the stellar metallicity must be studied to interpret correctly the incoming large dataset supernova light curves. So, a new magneto-hydrodynamical vision of stars will emerge within the next decade, with consequences for supernova progenitors.

In the present review, I shall concentrate on the solar case because a lot of results have appeared these last years on the astrophysical side and the particle physics side which justify summary, analysis and perspectives.

Table 1: Nuclear processes leading to neutrino emission.

ppI chain:	$p + p \rightarrow D + e^+ + \nu_e$ (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)

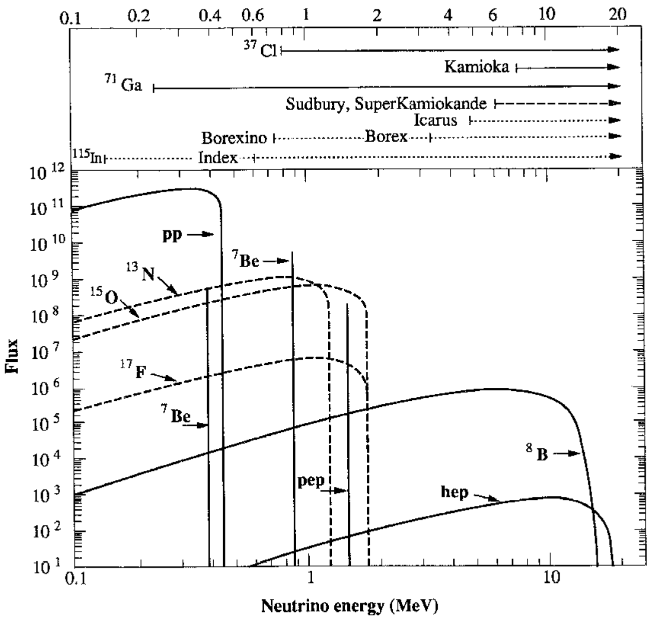


Figure 1: Energy dependence of the neutrino sources and the range of energy covered by the neutrino detectors. From [2].

The Sun is a unique case for which we have today 30 years of observations: five neutrino experiments using different techniques, 3 helioseismic ground networks and 3 spatial helioseismic experiments aboard SoHO running since 7 years. The Sun emits neutrinos through the weak interaction, the different sources are recalled in table 1. The difference of energy of these different sources, recalled in figure 1, has contributed to complicate the interpretation of the results as the gallium (threshold: 0.24 MeV) and the chlorine (threshold: 0.8 MeV no detection of pp neutrinos) experiments detect simultaneously neutrinos from different sources. Only Superkamiokande and SNO detect one source of neutrinos, those emitted by the marginal ppIII chain, largely dependent on the solar internal plasma (see table 3 which will be discussed later).

2. Standard solar model and neutrino emitted fluxes

Theoretical emitted fluxes for the different sources of neutrinos, described in table 1, are extracted from solar models which describe the temporal and radial evolution of the Sun in the classical framework of stellar evolution. These models do not introduce any condition on the kinematics of the reactions, the energy dependence of the neutrino fluxes is deduced from the knowledge of the nuclear processes. We use in the solar models a mean energy for each source. By solving the following four structure equations, one performs an ab initio complete calculation which requires a good description of the nuclear and atomic processes. No free parameter is introduced in these predictions.

The first equation assumes hydrostatic equilibrium (each gas shell is balanced by the

Table 2: Location in the Sun where some specific elements can check, through the mentioned observables, some particular processes

radius in solar unit	element	observables	physical processes	problem solved ?
0.98	^{4}He	Γ_1	microscopic diffusion	[3]
0.71	^{16}O	κ	transition radiation/convection	[4]
0.70	^{7}Li	c^2, rotation	nuclear process,turbulence	[5]
			generation of magnetic tubes	no
0.57	^{9}Be	c^2	nuclear process, turbulence	[5]
0.25	^{3}He	c^2, density	mixing ?	[6]
0.05	^{7}Be	c^2, density	mixing ?	[6]
0.- 0.1	^{56}Fe	κ	central temperature ?	[7]

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, independently of the change of flavour, about $6\,10^{10}\nu_e$ reach the earth /s coming from the fundamental pp interaction which produces $1.68\,10^{38}\nu_e$/s. This main source of neutrinos coming from the Sun has unfortunately a small neutrino energy and this flux has never been measured totally and separetely. The other sources are smaller: typically 1.3 $10^{37}/s$ for ^7Be neutrinos 1.3 $10^{34}/s$ for ^8B, 1.3 $10^{36}/s$ for ^{13}N, 1.1 $10^{36}/s$ for ^{15}O, the last one is extremely small. These secundary 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 and the characteristics of the plasma.

The above representation of the Sun is the most economical way to describe a star and supposes that there is no important effect of rotation, magnetic field and that the present photospheric abundance is used to determine the initial composition of the Sun. In this framework, 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 only adjusted variable is the initial helium content in order to reproduce these observations at the present time

The helioseismic probes are used since 1988 to check if :

- these hypotheses are correct,
- they can help to improve the quality of the physics included
- extra processes must be introduced.

Table 2 summarizes the different processes and locations where helioseismology can chck the quality of the models. This is the reason why the solar model and the physical processes included in the equations through the composition, the nuclear reaction rates, the equation of state and the opacity coefficients, have received a lot of attention these last 15 years.

3. An internal vision from acoustic and gravity modes

In this section, we will briefly review the bases of the helioseismic tool. Acoustic waves are generated by the surface granulation and propagate inside the whole Sun. The travel depends on the initial velocity. They generate very slightly motions in the atmosphere of the Sun which are visible and detectable. As these perturbations are small and as the Sun is reasonably spherical, we can formely treat this information through a perturbed theory.

