

Oscillation Effects On Neutrinos From The Early Phase Of a Nearby Supernova

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Abstract

Neutrinos emitted during stellar core collapse leading to a supernova are primarily of the electron neutrino type at source which may undergo oscillation between flavor eigenstates during propagation to an earth-bound detector. Although the number of neutrinos emitted during the pre-bounce collapse phase is much smaller than that emitted in the post-bounce phase (in which all flavors of neutrinos are emitted), a nearby supernova event may nevertheless register a substantial number of detections from the pre-bounce phase at SuperKamiokande (SK) and the Sudbury Neutrino Observatory (SNO). The calorimetric measurement of the supernova neutrino fluence from this stage via the charge current and neutral current detection channels in SNO and the corresponding distortion of detected spectrum in SK over the no-oscillation spectrum, can probe information about neutrino mass difference and mixing which are illustrated here in terms of two- and three-flavor oscillation models.

Keywords: Stars, supernovae, general – Elementary particles

Introduction

Large underground experiments with the main purpose of detecting solar neutrinos are already on-line (*e.g.* SuperKamiokande, hereafter SK - see Totsuka 1990) or shortly expected to be operational (Sudbury Neutrino Observatory, hereafter SNO 1987). The latter experiment, because of its capability to detect neutrinos *via* both charged-current as well as neutral-current detection channels is expected to probe the role of neutrino oscillation in the reduction of solar neutrino flux from its “standard” value (Bahcall 1989, SNO 1987). These experiments will also be able to easily detect neutrinos from a supernova explosion anywhere in the Milky Way galaxy. If a core collapse supernova occurs sufficiently nearby (typically 1-2 kpc away), then they should detect a substantial number of neutrinos even from the stellar core collapse phase (Sutaria & Ray 1997 (SR)) which are far less copious than the neutrinos from the post-bounce phase (Burrows 1990; Burrows et al. 1990, Totani et al. 1997). Neutrinos from the core-collapse phase, like the solar neutrinos, are mainly of the electron neutrino type - the product of continuum electron capture on free protons and neutron-rich nuclei present in the stellar core. Thus, if the calorimetric measurement of the neutrino fluence in the neutral current channel in SNO - which is neutrino flavor insensitive - exceeds the energy integrated neutrino fluence in the charged current channel, after accounting for corresponding detection efficiencies, then this would be a clear signal of neutrino flavor oscillation during propagation. Such an event and its detection will probe the neutrino mass and mixing parameters in a very different regime than that possible from measurement of solar, atmospheric and accelerator neutrinos.

Totani (1998) has considered the possibility of neutrino mass determination by using arrival time sequence analysis at different energies of the abundant post-bounce (anti)neutrinos in the Super-Kamioka detector. This proposed method of neutrino mass determination has been argued to remain valid in the case of almost degenerate hierarchy of neutrino masses ($m_{\nu_e} \simeq m_{\nu_\mu} \simeq m_{\nu_\tau}$) even with neutrino flavour oscillations. In this paper we consider the complementary information that can be probed from supernova about neutrino mass *differences* and other associated parameters due to neutrino oscillation between different flavor eigenstates in a nearly degenerate mass hierarchy by using a combination of spectra and total number of events in certain chan-

nels provided by these two different experiments. Totani (1998) indicates that m_{ν_e} of ~ 3 eV can be probed by a future galactic supernova, whereas we show here that a mass *difference* scale $\sqrt{\Delta}$ will be probed at 10^{-9} eV should the core collapse phase neutrinos be detected by SK and SNO.

