Supernova Neutrino Oscillations*

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Abstract

Observing a high-statistics neutrino signal from a galactic supernova (SN) would allow one to test the standard delayed explosion scenario and may allow one to distinguish between the normal and inverted neutrino mass ordering due to the effects of flavor oscillations in the SN envelope. One may even observe a signature of SN shock-wave propagation in the detailed time-evolution of the neutrino spectra. A clear identification of flavor oscillation effects in a water Cherenkov detector probably requires a megatonne-class experiment.

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1 Introduction

While galactic supernovae are rare, the proliferation of existing or proposed large neutrino detectors has considerably increased the confidence that a high-statistics supernova (SN) neutrino signal will eventually be observed. The scientific harvest would be immense. Most importantly for particle physics, the detailed features of the neutrino signal may reveal the nature of the neutrino mass ordering that is extremely difficult to determine experimentally (e.g. Ref. [1] and references). On the other hand, a detailed measurement of the neutrino signal from a galactic SN could yield important clues on the SN explosion mechanism. Neutrinos undoubtedly play a crucial role for the SN dynamics and in particular neutrino energy deposition behind the SN shock is able to initiate and power the SN explosion [2, 3]. However, it is still unclear whether this energy deposition is sufficiently strong because current state-of-the-art models still have problems to produce robust explosions [4]. Empirical constraints on the physics deep inside the SN core would be extremely useful because neutrinos are the only way for a direct access [5] besides gravitational waves [6].

The neutrinos emitted by the collapsed SN core will pass through the mantle and envelope of the progenitor star and on the way encounter a vast range of matter densities \(\rho\) from nearly nuclear at the neutrinosphere to that of interstellar space. The Wolfenstein effect [7] causes a resonance in neutrino oscillations [8] when \(\Delta m^2_{\nu} \cos 2\theta / 2E_\nu = \pm \sqrt{2} G_F Y_e \rho\), where the plus and minus sign refers to neutrinos \(\nu\) and antineutrinos \(\bar{\nu}\), respectively. Therefore, depending on the sign of \(\Delta m^2_{\nu}\), the resonance occurs in the \(\nu\) or \(\bar{\nu}\) channel [9]. For the “solar” neutrino mass-squared difference of \(\Delta m^2_{21} \approx 79\,\text{meV}^2\) [10] one refers to the “L-resonance” (low density) while for the “atmospheric” one of \(|\Delta m^2_{32}| \approx 2300\,\text{meV}^2\) [11] to the “H-resonance” (high density). The resonance is particularly important for 13-oscillations because the 13-mixing angle is known to be small so that the classic MSW enhancement of flavor conversion in an adiabatic density gradient is a crucial feature [12].

Effects of neutrino flavor oscillations will be observable only if the fluxes and/or spectra emitted at the source depend on the neutrino species. Therefore, I will summarize in Sec. 2 the current understanding of SNe as flavor-dependent neutrino sources. In Sec. 3 the effect of neutrino flavor oscillations in different mixing scenarios will be summarized. Sec. 4 is devoted to experimentally observable signatures before turning to conclusions in Sec. 5.

2 Core-Collapse Supernovae as Neutrino Sources

The collapsed core of a SN is essentially a blackbody source for neutrinos of all flavors with a temperature of several MeV, corresponding to the temperature of the medium near the proto-neutron star’s surface. In detail, however, the fluxes and spectra differ between the different species because of their different interaction channels. Electron neutrinos and anti-neutrinos interact only by charged-current processes on nucleons while the other species interact primarily by neutral-current reactions because the relevant energies and densities are too low to produce muons or tau-leptons. Therefore, \(\nu_\mu\), \(\bar{\nu}_\mu\), \(\nu_\tau\), and \(\bar{\nu}_\tau\) will be emitted with identical fluxes and spectra and are thus collectively referred to as \(\nu_x\).
The standard delayed-explosion scenario of SN evolution and thus the neutrino emission is characterized by four distinct phases, schematically indicated in Fig. 1: (1) Core collapse and bounce. (2) Shock propagation and breakout. (3) Accretion and mantle cooling while the shock wave stagnates. (4) Kelvin-Helmholtz cooling of the neutron star after the explosion. Actually, for a very close star the neutrinos emitted during the silicon-burning phase for the last few days before collapse may be observable [13], a possibility that I will not further consider here.