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

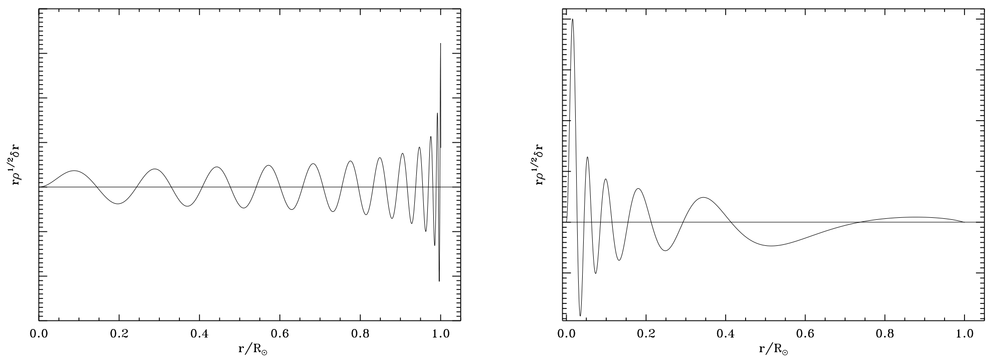


Figure 2: Eigenfunctions of an acoustic mode (ℓ =0 radial mode, n=23), and of a gravity mode (ℓ =2, n=10).

Y_l^m, we write any scalar perturbations as (in the case of the pressure $p^{'}$) [8]

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

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

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

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 (the total horizontal wave number at the surface is $k_h \sim L/R_\odot$, with $L = \sqrt{l(l+1)}$) and the azimuthal order (number of nodes along the equator with $|\vec{m}| \leq l$). Restricting the phenomenon to adiabatic oscillations within the Cowling approximation ($\Phi^{'}$ neglected) and considering only small radial wavelengths compared to $R_\odot$, we reduce a 4th-order system equations to a second-order wave equations, with the following dispersion relation [8]

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

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 ($\sim$ 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 2 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).

About 3500 acoustic modes (the so-called 5-min oscillations) have been already observed. A refined analysis of their properties allows nowadays to get a stratified information about the solar internal structure from the surface to the solar core. The gravity waves stay the best probes of the region of neutrino emission. They are actively looked for with the SoHO satellite and will be discussed in section 6.

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 exploit two variables extracted from the spatial instruments GOLF (Global oscillations at low frequency [9]) and MDI (Michelson Doppler Imager [10]) aboard SoHO, namely the sound speed profile and the internal rotation profile and compare them to uptodate solar models. It allows to improve these models if the agreement is not satisfactory, introduce in the models some extra phenomena to see if the agreement is worse or better. In fact a lot of phenomena have very specific signature which are informative. We have potentially also an information on the magnetic field but today we put mainly limits due to the difficulty to extract such quantity. A lot of efforts is dedicated to this point now to be able to extract such important ingredient [11, 12].

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

Since the launch of SoHO in 1995, we can extract more and more properly the solar sound speed profile from the helioseismic data. Consequently, if we could demonstrate that there is a significant deviation between the Sun and the theoretical model, this could be the opportunity to go beyond the considered theoretical model. So, along time, we have improved it up to the level where we can deduce neutrino fluxes constrained by our seismic observation of the Sun.

Before commenting on the role of the seismic probe, it is interesting to compare the sensitivity of the two probes, neutrinos and sound speed, to the central conditions of the Sun. We have already recalled the ^8B neutrino flux dependence on the central temperature. We 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 about 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 3, we 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}) in order to observe some deviation of the temperature of less than 1%. This is exactly what is required for questionning the present solar structure (see table 3 giving the sensitivity of the sound

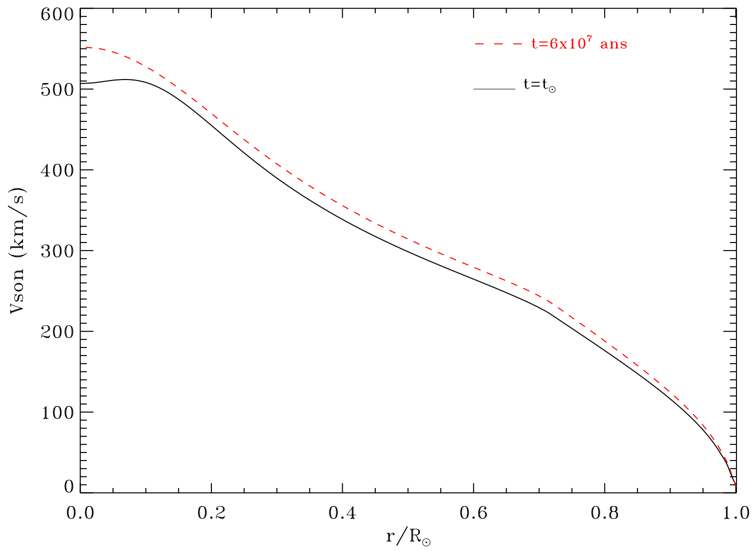


Figure 3: Evolution of the sound speed along the hydrogen burning.

speed to the different ingredients of the solar model). We know that a doubt of 2 % on the central temperature leads to a reduction by a factor of 2 on the ^8B neutrino flux. This is the demanding challenge of the SuperKamiokande and SNO. By chance, we can expect such precision if we have a proper knowledge of the acoustic mode characteristics.

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. Nevertheless, if we have strong constraints on the density and pressure, we have indirect but strong constraint on the central temperature.

In parallel to the progress on neutrino detections, major efforts have been carried out to improve the quality and the accuracy of the seismic indicators. It is an absolute necessity because the acoustic modes are largely influenced by the outer layers. A lot of activities have been dedicated to this aim. The difficulty to get reliable values for investigating the physics of the solar core is due by three phenomena:

- the stochastic excitation
- the influence of the solar cycle
- the asymetry of the mode distribution due to the interaction of the mode with the solar background.