Oscillation of Neutrinos From Stellar Core Collapse Phase

The recent SuperKamiokande announcement of the discovery of neutrino mass and oscillation in their atmospheric ν data (Kajita 1998) is a milestone in the physics of neutrinos with wide implications for astrophysics and particle physics. It has, of course, been widely held for some time that oscillations of ν_e to a neutrino of a different flavor may hold the key to a solution of the long-standing solar neutrino problem. Encouraged by these developments, we first discuss the effect on the SN signal of the oscillation of ν_e with one other neutrino type in some detail. This study indicates that for certain ranges of the mass-difference and the mixing angles one gets considerable depletion in the number of detected neutrinos. The study is carried out for two different sets of zero age main sequence stellar masses corresponding to different sets of initial conditions prior to core collapse, *i.e.* for a $15M_{\odot}$ and a $25M_{\odot}$ star, though we present results mostly for the former case. The LEP experiments at CERN have established that there are three light neutrino flavors. In view of this, we also extend the analysis to the case of three-neutrino mixing. In this scenario, we choose the three neutrino masses so that one of the oscillation lengths is of the order of the sun-earth distance while the other is of a distance corresponding to a galactic supernova in the solar neighbourhood.

The core of a massive star collapses under its own gravity once the nuclear burning stops and the pressure support from degenerate electrons is reduced due to electron capture. Neutrinos are emitted from the supernova at two stages: the first during collapse in a burst of about ten milliseconds from neutronization through electron capture until neutrino trapping sets in and the second one in the hotter post-bounce era in the form of thermal neutrinos of all three flavors in a time-scale of a few seconds. In this report we shall concern ourselves with the first stage though the flux of post-

bounce neutrinos is higher.

Expected number of detections in SNO and SK have been calculated for neutrinos from a typical $15M_{\odot}$ star undergoing core collapse at a distance of 1 kpc during its neutronization phase (SR). The neutrino spectra observable by these experiments, for a realistic range of nuclear physics input and stellar masses on the main sequence were also given. Neutrinos which are emitted before they undergo inelastic scattering and trapping by overlying stellar matter carry with them information about the physical conditions within the core as well as its nuclear configuration and hence their detection can be important to understand the supernova dynamics. SR use a one-zone collapse code (Ray et al. 1984) to generate the energy spectrum of the emitted neutrinos and consider the electron capture on both free protons and heavy nuclei (in the fp shell) the abundance distribution of which are self consistently determined with the evolution of thermodynamic conditions as collapse proceeds using an analytical equation of state of warm dense matter due to Bethe et al. (1979) as modified by Fuller (1982).

SR (see also Sutaria 1997) presented a cumulative neutrino fluence till the stellar core reaches a mean density of 2.4×10^{11} gm/cm³ beyond which stage the neutrinos begin to be trapped and undergo inelastic scattering. For completeness, we present in Fig. 1 the results for both the $15M_{\odot}$ (solid line) and $25M_{\odot}$ (dashed line) cases taking the distance to be 1 kpc. The spectra depicted are a sum of contributions from electron capture on both free protons and heavy nuclei, while SR presented the separate contributions of these components for the $15 M_{\odot}$ case. The fluence is folded with the cross-section for the charge current (CC) reaction in the D₂O detector at SNO – $\sigma_{c.c.} = 1.7 \times 10^{-44} \text{cm}^2 (E_{\nu} - 1.44)^{2.3}$ (Burrows, 1990) – to predict the number of neutrinos detectable as a function of the energy. These results are shown for the $15M_{\odot}$ star in Fig. 2 (upper panel - solid curve). In addition, the neutrinos also undergo neutral current interactions but for this process the detector cannot give incident ν -energy information and only calorimetric measurements are possible. We have also folded the fluence with the neutral current (NC) cross-section – $\sigma_{n.c.} = 0.85 \times 10^{-44} \text{cm}^2 (E_{\nu} - 2.2)^{2.3}$ (Burrows 1990) – to obtain a result which is not affected by oscillations since the NC interaction is flavor-blind. We find that the total (*i.e.*, energy integrated) signal due to the neutral current reaction is less than that for the charged current case due to differing detection

efficiencies. It is seen that the ratio of the total NC signal and the corresponding CC signal at SNO – which is relatively insensitive to the details of the initial star – is a useful measure for oscillations (see later).

