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Research Note

Local mixing near the solar core, neutrino fluxes and helioseismology

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Abstract. We have computed solar models similar to those published in Richard, Vauclair, Charbonnel, Dziembowski (1996), in which we have added local mixing near the solar core in order to decrease the neutrino production. The results show that the neutrino fluxes are reduced as expected (although not enough to account for the observed values), but the obtained models are incompatible with the inversion of the helioseismic modes. We have specially tested the parametrized mixing proposed by Morel and Schatzman (1996). The resulting solar models are far from the seismic model and thus unrealistic.

Key words: diffusion – Sun: abundances; interior; rotation; oscillations

We have computed new solar models using the same stellar evolution code as described in Charbonnel, Vauclair and Zahn (1992). This code, originating from Geneva, now includes the computation of element segregation for helium and 12 heavier isotopes. It may also include any type of mixing of the stellar gas, provided this mixing may be parametrised with an effective diffusion coefficient as a function of radius.

In the present computations, we have introduced in the solar model 4 of Richard et al (1996) (hereafter model T1) a parametrized mixing region located at the edge of the nuclear burning core. Such a mixing, which could be induced by Stochastic Internal Waves (Morel and Schatzman 1996), remains as an a priori possibility to decrease the solar neutrino flux. The basic reason is that it brings ^{3}He down towards the solar center (Fig. 1) and increases the rate of the ^{3}He (^{3}He, 2p) ^{4}He nuclear reaction yield, while the ^{3}He (^{4}He, α) ^{7}Be reaction is reduced.

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Table 1. Main physical parameters of the three models, at the base of the convective zone and at the center.

model	$r_{cz}/R_\odot$	T_{cz} (10^6K)	ρ_{cz} (g.cm^{-3})	Y_c	X_c	T_c (10^6K)	ρ_c (g.cm^{-3})
T1	0.717	2.162	0.185	0.6431	0.3368	15.63	154.17
T2	0.724	2.060	0.156	0.5687	0.4113	14.96	127.05
T3	0.717	2.151	0.181	0.6337	0.3462	15.45	148.93

Table 2. Gaussian parameters and neutrino fluxes for the three models.

model	$r_c/R_\odot$	$\Delta/R_\odot$	D_0 (cm^{2}s^{-1})	$\phi(^8$B) (10^6 cm^2 s^{-1})	$(\phi\sigma)$Cl (SNU$_S$)	$(\phi\sigma)$Ga (SNU$_S$)
T1	-	-	-	6.06	8.14	130.84
T2	.20	.040	1000	2.60	3.90	108.75
T3	.15	.025	100	3.85	5.45	115.80

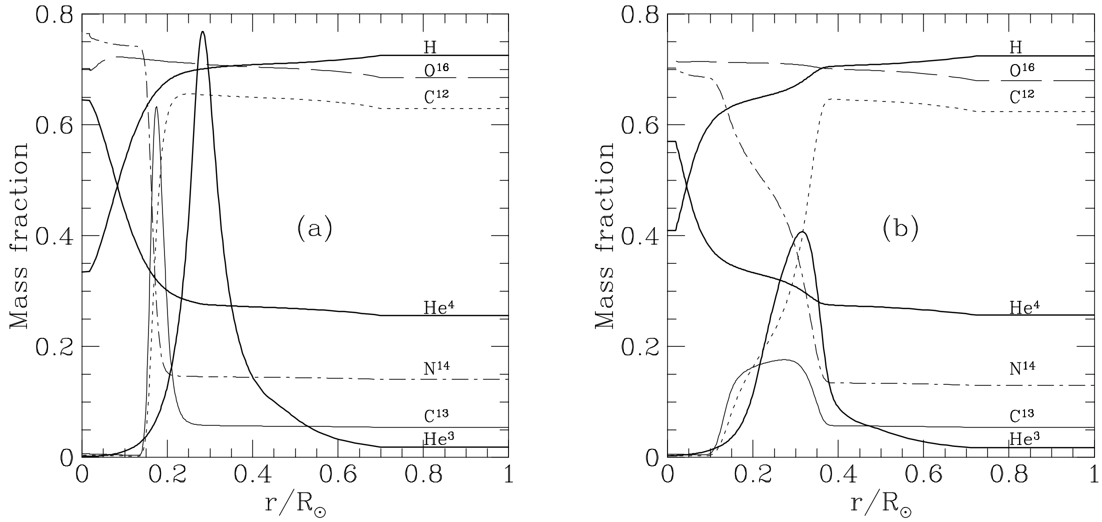
Table 3. Detected values of the solar neutrino fluxes (from Stolarczyk 1997).