Several papers have treated these different points. A comparison of the different instruments, checking the impact of different techniques has contributed to identify the biases in the data determination [13],[14]. We have then analyzed the consequences on the extracted physics [15, 16, 17]. SoHO has effectively allowed to detect modes of low frequency which have a long lifetime and cavities in which the indirect deterioration coming from the stochastic excitation and the effect of the solar cycle is reduced. Consequently the quality of the information extracted from the central solar region has been improved by an order of magnitude. We are now confident that the information on the radiative zone is

Table 3: Sensitivity of the sound speed to the physical processes

Quantity	variation	$\Delta c^2/c^2$ variation
T	1 %	1%
κ	1 %	0.1 %
$X_c\,^{56}Fe$	4 %	0.1 %
$X\,^3He$	25%	0.1 %
(p,p) reaction rate	1%	± 0.1%
(^{3}He, ^{3}He) reaction rate	- 25 %	- 0.1 %
(^{3}He, ^{4}He) reaction rate	-25%	+0.2%
(p, ^{7}Be) reaction rate	10%	none
(p, ^{16}O) reaction rate	-50%	- 0.1-0.2 % just at the center

properly obtained at the level required for establishing quantitatively the neutrino fluxes for all the sources with a good, even yet classical, view of the solar core (see figure 1 of [17]). Nowadays, with more than 7 years of SOHO data and long time series ground based observations, we have reached a stage where we can describe the mean behaviour of the solar core, but we have not yet reached the dynamical aspect of it, which necessitates the detection of gravity modes.

5. The Sun, a laboratory for plasma physics

Figure 4 shows the difference between the squared of the sound speed obtained with acoustic modes and one obtained with a good solar model for which the physics has been improved but the equations are still totally classical, as presented in section 2. We can appreciate the impressive progress done since the situation before the launch of SoHO (see for example the figures shown in [2]) where there was no indication on the core and deviation up to 2% in the radiative region. So due to our efforts to build reliable and performant instruments, it is convincing that we may put strong constraints on all the phenomena which may have an impact on the neutrino fluxes thanks to the helioseismic probe.

Since 1988, our group has controlled the emitted solar neutrino fluxes, in confronting the solar theoretical structure to the seismic one. Using this probe as a reference, constant progress has been noticed on the determination of the fluxes [18, 19, 20, 21, 5, 6, 7, 17]. Table 2 summarizes the location in the Sun where some specific physical phenomenon can be checked through seismology and the corresponding success of the community. Table 3 shows the sensivity of the sound speed to different ingredients of the calculation, it is important to notice that a lot of them leads to effect of about 10^{-3} of the sound speed in the core, this is why we have decided to improve the accuracy of this probe. For nuclear reaction rates, we include in the variation, possible uncertainties due to the effect of free electrons or neighboured ions which may perturb the distribution of reactant velocities. Table 4 shows the evolution with time of the ^{8}B neutrino flux prediction, in our group in Saclay. It is interesting to notice that, in 2001, we have reached the needed accuracy to finish to investigate all the different points mentioned in the previous tables. During the

Table 4: Evolution with time of the ^8B neutrino flux in $10^6 cm^{-2}s^{-1}$, of the central temperature in 10^6K, initial helium in mass fraction, and problem solved

^8B flux	Tc	Y initial	problem solved	reference
3.8 ± 1.1	15.6	0.276	CNO opacity, $^7Be(p,\gamma)$	[18]
4.4 ± 1.1	15.43	0. 271	CNO Fe abundances, screening	[19]
4.82	15.67	0.273	microscopic diffusion	[21]
4.82	15.71	0.272	turbulence tachocline	[5]
4.98 ± 0.73	15.74	0.276	seimic model	[7]
5.07 ± 0.76	15.75	0.277	seismic model, magnetic field	[17]

SNO results: 5.44 ± 0.99 [22] 5.09 ± 0.44($stat$) ± 0.45($syst$) [23]
$5.27 \pm 0.27(stat) \pm 0.38(syst.)$ [24]

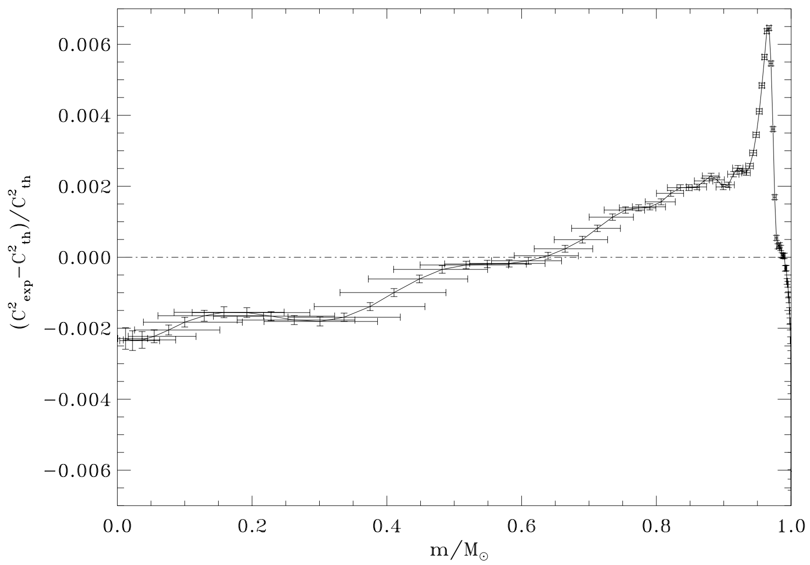


Figure 4: Relative difference between the squared sound speed in the Sun extracted from GOLF and MDI measurements and the squared sound speed of our reference solar model, in function of the mass.

same period of time, the prediction of Bahcall and collaborators has varied from 5.8 to 6.6 $10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$, then, after the launch of SoHO, using the same helioseismic constraints, they have converged to comparable numbers, but they have not checked the correctness of the different processes, as we have done nor took directly a seismic model to verify the convergence of the estimate.

