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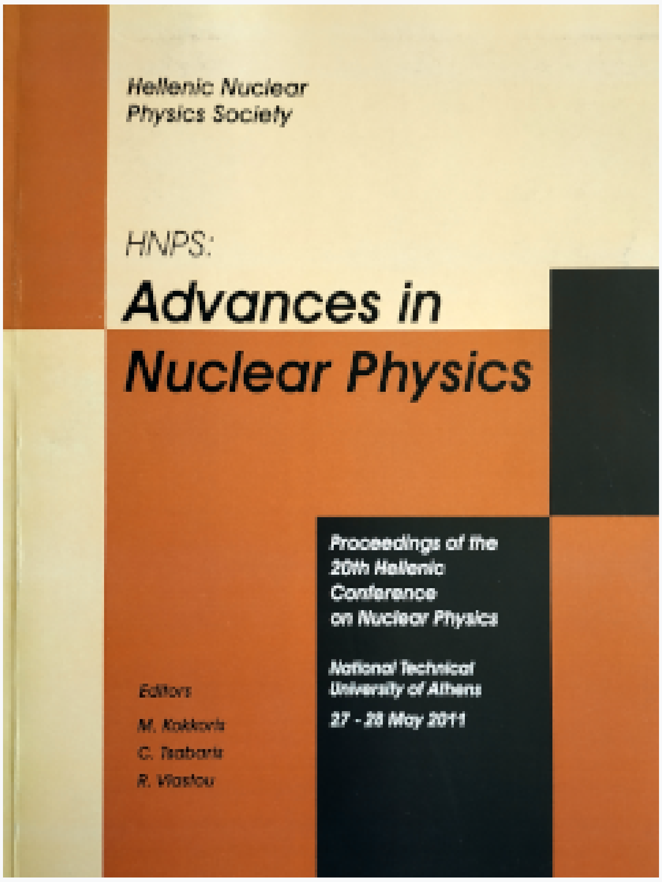

Updated solar neutrino fluxes with new heavy element abundances

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Updated solar neutrino fluxes with new heavy element abundances

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Abstract

In the present work we carry out an extensive study of the solar structure and solar evolution through the use of the TYCHO 6.92 code, which includes a variety of programs and subroutines. In this code we incorporate the most updated microphysical parameters such as screening, recent experimental measurements of the astrophysical factors-S (LUNA), several updated, recently measured, heavy element abundances, etc., and created new models describing crucial phenomena of the solar structure and solar evolution. We used this code to calculate and update nuclear reaction rates, solar neutrino fluxes, solar quantities which characterize the internal solar structure such as temperature, pressure, density, luminosity, heavy element abundances ($^4He,^{12}C,^{14}N,^{16}O$, etc.) as well as sound speed profile and depth of the convection zone.

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1 Introduction

Observations of stars give us information about the outer stellar layers, the photosphere, chromosphere and corona. The interior of stars, regions under the photosphere, is invisible in the electromagnetic spectrum. For the solar interior we can determine the solar mass, radius, photon spectrum, total luminosity, and chemical composition, through observations of solar neutrinos which are produced by nuclear reactions in the solar interior, and from helioseismology, during which frequencies for thousand of acoustic oscillation modes are observed at the solar surface. All the above information provides a unique opportunity to test theories of stellar structure and evolution [1].

Solar models in this work have been computed with a modified and improved version of the TYCHO code [2] [3]. One of our goals was to create solar models with the most updated input data, like astrophysical factor (S_{eff}), chemical element abundances (Z/X), etc., in order to predict solar neutrino fluxes which are originated in the interior of the Sun. In this paper we present our best results for solar neutrino fluxes of the proton-proton chain and the CNO cycle. We also compare our results with the detected solar neutrino fluxes on Earth. We compare the results of our models with the solar structure inferred through helioseismological measurements.

The TYCHO code, is a one dimensional code of stellar structure and evolution discussed by Young, Mamajek, Arnett, & Liebert (2001) and is written in structured FORTRAN77 with immediately connected graphic and with the use of PGPLOT. The code, has suffered essential additions and improvements in several areas. It is functional for stars in the hydrogen burning phase and for a big range of stellar masses, as well as for metallicities from Z = 0 up to the limit of the opacity tables OPAL [2]. We used TYCHO 6.92, the last upgraded version (2009) of this code. It executes detail simulations of solar models and of stellar evolution of stars with different masses. TYCHO, also, contains additional subprograms of analysis.

The Sun being the best observed star is used to check different codes of stellar structure and evolution. Helioseismological measurements of the sound speed give us information for the internal structure of the Sun which is not available by any other type of observation. A star with $1M_{\odot}$ it is the easiest star to study and it is relatively unaffected from the effects of mixing and mass loss. The solar models give us also the uncertainties in the calculations of different stellar parameters [4] [5].

