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## Letter to the Editor

# Influence of the axial-vector coupling constant on solar models; solar neutrino fluxes, helium content and oscillations

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**Summary.** The consequences for the solar structure of the present uncertainty on the axial-vector weak-interaction coupling constant  $g_A$  are examined with respect to the observational constraints on solar models (solar luminosity, radius, neutrino flux and oscillations).

It has been pointed out recently by Bertin et al. (1987) that a large uncertainty on the experimental determination of  $g_A$  still remains, and that since the cross section  $S_{pp}$  of the proton-proton reaction in the Sun depends on  $g_A^2$ , a better determination of  $g_A$  could weaken or even solve the solar neutrino problem.

Therefore we have determined the value of  $g_A$  which reconciles observation and theoretical prediction of the solar neutrino flux. Moreover, it is essential also to examine the implications coming from the strong constraints of helioseismology.

We have calculated calibrated models of the present Sun varying the value of  $S_{pp}(g_A)$  even beyond acceptable values of  $g_A$ . From the results it appears that a very high value of  $g_A$  ( $-g_A$  greater than 1.55) is required to reconcile the theoretical and observed neutrino fluxes. This value seems to be improbable with respect to the present range of measurements of  $g_A$ . Moreover a solar model with such a high  $g_A$ -value is associated to a helium content ( $Y \approx 0.3$ ) above the usually accepted value. Nevertheless such an increase of  $g_A$  is not ruled out by the strong constraints of helioseismology. It does little affect the frequency separation of the 5-minute p modes; but we point out that the predicted period spacing of gravity modes is significantly modified.

**Key words:** Sun-structure of- nuclear reactions- neutrinos- oscillations

### 1. Introduction

In order to obtain up-to-date numerical models for the present Sun the most recent values of the physical parameters are required. The solar models presently available appear to be quite good when compared with observations. However, some unresolved discrepancies remain since, for instance, the theoretical predic-

tions for the solar neutrino flux do not agree with observation. The solar neutrino flux depends on the nuclear reaction rates, and in particular on the axial-vector coupling constant  $g_A$  which governs the p-p reaction rate. If this rate (increasing with  $g_A^2$ ) were to be increased, the central temperature of the theoretical Sun would decrease and also the predicted neutrino flux.

Several experimental methods can be used to determine  $g_A = g_A(0)/g_V(0)$  the ratio of the axial-vector weak interaction coupling constant  $g_A(0)$  to the vector coupling constant  $g_V(0)$ . Bopp et al. (1986) reported on a sensitive measurement of the neutron-spin-electron-momentum angular correlation (the neutron  $\beta$  asymmetry) from which they obtained the precise value  $g_A = -1.262 \pm 0.005$ . On the other hand Bertin and Vitale (1984) have obtained from muon capture in hydrogen the value  $g_A = -1.24 \pm 0.04$  which is compatible with the result of Bopp et al. (1986). However Bertin et al. (1987) note that the other methods lead to  $g_A$  determinations which differ significantly since values of  $-g_A$  as low as 1.18 and as high as 1.34 have been proposed.

Using the results of Bahcall et al. (1985) and Cahen et al. (1986), Bertin et al. (1987) note that a value of  $-g_A$  larger than 1.33, but still compatible with the present experimental values, could reconcile the observed and theoretical solar neutrino fluxes. They argue that the uncertainties on  $g_A$  are too large to allow a significant comparison between the theoretical neutrino flux for the Sun and the flux measured in the  $^{37}\text{Cl}$  experiment.

This discussion is of importance in the context of the preparation of the Gallex experiment. We feel it is necessary to ascertain the conclusion of Bertin et al. (1987) and establish the precise relationship between the predicted neutrino flux and the value of  $g_A$ .

To do so, we have calculated "calibrated" solar models with different values of  $g_A$  in which the most recent physical parameters describing the solar material are used. We have studied in detail the influence of an increase of  $g_A$  on the central properties of the solar model related to the observational constraints fixed by neutrino experiment and helioseismology.

### 2. Characteristics of the solar models

Two sets of solar models (hereafter called type A and type B models) were calculated independently using two different stellar evolution codes. The basic numerical

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and physical ingredients entering the construction of the A-models are described in Lebreton and Maeder (1987). B-models are based on a version of the original Paczynski (1970) program, updated by the Nice Observatory group.