I shall recall here the main highlights which can be summarized in 5 points:

- 1) a proper determination of the interaction between photons and all the elements

This is very important for determining the central temperature, it supposes a good determination of the composition in particular helium, carbon, oxygen, iron composition

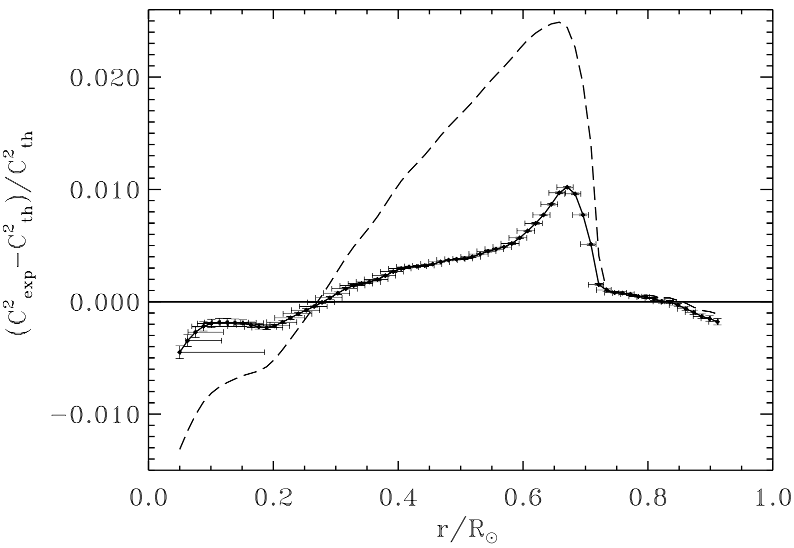


Figure 5: Relative difference between the squared sound speed in the Sun extracted from the first results of GOLF and MDI measurements and the squared sound speed of our reference solar model, in function of radius, compared with a model which does not contain the microscopic diffusion (dashed line). This last model predicts ^{8}B neutrino flux about 20% smaller but is not supported by helioseismology. From [21].

and a detailed calculation of the photon matter interaction, fifteen years have been useful to converge on this point. Recently a new reestimate of the photospheric oxygen by -20% [26] may lead to some slightly different model, it is why we prefer to deduce neutrino results directly from the seismic profile, which implicitly introduce further progress.

- 2) a proper description of the microscopic diffusion and of mixing in the radiation-convection region partly inhibiting the microscopic diffusion.

In [21] and [5], we show that the solar structure has been substantially improved by the introduction of diffusion not previously contained in classical stellar evolution 10 years ago and prescribed by the helioseismic constraints. This progress concerns the evolution of the elemental composition with time. Three terms (the secund part of the right member) 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, dominated by the gravitational settling, modifies the composition along the radial profile and the progress done by the introduction of the first and third term is clearly visible in figure 5. They have drastically improved the agreement with the observed sound speed. It has a direct 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). It also reconciles stellar evolution with the age determination from radioisotope measurement (see for example [27]). Contrary to what was assumed in the classical stellar evolution, the 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. 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. It is the only way to have a complete agreement with all the phostospheric observations ([5],[7]), as shown in figure 7.

- 3) a proper description of the plasma for the determination of the nuclear interaction Nuclear reaction rates between ions 1 and 2 are classically calculated as :

$$r_{12} \propto \int \mathrm{S(E)exp(-E/kT - b/\sqrt{E})\,dE} \qquad (9)$$

where S(E) is a smooth function of energy E, the first exponential factor is the Maxwellian velocity distribution, and the second one is the penetration function with b a factor depending on the ion charges and reduced mass.

Two problems must be verified due to the characteristics of the plasma:

- the adequation of a maxwellian distribution for the particle velocities

- the proper description of the acceleration of the reaction rate due to the presence of free electrons and some ions in the vicinity of the reactants.

For many years, it has been suggested that several physical mechanisms, such as diffusion, collision, or long range coulomb interaction, could lead to a very light depletion of the Maxwellian tail at high energy. If such an effect exists, as only the high energy of this distribution actually participates to the reaction rate, the consequence is a subtantial reduction of these rates and thus of the neutrino emissions.

The validity of such assumptions can now be tested with helioseismology. Taking δ as the coefficient modelling the Maxwellian tail depletion at high energy, the Maxwellian velocity distribution can be written:

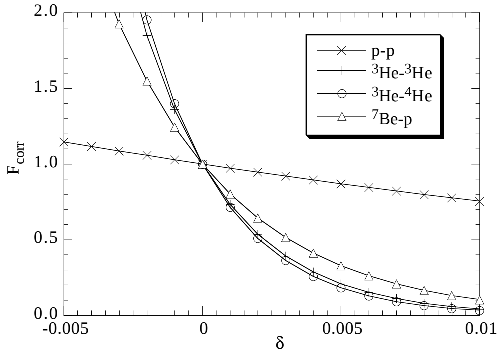
$$f(E) \propto \exp(-E/kT - \delta(E/kT)^2).$$

The new reaction rate can be expressed by the classical one via a corrective factor F_{corr}

$$(r_{12})_\delta = r_{12} F_{corr}(\delta)$$

A calculation to a first order in δ gives

$$F_{corr} = (1 + \frac{15\delta}{4})(1 - \frac{7\delta E_0}{3kT})\, e^{-\delta(\frac{E_0}{kT})^2} \qquad (10)$$



