Range of stability of solar neutrino flux from the SAGE experiment data

V. A. Koutvitsky, V. B. Semikoz, and D. D. Sokoloff

Abstract

We study the extent to which the SAGE experiment data indicate the permanence of the solar neutrino flux. It is shown that in the first approximation this flux is constant and its distribution function is unimodal. Using a more detailed analysis one finds out that data of the first years of experiment (1990-1992) demonstrate a time dependence which is slightly different from what was found for the subsequent years (1993-2006). The distinctive feature of the first years of experiment is a high dispersion of neutrino flux in comparison with the following epoch. We discuss possible astronomical consequences of this result.

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1 Introduction

The problem of a possible presence of solar neutrino flux periodicities in different neutrino experiments and the possibility to find correlations of flux changes with dynamics of different tracers of solar activity attracts permanent attention of researchers. For instance, in the works [1, 2] one states the presence of anticorrelation of the neutrino flux and solar activity while in the paper [3] one postulates the existence of rotational modulation of neutrino flux with the period $\sim 30$-60 days. In the first case, in the paper [2], the Homestake experiment data during 1970-1990 years [4] are confronted with variations of the solar surface magnetic fields. In the second case, GALLEX experiment data for 1992-1997 are analyzed. In the paper [3] one finds bi-modality of the neutrino flux distribution function in the GALLEX experiment. On the other hand, in the paper [5], the author could not find variations of the neutrino flux in the data of GALLEX-GNO experiments.
It is difficult to follow a relation of the Sun short-periodic rotation with the variations of solar neutrino flux [3] using mechanism of the neutrino resonant spin-flavor precession (RSFP) such as (i) conversion of the left-handed electron neutrino into the sterile right-handed one, $\nu_{eL} \rightarrow \nu_{sR}$, due to a large neutrino transition magnetic moment ($\mu_\nu \sim 10^{-11}\mu_B$) and (ii) slowly changing magnetic field in the convective zone (CZ) of the Sun [16]. The variations of magnetic field are related with rather longer periods of the order of solar cycle (see details below in Section IV).

In connection to the above it seems to be useful our returning to the question how much (in what measure) the SAGE experiment data allow to select variations of the solar neutrino flux. Moreover, if such variations are noticeable with a some probability in observations then which physical mechanisms can (or can not) govern such flux variations.

Carrying out the analysis of the SAGE experiment data we rely here on the solar neutrino data in that experiment for 1990-1997 [6], 1990-2001 [7] and also the data of the recent measurements until 2006 year [8] that allow us to analyze all neutrino events for the period 1990-2006 [3] (in Fig. 1), i.e. during the longest period of solar neutrino observations after the chlorine-argon (Homestake) experiment [9] accounting for the calibration of detector in the SAGE experiment [10].

Carrying out our statistical analysis we take into account the fact that duration of one run in the SAGE experiment is $\sim 30$ days that excludes selection of short-periodic processes. On the other hand, we have no reliable theoretical predictions of which kind of the neutrino flux changeability (periodicity, pulsed processes or something else) one could expect for given experiment data. Therefore, in the statistical analysis of the SAGE experiment data we try to use general statistical tests not requiring any model of expected variations specified by a certain dependence on unknown parameters (e.g. by frequencies of variations).

We do not discuss here neutrino flux variations happening outside the Sun. These are day/night variations arising due to regeneration of electron neutrinos traveling (in night) through the Earth, and seasonal variations appearing due to geometric effects such as $\sim L^{-2}$ from the Earth orbit eccentric-

\footnote{V.N. Gavrin, private communication. Authors thank V.N. Gavrin and Bruce Cleveland who put their materials at our disposal (including data for 2006 year) and acknowledge useful discussions with them. In the paper [8] the results of the global analysis of the registered solar neutrino fluxes are given using the method of the maximum likelihood, including SAGE data until December 2005.}
Figure 1: Time series for SAGE solar neutrino data for 1990-2007. Points are best fits of SNU. Error bars for best fits are shown.

Emissivity ($\varepsilon = 0.0167$) always taken into account in all radiochemical experiments in the correspondence with a data (month) of measurements. Finally nadir angle and latitude of a detector for events registered are taken into account (see e.g. in [11]). Here we discuss the possibility for more slower variations of neutrino flux using the SAGE experiment data and study their relation with phenomena inside the Sun that have periods $\sim$ years and much more.

