SEISMIC CONSTRAINTS ON NEUTRINO OSCILLATION PARAMETERS

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ABSTRACT

The neutrino fluxes calculated using a seismically inferred solar model are compared with measured fluxes from the three solar neutrino experiments. Treating the neutrino fluxes from seismic model as theoretical predictions, the latest solar neutrino data is analyzed assuming vacuum oscillation of neutrinos. The best-fit values of the neutrino mixing angle and mass squared difference are found and the allowed regions are determined.

Key words: Sun: oscillations; solar neutrinos; Sun: interior.

1. INTRODUCTION

It is well known that the measured fluxes of solar neutrinos in all experiments to date are significantly lower than the expected theoretical predictions. Furthermore, it is unlikely that this discrepancy can be removed by modifying the solar models (Heeger & Robertson 1996; Roxburgh 1996; Antia & Chitre 1997). With the accurate helioseismic data it is possible to calculate the sound speed and density profiles inside the Sun using inversion techniques (Gough et al. 1996). From the knowledge of sound speed and density, the temperature and hydrogen abundance profiles inside the Sun may be inferred, provided the Sun is assumed to be in thermal equilibrium and the heavy element abundance profile as well as the input physics like opacity, equation of state and nuclear reaction rates are prescribed (Shibahashi & Takata 1996; Antia & Chitre 1998). Such seismic models serve as the framework for calculating the neutrino fluxes.

Oscillations between neutrinos of different flavors are generally thought to be responsible for the low observed fluxes. Most of the studies so far have used the neutrino fluxes from a standard solar model (SSM) to investigate the solutions based on neutrino oscillations (e.g., Fogli & Lisi 1995; Bahcall et al. 1998; Gonzales-Garcia & Pena-Garay 2000). However, the neutrino fluxes calculated with the seismic model turn out to be somewhat different from those in the standard solar model and its effect on neutrino oscillation solution needs to be further investigated.

In this work we examine the role of vacuum oscillations of neutrinos in explaining the observed deficit of neutrino fluxes. For this purpose, we use the neutrino fluxes computed with a seismic model as theoretical predictions of electron neutrino fluxes coming out from the Sun.

2. THE SEISMIC MODEL

We use the mean frequencies from Global Oscillations Network Group (GONG) data for months 4–14 (23 August 1995 to 21 September 1996) to calculate the sound speed and density profiles inside the Sun using a regularized least squares inversion technique (Antia 1996). We adopt the inverted sound speed and density profiles, along with the heavy element abundance (Z) profile from the model of Richard et al. (1996) to calculate the seismic model using equations of thermal equilibrium (Antia & Chitre 1998). We use the OPAL opacities (Iglesias & Rogers 1996) and equation of state (Rogers et al. 1996), and nuclear reaction rates from Adelberger et al. (1998), except for the proton-proton reaction rate, which is slightly adjusted to yield the correct solar luminosity (Antia & Chitre 1999).

With the temperature, density and composition profiles from the seismic model, neutrino fluxes are calculated and the results are shown in Table 1. Apart from inversion errors, other main sources of uncertainties in these calculated fluxes are the nuclear reaction cross-sections for the ^{3}He-^{3}He ($S_{3,3}$), ^{3}He-^{4}He ($S_{3,4}$), p-^{14}N ($S_{1,14}$), p-^{7}Be ($S_{1,7}$) reactions, as well as the solar luminosity, the heavy element abundance, Z and opacities, κ. To estimate the effect of these quantities on neutrino fluxes in the seismic model we calculate the logarithmic derivatives of neutrino fluxes with respect to each of these quantities (X_i) and these are also listed in Table 1. The last row in Table 1 lists the estimated relative errors in these quantities. The expected neutrino fluxes in various solar neutrino experiments can be calculated from Table 1 and these values are given in Table 2, for comparison with observed fluxes (Suzuki 2000) and those in standard solar models (Bahcall et al. 1998; Brun et al. 1998, 1999).