The nuclear cross section factors for the proton-proton chain were chosen following the prescription of Parker (1987). For the p-p reaction, which is of main interest here, the analysis by Parker leads to an updated value of the neutron half-life  $t_{1/2} = 625 \pm 6$  sec and to the cross section factor  $S_0(p-p) = 4.06 \pm 0.08 \cdot 10^{-25}$  MeV.barn (hereafter  $S_{pp}(\text{Ref})$ ). For the CNO cycle we have used the nuclear reaction rates of Harris et al. (1983), Fowler et al. (1975). In A-models, Rolfs's (1985) value for  $^{14}\text{N}(p,\gamma)^{15}\text{O}$  is adopted. The thermo-nuclear reaction rates were used to derive the abundance variations and the specific rate of energy production. On each mass shell of the evolutionary models we have followed the abundances of  $^1\text{H}$ ,  $^3\text{He}$ ,  $^4\text{He}$ ,  $^7\text{Be}$ ,  $^7\text{Li}$ ,  $^{12}\text{C}$ ,  $^{13}\text{C}$ ,  $^{14}\text{N}$ ,  $^{15}\text{N}$ ,  $^{16}\text{O}$ ,  $^{17}\text{O}$ ,  $^{18}\text{O}$ . The standard abundances of all elements heavier than H and He were taken from Grevesse's (1984) data (A-models) or Ross and Aller's (1976) data (B-models). The solar metallicity adopted is  $Z=0.02$ .

Opacities are taken from the Los Alamos Opacity Library (hereafter LAL, Huebner et al., 1977); at low temperatures ( $kT < 1\text{eV}$ ) we have used molecular absorption coefficients (Cox, 1981). For comparison purposes one of the A-models was obtained using Cox and Stewart (CS, 1970) opacity tables.

The individual neutrino fluxes are derived. The predicted capture rates on earth for the  $^{37}\text{Cl}$  and future  $^{71}\text{Ga}$  detector are calculated with the neutrino absorption cross sections used by Bahcall and Ulrich (1988).

A solar model of one solar mass ( $M_\odot = 1.991 \cdot 10^{33}\text{g}$ ) must reach the solar luminosity ( $L_\odot = 3.86 \cdot 10^{33}\text{erg. s}^{-1}$ ) and radius ( $R_\odot = 6.9599 \cdot 10^{10}\text{cm}$ ) at solar age ( $t_\odot = 4.6 \cdot 10^9\text{yr}$ ). The model is calibrated by using these constraints to determine the values of  $Y$ , the solar initial helium content by mass, and of  $\alpha$ , the ratio of the mixing length to the pressure scale height, which enters in the usual treatment of convection (see e.g. Christensen-Dalsgaard, 1982).

### 3. Results

In order to examine the effects on the theoretical solar neutrino flux of the value adopted for  $g_A$  we have calculated several evolutionary sequences of the Sun with different values of  $S_{pp}$ . For A-models we present a standard reference model (model 1a, with  $S_{pp}(\text{Ref})$ ) and four models with different values of  $S_{pp}$  ( $S_{pp}/S_{pp}(\text{Ref}) = 0.9, 1.1, 1.2, 1.3$  for models 2, 3a, 4a, 5a respectively). Model 6 uses  $S_{pp}(\text{Ref})$ , but is calculated with the old opacity data (CS). We have also calculated 6 models of type B ( $S_{pp}/S_{pp}(\text{Ref}) = 1., 1.1, 1.2, 1.3, 1.4$  and  $1.7$  for models 1b, 3b, 4b, 5b, 7, 8, respectively).

In table 1 we give some basic properties of these evolutionary models, each model having reached  $L_\odot$  and  $R_\odot$  within  $10^{-4}$ .  $N_\nu(^{37}\text{Cl})$  and  $N_\nu(^{71}\text{Ga})$  are the expected values for the rate of solar neutrino events in the  $^{37}\text{Cl}$  apparatus and the Gallex experiment, respectively.  $T_c$ ,  $\rho_c$ ,  $X_c$  are central temperature, density and hydrogen content respectively;  $T_{\text{OCZ}}$  and  $\rho_{\text{OCZ}}$  are temperature and density at the bottom of the outer convective zone (OCZ),  $1-R_{\text{OCZ}}/R_\odot$  is the depth of the