The SuperKamiokande detector uses 32 ktons of light water in which electrons scattered by ν_e – through both charged and neutral current interactions – are detected *via* Čerenkov radiation. In this case, the cumulative fluence is folded with the $\nu_e - e^-$ scattering cross-section – $\sigma = 0.94 \times 10^{-43} \text{cm}^2 (E_\nu/10\text{MeV})$ (Sehgal, 1974). The results for this detector are shown for the $15M_\odot$ star in Fig. 2 (lower panel - solid curve).

In this paper we estimate the effect on both the SNO and SK signals when neutrino oscillations are operative. We consider oscillations of the electron neutrinos to other sequential neutrinos: *i.e.*, ν_μ or ν_τ . (We make some comments about oscillation to sterile – *non-interacting* – neutrinos towards the end). In the two-flavor case, the probability of an electron neutrino of energy E_ν to oscillate to a neutrino of a different type – $\nu_x, x \equiv \mu$ or τ – after the traversal of a distance L is:

$$P_{\nu_e \rightarrow \nu_x} = \sin^2(2\theta) \sin^2\left(\frac{\pi L}{\lambda}\right) \quad (1)$$

where θ is the mixing angle and the oscillation length is given in terms of the mass-squared difference Δ by:

$$\lambda = 2.47 \left(\frac{E_\nu}{\text{MeV}}\right) \left(\frac{\text{eV}^2}{\Delta}\right) \text{ meter} \quad (2)$$

From probability conservation: $P_{\nu_e \rightarrow \nu_e} = 1 - P_{\nu_e \rightarrow \nu_x}$.

Consider now the effect of oscillations on the neutrino signal from the early phase of a galactic supernova. At SNO, the ν_μ or ν_τ generated by oscillations cannot interact *via* the charged current. The prediction for this signal is obtained by folding $P_{\nu_e \rightarrow \nu_e}$ with the fluence and the charged current neutrino absorption cross-section. It undergoes a depletion shown for some typical cases – $\Delta = 1 \times 10^{-18} \text{ eV}^2$ and $\theta = 30^\circ$ (long-dashed curve) and $\Delta = 2.5 \times 10^{-18} \text{ eV}^2$ and $\theta = 35^\circ$ (small-dashed curve) – in Fig. 2. The oscillatory behavior of neutrinos, though modulated by the fluence, is clearly perceptible and change with Δ as expected. In particular, for the chosen Δ the signal at the high energy end suffers a strong depletion.

The smallness of our choice of Δ might call for a remark. The energy and length scales associated with supernova neutrinos provide a unique window for very small mass splittings – a point noted earlier by Reinartz and Stodolsky (1985). Small though this may appear at first sight, it is only five orders of magnitude smaller than that for K^0 s.

The μ or τ neutrinos contribute to the SuperKamioka signal only through neutral current interactions for which the cross-section is $\sigma(\nu_x \rightarrow e) = 1.6 \times 10^{-44} \text{cm}^2 (E_\nu/10 \text{MeV})$, $x = \mu$ or τ (Kolb et al. 1987). The effect on the detected signal in this case is presented in Fig. 2 (lower panel). The oscillatory behavior of the signal in this case is again apparent, more so since the SK signal is much broader than that of SNO.

In SNO, the ν_μ and ν_τ neutrinos will not induce charged current reactions but will undergo neutral current interactions with full strength. Since the neutral current signal at SNO is immune to oscillations, the ratio, R_{SNO} , of the calorimetric detection of the neutrino fluence via the NC channel to the total (energy integrated fluence) detection via the CC channel ($5 \text{ MeV} \leq E_\nu \leq 25 \text{ MeV}$) is a useful probe for oscillations. Some results for this ratio are presented in Table 1. For comparison we have shown the results for R_{SNO} without and with oscillation for both $15M_\odot$ and $25M_\odot$ stars. It is seen that the value of R_{SNO} is not sensitive to the typical examples of stellar collapse shown here, which includes a combination of initial conditions as reflected in the zero age main sequence mass of the pre-supernova star, matrix elements of the electron capture on heavy nuclei etc. – it remains fixed at 0.434 while going from $15M_\odot$ to $25M_\odot$. Therefore, if R_{SNO} is observed to be significantly larger than the predicted no-oscillation value then this difference cannot be attributed to the range of variations expected from astrophysical and nuclear physics grounds. The relative strengths of the Supernova neutrino signal from electron capture on free protons and on heavy nuclei is determined by the dynamics and thermodynamics of the initial star. It is seen from Table 1 that the range of variation of R_{SNO} due to capture only on protons or only on heavy nuclei (which encompass any intermediate possibility) is not large – *e.g.* for the $15M_\odot$ case, it varies from 0.444 to 0.396 – and, in particular, cannot mimic the effect of oscillation which can yield values as large as 0.776. Therefore a measured value of R_{SNO} different from the theoretical prediction will be indicative of neutrino oscillations. In Fig. 3 we present contours of constant R_{SNO} in the $\Delta - \theta$ plane. The