![Figure 1: Schematic SN neutrino “light curves” for different neutrino flavors [14].](image)

The $\nu_e$ “light curve” shows a distinct peak, the “prompt deleptonization burst,” that occurs when the shock-wave breaks through the neutrino sphere, dissociates iron and thus allows for the quick $e^- + p \rightarrow n + \nu_e$ conversion and thus for the prompt deleptonization of the outermost core layers. The flux and spectral characteristics of this burst are probably the least model-dependent features of SN neutrino emission [15, 16]. During the phase of shock-wave stagnation that may last for several hundred milliseconds, the neutrino emission is largely powered by the accretion of matter. After the shock wave has been rejuvenated by neutrino energy deposition and has ejected the stellar mantle and envelope, the neutron star remnant will cool, i.e. the neutrino emission is powered by energy stored deep in the core that diffuses to the surface on a time scale of several seconds.

In the literature it was often assumed that the neutrino emission during the accretion and Kelvin-Helmholtz phases was characterized by an approximate equipartition of the flavor-dependent neutrino luminosities $L_{\nu_e} \approx L_{\bar{\nu}_e} \approx L_{\nu_x}$ and by a strong hierarchy of average energies $\langle E_{\nu_e} \rangle \ll \langle E_{\bar{\nu}_e} \rangle \ll \langle E_{\nu_x} \rangle$. This behavior is borne out, for example, by the numerical simulations of the Livermore group [5]. However, traditional treatments of neutrino transport involve a number of physical and numerical simplifications that were
justified for the purposes of those calculations but are not accurate enough to judge the flavor dependence of the neutrino fluxes and spectra. In a series of papers we have studied this problem and have concluded that the differences between $\langle E_{\bar{\nu}_e} \rangle$ and $\langle E_{\bar{\nu}_x} \rangle$ are probably not more than about 20% or less [17, 18, 19, 20]. On the other hand, the equipartition of energy among the flavors is certainly not exact—the luminosities can differ perhaps by up to a factor of 2. Moreover, it appears that during the accretion phase $L_{\bar{\nu}_x} < L_{\bar{\nu}_e}$ while $L_{\bar{\nu}_e} < L_{\bar{\nu}_x}$ during the cooling phase [19, 20].

While several recent numerical simulations with a modern treatment of neutrino transfer confirm this picture for the accretion phase, no up-to-date simulations have treated the long-term evolution of the neutrino signal during the cooling phase. Since current numerical models to not produce robust explosions and since a full Boltzmann treatment of neutrino transport is very CPU intensive, numerical studies of the flavor-dependence of the late neutrino signal are not available at the present time. Therefore, forecasting possible effects of neutrino oscillations in the signal from a future galactic SN is unavoidably schematic and must rely on generic assumptions about the flavor-dependent neutrino fluxes and spectra.

3 Impact of Flavor Oscillations

The neutrino or anti-neutrino fluxes arriving at Earth from a SN are determined by the primary spectra at the source as well as neutrino oscillation effects. For $\nu_e$, the flux arriving at Earth may be written in terms of the energy-dependent “survival probability” $p(E)$ as

$$F_{\nu_e}(E) = p(E)F^0_{\nu_e}(E) + [1 - p(E)]F^0_{\bar{\nu}_x}(E),$$

where the superscript zero denotes the primary fluxes and $\nu_x$ stands for either $\nu_\mu$ or $\nu_\tau$. An analogous expression pertains to $\bar{\nu}_e$ with the survival probability $\bar{p}(E)$.

When neutrinos propagate through the SN mantle and envelope, the MSW resonance corresponding to the solar mixing angle is adiabatic and is always in the neutrino channel. On the other hand, the H-resonance, corresponding to 13-oscillations, is in the neutrino channel for normal neutrino mass ordering while it is in the anti-neutrino channel in the inverted case. This resonance is adiabatic for all relevant energies if the mixing angle $\theta_{13}$ is “large” in the sense of $\sin^2 \theta_{13} \gtrsim 10^{-3}$. It is non-adiabatic if the mixing angle is “small” in the sense of $\sin^2 \theta_{13} \lesssim 10^{-5}$. For intermediate values, the adiabaticity depends on energy and the situation is more complicated. The survival probabilities thus depend on the magnitude of the 13-mixing angle and on the nature of the mass ordering so that, in principle, the observation of a SN neutrino signal can distinguish between different mixing scenarios [12]. Table 1 summarizes the survival probabilities for different mixing scenarios where $\theta_\odot$ refers to the “solar” mixing angle.