The data which we extract from the TYCHO code are the values of temperature T, pressure P, luminosity L, density ρ, sound speed v_s and element abundances of $^4He,^{12}C,^{14}N,^{16}O$, etc., as a function of the distance from the solar center, $R/R_{\odot}$. We also obtain the depth of the convection zone and solar neutrino fluxes.

2 Solar neutrino fluxes and sound speeds obtained with TYCHO 6.92

In order to find the solar neutrino fluxes for the pp, pep, hep, ^7Be, ^8B, ^{13}N, ^{15}O and ^{17}F solar neutrinos, we first need to calculate the nuclear reaction rates-R, for each nuclear reaction which occurs in the center of the Sun.

We used the TYCHO-code to calculate the nuclear reaction rate through the expression

$$R_{\alpha X} = n_\alpha n_x \int_0^\infty \upsilon_r \sigma(\upsilon_r) f(\upsilon_r) d\upsilon_r = n_\alpha n_x \langle \sigma \upsilon_r \rangle, \qquad (1)$$

for a typical thermonuclear reaction which is represented by $\alpha + X \to Y + b$, where a nucleus X is bombarded by a uniform flux of particles of type α moving with velocity υ_r. The quantities n_X and n_α are the number density of the interacting nuclei, and σ is the cross section [6][7].

The average product of cross section times velocity can be written in the compact form

$$\langle \sigma \upsilon_r \rangle = (\frac{2}{\mu kT})^{1/2} (\Delta E_0/kT) S_{eff} \exp(-3E_0/kT), \qquad (2)$$

where

$$S_{eff} = S(0)[1 + \frac{5kT}{36E_0}] + S'(0)E_0[1 + \frac{35kT}{36E_0}] + \frac{1}{2}S''(0)E_0^2[1 + \frac{89kT}{36E_0}]. \qquad (3)$$

Nuclear astrophysics experiments measure the components of the effective astrophysical factors S_{eff} i.e. $(S(0), S'(0)...)$ [8].

Given the above values for the reaction rate we calculated the neutrino fluxes on the Earth' s surface,

$$neutrino \quad fluxes = \frac{rate}{4\pi r^2}, \qquad (4)$$

where r is the distance of Earth - Sun.

We used the initial model of TYCHO 6.92 code and the subroutine exportenergy.f, which we modified in order to calculate new upgraded thermonuclear reaction rates and improved solar neutrino fluxes. We created four new solar models (TSK 1, TSK 2, TSK 3, TSK 4) with the use of the auxiliary program, genex, and TYCHO code, using four different values of the heavy element abundances, Z/X, where Z=C, N, O, Ne etc. and X=H-hydrogen [9] [10] [11] [12]. In Table 1 we present the solar neutrino fluxes for the solar models of the present work.

The differences in solar neutrino fluxes between TSK 1 and TSK 3 models are in the order of 3.7% for the ^7Be neutrinos, $\sim$ 10.5% for the ^8B, 29.9% for the ^{13}N neutrinos, 32.1% for the ^{15}O and 27.6% for the ^{17}F neutrinos. The

	Predicted solar-ν flux				*Observed solar-ν flux*
ν*-sources*	*TSK 1*	*TSK 2*	*TSK 3*	*TSK 4*	
	Z/X	Z/X	Z/X	Z/X	
	0.0229	0.0165	0.0178	0.0181	
pp	5.96	6.03	6.00	6.00	
pep	1.42	1.45	1.43	1.40	
hep	8.02	8.16	8.12	8.09	
^7Be	4.89	4.62	4.71	4.83	5.18 (Borexino) 2008
^8B	5.51	4.69	4.93	5.34	5.54 (SNO) 2008
					2.32 (Super-Kamiokande) 2001
^{13}N	2.98	2.01	2.09	2.25	
^{15}O	2.24	1.31	1.52	2.09	
^{17}F	4.89	3.23	3.54	3.88	

Table 1
The predicted solar neutrino fluxes for the pp-chain and the CNO cycle, in units of 10^{10}(pp), 10^9(^7Be), 10^8(pep, ^{13}N, ^{15}O), 10^6(^8B, ^{17}F) and 10^3 (hep) $cm^{-2}s^{-1}$, which we calculated with four different values of the heavy element abundances Z/X and the observed ^7Be and ^{8} solar neutrino flux derived from Borexino, SNO and Super-Kamiokande detector.

agreement of the predicted flux of ^7Be and ^8B neutrinos with corresponding observations derived from the detectors Borexino (2008) and SNO (2008) [13] [14], are satisfactory and varies from 0.5% to 15%. Similarly there is very good agreement, $3.6 - 6.7\%$, for the models TSK 1 and TSK 4, with Z/X = 0.0229 and Z/X = 0.0181, respectively, with the Borexino and SNO detections on Earth.