The paper is organized as follows: in Section 2 we present SAGE solar neutrino datasets and give the simplest statistical analysis of the SAGE datasets. From the statistical analysis of the SAGE solar neutrino data we find in Section 3 two epochs, 1990-1992, and 1993-2006, which have some slightly distinguishable capture rate profiles which could be associated with some kind of the varying solar activity. In Section 4 we discuss possible mechanisms responsible for the variation of the solar neutrino data and stress their imperfection from the point of view of particle physics and solar physics. In the last Section 5 we discuss results of our analysis confronting them with the mechanisms discussed in the previous Section.
2 Statistical analysis of neutrino flux

Below we perform a statistical analysis of the SAGE data in order to address the following problems: (i) to what extent the data can be considered as a realization of a stationary random process, e.g. Poisson process; (ii) if this is the case, what is the probability distribution function (pdf) of that random process? Let us note that if a random process is essentially unsteady then data of one time-series do not allow to restore a distribution function because it changes essentially over time and we dispose at each time moment only one measurement to determine pdf.

We address the first question using a simple test presented in Fig. 3. If the time series presented in Fig. 1 can be considered as a realization of a stationary random process \( f \) with nonvanishing mean value \( \langle f \rangle \) then the cumulative capture rate \( g(n) = \sum_1^n f(n) \) summing over the exposition run number \( n \) has to grow with \( n \) as \( \langle f \rangle n + \ldots \) where the symbol \( \ldots \) mean terms which grow slower than \( n \). If the plot does not demonstrate a linear shape we have to reject the hypothesis that \( f \) is a stationary random process. Note that if there are some gaps in time-series we have just to omit corresponding months in the calculation of the exposition run numbers. The plot of \( g(n) \) as it is obtained in accordance with the SAGE data is presented by solid line in Fig. 3. We see that the plot is amazingly linear for \( n > N \approx 30 \). Its slope gives \( \langle f \rangle \approx \text{const} \) for the epoch after 1993.

Hence not considering small deflections from the linear law during first 2-3 years of experiment we have no grounds to speak about any variations of neutrino flux (i.e. about deflections from the linear law given by the function \( g(n) \)), in any case at the time scales acceptable for analysis of the given experiment.

Then we can plot the distribution function of the studied random process which is considered as a steady one. Since the volume of analyzed sampling is small we do not rely on evaluation of the probability density based on histograms that show the relative number of exposures corresponding to a given interval of neutrino fluxes. Instead of that we plot the corresponding integral value, namely empirical distribution function, i.e. the relative exposure number with the capture number less than the given one (in Fig. 4). As any distribution function it vanishes for small \( x \) (in fact, at \( x = 0 \)) and tends to the unity for large \( x \). In the given case the obtained dependence changes smoothly between those limiting values. This pdf is similar to the gaussian distribution shown in the same Figure (panel b). Let us note that such pdf
can not be exactly gaussian since it is not negative due to its physical sense. As a whole Fig. 4) demonstrates unimodal distribution of the neutrino flux. The same conclusion follows from the analysis of histograms for distribution density comprising all experiment period (see in Fig. [2]). One can easily see that after a reasonable bunching of data (over 16 bins) the corresponding histogram has no features of bimodality. The more detailed histograms shown in Fig. [2, b,c,d) demonstrate only significant dispersion of experimental data and also can not be as indication a bimodality of the considered distribution.

Figure 2: The histograms of the SAGE data grouped by SNU value into 16, 32, 64, and 128 bins.
3 Statistical properties of SAGE experiment data during 1990-1993

Let us note that data of the first 30 exposure runs precipitate from the description given above as it is seen in the beginning of curve shown by the solid line in Fig 3. In order to demonstrate that the 30 exposure runs are sufficient to isolate a linear growth we perform the same test omitting first 30 exposure runs (dashed line in Fig. 3). We see that the line obtained demonstrates a linear growth almost from its beginning and the slope is the same as for the solid line.

![Figure 3: Cumulative capture rate (SNU) versus the exposition run number (solid line). Dashed line presents the cumulative capture rate versus the exposition run number for the last part of the SAGE experiment (after the year 1993; dashed line).](image)

We conclude also that the probability distribution function (pdf) of the random process \( f \) has to be considered for epoches I and II separately. We
present corresponding data in Fig. 4 for epoch I by dashed line and for epoch II by solid line. For that summing over exposure run numbers with a given rate (SNU) and normalizing partial sums on the run numbers (=30) during epoch I and (=127) during epoch II we get corresponding pdf curves.

We see that pdf for epoch I was much wider than for epoch II. The mean value $< f >$ for epoch I is slightly larger than the mean value for epoch II. This means that during epoch I a noticeably larger dispersion of the neutrino flux was registered than during epoch II. The distribution functions for both epochs indicate a unimodal distribution while these distributions are different. Let us stress that data under analysis are not sufficient to insist on a stability of random process considered during the epoch I, i.e., the interpretation of the corresponding empirical distribution function remains to some extent as only conventional.