The indicated survival probabilities pertain to a situation where neutrino oscillations occur only in the SN mantle and envelope. If the SN is shadowed by the Earth for the relevant detector, additional modifications of the survival probabilities arise due to Earth matter effects, causing an energy-dependent modulation of $p(E)$ or $\bar{p}(E)$. Table 1 indicates the channel where Earth effects would arise for different mixing scenarios.
### Table 1: Survival probabilities for neutrinos, $p$, and antineutrinos, $\bar{p}$, in various mixing scenarios. The channels where one expects Earth effects, shock-wave propagation effects, and where the full $\nu_e$ burst is present or absent are indicated.

| Scenario | Hierarchy | $\sin^2 \theta_{13}$ | $p$ | $\bar{p}$ | Earth effects | Shock wave | $\nu_e$ Burst |
|----------|-----------|-----------------------|-----|----------|---------------|------------|--------------|
| A Normal | $\gtrsim 10^{-3}$ | 0 | $\cos^2 \theta_\odot$ | $\bar{\nu}_e$ | $\nu_e$ | absent |
| B Inverted | $\gtrsim 10^{-3}$ | $\sin^2 \theta_\odot$ | 0 | $\nu_e$ | $\bar{\nu}_e$ | present |
| C Any | $\lesssim 10^{-5}$ | $\sin^2 \theta_\odot$ | $\cos^2 \theta_\odot$ | $\nu_e$ and $\bar{\nu}_e$ | — | present |

The SN shock wave will pass the density region corresponding to the H-resonance a few seconds after core bounce, breaking the adiabaticity of the 13-resonance. The resulting transient modification of the survival probabilities may be observable \[21\]. They arise in the channels indicated in Table 1.

### 4 Experimental Signatures

The most distinct effects of flavor oscillations arise in the $\nu_e$ channel because it sports the prompt deleptonization burst and even during the accretion and cooling phases, the expected spectral differences are much larger between $\nu_e$ and $\nu_x$ than between $\bar{\nu}_e$ and $\bar{\nu}_x$. On the other hand, the existing and realistically expected large detectors, notably Super-Kamiokande, IceCube, and a future megatonne-class water Cherenkov detector, are mostly sensitive to the inverse beta decay $\bar{\nu}_e + p \rightarrow n + e^+$, although the $\nu_e$ channel can be measured by the elastic scattering reaction $\nu_e + e^- \rightarrow e^- + \nu_e$. The largest existing $\nu_e$ detector is the Sudbury Neutrino Observatory (SNO) that will be shut down after completing its solar neutrino programme and thus will not be available for a long-term SN watch. Of course, if an efficient $\nu_e$ detector such as as a large liquid Argon TPC should become available, it would have unique capabilities for studying SN neutrino oscillations \[22, 23\].

In a water Cherenkov detector, the $\nu_e$ signal can be identified by the directionality of the $\nu_e$-$e^-$ elastic scattering reaction. Moreover, if future water Cherenkov detectors are doped with enough gadolinium to tag the neutron from $\bar{\nu}_e + p \rightarrow n + e^+$ \[24\], the identification of the prompt SN $\nu_e$ burst will become a realistic possibility. However, in Super-Kamiokande the total number of expected events from the $\nu_e$ burst of a “fiducial SN” at a distance of 10 kpc is so small (about a dozen) that a clear identification of the presence or absence of the burst is not likely. In a megatonne detector, on the other hand, the full $\nu_e$ burst will produce about 200 events. Therefore, the time structure of the SN signal during the first few tens of milliseconds can provide a clean indication if the full $\nu_e$ burst is present or absent \[16\] and therefore allows one to distinguish between different mixing scenarios as indicated by the last column of Table 1. For example, if the mass ordering is normal and the 13-mixing angle is large, the $\nu_e$ burst will fully oscillate into $\nu_x$. If the 13-mixing angle is measured in the laboratory to be large, for example by one of the forthcoming reactor experiments \[25\], then one may distinguish between the normal and inverted mass ordering. On the other
hand, if the mixing scenario is independently identified by laboratory experiments, these observations allow one to determine the distance to the SN with a precision of about 5%, even in the likely case that it is optically obscured [16].

