Status of the Solar Neutrino Puzzle

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Using the latest results from the solar neutrino experiments and a few standard assumptions, I show that the popular solar models are ruled out at the 3σ level or at least *two* of the experiments are incorrect. Alternatively, one of the assumptions could be in error. These assumptions are spelled out in detail as well as how each one affects the argument.

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The solar neutrino puzzle has been with us for many years; an excellent review of the subject can be found in Ref. [1]. Recently the gallium solar neutrino experiments have reduced their uncertainties so that a very simple argument can be made demonstrating the difficulty of explaining the experimental results using only known physics. The simplest form of this argument is presented in this Letter. Additional features could be introduced which would strengthen this argument, but for the sake of simplicity and clarity they have not been included.

The argument, first used in Ref. [2], makes the following assumptions about the Sun, neutrino properties, and neutrino interaction cross sections.

(i) The pp solar cycle is the dominant energy source of the Sun.

(ii) The Sun is in a quasiequilibrium, i.e., the solar luminosity a few $\times 10^6$ yr from now will be approximately the same as today.

(iii) The neutrinos are unaffected during their propagation from production in the solar core to their detection at the Earth.

(iv) The neutrino interaction cross sections for the three types of experiments are correct.

With these four assumptions the main contributions to the solar neutrino experiments are determined by two parameters, the ^{7}Be and ^{8}B neutrino fluxes. Therefore with three solar neutrino results one can compare the standard solar models with the experimental results taken two at a time.

The main sequence of reactions that make up the pp solar cycle can be summarized as

$$4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e^{pp} \quad (1)$$

$$\rightarrow {}^4\mathrm{He} + \nu_e^{pp} + \nu_e^{{}^7\mathrm{Be}} \quad (2)$$

$$\rightarrow {}^4\mathrm{He} + \nu_e^{pp} + \nu_e^{{}^8\mathrm{B}}. \quad (3)$$

The total energy release in these reactions is 26.731 MeV but the ν_e^{pp}, $\nu_e^{{}^7\mathrm{Be}}$, and $\nu_e^{{}^8\mathrm{B}}$ carry off on average 0.265, 0.861, and 7 MeV, respectively. Therefore the energy release, not including the average neutrino energies, is 26.2, 25.6, and 19.5 MeV.

If the solar luminosity $L_\odot$ is approximately constant over a time scale of few $\times 10^6$ yr, then there is a relation between the current solar luminosity and the current solar neutrino fluxes, Φ^i. This relation can be written as

$$L_\odot = 13.1(\Phi^{pp} - \Phi^{{}^7\mathrm{Be}} - \Phi^{{}^8\mathrm{B}}) + 25.6\Phi^{{}^7\mathrm{Be}} + 19.5\Phi^{{}^8\mathrm{B}}.$$

For convenience it is useful to normalize the neutrino fluxes to those of the solar model of Bahcall and Pinsonneault [3],

$$\phi^i = \Phi^i/\Phi^i_{\mathrm{BP}}, \quad (4)$$

where

$$\Phi^{pp}_{\mathrm{BP}} = 6.0 \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1},$$
$$\Phi^{{}^7\mathrm{Be}}_{\mathrm{BP}} = 4.9 \times 10^{9}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1},$$
$$\Phi^{{}^8\mathrm{B}}_{\mathrm{BP}} = 5.7 \times 10^{6}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}.$$

In these normalized flux units the solar luminosity constraint is simply

$$1 = 0.913\phi^{pp} + 0.071\phi^{{}^7\mathrm{Be}} + 4 \times 10^{-5}\phi^{{}^8\mathrm{B}}. \quad (5)$$

This will be used to determine ϕ^{pp} in terms of $\phi^{{}^7\mathrm{Be}}$.

The contribution of the ν_e^{pp}, $\nu_e^{{}^7\mathrm{Be}}$, and $\nu_e^{{}^8\mathrm{B}}$ to the chlorine, water, and gallium solar neutrino experiments is

$$S^{\mathrm{th}}_{\mathrm{Cl}} = 6.2\phi^{{}^8\mathrm{B}} + 1.2\phi^{{}^7\mathrm{Be}}\ \text{solar neutrino units (SNU)}, \quad (6)$$

$$S^{\mathrm{th}}_{\mathrm{H_2O}} = \phi^{{}^8\mathrm{B}}\Phi^{{}^8\mathrm{B}}_{\mathrm{BP}}, \quad (7)$$

$$S^{\mathrm{th}}_{\mathrm{Ga}} = 14\phi^{{}^8\mathrm{B}} + 36\phi^{{}^7\mathrm{Be}} + 71\phi^{pp}\ \mathrm{SNU}. \quad (8)$$

The coefficients in Eqs. (6)–(8) are determined using the assumptions that the state of the neutrinos is unaffected by the passage from the solar core to the terrestrial detectors, i.e., there is no change in the flavor, helicity, or energy spectrum, and that the neutrino interaction cross sections used are corrected. The uncertainty on these cross sections is estimated to be a few percent.

