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SOLAR NEUTRINO EMISSION DEDUCED FROM A SEISMIC MODEL

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ABSTRACT

Three helioseismic instruments on the *Solar and Heliospheric Observatory* have observed the Sun almost continuously since early 1996. This has led to detailed study of the biases induced by the instruments that measure intensity or Doppler velocity variation. Photospheric turbulence hardly influences the tiny signature of conditions in the energy-generating core in the low-order modes, which are therefore very informative. We use sound-speed and density profiles inferred from GOLF and MDI data including these modes, together with recent improvements to stellar model computations, to build a spherically symmetric seismically adjusted model in agreement with the observations. The model is in hydrostatic and thermal balance and produces the present observed luminosity. In constructing the model, we adopt the best physics available, although we adjust some fundamental ingredients, well within the commonly estimated errors, such as the *p-p* reaction rate (+1%) and the heavy-element abundance (+3.5%); we also examine the sensitivity of the density profile to the nuclear reaction rates. Then, we deduce the corresponding emitted neutrino fluxes and consequently demonstrate that it is unlikely that the deficit of the neutrino fluxes measured on Earth can be explained by a spherically symmetric classical model without neutrino flavor transitions. Finally, we discuss the limitations of our results and future developments.

Subject headings: neutrinos — Sun: interior — Sun: oscillations

1. INTRODUCTION

The neutrino puzzle has been one of the more exciting unsolved problems in astrophysics for several decades (Bahcall & Ostriker 1997). It has stimulated much activity in both theoretical and experimental areas, with very effective progress in both. The objectives of the research have evolved, from the beginning when neutrinos were considered to provide information about central conditions in the Sun to the present time, where our hope is to ascertain, from independent knowledge of those conditions, properties of electron neutrinos that are unobtainable otherwise. We can be optimistic in this hope, partly because of the increased number of excellent solar neutrino detectors and partly because of the rise of helioseismology as a discipline that is a unique probe for studying the solar interior.

Much of the interest in the helioseismic constraints on solar structure derives from the possibility of constraining the flux of neutrinos emitted by nuclear reactions in the core. Seismic analysis has been able to eliminate some proposals for the solution to the neutrino problem, such as central mixing or weakly interactive massive particles (e.g., Elsworth et al. 1990; Christensen-Dalsgaard 1992; Turck-Chièze et al. 1993, 2001a), although there remain others, such as asymmetric macroscopic motion in the core (Gough 1999), which may alter the predictions of the neutrino fluxes. In addition, through helioseismic inversion it is possible to construct seismic models consistent with the oscillation data and hence to predict the neutrino flux (e.g., Gough & Kosovichev 1990; Roxburgh 1996; Antia & Chitre 1997; Takata & Shibahashi 1998). The present Letter applies this procedure with improved observations and stronger constraints. In fact, the nuclear-reacting core is the region of the Sun most difficult to probe with acoustic modes, because it has the least influence on the oscillation frequencies (Gough & Thompson 1991; Turck-Chièze 2000); it is here that the sound speed is greatest, the acoustic wavelength the longest, and therefore the spatial resolution the poorest. We have access to about 120 modes to explore the nuclear region, but most of them are seriously influenced by turbulence and surface magnetic perturbations. For the first time, with three different instruments on the *Solar and Heliospheric Observatory* (*SOHO*) dedicated to seismic observations, we become more confident in the way we extract the information (Toutain et al. 1997; Nigam & Kosovichev 1999; Thiery et al. 2000, 2001; Basu et al. 2000). Thanks to the long duration of continuous measurements and the stability of the spacecraft, we have succeeded in measuring some of the low-order modes ($n < 9$) of lowest degree ($l = 0, 1, 2$), which are relatively insensitive to the uncertain structure and dynamics of the turbulent surface layers of the Sun.