![Figure 4](image_url)

**Figure 4:** Cumulative distribution functions (probability, i.e. relative number, to obtain capture rate less than $x$ SNU) versus $x$: a) - for epoch I (dashed line) and epoch II (solid line); b) - for all SAGE data (solid line), gaussian distribution (dashed line).

The assumption that the difference between epochs I and II corresponds to some real processes in the Sun leads immediately to the serious astronomical conclusions. In the next Section we show that it is difficult to interpret this distinction through processes occurring within the solar convective zone.
4 Solar magnetic fields and possible mechanisms responsible for solar neutrino flux variation

The solar activity is connected with changing magnetic fields within solar interior, e.g. in terms of the dynamo theory of the solar cycle [12]. Some traces of these changing magnetic fields are observed in the bipolar active regions consisting of sunspots as bundles of magnetic loops floating upwards from an initially horizontal magnetic field in the convective zone (CZ). The polarity rules of the active regions on the sun show: (i) that the horizontal magnetic field below the surface is nearly East-West oriented, (ii) that the toroidal field $B_{\text{tor}}$ direction is opposite in each hemisphere, and (iii) that a polarity reversal takes place from one cycle to the next. Though magnetic fields in sunspots (surface fields $B_s$) were discovered long time ago we do not know how they change in time and how these variations are related to the large-scale (toroidal $B_{\text{tor}}$) magnetic field at the bottom of CZ. Moreover, $B_s$-measurements do not provide magnetic field at each point in the Sun (and, which is still more important, not the field on the "solar center-observer" line), but rather an uncompensated part of the general field whose relation to $B_\perp$ influencing neutrino spin-flip is unknown. Thus, these surface magnetic field data (as well as the Wolf numbers) can be used only as indirect information on $B_\perp$ and CZ magnetic fields.

4.1 Spin-flavor precession (SFP) scenario of the neutrino flux variation

In both cases of long time neutrino datasets mentioned above the authors [2,3] assumed the presence of a non-zero neutrino magnetic moment $\mu_\nu \neq 0$ due to which some part of the electron neutrino flux can be converted in the changing solar magnetic fields to another neutrino species not registered in radiochemical experiments which are sensitive to the charge current interactions provided by the left-handed electron neutrinos $\nu_{eL}$.

For instance, this process can be an efficient (vacuum non-resonant) active-active Majorana neutrino spin-flavor precession $\nu_{eL} \rightarrow \bar{\nu}_{aR}, \nu_{aL} \rightarrow \bar{\nu}_{eR}$ in random magnetic fields within the diluted solar CZ that happens after the dominant LMA MSW conversion $\nu_{eL} \rightarrow \nu_{aL}$ in dense matter of the radiative zone (RZ) [13] for which the LMA neutrino mixing parameters at 1 $\sigma$ (3$\sigma$)
level [14],

\[ \Delta m_{21}^2 = 7.67^{+0.22}_{-0.21} \left(^{+0.67}_{-0.61}\right) \times 10^{-5} \text{ eV}^2, \quad \theta_{12} = 34.5 \pm 1.4 \left(^{+4.8}_{-4.0}\right), \quad (1) \]

are firmly established from all neutrino experiments including KamLAND with reactor antineutrinos \( \bar{\nu}_e \) [15]. There remains an open problem for the scenario with the \( \text{rms} \) magnetic field \( b(t) = \sqrt{b^2} \), namely, how it depends on time during solar activity to be relevant for our discussion of varying neutrino fluxes.

Another possibility is a more speculative RSFP conversion to an additional sterile neutrino in a regular CZ magnetic field with the appropriate \( \Delta m_{10}^2 = O(10^{-8}) \text{ eV}^2 \) that proceeds after the dominant LMA MSW in RZ with the mixing parameters for active neutrino species given by Eq. (1) [16]. In addition to the unknown connection of a strong regular CZ magnetic field \( (B_\perp \sim 300 \text{ kG}) \) with the measured varying surface magnetic fields \( B_s \) in sunspots \( (\sim \text{kG}) \) the assumption of a light sterile neutrino together with unknown magnetic moment are too doubtful.

The present laboratory bounds on the neutrino magnetic moment are given by the reactor antineutrino scattering off electrons at low energies as \( \mu_\nu \leq 9 \times 10^{-11} \mu_B \) in the MUNU experiment [17] and \( \mu_\nu \leq 5.8 \times 10^{-11} \mu_B \) by GEMMA spectrometer [18] while there are more severe astrophysical bounds \( \mu_\nu \leq 3 \times 10^{-12} \mu_B \) [13, 19].