Using the luminosity constraint to eliminate the ν_e^{pp} flux, the contribution to the gallium experiments can be written as

$$S^{\mathrm{th}}_{\mathrm{Ga}} = 14\phi^{{}^8\mathrm{B}} + 30\phi^{{}^7\mathrm{Be}} + 78\ \mathrm{SNU}. \quad (9)$$

The additional contributions from other species of neutrinos is less than 10% in the standard solar models [4].

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Over the past summer new results from the four solar neutrino experiments have been reported. The results for Homestake [5], Kamiokande [6], Gallex [7], and SAGE [8] are

$$S^{\rm ex}_{\rm Home} = 2.55 \pm 0.17 \pm 0.18 \text{ SNU},$$
$$S^{\rm ex}_{\rm Kam} = (0.51 \pm 0.04 \pm 0.06)\,\Phi^{\rm 8B}_{\rm BP},$$
$$S^{\rm ex}_{\rm Gallex} = 79 \pm 10 \pm 6 \text{ SNU},$$
$$S^{\rm ex}_{\rm SAGE} = 69 \pm 11^{+5}_{-7} \text{ SNU},$$

where the first uncertainty is statistical and the second systematic. To form a combined result for gallium, the mean and statistical errors for SAGE and Gallex were combined in the standard way but a common systematic error of 6 SNU was used. Then the statistical and systematic errors are combined in quadrature for each experimental result giving

$$S^{\rm ex}_{\rm Cl} = 2.55 \pm 0.25 \text{ SNU}, \tag{10}$$
$$S^{\rm ex}_{\rm H_2O} = (0.51 \pm 0.072)\,\Phi^{\rm 8B}_{\rm BP}, \tag{11}$$
$$S^{\rm ex}_{\rm Ga} = 74 \pm 9.5 \text{ SNU}. \tag{12}$$

These results are now used to fit the two parameters, $\phi^{\rm 7Be}$ and $\phi^{\rm 8B}$, of the model, Eqs. (6), (7), and (9). The χ^2 variable was calculated for the four cases; all three results together and the three ways of choosing two out of three. Since the minimum value of χ^2 occurs at negative values of $\phi^{\rm 7Be}$ for all four cases, the constraint

$$\phi^{\rm 7Be} \geq 0 \tag{13}$$

was imposed [9]. Table I contains the minimum value of χ^2 with this constraint, which all occur along $\phi^{\rm 7Be} = 0$, as well as the value of $\phi^{\rm 8B}$ at the minimum.

Figures 1 through 4 are the contour plots of χ^2 as a function of $\phi^{\rm 7Be}$ and $\phi^{\rm 8B}$ for the four cases: chlorine plus water plus gallium, chlorine plus water, chlorine plus gallium, and water plus gallium, respectively. The 1σ to 5σ contours are determined by $\Delta\chi^2 = 2.3$, 6.2, 11.8, 19.4, and 28.7, respectively [10], from the minimum with $\phi^{\rm 7Be} \geq 0$. Also included on these plots are the total theoretical ranges of the standard solar model predictions of Bahcall and Pinsonneault [3], Turck-Chièze and Lopes [11], and the *ad hoc* solar "model" where the central temperature of the Sun is a free parameter [12].

Since the standard models of Bahcall and Pinsonneault and Turck-Chièze and Lopes are consistent with our assumptions, both of these models are excluded by many sigma independent of which set of experimental results are included. Figure 2, using only chlorine plus water, is just a reformulation of the argument by Bahcall and Bethe [13], but here the exclusion is at the 5σ confidence level. Figure 3 demonstrates a similar case for chlorine plus gallium. The least convincing case occurs with water plus gallium, Fig. 4, and even then the two standard solar models are excluded at almost the 3σ level. The *ad hoc* model, where the central temperature of the Sun is a free parameter, is excluded at the 2σ level independent of which two experimental results are chosen. It is worth noting that the case using water plus gallium excludes this model at a higher level of confidence than either

TABLE I. Minima of χ^2 for $\phi^{\rm 7Be} \geq 0$ and the value of $\phi^{\rm 8B}$ at the minimum. All four minima occur along $\phi^{\rm 7Be}$ equals zero.