2. THE SOUND-SPEED PROFILE

We use the frequencies of modes with $l = 0, 1, 2$ and $n \leq 9$ proposed recently by García et al. (2001) from an analysis of Global Oscillations at Low Frequencies (GOLF) data and frequencies of modes with $l = 0, 1, 2$ and $n > 9$ obtained by Bertello et al. (2000b) from GOLF and Michelson Doppler Imager (MDI) data coupled with the frequencies of modes with $l = 3$–300 obtained by Rhodes et al. (1997) from MDI data.

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An optimally localized averaging inversion method developed by Kosovichev (1999) is used to determine the hydrostatic structure of the Sun. Figure 1*a* illustrates the differences between the square of the sound speed (c^2) inferred from the Sun using these data and corresponding values of c^2 in two reference solar models (model S of Christensen-Dalsgaard et al. 1996 and Saclay reference model of Brun, Turck-Chièze, & Zahn 1999, hereafter BTCZ99). The differences between the two models are due to the different adopted ages and to recent advances in solar interior physics included in the second model:

1. Improved study of specific cross sections such as (^{3}He, ^{3}He), (^{7}Li, *p*), (^{7}Be, *p*) in the laboratory and of the theoretical screening in stellar plasmas, which must be incorporated into the calculation of nuclear reaction rates. These are summarized by Adelberger et al. (1998 and references therein; see also Morel et al. 1999). The improvements have modified slightly the central sound-speed profile in the models (Fig. 1) and reduced the associated ^{8}B neutrino flux by 20% and its uncertainty (Hammache et al. 1998).
2. The updated equation of state and opacity calculations by Iglesias & Rogers (1996) introduce 21 elements in order to take account of significant contributions (from P, Cl, K, Ti, Cr, Mn) at the level of accuracy demanded by the seismic analysis. This improvement has had two repercussions: (*a*) a reduction of the sound speed in the theoretical model in the vicinity of $r = 0.6\ R_\odot$ (Fig. 1) and (*b*) a slight overall increase in the discrepancy between the Sun and the model. Frequencies of the low-degree low-order *p*-modes have a substantial impact on the inversion for the whole radiative zone as the errors are smaller. The bumps in the inferred c^2 profile might be real or not (because of residual uncertainty on this range of frequency). Some of them may be attributable to processes related directly to certain chemical elements (Turck-Chièze 1998). We have indicated by arrows the locations where selected elements influence significantly the opacity coefficients and, consequently, the sound speed. The amplitudes of the present bumps (0.1% or 0.2%) correspond to a variation of 1% or 2% of the total opacity coefficients and put interesting limits on the uncertainty of abundances of minor species.

The particular importance of the acoustic modes of low order is that their outer turning points lie deeper in the convection zone, and consequently they are less sensitive to the outer turbulent layers: their frequencies are less susceptible to any bias induced by random surface processes or time variations of the outer layers associated with the solar cycle. This reduces the difficulties of coupling modes of low and high degree obtained from different instruments in different epochs. The influence of such coupling errors can be judged by comparing the upper and lower panels of Figure 1, which depict inversions carried out with and without modes of orders $n \geq 16$, with $l = 0$, 1, and 2. We have found that the scatter among such inversions is smaller when the higher order modes are absent (Turck-Chièze et al. 2001b). The sound-speed profile below $0.1\ R_\odot$ is slightly different, as expected, but we note that the difference is no more than 0.1%, establishing some measure of confidence in the global procedure and the general coherence of the analysis.