shape of these contours can be readily explained using eq.(1).

The Three Flavor Case

Now let us turn to the case of three flavors. Though we restrict ourselves to three flavors for simplicity, the experimental indications point towards four or more neutrino types. This is because the explanation of the solar, atmospheric, and LSND ν results within the neutrino oscillation framework requires vastly different mass differences. In view of the findings of the LEP experiments, this would require the introduction of one or more sterile neutrinos.

The two flavor case can always be recovered from the three flavor one by a suitable choice of the mixing angles. But the three flavor scenario has some additional features which merit examination. The general expression for the probability for a ν_α to oscillate to ν_β after traversing a distance L is given by (Goswami et al. 1997)

$$P_{\nu_\alpha\nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{j>i} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \sin^2 \left(\frac{\pi L}{\lambda_{ij}} \right) \quad (3)$$

Here the flavor basis is identified by greek indices while the mass eigenstates are represented by roman indices. L is the distance from the detector to the source and $\lambda_{ij} = 2.47 (E_\nu/\text{MeV}) (\text{eV}^2/\Delta_{ij})$ meter, is a characteristic oscillation length. In the above, $\Delta_{ij} = m_j^2 - m_i^2$. The matrix U , which relates the flavor eigenstates to the mass eigenstates, can be represented in the three-flavor case in terms of three mixing angles θ_{ij} as:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}c_{23} - s_{13}s_{23} & c_{13}s_{12}s_{23} + s_{13}c_{23} \\ -s_{12} & c_{12}c_{23} & c_{12}s_{23} \\ -s_{13}c_{12} & -s_{13}s_{12}c_{23} - c_{13}s_{23} & -s_{12}s_{13}s_{23} + c_{13}c_{23} \end{pmatrix} \quad (4)$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. Since we are not interested in CP-violation in the neutrino sector, U has been chosen real. The flavor states are: $\alpha = 1$ (e), 2 (μ), and 3 (τ).

In line with the discussion earlier, we consider one of the mass splittings Δ_{23} to be around 10^{-18}eV^2 so that the the oscillation length λ_{23} for neutrinos of energies in the 10 MeV range is around 1 kpc. We choose the other splittings $\Delta_{12} \simeq \Delta_{13} = 10^{-10}$

eV² so that $\lambda_{12} \simeq \lambda_{13}$ corresponds roughly to the earth-sun distance (assuming that the discrepancy of measured and astrophysically predicted solar neutrino fluxes is due to neutrino flavor oscillations on such length scales). In the present case of a galactic Supernova, we set L to 1 kpc ($\gg \lambda_{12} \simeq \lambda_{13}$) and one has:

$$\begin{aligned}
P_{\nu_e \rightarrow \nu_e} &= 1 - 2c_{13}^2 c_{12}^2 + 2c_{13}^4 c_{12}^4 \\
&- 4(c_{13} s_{12} c_{23} - s_{13} s_{23})^2 (c_{13} s_{12} s_{23} + s_{13} c_{23})^2 \sin^2 \left(\frac{\pi L}{\lambda_{23}} \right)
\end{aligned} \tag{5}$$

We do not present the explicit forms of $P_{\nu_e \rightarrow \nu_\mu}$ and $P_{\nu_e \rightarrow \nu_\tau}$ which can be readily obtained.

