The mixing in the solar core and the neutrino fluxes

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Abstract

The question is addressed whether it is possible to introduce a mixing in the solar model not in a contradiction with the present data of helioseismology. As a new thing it is shown that there is indeed a spherical geometry with mixing for which the sound speed profile would be consistent with the helioseismic data. The effect of such mixing in a spherical shell in the central zone of the Sun would be the substantial increase of the neutrino flux from $^{13}N$ while all other neutrino fluxes will stay practically unchanged. The implications for future experiments are discussed.

Introduction.

Neutrinos are generated in the Sun in the reactions of pp-chain and in CNO cycle. The latter contributes only about 1% to the total solar energy, but neutrinos generated in this cycle may carry very substantial information about the processes deep in the interior of the Sun. The fluxes of CNO neutrinos depend primarily on the abundances of C and N in the solar core where CNO neutrinos are generated. This was stated by G.Zatsepin and V.Kuzmin [1] and also by J.Bahcall [2] on the eve of the solar neutrino research, particularly, formulating the motivation for a lithium experiment on solar neutrinos. Since that time a tremendous success in the study of solar neutrinos has been achieved [3]–[18]. The high temperature dependence of the reactions of CNO cycle is no more our prime concern, because the flux of $^8B$ neutrinos has been proven to be very close (within 1σ) to the prediction of the solar model [19]. Due to the correlation of the fluxes of $^8B$ and CNO neutrinos...
neutrinos, as it was first emphasized in [20] and then was presented in more
details in [21], the uncertainty in the temperature should not be the greatest
factor varying the fluxes of CNO neutrinos. But what about the abundances
of carbon and nitrogen, can this be a major factor? The data on photospheric
abundances of the Sun indicate the lower composition of metals than the
standard model suggests, but this conflicts with the results of helioseismology
[22]–[31]. Thus, we have by now two alternatives: an old model with high
metallicity which is in a very good agreement with helioseismology and a
new model with low metallicity which is at odds with helioseismology [32].
The fluxes of neutrinos predicted by these models [31, 33] are quite different,
especially what concerns CNO neutrinos. There’s another aspect of this
question. As one can see from Figure 1, the profiles of the abundances of
these elements across the Sun are also very different. The abundance of $^{14}N$
varies by a factor of 4 while the abundance of $^{12}C$ varies by more than two
orders of magnitude. This may have a dramatic influence on the fluxes of
solar neutrinos. In our previous paper [34] it was shown that the flux $F_{13}$
of $^{13}N$ neutrinos can be substantially (more than 30%) increased by local
mixing in a spherical shell of the central region of the Sun. The fluxes $F_7$ of
$^7Be$ and $F_{15}$ of $^{15}O$ neutrinos experience by this mixing only a tiny change
on the level of a few percent. Remarkably that the mean molecular weight
averaged for the central zone of the Sun, $\mu_c$, has been changed by this mixing
only on a level of less than 0.5% what, in fact, is in agreement with the most
accurately determined value fixed at present by helioseismology. However,
the local changes of the mean molecular weight within the area of mixing can
reach the value of a few percent. Then it may result in a substantial deviation
of the sound speed profile in this region. The sound speed is connected with
$\mu$ by the expression:

$$c = \sqrt{\frac{\gamma kT}{\mu}} \quad (1)$$

where $\gamma \approx 5/3$ – the adiabatic constant, $k$ – the Boltsman constant. So
it is quite interesting to see whether there could be a mixing which would
not change the parameters fixed by helioseismology and the fluxes of solar
neutrinos generated in pp-chain precisely determined by experiments [2]–[8]
and at the same time will produce substantial increase of $F_{13}$ while the flux
$F_{15}$ will stay practically unchanged. Here it is worth to note that for the
solar models with high (GS98) [21] and low (AGS09) [35] abundance of CNO
elements the difference of the fluxes $F_{13}$ and $F_{15}$ is about 30% while for the ratio of these fluxes the difference is less than 10% (see, for example, Table 2 of [33]). Thus the ratio $F_{13}/F_{15}$ appears to be a sensitive indicator of mixing in the solar core what can be exploited in the future experiments on solar neutrinos.