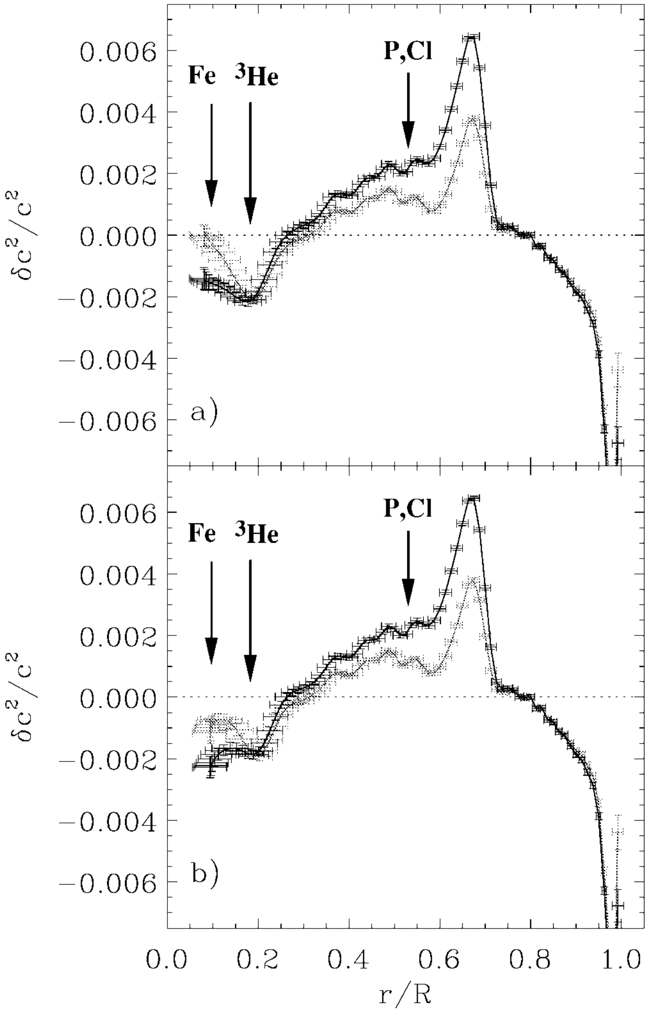

FIG. 1.—Relative difference between the square of the sound speed in the Sun and that of two different solar models: model S of Christensen-Dalsgaard et al. (1996; *gray line*) and Saclay reference model of Brun et al. (1999; *black line*). (*a*) Inversions of the frequencies of modes with $l = 0$–2 ($\nu < 1.5$ mHz) of García et al. (2001), of modes with $l = 0$–2 ($\nu > 1.5$ mHz) of Bertello et al. (2000b), and of modes with $l = 3$–300 from Rhodes et al. (1997). (*b*) Similar inversions after removal of modes with $l = 0$–2 and $n \geq 16$. The arrows indicate the regions where specified species (Fe, ^{3}He, P, Cl) contribute significantly to the opacity.

3. THE SEISMIC MODEL

In this section, we compare Saclay solar models to helioseismic inferences based on a joint study of GOLF and MDI for $l = 0$, 1, 2 and orders $n \leq 9$ (Bertello et al. 2000a). For higher orders or degrees, we use the same observations as previously. The results are shown in Figure 2. The consistency between pure GOLF data and those from GOLF/MDI can be judged by comparing the black line in Figure 1*b* and the solid line in Figure 2*a*. Comparison with Figure 6 of Turck-Chièze et al. (1997) shows the progress made from ground networks to space results. We list in Table 1 some values of the sound speed *c* obtained from this work, together with estimates of the uncertainties. These values are actually averages over regions with characteristic half-width Δr. It is presumed that *c* is sufficiently smooth that it takes the value of that average within $\pm\Delta r$ of the radius *r*. The quoted uncertainties $\Delta c/c$ include only the contribution arising from the frequency observations.

Figure 2 illustrates the progress that may be achieved by improving the model. The first model (*solid line*) is the Saclay reference model previously described. The second model (*dashed line*) is the model with the diffusive treatment of the tachocline B_{tz} (cf. BTCZ99) where we have taken account of material redistribution by macroscopic motion in the tachocline