As noted earlier, the ν_μ and ν_τ cannot produce the charged current signal at SNO. Due to three-flavor oscillation, this signal undergoes a depletion shown for the purposes of illustration for a typical choice of mixing angles in Fig. 4 (upper panel - dashed line) where we have chosen $\theta_{12} = 6.5^\circ$, $\theta_{13} = 25^\circ$ and $\theta_{23} = 10^\circ$ and find a reduction in the signal of $\sim 30\%$. The results for SuperKamioka are similar and are presented for the same choice of neutrino mixing parameters in Fig. 4 (lower panel).

In Fig. 4, the results for the parameter set $\theta_{12} = 6.5^\circ$, $\theta_{13} = 25^\circ$ and $\theta_{23} = 10^\circ$ have been presented. We have examined the effect of varying all the three angles and have found that the reduction for both SNO and SK is only mildly sensitive to θ_{23} and depends more on θ_{12} and θ_{13} . For example, if θ_{12} is increased from 6.5° to 15° while the other mixing angles are unchanged, then the percentage reduction for SNO (SK) increases from $\sim 30\%$ ($\sim 26\%$) to $\sim 37\%$ ($\sim 31\%$). Similarly, a change of θ_{13} from 25° to 10° , keeping the other two angles fixed, results in a drop of the reduction to $\sim 17\%$ ($\sim 16\%$). These results can be readily understood from eq. (5) from where it can be concluded that so long as the θ_{ij} mixing angles are small, the leading θ_{12}, θ_{13} contributions depend quadratically on the angles while the leading θ_{23} dependence is multiplied by a quartic product of the other angles.

If the neutrino mass-squared difference Δ_{23} is much smaller than the chosen 10^{-18} eV², then the corresponding oscillation length will be larger than L and the effect of this mode will not be seen – *e.g.*, the last term in eq. (5) will be absent. On the other hand, if Δ_{23} is much bigger than the chosen value then the oscillatory term in these equations – $\sin^2(\pi L/\lambda_{23})$ – will be averaged to $\frac{1}{2}$. Thus the detection of a distorted spectrum

of neutrinos from the core collapse phase of a supernova by SuperKamioka and SNO would probe a different range of the mass-mixing parameters (than the solar neutrino parameters) - which is determined by the distance to the supernova - an observable quantity which can be astronomically determined *a posteriori*. If the distance to the supernova is however much larger than 1 kpc, the number of detectable neutrinos from this phase may be too small to effectively probe the corresponding mass-mixing region of the neutrino flavors. An undistorted spectrum on the other hand, would be a null experiment since the parameters as discussed above may be different from what is being probed via such experiments.

The neutrinos produced in the pre-bounce stage are all of the electron-type and are produced in a time span of the order of tens of milliseconds. Through oscillations, neutrinos of other flavors are generated. On the other hand, in the post-bounce era, neutrinos and anti-neutrinos of all three flavors are produced. If the difference in the time of travel, ΔT , due to neutrino mass splitting is so large as to wipe out the time gap between the signals from the pre- and post-bounce phase then the detection of ν_μ or ν_τ in the observed beam cannot be unequivocally attributed to oscillations. However, for the mass ranges that would be probed by a SN at 1 kpc, ΔT is much smaller than the duration of the stellar core collapse ($\simeq 10$ ms). This is readily seen as follows. In order to avoid irrelevant complications consider the two-flavor scenario. Here we have:

$$\Delta T = \frac{L}{c} \left[\frac{1}{\beta_1} - \frac{1}{\beta_2} \right]$$

Here, $E/m = 1/\sqrt{1-\beta^2}$ whence $(\beta_2^2 - \beta_1^2) = m_1^2/E_1^2 - m_2^2/E_2^2 \simeq \Delta/E^2$. Choosing $\Delta = 10^{-18}$ eV², taking $E = 10$ MeV ($\beta \sim 1$), and with $L = 1$ kpc, $\Delta T \simeq 10^{-21}$ sec.