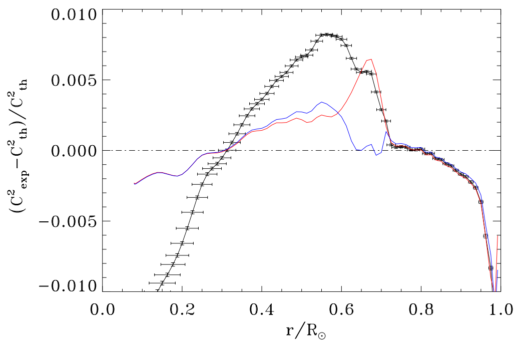


Figure 6: Left: Variation of the correction factor of the reaction rates of the pp chain for different values of the parameter δ describing the deformation of the Maxwellian distribution of the reactant velocities. Right: Effect on the squared sound speed difference of a deviation by 0.5 pour cent compared to classical models (without turbulent diffusion dashed line or with turbulent diffusion continuous line). From [6].

where k is the Boltzmann constant, T is the temperature and E_0 is the so-called Gamow energy given by

$$E_0 = (\pi\alpha\frac{c}{\sqrt{2}}MZ_1Z_2kT)^{2/3}$$

with α the fine structure constant, c the vacuum speed of light, $Z_{1,2}$, and M the ion charges and reduced mass respectively.

It is possible to observe that if this kind of effect is very small on the pp reaction, it affects the other reactions very quickly by a large factor (figure 6 left). For example, a very small deviation of 0.5 % of this Maxwellina distribution leads a change in reaction rate of 5% in pp reaction, -36% in ${}^3He,{}^3He$, -50% in ${}^7Be,p$ and -67cycle. The same kind of consequences is noticed if we estimate incorrectly the acceleration of the reaction due to the presence of negative free electrons called also "screening factor" which is in our case [20] of about 5% for pp, 1.2 for the other reactions of the pp chains and 1.3 for the CNO reactions according to the fact that we consider the solar plasma as an intermediate plasma and not a pure weak plasma as it was supposed ten years ago.

Figure 6 right clearly shows that if we micmic some deviation of the maxwellian distribution (here 0.5%) or a strong variation of the classical expression, we strongly increase the disagreement with the observed sound speed. So up to now we may consider that such spurious effect is not encouraged by the present knowledge of the solar core.

- 4) the existence or not of a potential mixing in the very central core

One way to reduce the ${}^8B$ neutrino flux is to introduce a central mixing in the core which reduces the ${}^7Be$ composition which is extremely sharp together with the ${}^3He$ content (see figure 3 top of [6]). It is not totally ad hoc to imagine such effect as it is well known that the central sun is not far from the convective instability and as we know very few about the very central part of the Sun where the ${}^8B$ neutrinos are produced. So we have also tried to produce such a mixing and looked to the effect. We observe that to get a drastic effect on the neutrino predictions, we need to destabilize the whole radiative zone, and one more this is not support by the seismic results [6].

A similar question has been ruled out also. It was the idea that the central core may be cooled by the presence of WIMPS in the solar core which act as a conductive ingredient, transfering heat from the very center to the rest of the radiative zone. Ten years ago, we have used seismology to show that it is not favoured [28]. At that time the constrains on the core was not so big, it is interesting to see the level of mass limit we may deduce from the present result, this has been reestimated recently by [29].

- 5) the proper description of the pp reaction rate

The pp reaction rate is only known theoretically, and the sound speed is extremely sensitive to it, so it is now possible to improve its determination through seismology. This one indirect result from the study of acoustic modes, which supposes to have previously check all the different hypotheses of stellar evolution, we have proposed a reestimate of this number [7] which must be of course be reconsidered after the determination of the central magnetic field.

It is because we have found answers to all these questions that neutrino predictions coming from different groups have converged. The microscopic diffusion effect has been calibrated thanks to the ground observations, but the SoHO satellite has been determinant to reach the proper accuracy for checking most of these points. In checking all these terms, we have got confidence on the quantitiative use of the structure equations. At this stage, we have not noticed serious anomaly or forgotten phenomenon, though we know that this picture of the Sun is not complete. We have also introduced some effect of the potential magnetic field through magnetic pressure to see the influence on the neutrino predictions with an increased of 4% [17]; the consequences on neutrino predictions of a central magnetic field has not yet been checked and is under study.

Including progress on theoretical, instrumental and observational sides, we have finally produced seismic theoretical models [7, 17]. Figure 7 shows one of them for which we have mainly modified the pp reaction rate by 1% and the initial composition by 3.9% in order to get no difference with the real Sun in the radiative zone. From this model we are confident to quantify the neutrino fluxes with the best information on the solar interior. But we can observe that the density profile is not totally satisfactory and that this model is certainly not a physical model of the Sun. But we may consider that the number of emitted neutrino fluxes, and in particular the ^8B neutrinos, is already constrained by the helioseismic probes. A flux of 4.95 0.72 $10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$ for the ^8B neutrinos has been determined [7, 17] with an error bar of only 14%, including physics beyond standard hypotheses.

The perfect agreement of this prediction with the results of the SNO detections is determinant to solve the neutrino puzzle. We precise that it is drained by the improved physics, and validated by helioseismology. It is a strong demonstration that astrophysical representation of stars is now quantitative at least for this case and it puts already strong constraints on energy production including CNO cycle. Effectively, the previous study on the reaction rates, added to the results of SNO puts already strong constraints on CNO contribution. Presently we can exclude variation of CNO reaction rates greater than 25%