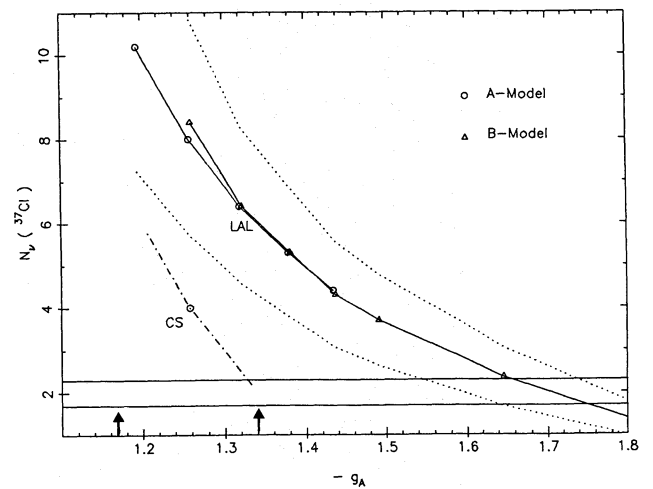


Fig. 1. Expected values (including theoretical uncertainties) for the solar neutrino flux  $N_\nu(^{37}\text{Cl})$  as a function of  $g_A$  for A and B models with LAL or CS opacities. The horizontal band represents the observed flux (Davis, 1986). The arrows show on the abscissae the lower and upper experimental values for  $g_A$

OCZ measured in units of one solar radius. Moreover, for B-models we have calculated quantities relevant to helioseismology: the frequency separation of the 5-minute p modes of degree and radial order  $l = 2, n$  and  $l = 0, n-1$  ( $\delta\nu_{0,2}$ ), and the asymptotic characteristic period of the gravity modes  $P_0$  (see e.g. Provost, 1984). Last column of table 1 gives the same quantities for the recent standard solar model of Bahcall and Ulrich (1988). Fig. 1 shows the variation of  $N_\nu(^{37}\text{Cl})$  as a function of  $g_A$  both for models with recent opacities (LAL) and older ones (CS).

We note that the calculations of Bahcall and Ulrich (1988) performed with  $-g_A = 1.26$ , with similar input physics but using a different evolution code lead to  $N_\nu = 7.9$  SNU at solar age. We point out that our results are in excellent agreement with Bahcall and Ulrich's results.

The variation of  $N_\nu$  as a function of  $g_A$  is not linear: in fact as  $g_A$  increases, the decrease of  $N_\nu$  becomes less important (Fig. 1). The extrapolated value of  $g_A$  ( $-g_A \approx 1.7$ , Fig. 1) which would yield the observed value of  $N_\nu$  (i.e.  $N_\nu = 2.0 \pm 0.3$  SNU, Davis 1986) is much larger than that estimated by Bertin et al. (1987). Moreover not only  $S_{pp}$  but also the cross section for neutrino capture by  $^{37}\text{Cl}$ ,  $\sigma$ , depends on  $g_A$ . The way by which  $\sigma$  is estimated (Bahcall, 1964) eliminates most of the explicit dependence on  $g_A$ . The global uncertainty on the predicted flux (dotted lines, Fig. 1) was calculated with the uncertainties on  $\sigma$  and on the physical inputs of Bahcall and Ulrich (1988) (except the one on  $S_{pp}$ ). It appears that if  $-g_A$  was to be greater than 1.55 the predicted flux would be compatible with observations. However this  $g_A$ -value is highly improbable with regard to the present upper limit ( $-g_A = 1.34$ ) given by the measure of the muon capture by deuterons.

The increase of the opacities from CS to LAL leads to a larger predicted neutrino flux. If, as it is generally suspected, the LAL opacities are still underestimated, the agreement with observation will be even more difficult to achieve.

Table 1. Main characteristics of calibrated solar models of type A and B compared to Bahcall and Ulrich's (1988) results. The small differences in neutrino fluxes are mainly due to the different  $^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$  reaction rates adopted (see text)

Model	1a A 1b B	2 A	3a A 3b B	4a A 4b B	5a A 5b B	7 B	8 B	6 A	Bahcall Ulrich, 1988
$-\theta_A$	1.26	1.19	1.32	1.38	1.43	1.49	1.64	1.26	1.26
Y	.287 .291	.284	.289 .294	.291 .296	.293 .297	.299	.300	.239	.271
$\alpha$	2.18 2.11	2.12	2.25 2.16	2.31 2.21	2.36 2.24	2.29	2.40	1.35	
$N_\nu(^{37}\text{Cl})$ (SNU)	8.0 8.4	10.2	6.4 6.4	5.3 5.3	4.4 4.3	3.7	2.4	4.0	7.9
$N_\nu(^{71}\text{Ga})$ (SNU)	129 134	138	122 124	116 117	112 112	108	99	110	132
$T_c$ ( $10^6\text{K}$ )	15.6 15.6	15.8	15.4 15.5	15.2 15.3	15.1 15.1	15.0	14.6	15.0	15.6
$\rho_c$ ( $\text{gcm}^{-3}$ )	150 154	157	145 148	141 143	136 140	135	126	152	148
$X_c$	.344 .330	.342	.345 .333	.346 .335	.348 .337	.338	.340	.392	.341
$T_{\text{Ocz}}$ ( $10^6\text{K}$ )	1.94 2.03	1.88	2.00 2.06	2.05 2.14	2.09 2.16	2.18	2.31	2.09	1.92
$\rho_{\text{Ocz}}$ ( $\text{gcm}^{-3}$ )	.125 .166	.113	.140 .187	.153 .192	.164 .215	.219	.280	.17	.12
$1 - R_{\text{Ocz}}/R_\odot$	.257 .263	.251	.263 .265	.267 .273	.271 .275	.282	.286	.282	.26
$\delta\nu_{0,2}$ ( $\mu\text{Hz}$ )	- 10.2	-	- 10.15	- 10.10	- 9.80	- 9.70	- 9.40	-	10.6
$P_0$ (min)	- 35.1	-	- 35.9	- 36.8	- 37.5	- 38.2	- 40.0	-	37.7