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Table 1. Neutrino fluxes in seismic model

Neutrino	Flux, F_ν ($cm^{-2}\,s^{-1}$)	Logarithmic derivatives $\frac{\partial \ln F_\nu}{\partial \ln X}$ $S_{3,3}$	$S_{3,4}$	$S_{1,14}$	$S_{1,7}$	$L_\odot$	Z	κ
pp	$(6.13 \pm 0.01) \times 10^{10}$	0.03	−0.07	−0.02	0.00	0.96	−0.06	−0.13
pep	$(1.44 \pm 0.01) \times 10^{8}$	0.03	−0.07	−0.02	0.00	0.76	−0.17	−0.31
hep	$(2.12 \pm 0.01) \times 10^{3}$	−0.41	−0.07	−0.01	0.00	0.09	−0.21	−0.41
^{7}Be	$(4.48 \pm 0.12) \times 10^{9}$	−0.44	0.95	0.00	0.00	2.06	0.68	1.45
^{8}B	$(3.97 \pm 0.26) \times 10^{6}$	−0.49	1.04	0.01	1.00	3.85	1.65	3.40
^{13}N	$(4.33 \pm 0.25) \times 10^{8}$	−0.08	0.14	0.85	0.00	2.39	1.24	2.52
^{15}O	$(3.87 \pm 0.26) \times 10^{8}$	−0.09	0.17	1.00	0.00	2.93	1.52	3.07
^{17}F	$(4.60 \pm 0.32) \times 10^{6}$	−0.10	0.18	0.01	0.00	3.07	1.59	3.21
Rel. error		0.060	0.094	0.143	0.11	.004	0.033	0.02

Table 2. Predicted neutrino fluxes in various solar neutrino experiments

Experiment	Homestake (^{37}Cl) (SNU)	SK (H_2O) ($10^6 cm^{-2}s^{-1}$)	Gallex, SAGE (^{71}Ga) (SNU)
Measured Flux	2.56 ± 0.22	2.40 ± 0.09	72.5 ± 5.6
SSM (BP95)	9.3 ± 1.3	6.6 ± 1.0	137 ± 8
SSM (BP98)	7.7 ± 1.2	5.2 ± 1.0	129 ± 8
SSM (TC98)	7.2	4.8	127
SSM (TC99)	6.7	4.7	125
Seismic model	6.2 ± 0.9	4.0 ± 0.7	123 ± 6

3. VACUUM OSCILLATIONS OF NEUTRINOS

For two ν flavors, the ν_e survival probability after traversing a distance L is

$$P_{\nu_e|\nu_e} = 1 - \sin^2 2\theta \sin^2 \pi L/\lambda,$$

where

$$\lambda = 2.5m \frac{E_\nu}{\text{MeV}} \frac{eV^2}{\Delta m^2}$$

is the vacuum oscillation wavelength for neutrinos of energy E_ν and Δm^2 is the neutrino mass squared difference and θ denotes the mixing angle in vacuum.

To find the preferred values of θ and Δm^2, we minimize the χ^2 defined by

$$\chi^2 = \sum_{i,j} \left(R_i^{\rm th} - R_i^{\rm exp}\right)\left(\sigma_{ij}^{-2}\right)\left(R_j^{\rm th} - R_j^{\rm exp}\right)$$

where $R_i^{\rm exp}$ is the total measured rate in the i-th experiment, while $R_i^{\rm th}$ is the rate computed theoretically after incorporating vacuum oscillations of neutrinos. The summation is taken over the three experiments for fitting only total rates observed in all experiments. For combined fits to rates as well as spectral information from Super-Kamiokande the summation includes the 18 bins in neutrino energy for which spectral data is available and the total rates in Cl and Ga experiments. The total rate from Super-Kamiokande is not included as it is not independent of the spectral information. The error matrix, σ_{ij} contains the experimental errors, the theoretical error and their correlations. We follow the procedure of Goswami et al. (1999,2000) for calculating the error matrix.

The theoretical predictions and the errors are different in the seismic model and SSM. Hence we perform the analysis separately for both the models. First we perform the analysis using only the observed rates in the three experiments. The minimum χ^2 is found to be 0.62 for SSM and 1.26 for the seismic model. The allowed regions in $(\sin^2 2\theta - \Delta m^2)$ plane for 95% confidence level are shown in Fig. 1. We also perform the analysis using both the rates and the spectral information, which involves fitting 20 observed quantities with 2 free parameters. The results are shown in Fig. 1. In this case the minimum χ^2 is 20.14 for SSM and 13.79 for seismic model. Clearly, the seismic model gives a distinctly better fit as compared to SSM.