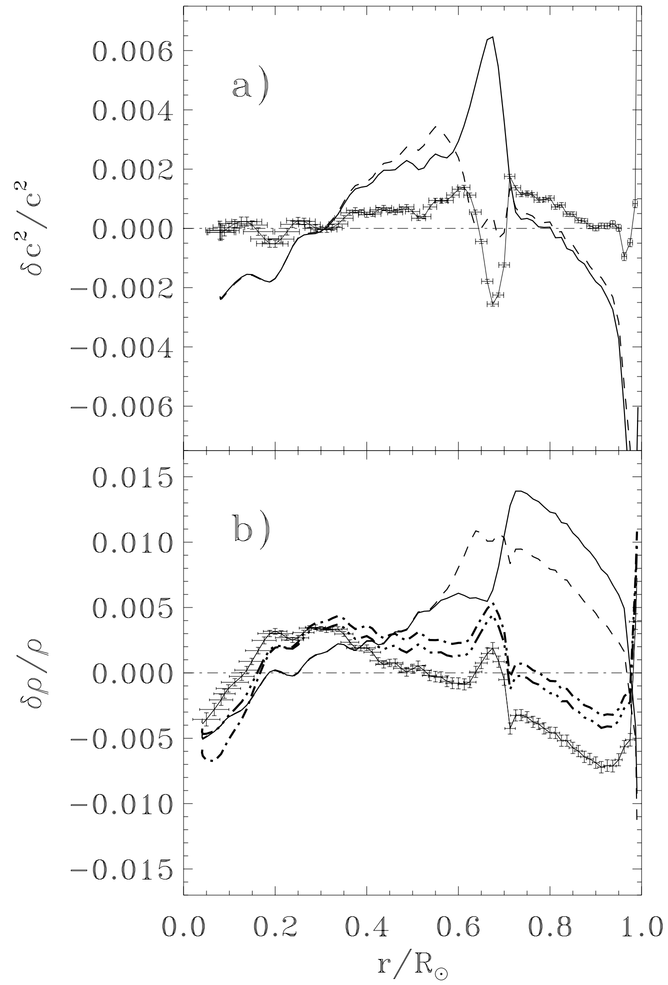


Figure 7: Relative differences between (a) the square of the sound speed and (b) the density deduced for the Sun using the GOLF/MDI frequencies [16, 14] and those of different Saclay models. The models are: classical solar model including microscopic diffusion [21] (continuous curve), classical solar model including microscopic diffusion and turbulent diffusion [5] (dashed curve), and seismic model [6] (points with error bars joined by straight lines). Superimposed on the density profile, two other models: model with reaction rate of (^{3}He, ^{4}He) reduced by 10% (dot-dot dashed curve), model with the reaction rates of the CNO cycle reduced by 70% (dot-dashed curve) relatively to the seismic model.

in using the two probes: neutrinos and seismology. It will be extremely difficult to go beyond this limit as neutrinos from CNO is not a large contribution of the Homestake and gallium experiments, nor the CNO luminosity in the stellar models (no more than 1.5% for the Sun). On the other hand, CNO is the main coontributor to luminosity of massive stars, consequently, through supernova neutrinos, we will probably improve such information. The story of solar neutrinos may stop here but it will be dangerous to do so, and the astrophysical perspectives encourage to be careful and to continue solar neutrino observations at low energy. Thanks to helioseismology, we have probably a proper determination of most of the neutrino fluxes, with a different reduction due to the MSW effect, than in the case of SK, SNO and Kamland.

6. Is the Sun standard or not ?

Helioseismology has also revealed that the Sun is not standard. Effectively, the main objectives of this probe is to go beyond the simple representation which neglects the effects of the macroscopic motions. It is now shown that the observed internal rotation or indirect magnetic field are not sufficiently large for modifying the internal structure, but they are present and the consequences are under investigation.

During this year, variabilities of the global acoustic mode characteristics connected to the evolution during the solar cycle have been extracted from the global acoutic oscillations [11, 12] and internal migrating flows are observed. We note a long trend and some very localized effects which are due to the fact that the evolution of activity is not only a smooth function of time. The history of the angular momentum evolution is crucial to understand the dynamo process and the range of internal magnetic field which is an essential property of the solar plasma.

Due to the solar rotation and magnetic field, the frequencies of two modes of the same degree ℓ and order n are splitted in m components varying between $\pm\ell$. The corresponding splitting contains information on the internal rotation. Differential rotation is now well established in the convective zone and several times shown. The region of the transition between radiation and convection, is called now the tachocline due to the rapid evolution of this differential rotation towards a rigid rotation, there is the origin of the turbulent mixing due to horizontal motions provoked by such sudden variations. Presently one can extract this rotation profile down to the limit of the nuclear core, typically 0.2 $R_\odot$, for the first time without ambiguity (see figure 8) thanks to the longevity, the stability and the position of the SoHO satellite [30]. It appears that the radiative zone rotates as a solid body with a constant rate. Such a result is very interesting and encourage to put some constraint on the magnetic field in the radiative zone which has probably the main responsability in this profile. It is what we have done in our last neutrino prediction, where we introduce a magnetic field of 3 10^7 G near 0.2 solar radius, as a magnetic pressure in this zone, only to see the sensitivity of this prediction to this term, the effect on neutrino flux is small and even improves the agreement with the solar neutrino detection. Of course it will be better to perform a complete MHD calculation as suggested by Semikov (see his contribution in this proceeding) but such calculation is not yet available in the radiative zone and the order of magnitude of the magnetic field is not sufficiently known. So it is one more useful to return to the seismic data. In parallel MHD calculations begin to be developed in the convective zone in order to reproduce the rotation profile [31] and to begin to understand the history of the role of the magnetic field.