**Simulation of mixing.**

The calculation has been performed with the following limitations for mixing: the mass, density and temperature of the spherical shell is not changed by mixing. The process is very slow and there is time for these parameters to be restored. The resulted abundance of elements in the mixed shell is determined by several parameters: the position and thickness of the shell, the intensity of mixing, its duration etc. No attempts has been made to describe the physics of mixing i.e. to determine the driving force, the magneto hydrodynamics etc. Only one illustrative case of mixing has been considered with the aim to see what can be the effect of such mixing, provided this process is realized. It was assumed that mixing in the center of a shell is more intensive than on its periphery with a rather smooth transient function. In this case the profile for the abundances of different elements can look how it is presented on Figure 1. The initial profile was taken from the model AGS05 [36].

The sound speed profile by this mixing will be changed differently for two sub shells relatively to the one fixed by helioseismology as it is shown on Figure 2.

As one can see from this figure there’s improved agreement of the mixed model with the helioseismic data for the external part of the mixed shell. The maximal deviation of the calculated value $\delta c/c$ from helioseismic data $< 1\%$ at the depth $0.12R_{\odot}$. The change of the mean molecular weight of the solar core is $< 0.2\%$. The flux $F_{13}$ is determined by the reaction rate $\alpha_{112}$ of the reaction $^{12}C + p \rightarrow ^{13}N + \gamma$ and the abundances $X_1(r)$ and $X_{12}(r)$ of isotopes $^1H$ and $^{12}C$ along the solar radius. The nucleus $^{13}N$ produced in this reaction quickly decays generating $^{13}N$-neutrino and positron.

$$F_{13}(t) = 4\pi N_A R_\odot^3 \int_0^1 r^2 \rho(r) X_1(r,t) \frac{X_{12}(r,t)}{12} \alpha_{112}(r) dr \quad (2)$$

The similar expressions can be written for the fluxes $F_{15}$ and $F_7$ of $^{15}O$- and $^7Be$-neutrinos. The results of the calculation are presented in Table 1. The fluxes without mixing were obtained in a toy model with the parameters
Figure 1: The profile for the abundance of $^1H$, $^3He$, $^4He$, $^{12}C$ and $^{14}N$ without (dashed line) and with (solid line) mixing.

Figure 2: The differences between the helioseismic and predicted sound speed as a function of depth without $^{32}$ (black line) and with (red line) mixing close to AGS05. As one can see from Table 1 only the flux $F_{13}$ experiences a
substantial increase (∼ 90%) in the model with mixing. The change is high enough to be observed by experiment.

Table 1: Solar neutrino fluxes with and without mixing, in units of $10^9(F_7)$ and $10^8(F_{13}, F_{15}) \text{cm}^{-2}\text{s}^{-1}$

| Flux | No mix | Mix flux | Difference, % |
|------|--------|----------|---------------|
| $F_7$ | 4.43   | 4.65     | 4.8           |
| $F_{13}$ | 1.99     | 3.77E    | 89.8          |
| $F_{15}$ | 1.58     | 1.57     | -0.14         |

Conclusions.
The abundance of $^{12}C$ along the radius of the Sun has a peculiar feature at the depth of 0.15 of solar radius where it experiences a sharp increase by more than two orders of magnitude. If there is a mixing, even a very mild one, in the shell at this depth, the result can be a substantial increase of the flux of $^{13}N$ neutrinos. The problem is that present data of helioseismology, especially the sound speed profile, restrict severely the possibility of such mixing. As a new thing, here it is shown that there is indeed a spherical geometry with mixing for which the sound speed profile would be consistent with the helioseismic data. In case of such mixing it shown also that all other neutrino fluxes are left unchanged, at most they will vary on a level of a few percent. The difference of the fluxes $F_{13}$ and $F_{15}$ for models with high and low abundance of CNO elements reach a substantial value of about 30% while the difference for the ratio of these fluxes is < 10%. It appears to be that the ratio $F_{13}/F_{15}$ is a parameter very sensitive to mixing in the solar core. Only future experiments may clarify the question whether the mixing exists or not. The experiments on solar neutrinos are in a mature phase now. The sensitivity and precision increased remarkably during last 30 years [37]–[39]. The new projects LENA [40], SNO+ [41] etc. have increased sensitivity to CNO neutrinos. Here we would like to draw attention to the discovering potential of finding the anomalous high flux $F_{13}$ and may be the ratio of $F_{13}$ to $F_{15}$. This would indicate a mixing in the core of the Sun and other solar type stars of main sequence.

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