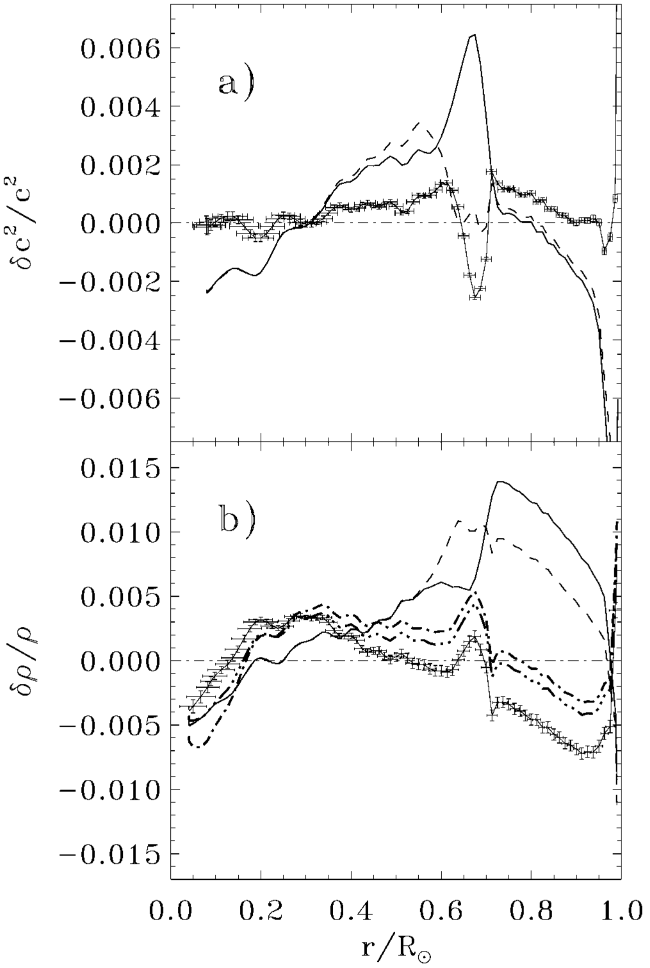

FIG. 2.—Relative differences between (*a*) the square of the sound speed and (*b*) the density deduced for the Sun using the GOLF/MDI frequencies described in § 3 and those of different Saclay solar models. The models are reference model (*continuous curve*), model B_{tz} of BTCZ99 (*dashed curve*), and the seismic model (points with error bars joined by straight lines). Superposed on the density profile are two other models: model with reaction rate of (^{3}He, ^{4}He) reduced by 10% (*dot-dot-dashed curve*) and model with the reaction rates of the CNO cycle reduced by 70% (*dot-dashed curve*) relative to the seismic model.

immediately beneath the convection zone (see also Guzik & Cox 1993; Elliott, Gough, & Sekii 1998). It leads to an inhibition of the gravitational settling of elements (by ~20%)—a process that was originally introduced before the launch of *SOHO* (Christensen-Dalsgaard, Proffitt, & Thompson 1993), encouraged largely by the first results of the ground-based seismic observations. This model achieves almost complete agreement with observed photospheric abundances, including that of lithium.

The third model, with observational uncertainties, is the seismic model. It includes possible modifications to the model aimed at reducing the residual differences between the sound speed in the Sun and in the solar models. The interest is twofold: first, to see whether there are significant deviations that can modify the seismic properties of the model; second, to deduce neutrino fluxes compatible with the seismic observations. The model is spherically symmetrical and in hydrostatic and thermal balance. In contrast to seismic models such as those of Gough (1990) and Takata & Shibahashi (1998), which are derived directly from seismic data, it is obtained from the classical hypotheses of stellar evolution theory in such a manner as to reduce the differences between the Sun and models (further details given by S. Couvidat, S. Turck-Chièze, & A. G. Kosovichev 2001, in preparation). Specifically, the (p, p) reaction rate was changed by $+1\%$ and the total heavy-element abundance by $+3.5\%$. Also, the solar radius R was taken to be 695.865 Mm, intermediate between the usual value (695.99 Mm) and the seismic values deduced from *f*-modes (Schou et al. 1997; Antia 1998), in order to improve the agreement in the convection zone. For the treatment of the tachocline, we invoke the diffusive process of BTCZ99, with a time-dependent diffusion coefficient producing a characteristic present width of 0.025 $R_\odot$, in agreement with seismic results and an improved treatment of the pre–main sequence, including a separation between star and disk at 10 Myr, supposing the Sun to have been a slow rotator (Piau & Turck-Chièze 2001). The sound speed of the resulting model is in fair agreement with the solar sound speed, except in regions where dynamical processes are evidently present, namely, in the tachocline at the base of the convection zone and in the very outer layers. In these regions the physics of our one-dimensional model is certainly not adequate to describe the Sun at the desired level of accuracy.