We calculated, with TYCHO 6.92, the sound speed in different regions of the solar interior. We estimated the quantity $\frac{\delta c}{c}$, which is the difference between the predicted (from the models) sound speed (c_m) and the observed sound speed (c_h) from the helioseismological observations (LOWL-BISON-detector),

$$\frac{\delta c}{c} = \frac{c_m - c_h}{c_h}. \tag{5}$$

The predicted values of sound speed, $\frac{\delta c}{c}$, with respect to the distance from the center of the Sun, for the four solar models mentioned above with four different Z/X values, are presented in Fig. 1. The colored curves correspond to the four solar models of the present work and to four other models from Bahcall et al.

[15] [16]. The models BP04, BS05, BP00 and TSK 1 have calculated sound speed by using older values for the heavy element abundances, Z/X = 0.0229. These models have very small differences ($\leq 0.003\frac{\delta c}{c}$) and agree quite well with the helioseismological observations.

The profiles of our models, TSK 2, TSK 3, TSK 4, which use new, smaller heavy element abundances (Z/X) diverge considerably from those of helioseismology. We are trying to explain this large discrepancy.

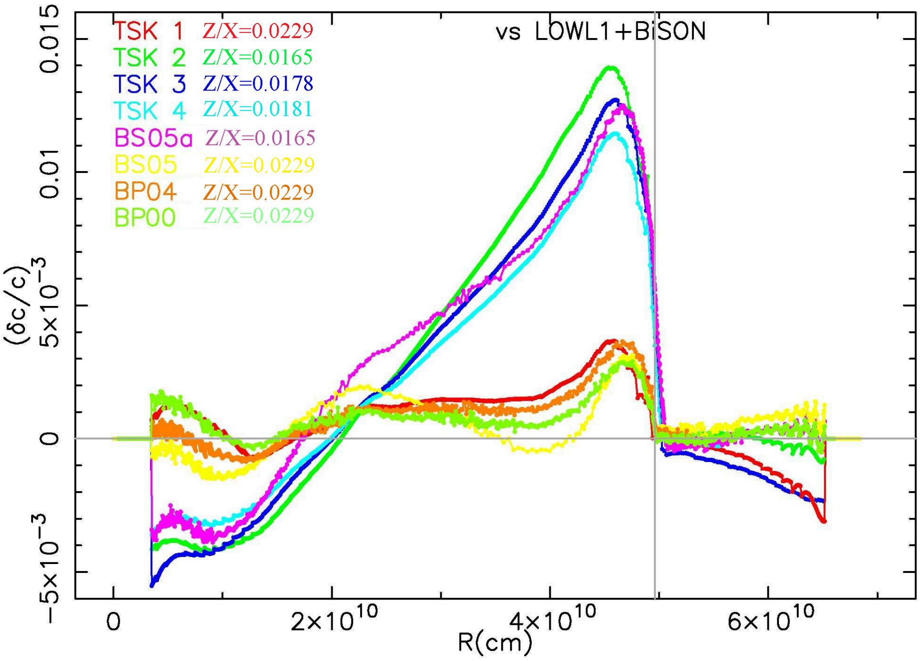

Fig. 1. The profiles depict the differences $\frac{\delta c}{c}$ between the predicted values of sound speed (c_m) of the models TSK 1, TSK 2, TSK 3, TSK 4 and these observed by the LOWL1+BISON detectors (c_h). Similar $\frac{\delta c}{c}$ differences are plotted for the four Bahcall models.

3 Results and Conclusions

In the present work we have calculated new improved solar neutrino fluxes by using an analytical and precise formalism and new, very recent input parameters, like experimental astrophysical factors and metal abundances Z/X. The ^7Be, ^8B neutrino fluxes are in very good agreement with the very recent neutrino detector measurements of Borexino and SNO (2008). The predicted fluxes deviate by $0.5 - 5.7\%$ from the detector measurements. This is a very good agreement if one considers that the experimental errors are $\sim 2\%$ and the theoretical uncertainties $\sim 8\%$.

The predicted sound speed profiles converge satisfactorily to the helioseismologically observed sound speed profile, when we use the older, higher, Z/X abundance 0.0229. We find large differences in the predicted sound speed profiles and those of helioseismology, when we make use of the new, lower, measurements of the heavy element abundances, $Z/X = 0.0165, 0.0178, 0.0181$. We observe that, as Z/X increases and approaches the value of 0.0229, the predicted by the models sound speed profiles approach the helioseismological profiles.

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