The best way to extract dynamical motions in the radiative zone will come from the gravity waves. Several attempts to detect them have been unsuccessful due to the weakness of their amplitudes at the surface [32, 33]. It is why we have performed a very complete

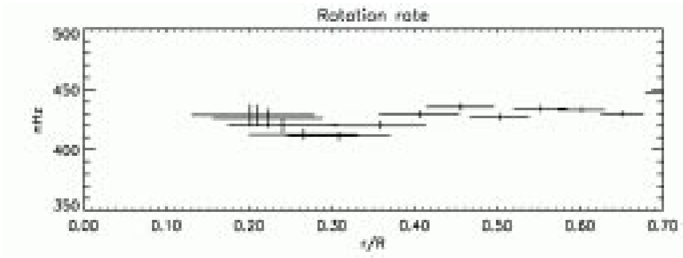


Figure 8: Rotation profile in the radiative zone.

analysis of the GOLF data for a long observation of 2-3 and then 5 years to look for multiplet gravity modes. Using this original method which allows to look for modes with a velocity of no more than 2mm/s at the surface of the Sun, we have determined gravity mode candidates which appear with more than 90% confidence level in the period where the Sun is quiet. The evolution with time of the patterns observed shows that, if the source of the signal is confirmed, they could be compatible with a small core rotating with a different axis than the rest of the radiative zone with a higher rotation rate. This could be a relics of the early rotation? Moreover the peaks are not so well defined and let the possibility of thinking about a variability of the cavity along time or an effect of the varying magnetic field [34]. This work will be continue during the whole SoHO mission and we hope, before the end of the observations, scheduled for 2007, to confirm or not such detection.

These present investigations lead us to the following question:

Could the Sun give us an opportunity to discover other properties of the neutrinos ?

We know already that the effect must be smaller as we can explain most of the observations through MSW effect but, as mentioned by Smirnov, some small inconsistencies may be interesting to look at. Variability of about 10% of the counting rates is not so easy to detect and may be the signature of some interesting behaviour. The important way to progress is to try to correlate neutrino detections to some solar indicator.

7. The search for other neutrino properties

We have delivered the radial electron and neutron density profiles for our seismic model on our web site

http://www-dapnia.cea.fr/Phys/Sap/Documents/soleil/solarmodel.html,

in order to be able to calculate any transformation of neutrinos. We have also given some limits on the magnetic field in different regions of the Sun [17]. Based on these values, we estimate the sensitivity to the magnetic neutrino moment: $\mu_\nu > 5\,10^{-15}\mu_B$ in the radiative zone and $\mu_\nu > 3\,10^{-12}\mu_B$ in the transition region between radiation and convection. We also give some probabilities on the RSFP transition for estimated magnetic field. Other more recent analyses have been performed by [35, 36].

Our present objectives are to look for some properties of the solar plasma which may play a role on the neutrino propagation or transformation. Previous works mention possible correlation between variabilities of the Sun and the neutrino counting rate [37] and refer-

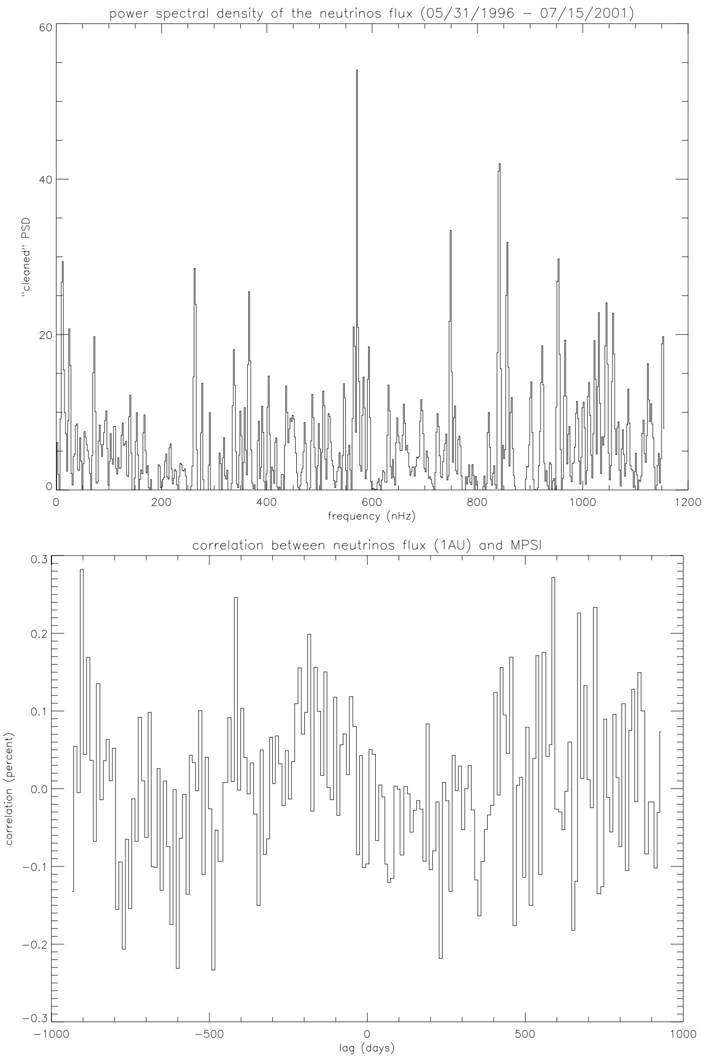


Figure 9: Spectrum analysis of the 10 days SK data and correlation analysis with MPSI indicator.

ences therein, [38]. An other approach is to try to put some constraints on the magnetic field from the properties of oscillation of the neutrinos [39].

We have performed an analysis of the released neutrino data. In particular, we have analyzed the Superkamiokande 10 days data. We note significant peaks around half the rotation of the Sun (figure 9 top), as was mentioned by [37], and some others with a period around the rotation, but the spectrum is not unambiguous as it is the case for acoustic modes. We have also studied the correlation between the neutrino dataset (SK and SAGE) and magnetic indicators. We may note some anticorrelation (at a small rate) and some small correlation with a delay of several hundred days, which may translate some internal interaction. Migration from the tachocline may take this time. The same analysis has been repeated with SAGE data. A more convincing anti correlation, as was previously mentioned [38], may be seen. But all the effects are not sufficiently significant. We may observe and demonstrate that it could be due to the duration of individual data set, it is why I have recommand in last May, at the LowNu03 conference, to deliver datasets of 5 days for Superkamiokande and SNO and to try to extract data in the low energy experiments (Gallex and SAGE) at the same time. Effectively, the magnetic activity evolves strongly at the scale of days. SK has done this effort and 5 days data set is now available [41], a first analysis has been done by [40]. We will continue this study rather soon.