$L_\odot$ plus	$\chi^2_{\rm min}$, $\phi^{\rm 7Be} \geq 0$	$\phi^{\rm 8B}$
Cl + H_2O + Ga	2.5	0.43
Cl + H_2O	1.4	0.44
Cl + Ga	1.0	0.41
H_2O + Ga	1.3	0.50

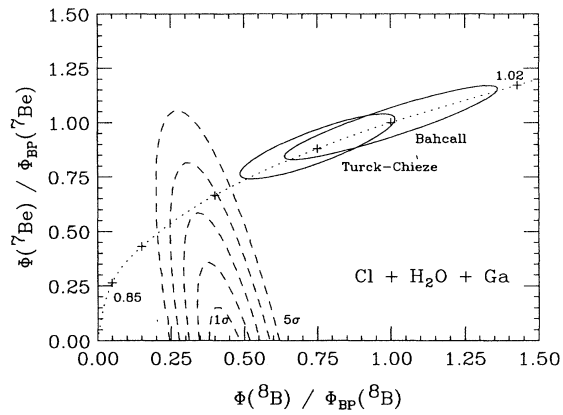

FIG. 1. The $\phi^{\rm 7Be}$ vs $\phi^{\rm 8B}$ plane using the results from the chlorine, water, and gallium solar neutrino experiments. The dashed curves are the 1σ to 5σ contours for the χ^2 variable. The solid ellipses are the predictions of the solar models of Bahcall and Pinsonneault and Turck-Chièze and Lopes. The dotted line is the curve $\phi^{\rm 7Be} = (\phi^{\rm 8B})^{8/18}$ and the crosses on this line are corresponding to solar core temperatures of (0.85, 0.90, 0.95, 0.984, 1.00, and 1.02) times the core temperature of the Bahcall and Pinsonneault model.

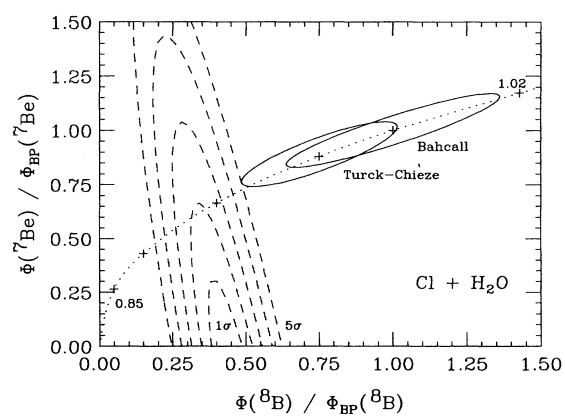

FIG. 2. The $\phi^{\rm 7Be}$ vs $\phi^{\rm 8B}$ plane using the results from the chlorine and water solar neutrino experiments. Curves as in Fig. 1.

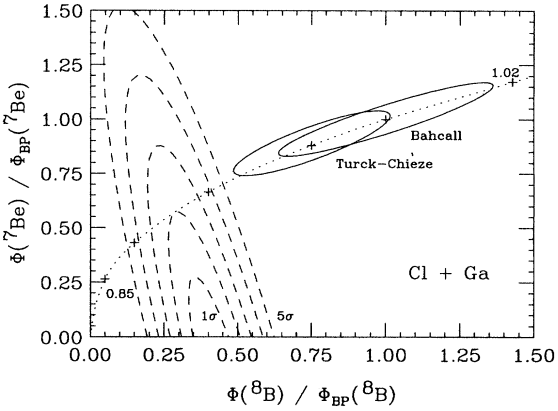

FIG. 3. The $\phi^{^7\mathrm{Be}}$ vs $\phi^{^8\mathrm{B}}$ plane using the results from the chlorine and gallium solar neutrino experiments. Curves as in Fig. 1.

of the chlorine plus water or the chlorine plus gallium cases. Of course the case chlorine plus water plus gallium gives the strongest exclusion to all models, Fig. 1. If the contribution from the *pep* and CNO neutrinos had been included, the confidence level of all exclusions would have been even stronger [14].