Discussion and Conclusions

In this work, we have considered the oscillation of ν_e to other sequential neutrinos. If instead, the oscillation is to sterile neutrinos - with no coupling to the electroweak gauge bosons - then the following changes will occur. In SNO, both the charged *and* neutral current interactions will suffer depletion and thus the ratio R_{SNO} (see Table 1) will be almost unchanged. However, in SK the sterile neutrinos will have no interaction

whatsoever (unlike the NC interactions of the sequential neutrinos) and hence the signal will be reduced even further. We hope to make a detailed, comparative assessment of the two scenarios in subsequent work.

The mass square differences we have considered – 10^{-18} eV² – dictated by the energy and length scales that characterize the situation are indeed very small. For a comparison note that the recent announcement of the discovery of neutrino oscillation in the atmospheric ν data by SuperKamiokande relies on neutrinos produced in the atmosphere with energies in the GeV scale and with path lengths ranging from tens of kilometres (downward going ν s) to around ten thousand kilometres (upward going ν s) (Kajita 1998). They are therefore sensitive to mass differences around 10^{-2} eV² which may be tested by the long baseline accelerator experiments. Solar neutrino experiments with typical MeV energies (Bahcall 1989) may signal mass differences in the 10^{-5} eV² (MSW) to the 10^{-10} eV² (vacuum oscillation) range. The results of the LSND experiment (Athanasopoulos et al., 1995) are indicative of $\nu_\mu \leftrightarrow \nu_e$ oscillation with mass differences of the order of eV². In view of these results and the current availability of large neutrino detectors, supernova neutrinos provide a means to probe a new scale of mass differences.

Although the *a priori* event rate of such nearby supernova explosion may be argued to be low, (Strom (1994) has given the historical supernova rate in the galaxy to be 5.7 per century while Cappellaro *et al.* (1997), based on SN rates in external galaxies give this rate for a galaxy similar to ours as 2.2 ± 1.3 SN/century), it is difficult to predict with confidence the time of the next such occurrence for such a low event rate phenomenon. In the Orion and other constellations there are a number of super-giant stars within about 500 pc of the sun which have spectral types and absolute magnitudes similar to the progenitor of Supernova 1987A – Sanduleak 69^o-202 – which apart from the classical candidate Betelgeuse – a red super-giant 200 pc away – are potential core-collapse supernova progenitors. It is well-known that SN of type II and Ib/Ic occur in or near the spiral arms of the galaxy from massive star progenitors. Therefore if the progenitors are uniformly strung across spiral arms, the relative number of supernovae within a distance r of the sun (normalised to the total galactic rate) would scale as the ratio of the cumulative lengths of the spiral arms within a distance r from the sun

compared to the total cumulative lengths of all spiral arms of the galaxy. Significant parts of three spiral arms of the galaxy (which are predominantly the sites of type II and Ib/Ic explosions) namely, Cygnus, Saggitarius and the Perseus arms, lie within about 1-2.5 kpc of the sun. The cumulative lengths of all spiral arms in the galaxy can be compared with the total lengths of the spiral arms within ~ 2 kpc of the sun from the Cygnus, Saggitarius and Perseus arms (see e.g. the figures from Taylor and Cordes (1993) and Yadigaroglu and Romani (1997)) - the latter being roughly 10% of the former. Thus the rate of nearby SNe (within about 2 kpc of the sun - so that both Super-Kamioka and SNO would be effective detectors of collapse phase neutrinos) would be about 10% of the galactic SN rate. Many of the historical SNe in the last millennium in our galaxy have taken place within 2-3 kpc of the sun. Therefore it is reasonable to expect from the above scaling arguments that the time interval between nearby supernovae (roughly at 1-2 kpc distance - at which SuperKamioka and SNO will still be able to detect the infall neutrinos) may be once every two to several hundred years. Kepler's SN occurred in 1604, and there has been short intervals of time between supernovae such as the type II Crab SN and SN 1181. The evolutionary status of the core of a massive star may remain uncertain within several thousands of years from the observed surface properties of a super-giant. As in the case of the progenitor of SN1987A, some of the super-giant stars in the solar neighbourhood may in reality be close to the stage of explosion and might eventually provide an opportunity during the projected lifetime of SK ($\simeq 50$ yrs) to experimentally constrain aspects of stellar core collapse and neutrino properties apart from the characteristics of explosion models.