### 4.2 Parametric resonance of MSW oscillations in the presence of matter density perturbations in radiative zone (RZ)

There is another possibility to observe time variations of solar neutrino fluxes not exploiting idea with neutrino magnetic moment while relying on the presence of magnetic fields in RZ and commonly held LMA MSW scenario of neutrino oscillations. This is an old idea of the parametric resonance for matter density perturbations influencing MSW oscillations [20] when the wave length \( \lambda_{\delta \rho} \) for the matter perturbation \( \delta \rho(t, r)/\rho \) in the total neutrino potential \( V_{\text{MSW}}(1 + \delta \rho/\rho) \) entering Schrödinger equation that governs neutrino oscillations coincides with the neutrino oscillation length, \( \lambda_{\delta \rho} \approx l_\nu = 4\pi E/\Delta m_{12}^2 \). This is impossible for the long p,g-mode waves in the standard helioseismol-
ogy, for which $\lambda_{p,g} \sim 10^4 - 10^5$ km is much bigger than $l_\nu \sim 100 - 200$ km for $O(MeV)$-neutrinos while this can be realized for short magneto-gravity (MG) waves in the horizontal RZ magnetic field, $\mathbf{B} \perp \nabla \rho$ [22].

The appearance of the Alfvén resonance for such geometry of magnetic field leads to the rise of many spikes of density perturbations separated by the distances of the order 100-200 km exactly as the solar neutrino oscillation length that provides the parametric resonance [22]. On the other hand, the cavity for magneto-gravity waves bounded by the center of the Sun and these spikes blocks g-mode propagation within RZ, or they become evanescent even deeper than the bottom of CZ. Since the the presence of MG resonance tends to decrease MSW effect, the prediction would be that the observed rate of solar electron neutrino events is maximized when the Earth is closest to the solar equatorial plane (December and June) and is minimized when the furthest from this plane (March and September) [22]. This happens because of 7-degree inclination of the Earth’s orbit relative the plane of the solar equator in which neutrinos registered at the Earth permeate the horizontal RZ magnetic field $\mathbf{B} \perp \nabla \rho$ and these seasonal $\nu$- flux variations are possible without neutrino magnetic moment, $\mu_\nu = 0$. Other periodicity connected with the low frequency MG waves (periods of order $\sim$ days, weeks) is less pronounced in [22] because of poor neutrino event statistics at present.

In addition to, the model of a central (RZ) magnetic field is less elaborated than models of CZ fields, and, moreover, MG modes if such form of g-modes exists should be invisible on the solar surface.

Resuming we would like to stress that all known mechanisms for the variations of electron neutrino flux deep the solar interior rely on varying magnetic fields which influence neutrino oscillations either in SFP assuming a nonzero neutrino magnetic moment or due to the parametric resonance of LMA MSW oscillations. In both cases there are still too much uncertainties of a solar MHD model to apply appropriate issues for neutrino propagation in the Sun.

\[2\]Note that helioseismology bound $\delta \rho/\rho < 0.01$ for matter density perturbations in RZ which is coming from the solution of inverse problem using the data with long wavelength p-modes [21] fails at short distances corresponding to the neutrino oscillation length.
5 Conclusions

Thus, we showed that except of the initial period 1990-1992 the SAGE experiment data describe the solar neutrino flux as a steady random process having the simplest one-modal distribution. The peculiarity of SAGE data for the initial period of observation is not some sort of periodic process with a period comparable with the whole time of SAGE experiment. Considering that data separately it is simpler to explain them as a display of some instability appearing from time to time in solar CZ. However the conclusion about the existence of such instabilities in CZ seems to be too radical and premature being based on these data only.

This is confirmed by a short analysis of MHD models and mechanisms of neutrino interaction with solar magnetic fields as given in the previous Section. On the first glance, after the maximum of the solar activity in 1990 CZ magnetic field strengths were decreasing resulting in an increase of the electron neutrino survival probability if we rely on the SFP scenario, let us say, for subdominant $\nu_e \rightarrow \nu_s$ conversion in CZ as in the paper [16]. Thus, SAGE registered more solar electron neutrinos during epoch I. However, we do not understand why when 11 years passed, e.g. in 2003-2006 we do not observe the same increase of the solar neutrino flux during next 23 cycle of the solar activity with its minimum somewhere in 2007. This turns us to think that another solar periodicity (with a longer period $> 11$ years) acts on solar neutrino flux during epoch I.

Nevertheless we think that the potential ability of such conclusion itself is enough to proceed SAGE experiment over a long period of time.

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