The density varies by several decades from the center to the surface and is quite sensitive to the physics of the interior, particularly in the convection zone. This sensitivity is illustrated in Figure 2*b*, which shows the density difference $\delta\rho/\rho$ relative to the previous models, inferred through inversion of the modes set using the Bertello et al. (2000a, 2000b) analysis. We have found a considerable improvement from the inclusion of the radial mode of orders $n = 3, 5, 6$, largely as a result of the very small errors quoted for these frequencies: the radial resolution in the inner regions has been improved by a factor of 3 relative to earlier results. However, this sensitivity also makes density inversion more susceptible to systematic errors in the data. For this reason, we have not fixed our seismic model based on the density results, which need to be improved with further data at low frequencies, including, if possible, gravity modes.

4. EMITTED NEUTRINO FLUXES AND DISCUSSION

From the seismic model, we can deduce the electron density profile, the neutrino emissions, and their uncertainties, compatible with the seismic data (Table 2). We notice that the neutrino flux predictions are very close to those of Bahcall,

TABLE 1

SOUND SPEED c AS A FUNCTION OF RADIUS r, EXTRACTED FROM 4 yr OF DATA FROM GOLF AND MDI, TOGETHER WITH THE RELATIVE STANDARD ERROR $\Delta c/c$ AND THE SPATIAL UNCERTAINTY Δr

r ($R_\odot$)	c (Mm s^{-1})	$\Delta c/c$ ($\times 10^{-4}$)	$\pm\Delta r$ (%)	r ($R_\odot$)	c (Mm s^{-1})	$\Delta c/c$ ($\times 10^{-4}$)	$\pm\Delta r$ (%)	r ($R_\odot$)	c (Mm s^{-1})	$\Delta c/c$ ($\times 10^{-4}$)	$\pm\Delta r$ (%)
0.07 ……	0.5105	3.02	3.6	0.30 ……	0.3899	0.89	2.1	0.65 ……	0.2489	2.15	1.3
0.10 ……	0.5078	1.39	3.1	0.40 ……	0.3391	1.10	1.8	0.70 ……	0.2299	2.16	1.2
0.15 ……	0.5056	1.32	2.9	0.50 ……	0.2992	1.75	1.6	0.80 ……	0.1762	2.17	0.9
0.20 ……	0.4547	1.03	2.6	0.55 ……	0.2819	2.00	1.5	0.90 ……	0.1161	2.22	0.8
0.25 ……	0.4210	0.92	2.3	0.60 ……	0.2654	2.13	1.4	0.99 ……	0.0284	4.96	6.

TABLE 2

Uncertainties and Neutrino Flux Predictions of the Seismic Model Compared with the Observations

Sources S	$\delta S/S$ (%)	^{71}Ga (%)	^{37}Cl (%)	Water (%)
(p, p)	1	0.9	−1.9	−2.4
(^{3}He, ^{3}He)	10	Negligible	3	4
(^{3}He, ^{4}He)	10	2.5	7.5	8.2
(^{7}Be, p)	7	<1	5.5	7
(CNO, p)	25	1.1	1.6	2.9
$L_\odot$	0.05	0.3	1.6	2
Z/X	5	0.9	4.5	4.9
Age	2	<1	2	2.5
Central κ	2	<1	5	6
Absorption cross section		6	4	…
Predicted Earth detection		127.8 ± 8.6	7.44 ± 0.96	4.95 ± 0.72
Detections		74.7 ± 5	2.56 ± 0.23	2.4 ± 0.08

Note.—The Superkamiokande neutrino flux (water) is given in 10^6 cm^{-2} s^{-1}. Gallium and chlorine detections are in SNU; 1 SNU $= 10^{-36}$ captures atom^{-1} s^{-1}. Central κ is central opacity; predicted Earth detection is for fluxes emitted by the seismic model.