	$\phi(^8\mathrm{B})$	=	$2.80 \pm 0.19 \pm 0.33 \times 10^6$ cm^2 s^{-1}
	$(\phi\sigma)_{\mathrm{Cl}}$	=	$2.54 \pm 0.14 \pm 0.14$ SNU$_S$
Sage:	$(\phi\sigma)_{\mathrm{Ga}}$	=	72^{+12+5}_{-10-7} SNU$_S$
Gallex:	$(\phi\sigma)_{\mathrm{Ga}}$	=	$69.7 \pm 6.7^{+3.9}_{-4.5}$ SNU$_S$

We have introduced this extra-mixing in the form of a gaussian, of the type:

$$D = D_0 \exp\left[-\left(\frac{r - r_c}{2\Delta}\right)^2\right]$$

The comparisons of the $u = P/\rho$ function in these models and in the seismic Sun as a function of radius are unsatisfactory. The very good agreement obtained by Richard et al (1996) for the models including microscopic diffusion and a mild mixing below the convection zone is destroyed in most models which include the core mixing. It is possible to keep the good agree-



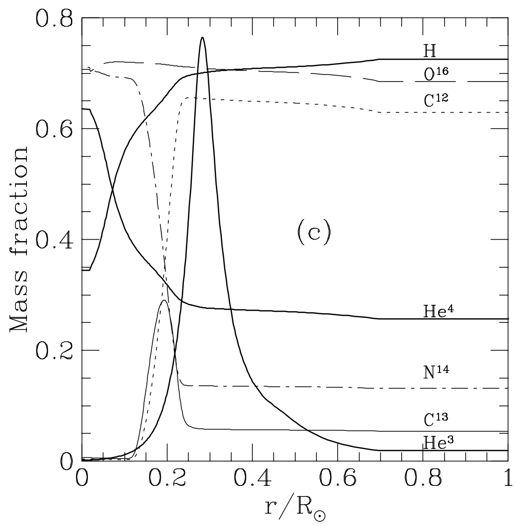


Fig. 1a–c. Abundance profiles for some elements in the three models (The mass fractions are multiplied by 250 for ^{3}He, by 200 for ^{12}C, by 100 for ^{13}C, by 140 for ^{14}N and by 75 for ^{16}O): graph **a** for model T1; graph **b** for model T2; graph **c** for model T3.

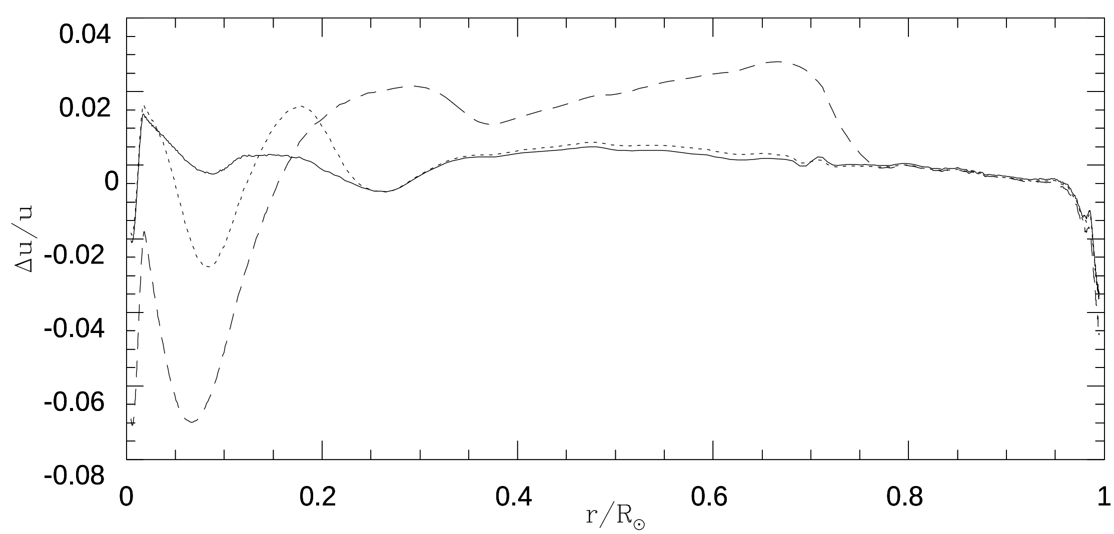


Fig. 2. Difference between the $\left(u = \frac{P}{\rho}\right)$ deduced from helioseismology and the computed one. The ordinates represents: $\frac{\Delta u}{u} = \frac{u\,(\text{seismic}) - u\,(\text{model})}{u\,(\text{seismic})}$. Solid line: model T1; dashed line: model T2; dotted line: model T3. These two last models, which include local mixing near the solar core, are not compatible with the helioseismic results.

ment in the outer parts of the Sun while perturbating only the central regions: for this a "cut-off" of the mixing effect must be introduced at a fractional radius of $r/R_\odot$ = .4. However, even in this case, the u values in the core are incompatible with the seismic Sun (Fig. 2).

Here we show the results obtained for two different models, model T2 (similar to model 20431 in Morel and Schatzman 1996) with the following values for the gaussian parameters:

$r_c/R_\odot = .2 \qquad D_0 = 1000\ \mathrm{cm^2 s^{-1}} \qquad \Delta/R_\odot = .04$

and model T3 with the following values for the gaussian parameters:

$r_c/R_\odot = .15 \qquad D_0 = 100\ \mathrm{cm^2 s^{-1}} \qquad \Delta/R_\odot = .025$

with a cut-off of the gaussian function at $r/R_\odot$ = .4 The main physical parameters of these models are given in Table 1.

In all cases we obtain a decrease of the neutrino fluxes, although they remain too large to be compatible with the detected values (Tables 2 and 3). The comparison with the helioseismological results (Richard et al.1996) show however that these models are not realistic (Fig. 2).

In conclusion, although some local mixing inside the Sun may help reducing the neutrino fluxes, it cannot be reconciled with helioseismology. The helioseismic data prove to be a very powerful tool in constraining the remaining parameters of the solar structure. It will improve even more in the central parts when observations of gravity waves will be possible.

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