In summary, the neutrino signal from the early phase of a nearby Supernova can undergo significant and detectable modification if neutrino oscillations are operative. Such a distortion of the signal may provide a means to shed new light on neutrino masses and mixing. In particular, it is a unique probe of mass differences ($\Delta \sim 10^{-18}$ eV²) much smaller than those relevant to the solar neutrino problem (typically $\sim 10^{-10}$ eV² for vacuum oscillations) or the atmospheric neutrino anomaly ($\sim 10^{-2}$ eV²).

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Table 1: The ratio, R_{SNO} , of the neutral current detections to the charge current detections at SNO ($5 \text{ MeV} \leq E_{\nu_e} \leq 25 \text{ MeV}$) with and without two flavor neutrino oscillations ($\theta = 30^\circ$ and $\Delta = 1 \times 10^{-18}$).

Star Mass	R_{SNO} without oscillation			R_{SNO} with oscillation		
	free protons	heavy nuclei	total	free protons	heavy nuclei	total
15 M_\odot	0.444	0.396	0.434	0.840	0.577	0.776
25 M_\odot	0.440	0.394	0.434	0.787	0.581	0.754

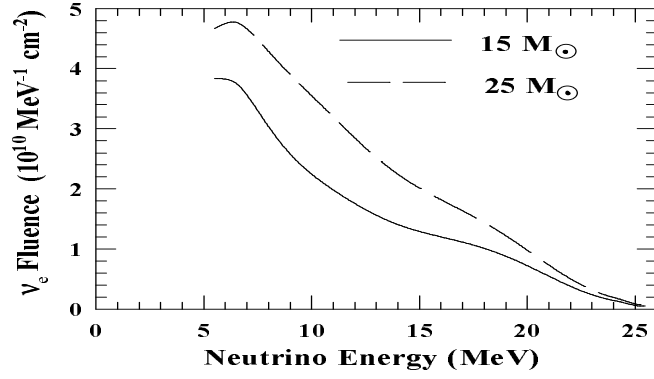


Figure 1: Cumulative incident neutrino fluence till mean stellar density ρ reaches $2.42 \times 10^{11} \text{ gm cm}^{-3}$ for $15 M_{\odot}$ (solid line) and $25 M_{\odot}$ (dashed line) stars 1 kpc away assuming no flavor oscillations.

