STANDARD AND NON STANDARD SOLAR MODELS

Morel P.[1], **Provost J.**[1], **Berthomieu G.**[1], **Audard N.**[1,2]

[1] Laboratoire Cassini CNRS URA 1362 O.C.A. Nice France
[2] Institute of Astronomy, University of Vienna, Austria

ABSTRACT

Standard and Non Standard Solar Models including helium and microscopic diffusion of heavy elements and mass loss have been computed from the Pre Main Sequence Stage to the actual solar age. Their properties are compared to observational data: helioseismic constraints, lithium depletion and experimental measured neutrino capture rate.

1. PHYSICS OF MODELS

The models are computed with the CESAM code (Morel, 1996) using either the CEFF or OPAL equation of state (Rogers 1994, Rogers et al. 1996), OPAL opacities, standard mixing-length and thermonuclear reaction rates for PP and CNO cycles of Caughlan & Fowler (1988); The general nuclear network contains the following **12** species : ^{1}H, ^{2}D, ^{3}He, ^{4}He, ^{7}Li, ^{7}Be, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O. The initial abundances are the meteoritic abundances of Anders & Grevesse (1989). The models are calibrated at present solar age for mass, luminosity, radius and photospheric observed $Z/X = 0.0245$ value. Standard Solar models are labeled with "**S**", models with microscopic diffusion with "**D**". **Opacity data :** model S1: OPAL 1992 + Kurucz low temperatures (1991), linear interpolation; models S2, D1, D2, D3 & D4 : OPAL 1995 + Kurucz low temperatures, birational spline interpolation (Houdek & Rogl, 1996). The **diffusion** and nuclear equations are solved simultaneously; the mixing of chemicals in convective zones is made by a strong turbulent diffusion. The microscopic diffusion coefficients are computed according to Michaud & Proffitt (1993); ^{1}H & ^{4}He are diffused, the other species are trace elements. In model D2 a fictitious "extra mean heavy element" of atomic weight 27 and charge 13 describes, as a whole, the no CNO heavy elements. The **amount of heavy elements** Z^O employed for EOS and opacity calculations has been treated in different ways: S1, D1& D4 : $Z^O \equiv Z_{\rm i}$, the initial value, S2 : $Z^O \equiv 1 - {}^1{\rm H} - {}^4{\rm He} - {}^3{\rm He}$, D2 & D3 : Z^O includes all the heavy elements of the diffusion network (see Table 1). For a model of mass $M \sim 1.1 M_\odot$, in the early main sequence, at mass levels $M_{\rm r} \sim M_\odot$ the temperature is large enough to deplete ^{7}Li and the external convective zone does not penetrate so deep. A high rate mass loss, occurring at that time, ejects the outer parts and the ^{7}Li depleted zones lying at $M \sim 1.M_\odot$ are, afterwards, included and mixed in the present day solar convective zone; it follows an enhancement of ^{7}Li depletion at solar age. In model **D3** a e-folding mass moss mate : $\dot{M} = -2\,10^{-10} \exp(t/0.45)\ M_\odot\, yr^{-1}$, (Guzik & Cox, 1995) have been investigated (t is the age of the model, in $G\,yr$).

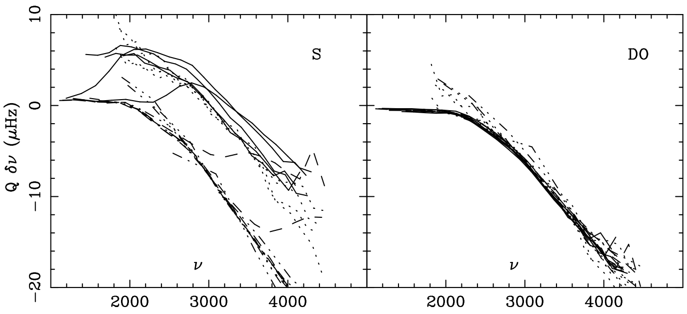

Figure 1: For models **S1** and **D4**, the normalized frequency differences between the GONG frequencies and the theoretical frequencies are given for different degrees as a function of the frequency: For each degree, the points are linked by a continuous line: $\ell = 2, 3, 4, 5, 10, 20$ (dotted line); $\ell = 30, 40, 50$ (full line) and $\ell = 70, 100, 120, 140$ (dashed line).