Table 3 summarizes the results for total rates obtained from best fit parameters in all four cases. This table also gives the goodness of fit (gof) estimated from the minimum χ^2. The best fit spectra obtained using SSM and seismic models are shown in Fig. 2. It is clear from the fits and the χ^2 values that the seismic model gives a better fit to observed data as compared to SSM.

All the foregoing results have been obtained for vacuum oscillations to active neutrinos. If we assume that neutrino oscillate to sterile neutrinos, then results will be slightly different. We have repeated the calculations for this case also. Table 3 summarizes the results for vacuum oscillations to sterile neutrinos. In general, the fits for sterile neutrinos are not as good as those for active neutrinos. The fit to spectrum is shown in Fig. 2. For oscillations to sterile neutrinos also the fit is better for seismic model as compared to that for SSM.

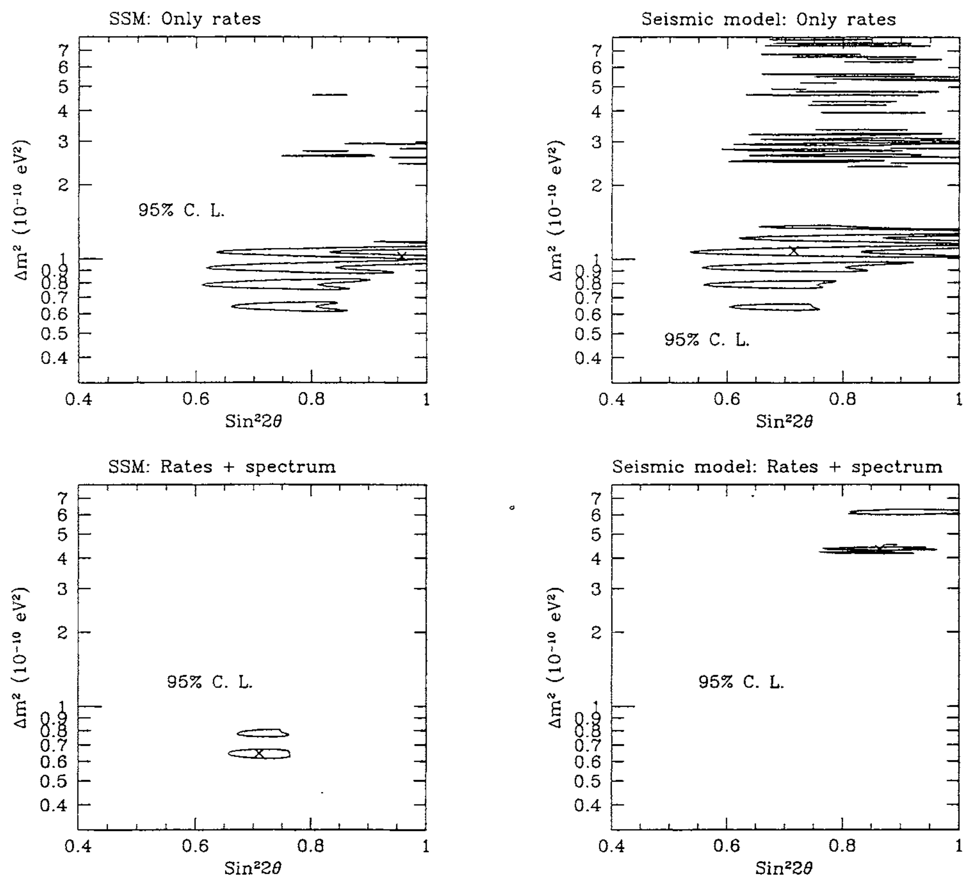

Figure 1. Analysis of rates only and rates plus spectrum using the SSM and the seismic model. The contours show the allowed region with 95% confidence level. The cross marks the best fit values corresponding to minimum χ^2.