A megatonne water Cherenkov detector is a realistic future possibility in view of the world-wide drive towards precision long-baseline oscillation experiments, but it is less clear if a gadolinium-doped detector of such size will ever come into existence. Therefore, I now turn to the main $\bar{\nu}_e$ detection channel of an ordinary water Cherenkov detector. In this channel the main problem is that one can not rely on theoretical predictions of the flavor dependence of the source fluxes and spectra. Therefore, one has to rely on model-independent signatures. A clear positive detection of such a signature would indicate a specific mixing scenario while the absence would be ambiguous: It could either imply a different mixing scenario or could imply that the flavor-dependent source spectra and fluxes were too similar to provide significant oscillation effects.

One unequivocal indication of oscillation effects would be the energy-dependent modulation of the survival probability $\bar{p}(E)$ caused by Earth matter effects. Even without an identification of the SN location in the sky in the electromagnetic spectrum, its direction can be established with sufficient accuracy by the $\nu_e$-$e^-$ elastic scattering signal alone [26, 27]. With a megatonne-class detector, the modulation signal could be well established unless the flavor-dependent flux differences are surprisingly small [28, 29]. The Earth effect would show up in the $\bar{\nu}_e$ channel for the normal mass hierarchy, assuming that $\theta_{13}$ is large (Table 1).

Another possibility to establish the presence of Earth effects is to use the signal from two detectors if one of them sees the SN shadowed by the Earth and the other not. As one needs to compare the two signals on the level of a few percent, sufficiently large detectors are needed. The statistical fluctuations may be too large in Super-Kamiokande so that, again, a megatonne-class detector is needed, perhaps in combination with IceCube [30]. IceCube at the South Pole and Hyper-Kamiokande in Japan would be geographically complementary in that about 70% of the sky would be seen directly in one detector and shadowed by the Earth in the other.

At the time of the next galactic SN, the neutrino mixing parameters may already be known from long-baseline laboratory experiments. In that case it may become possible to use the SN neutrino signal in reverse to perform a “tomography” of the Earth’s density profile [31].

A few seconds after core bounce, the SN shock wave will pass the density region in the stellar envelope corresponding to the H-resonance and thus break the adiabaticity of $13$-oscillations, causing a transient modification of the survival probability and thus a time-dependent signature in the neutrino signal [21, 32, 33, 34, 35, 36]. Probably the most significant signature is the time variation of the average energy of the detected positrons from the $\bar{\nu}_e + p \rightarrow n + e^+$ reaction. It would show a characteristic dip when the shock wave passes, or a double-dip feature if a reverse shock occurs [36]. This signature may be observable in Super-Kamiokande and almost certainly can be seen in a megatonne-class detector. Of course, apart from identifying the neutrino mixing scenario, such observations would test our theoretical understanding of the core-collapse SN phenomenon.
The shock-wave propagation signature arises in the complementary channel to the Earth effects (Table 1), i.e. it shows up in the $\bar{\nu}_e$ channel for large $\theta_{13}$ and the inverted mass hierarchy. Therefore, unless the flavor-dependent source spectra are unexpectedly similar, a megatonne water Cherenkov detector is assured to see either shock-wave propagation effects or Earth effects, although in the latter case it is required, of course, that the SN is shadowed by the Earth. Conversely, if neither Earth effects nor shock-wave propagation effects are seen one has a serious empirical handle on the flavor dependence of the source spectra in that they must be unexpectedly similar.

5 Conclusions

Observing neutrinos from the next galactic SN would provide invaluable information on the astrophysics of the core-collapse explosion phenomenon and on neutrino mixing parameters. Existing or near-future detectors such as Super-Kamiokande and IceCube are sufficient to measure a precise $\bar{\nu}_e$ light curve and thus can establish, for example, the duration of the accretion phase or perhaps detect unexpected new features. However, these detectors are probably too small to detect unambiguous evidence for neutrino oscillations. On the other hand, a megatonne-class water Cherenkov detector is assured to detect either Earth effects (assuming the SN is shadowed by the Earth) or shock-wave propagation effects, depending on the neutrino mixing scenario. Such observations will help to identify the neutrino mixing scenario and test detailed aspects of theoretical SN physics. Depending on the neutrino mixing information that will be established by laboratory experiments alone and depending on theoretical progress in our understanding of core-collapse SNe, one or the other aspect of these observations will be of greater interest at the time of the next galactic SN. Either way, the importance of such an observation as a probe of neutrino physics and of the astrophysics of supernovae can not be overstated.

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