Acknowledgments

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References

[1] Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., Hartmann, D. H., *Astrophys. J.* **591** (2003) 288

[2] Turck-Chièze, S., Däppen, W., Fossat, E., Provost, J., Schatzman, E. & Vignaud, D., *Physics Rep.* **230** (2-4) (1993) 57-235

[3] Vorontsov, S. V., *Astron. Zh.* **68** (1991) 808 (English translation: *Sov. Astron.* **35** 400).

[4] Christensen-Dalsgaard, J., Gough, D.O., Thompson, M. J., *Astrophys. J.* **378** (1991) 413

[5] Brun, S., Turck-Chièze, S., Zahn, J.P., *Astrophys. J.* **525** (1999) 1032

[6] Turck-Chize, S., Nghiem, P. , Couvidat, S., & Turcotte, S., *Sol. Phys* **200** (2001) 323

[7] Turck-Chize, S., et al., *Astrophys. J.* **555** (2001) L69

[8] Christensen-Dalsgaard, J. & Berthomieu, G., *in Solar interior and atmosphere* 2001 eds A. N. Cox, W.C. Livingston and M. Matthews, Space Science Series, p 401.

[9] Gabriel, A. H., Grec, G., Robillot, J.M., Roca-Cortes, T., Turck-Chièze, S. et al., *Sol. Phys.* **162** (1995) 61

[10] Scherrer, P. H., et al., *Sol. Phys.* **162** (1995) 129

[11] Jimnez-Reyes, S. J., García, R. A., Jimnez, A. & Chaplin, W. J., *Astrophys. J.* **595** (2003) 446

[12] Jimnez-Reyes, S. J., Chaplin, W. J., Elsworth, Y., & García, R., A.*Astrophys. J.* **in press** (2004)

[13] Toutain, T. et al., *Sol. Phys.* **175** (1997) 31

[14] García, R. A., et al., *Sol. Phys.* **200** (2001) 361

[15] Basu, S., Turck-Chièze, S., Berthomieu, G. et al., *Astrophys. J.* **535** (2000) 1078

[16] Bertello, L., Varadi, F., Ulrich, R. K., Henney, C. J., Kosovichev, A. G., García, R. A., & Turck-Chièze, S., *Astrophys. J.* **537** (2000) L143

[17] Couvidat, S., Turck-Chièze, S, Kosovichev, A., *Astrophys. J.* **599** (2003) 1434

[18] Turck-Chièze, S., Cahen, S., Cassé, M. & Doom, C., *Astrophys. J.* **335** (1988) 415

[19] Turck-Chièze, S. & Lopes, I., *Astrophys. J.* **408** (1993) 347

[20] Dzitko, H., Turck-Chièze, S., Delbourgo-Salvador, P., & Lagrange, G., *Astrophys. J.* **447** (1995) 428

[21] Brun, S., Turck-Chièze, S., Morel, P., *Astrophys. J.* **506** (1998) 913

[22] Ahmad, Q.R., and the SNO collaboration, *Phys. Rev. Lett.* **87** (2001) 11301

[23] Ahmad, Q. R. and the SNO collaboration, *Phys. Rev. Lett.* **89** (2002) 071301

[24] Ahmed, S. N. and the SNO collaboration, (2003) nucl-ex/0309004.

[25] Turck-Chièze, S. *in Solar composition and its evolution, from core to corona* ed. S. Steiger, *Space Science Review* (1998) 125.

[26] Holweger, H., in *Joint SOHO/ACE workshop "Solar and Galactic Composition".* edited by Robert F. Wimmer-Schweingruber. Publisher: American Institute of Physics Conference proceedings vol. 598 location: Bern, Switzerland 2001 p.23

[27] Cayrel, R., et al., *Nature* **409** 2001 691

[28] Kaplan, J., Martin de Volnay, F., Tao, C., & Turck-Chièze, S., *Astrophys. J.* **378** (1991) 315

[29] Lopes, I., Gianfranco, B.& Silk, J., *MNRAS* **337** 2002 1179

[30] Couvidat, S., García, R. A., Turck-Chize, S., Corbard, T., Henney, C. J. & Jimnez-Reyes, S., *Astrophys. J.* **597** (2003) L77

[31] Brun, A. S. & Toomre, J., *Astrophys. J.* **570** (2002) 865

[32] Appourchaux et al., *Astrophys. J.* **538** (2000) 401

[33] Gabriel, A. et al., *Astron. Astrophys.* **390** (2002) 1119

[34] Turck-Chièze, S., García, R. A., Couvidat, S. & et al., *Astrophys. J.* **,** (appear in 20th March 2004)

[35] Pulido, J., *Astropart. Phys.* **18** (2002) 173

[36] Chauhan, B. C., Pulido, J., *Phys. Rev.* **D** **68** (2003) 3015

[37] Sturrock, P. A., *Astrophys. J.* **594** (2003) 1102

[38] Gavryuseva, E. & Gavryusev, V., *Proceedings of the second solar cycle & Space weather Euroconferences* ESA SP-4772003 221

[39] Burgess, C., et al., *Astrophys. J.* **588** (2003) L65

[40] Caldwell, D.O. & Sturrock, P. A., (2003), hep-ph/0309191.

[41] Yoo, J., Superkamiokande collaboration, (2003) hep-ex 0309048.