The conclusion from these figures is that, given the assumptions delineated above, either the standard solar models are ruled out at the 3σ level or at least two of the solar neutrino experiments are incorrect [15]. Prior to the release of the latest experimental results, only one of the solar neutrino experiments is needed to be incorrect to remove the discrepancy between the standard solar models and the data. Now, at least two experiments must be incorrect to remove this discrepancy. The probability that two independent experiments are incorrect is considerably smaller than 1. This is a strong argument in favor of the conclusion that one of the above

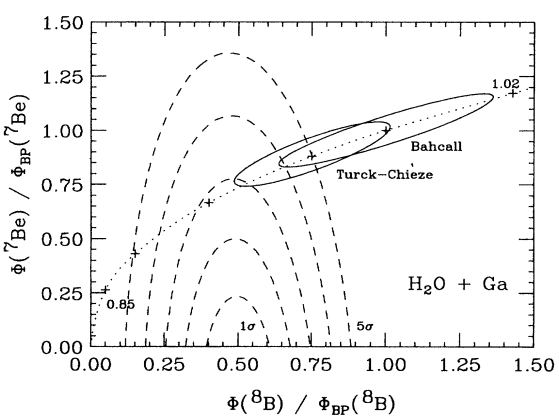

FIG. 4. The $\phi^{^7\mathrm{Be}}$ vs $\phi^{^8\mathrm{B}}$ plane using the results from the water and gallium solar neutrino experiments. Curves as in Fig. 1.

assumptions is wrong or that there is solar physics we do not understand. One of the above assumptions is that neutrinos are unaffected in their transition from the solar interior to the terrestrial detectors. The possibility that this assumption is incorrect has been discussed by many authors who have suggested neutrino oscillations and/or neutrino spin flip as explanations of the above discrepancy.

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[1] J.N. Bahcall, *Neutrino Astrophysics* (Cambridge University Press, Cambridge, 1989).

[2] M. Spiro and D. Vignaud, Phys. Lett. B **242**, 279 (1990); V. Castellani, S. Degl'Immocenti, and G. Florentini, Astron. Astrophys. **271**, 601 (1993); N. Hata, S. Bludman, and P. Langacker, Phys. Rev. D **49**, 3622 (1992).

[3] J.N. Bahcall and M.H. Pinsonneault, Rev. Mod. Phys. **64**, 885 (1992).

[4] Even if the CNO and *pep* neutrinos were included in the luminosity constraint, the coefficients of ϕ^{CNO} and ϕ^{pep} would be positive in Eq. (9) so that any contribution from these sources would strengthen the argument.

[5] Homestake Collaboration, K. Lande *et al.*, Neutrino '94, Israel, June 1994 (to be published).

[6] Kamiokande III Collaboration, Y. Suzuki *et al.*, Neutrino '94 (Ref. [5]).

[7] Gallex Collaboration, T. Kirsten *et al.*, Neutrino '94 (Ref. [5]).

[8] SAGE Collaboration, J. Nico *et al.*, Proceedings of the 27th International Conference on High Energy Physics, United Kingdom, July 1994 (to be published).

[9] This is the procedure recommended by the Particle Data Group [Phys. Rev. D **45**, S1 (1994)], and gives a more conservative result than not imposing this constraint.

[10] This assumes all errors are Gaussian distributed.

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

[12] In the *ad hoc* model, $\Phi^{^7\mathrm{Be}} \sim T_c^8$ and $\Phi^{^7\mathrm{Be}} \sim T_c^{18}$, where T_c is the solar core temperature. Therefore this model is represented by the line $\phi^{^7\mathrm{Be}} = (\phi^{^8\mathrm{B}})^{8/18}$.

[13] J.N. Bahcall and H. Bethe, Phys. Rev. Lett. **65**, 2233 (1990).

[14] Unfortunately this argument in this simple form is not strong enough to exclude $\phi^{^7\mathrm{Be}} \geq \phi^{^8\mathrm{B}}$ by more than about 1.2σ unless all three results are included. Additional features are needed.

[15] Similar conclusions, using a different argument, were presented in J. Bahcall, Institute for Advanced Studies Report No. IASSNS-AST-94/37 (to be published), and by S.P. Rosen at the Proceedings of the 27th International Conference on High Energy Physics (Ref. [8]).