Moreover not only the neutrino flux, but also the helium abundance  $Y$  and mixing length ratio  $\alpha$  are influenced by the change of  $g_A$ . An increase of  $g_A$  leads to an increase of  $Y$  and  $\alpha$  in order to maintain solar luminosity and radius at solar age. After B-model n°8 it is clear that a model leading to the observed flux would have a  $Y$ -value larger than about 0.30. This value is of the order of the upper limit provided by spectroscopic studies (Meyer, 1984; Heasley and Milkey, 1978) and by the analysis of the solar wind (Geiss, 1982). The mixing-length ratio  $\alpha$  would also be increased, corresponding to a slight deepening of the surface convective zone. With such high values of  $\alpha$ , the extend of the convective zone becomes almost independent of  $\alpha$ , as the superadiabatic region becomes very small.

As  $g_A$  increases,  $T_c$  and  $\rho_c$  decrease (table 1). This modifies the sound velocity and mean molecular weight gradient in central layers which in turn affects the oscillation spectrum. We have calculated the oscillation frequencies by the same numerical procedure as Bahcall and Ulrich (1988) in order to

obtain the frequency separation  $\delta\nu_{0,2}$  of the 5-minute p modes. An increase of  $g_A$  leads to a slight decrease of  $\delta\nu_{0,2}$  (table 1) but the resultant values of  $\delta\nu_{0,2}$  are still in agreement with observations (Gelly et al., 1988). On the other hand the asymptotic integral expression of  $\delta\nu_{0,2}$  related to the derivative of the sound velocity varies very little in the opposite sense. Work is in progress to elucidate this difference of behaviour between asymptotic and numerical description of the modes. Concerning the gravity modes, the asymptotic characteristic period  $P_0$  significantly increases (from 35.1 to 38.2 min) because of the central decrease of the Brunt-Väisälä frequency. Unfortunately the observation of these modes does not allow the deduction of a unique reliable value of  $P_0$ , however there is a hope that future experiments will greatly improve the situation.

#### 4. Conclusions

Solar models are very sensitive to the physical ingredients (opacity, equation of state, nuclear reaction rates). One of these, the cross section factor for the p-p reaction  $S_{pp}$  depends on the square of the axial-vector coupling constant  $g_A$ . As far as the experimental determination of  $g_A$  is still subject to uncertainty,  $S_{pp}$  might be underestimated which would have incidence on the solar neutrino problem.

We have examined in detail the effects of a  $g_A$  change on the solar model outputs (helium content, neutrino fluxes, oscillations), assuming the other inputs of the models are well-known. Bertin et al. (1987) have estimated that if  $-g_A$  is greater than 1.33, then the expected value of the neutrino flux and observation become compatible. In our updated solar models the expected flux is in agreement with observation if  $-g_A$  is greater than 1.55. Such a value is far beyond the present range of experimental data, moreover it is associated to a short and improbable neutron half-life (i.e. about 30% smaller than the  $625 \pm 6$  sec given by Parker (1987)).

From our results it also appears that models leading to the observed neutrino flux would have a high initial helium content (about .30) which is greater than the usually accepted value. Concerning helioseismology, the  $g_A$ -increase induces a very small decrease of the well-observed frequency separation of low-degree p modes, while the spacing period of g modes increases significantly.

Therefore according to the present range of experimental data on  $g_A$ , it appears that an improvement of the  $g_A$  determination might possibly reduce the solar neutrino discrepancy problem without solving it. Further steps towards a solution are expected with both the future neutrino experiment (Gallex) and the helioseismological projects (Soho, Iris, Gong) which will provide powerful diagnostics of the innermost solar regions.

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