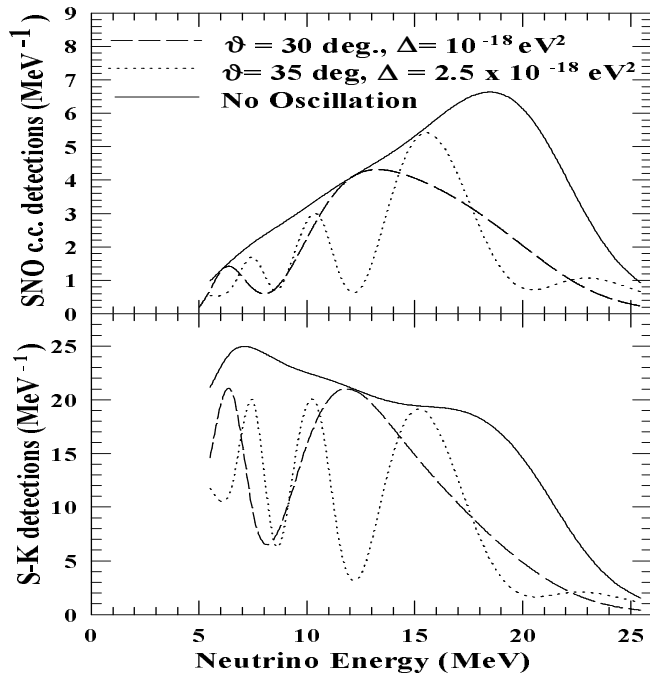


Figure 2: Charged current neutrino signal expected at SNO (upper panel) and SuperKamioka (lower panel) with and without oscillations for a $15M_{\odot}$ star 1 kpc away. The solid line represents the no-oscillation case while the large-dashed (small-dashed) line corresponds to two-flavor oscillations with $\Delta = 1 \times 10^{-18} \text{ eV}^2$ and $\theta = 30^{\circ}$ ($\Delta = 2.5 \times 10^{-18} \text{ eV}^2$ and $\theta = 35^{\circ}$) which corresponds to R_{SNO} (see later) = 0.776 (0.895).

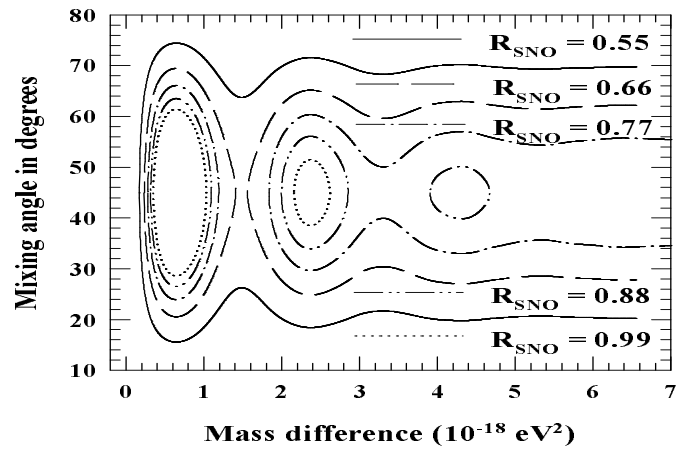


Figure 3: Contours of constant R_{SNO} – the ratio of the NC signal to the energy integrated CC signal at SNO – in the $\Delta - \theta$ plane. No neutrino oscillation corresponds to $R_{SNO} = 0.434$.

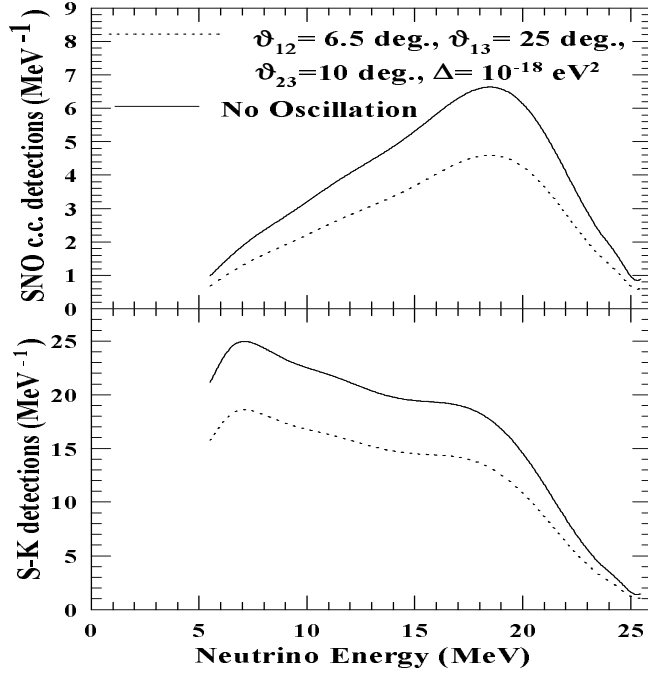


Figure 4: Charged current neutrino signal expected at SNO (upper panel) and at SuperKamioka (lower panel) with and without oscillations in the three-flavor case for a $15M_{\odot}$ star 1 kpc away. The solid line represents the no-oscillation case while the dashed line corresponds to three-flavor oscillations with $\Delta_{23} = 1 \times 10^{-18} \text{ eV}^2$ and $\theta_{12} = 6.5^{\circ}$, $\theta_{13} = 25^{\circ}$, and $\theta_{23} = 10^{\circ}$. This choice corresponds to $R_{SNO} = 0.629$.