Pinsonneault, & Basu (2001); this indicates a convergence in our ability to model the Sun. However, the present results are richer, although they will be revisited with future improvement in the seismic data.

Our results confirm the great sensitivity to the (p, p) reaction rate (Antia & Chitre 1999) and to the metallicity. It is the first time that we have been able to use an astrophysical object as a laboratory to determine a measure of an inaccessible yet fundamental nuclear reaction rate to an accuracy superior to that inferred from terrestrial experiment. Turck-Chièze et al. (2001a) have shown the low sensitivity of the sound speed to CNO reaction rates, but Figure 2*b* shows that a more reliable seismic inference of the density may place significant constraints on screening or any dynamical effects of these reaction rates.

The seismic analysis has substantial impact on the uncertainties attributed to the predictions of neutrino production (see for comparison Turck-Chièze et al. 1988), and in addition it excludes extra phenomena such as mixing or a high magnetic field in the core. We find also that consistency with the seismic inferences reduces the uncertainty in the composition (or opacities) by roughly a factor of 2 overall, subject to the assumptions of our study. We now estimate uncertainties of 5% in composition and 2% in central opacities (maybe less); we furthermore use the recent uncertainty on (^{7}Be, p) cross section (Hammache et al. 1998). The resulting uncertainties in Table 2 were obtained by quadratic summing of individual contributions, assumed independent. We note that this may underestimate the effect of errors in the reaction rates (if screening effects are inadequately understood and corresponding uncertainties correlated). Further details will be provided by S. Couvidat et al. (2001, in preparation).

It should be noted that the resolution in the inner core is still relatively poor: about ±5% in mass, which is insufficient to detect potential discontinuities due perhaps to gravity-mode transport. That is an inevitable consequence of the inherent character of acoustic modes and justifies further searching for gravity modes. Associated with this is a search for time variability and an investigation into the significance or not of local deviations.

The seismic model of this Letter is certainly not a unique solution. If we had modified the age of the Sun, for example, we would probably have found another solution, but the results, as far as neutrino predictions are concerned, would not be significantly different. The results discussed in this Letter highlight the discrepancy between the measured neutrino flux and what we know about the Sun. They strongly favor some missing processes occurring between the emission of the neutrinos and the neutrino detections on Earth such as the Mikheyev-Smirnov-Wolfenstein effect (Gonzalez-Garcia & Pena-Garay 2000) or resonant spin flavor precession processes (Akhmedov & Pulido 2000). Detailed files of this seismically adjusted model of the Sun will be deposited on the World Wide Web[11] for use to determine some neutrino properties that may be at the origin of the current detection deficits. Of course, time variability must be looked for directly in the Sun and in the neutrino detections (Sturrock & Scargle 2001).

During the rest of the *SOHO* mission, with the help of ground-based measurements, we shall follow the variability of the Sun's internal structure and try to improve our knowledge of the details of the solar core and the role of the magnetic field on the neutrino puzzle. To this end, detection of possible temporal neutrino variation and detection of the neutrino energy spectrum will be extremely important.

We dedicate this Letter to P. Delache, who has contributed substantially to the development of this field. *SOHO* is a mission of international cooperation between ESA and NASA. The GOLF experiment is based on a consortium of institutes involving a large number of scientists and engineers, belonging to the IAS (France), the CEA (France), the IAC (Spain), and the observatories of Bordeaux and Nice (France). We would like to thank the referee, J. Guzik, for very interesting comments.

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[11] See http://cdfinfo.in2p3.fr/APCP7.

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