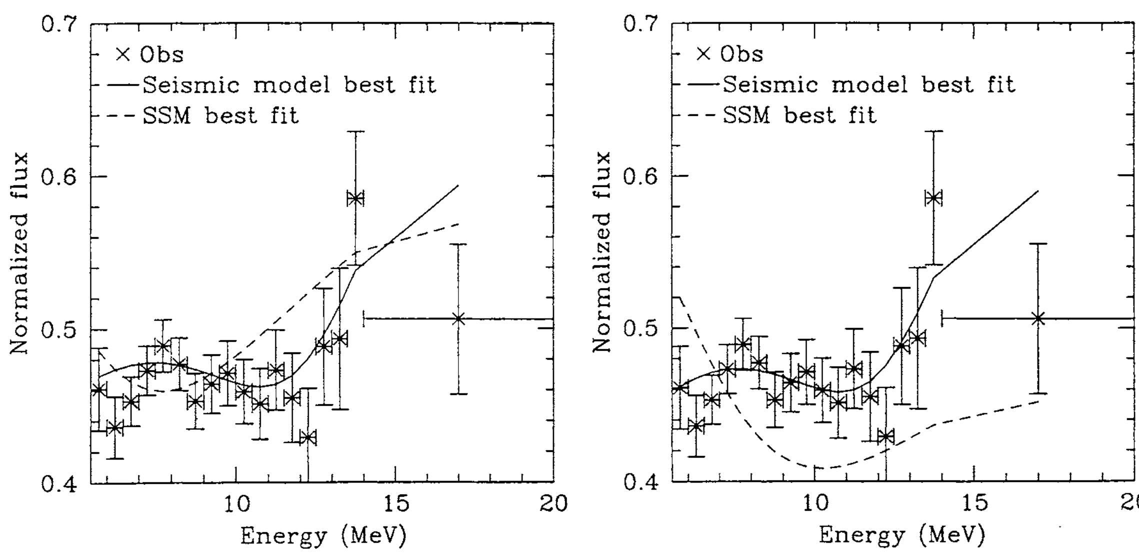

Figure 2. ^{8}B neutrino spectrum obtained from best fit model is compared with Super-Kamiokande observations. Left panel show the results for oscillations to active neutrinos while right panel is for oscillations to sterile neutrinos. All numbers are normalized with respect to SSM.

Table 3. Best fit neutrino fluxes in various solar neutrino experiments

Fit	χ^2	gof	$\sin^2 2\theta$	Δm^2 (10^{-10} eV^2)	Neutrino fluxes ^{37}Cl (SNU)	^{71}Ga (SNU)	^{8}B (10^6 cm^{-2} s^{-1})
Measured Flux					2.56 ± 0.22	72.5 ± 5.6	2.40 ± 0.09
Active neutrinos: Fit to rates only							
SSM	0.62	43.1%	0.957	1.03	2.57	69.1	2.42
Seismic model	1.26	26.2%	0.715	1.08	2.84	68.0	2.48
Active neutrinos: Fit to rates and spectrum							
SSM	20.14	32.5%	0.710	0.64	3.11	67.5	2.43
Seismic model	13.79	74.3%	0.864	4.32	2.68	69.4	2.45
Sterile neutrinos: Fit to rates only							
SSM	4.71	3.0%	0.798	1.08	3.14	64.3	2.59
Seismic model	3.87	4.9%	0.721	1.08	2.75	66.4	2.17
Sterile neutrinos: Fit to rates and spectrum							
SSM	33.70	1.4%	0.627	0.78	3.42	74.4	2.27
Seismic model	14.90	66.9%	0.747	4.33	2.89	70.3	2.42

4. CONCLUSIONS

The seismically inferred neutrino fluxes are somewhat different from those in the standard solar model and hence these should be used to investigate possible solutions of the solar neutrino problem. The global fit improves slightly with the seismic model as it predicts a lower ^{8}B flux than SSM. For higher Δm^2 values (5×10^{-10} eV^2) matter effects become important even for just-so oscillation. The effect of solar matter in this range as well as in the usual MSW regime will be studied in a future work.

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