The models have been compared to the **seismic model** of Basu et. al. (1996) through the quantity $\delta U/U$ with $U \equiv P/\rho$. The **frequencies** of linear, adiabatic, global acoustic modes of the solar models have been computed for degrees ℓ=0 to 400 and have been compared to observations (GONG data).

2. RESULTS and DISCUSSION

The comparison with the GONG data is given in Fig. 1 for degrees ℓ=3 to 150. The distance between low degree modes and high degree modes reflects essentially the bump in the sound speed difference below the convection zone; it is still reduced when the diffusion is taken into account.

The models differ principally from the seismic model in two regions of the Sun, the core and the upper part of the internal radiative zone. Diffusion increases the agreement between the seismic model and the theoretical ones in both regions (Fig. 2). The model **D3** with mass loss is in better agreement with the seismic model below the convection zone but has a core with a discrepancy of $\delta U/U$ of order 0.3%.

Clearly diffusion, new OPAL 1995 **opacity and EOS** data, lead to better fits between the theoretical model and "observations" : GONG data Fig. 1 and the seismic model Fig. 2; based on these com-

Table 1: Global characteristics of the Sun and calibrated models.

	$\odot$	S1	S2	D1	D2	D3	D4	Units
M_i		1.0	1.0	1.0	1.0	1.095	1.0	$M_\odot$
l/H_p		1.78	1.80	2.01	1.96	2.01	1.97	
Y_i		0.269	0.271	0.276	0.277	0.272	0.273	
Z_i		0.0175	0.0174	0.0191	0.0195	0.0188	0.0191	
$(Z/X)_\mathrm{i}$		0.0245	0.0245	0.0271	0.0278	0.0266	0.0270	
$Y_\odot$	0.25	0.269	0.271	0.246	0.247	0.247	0.244	
$Z_\odot$		0.0175	0.0174	0.0179	0.0179	0.0179	0.0180	
R_ZC	0.713	0.733	0.726	0.709	0.713	0.709	0.707	$R_\odot$
T_c		1.535	1.539	1.538	1.563	1.560	1.556	10^7K
ρ_c		146.3	147.1	151.6	150.7	154.0	150.9	g cm^{-3}
Y_c		0.615	0.619	0.637	0.639	0.644	0.635	
Li_ZAMS		3.18	3.15	3.02	3.01	3.13	2.88	Dex
$Li_\odot$	1.12	3.18	3.14	2.92	2.93	1.84	2.81	Dex
Φ_Ga	79	120	121	128	130	140	127	SNU
Φ_Cl	2.55	6.11	6.30	7.75	8.16	8.60	7.59	SNU
Φ_Ka	0.28	0.47	0.49	0.62	0.65	0.68	0.61	ev/day
$\delta\nu_{02}$	9.30	9.40	9.36	9.05	9.10	8.92	9.14	μHz
$\delta\nu_{13}$	16.50	16.72	16.69	16.25	16.31	16.05	15.99	μHz

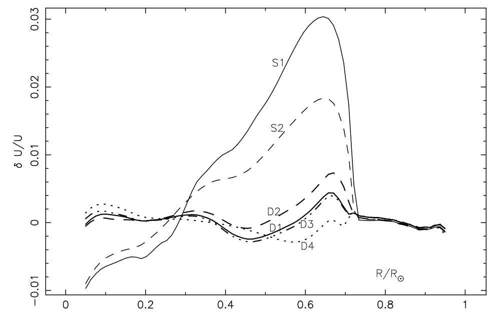

Figure 2: Relative differences $\delta U/U$ between models and the seismic model as a function of the radius.

parisons **D4** is our "best model". However, the **expected ^{7}Li depletion** for the model D3 is closest to the observations with almost no depletion occurring during the PMS as suggested by the observations of Pleiades (Soderblom et. al. 1991). Due the paucity of opacity data it was not possible to make discrimination, between models computed with a *fixed* value for Z^O, and model computed with a value of Z^O taking into account the changes in chemicals due to thermonuclear reactions and diffusion. All non standard models have larger expected **neutrino capture rate** than standard models.

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