Motivation to Build an Observatory for Neutrinos from Supernovae

R.N. Boyd[1,2], D. Cline[3], G.M. Fuller[4], T. Haines[5], A.S. Murphy[1], P.F. Smith[6]

ABSTRACT

When a galactic supernova occurs, two existing detectors, SuperKamiokande and the Sudbury Neutrino Observatory, will observe about 10,000 events, primarily from charged-current interactions. However, it is also important to detect a comparable number of μ- and τ-neutrinos, as much physics information will be contained in them. This includes details about the collapse process and the processes that produce the neutrinos emitted from a supernova, information about neutrino masses and oscillations, and possibly details of collapse to a black hole.

1. Introduction

A massive star evolves by consuming, through nuclear reactions, the nuclear fuels that comprise its different burning stages (Arnett 1996). After each fuel in its core is consumed the core compresses, raising its temperature to a level that ignites its next stage of fuel. When the core has been converted to iron and nickel, and has reached a temperature of several billion K, it cannot be stabilized with another fuel. It then collapses to a neutron star. The energy contained in the stellar core (Burrows 1990) is released in the seconds after the star's collapse. A tiny fraction, $\sim 1\%$, goes into a shock wave that explodes the star, and $\sim 0.01\%$ goes into the light that identifies a supernova (SN) that could be observed by conventional astronomy. Most of the energy, 99%, is emitted in $\sim 10^{53}$ ergs of neutrinos. The time distribution of neutrino emission is predicted in the standard model of stellar collapse (Burrows 1990; Qian et al. 1993) to first exhibit a sharp "neutronization spike" of predominantly ν_e's when the shock wave passes through the ν_e neutrino sphere, followed by a longer lasting hump, extending for several seconds, thought to contain comparable numbers of neutrinos in each flavor, with roughly the same amount of energy in each type of neutrino as in the corresponding antineutrino. The exception is the $\bar{\nu}_e$ distribution, which has significantly more energy than does the ν_e distribution. The twenty events seen from Supernova 1987a (Hirata et al. 1987, Bionta et al. 1987), shown in Fig. 1, were insufficient to allow more than a qualitative comparison of data and theory, but did indicate that at least some features of the physics contained in the standard model of stellar collapse are roughly correct. More definitive statements, however, are limited both by the statistically poor sample of events and the fact that they were probably only $\bar{\nu}_e$ initiated events.

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[1]Department of Physics, Ohio State University, Columbus, OH 43210

[2]Department of Astronomy, Ohio State University, Columbus, OH 43210

[3]Department of Physics, University of California at Los Angeles, Los Angeles, CA

[5]Los Alamos National Laboratory, Los Alamos, NM 87545

[4]Department of Physics, University of California at San Diego, La Jolla, CA

[6]Rutherford Appleton Laboratory, United Kingdom

It is important to remedy this deficiency by building an observatory for neutrinos from supernovae to increase substantially the statistical sample of neutral current events from the next galactic SN over what will be seen by Super-Kamiokande (SuperK) and the Sudbury Neutrino Observatory (SNO). Such a detector might consist of 10 to 20 kT of lead and iron which, when irradiated by neutrinos from a SN, would act as "converters" of neutrinos to neutrons that would be detected. One group, that developing OMNIS, the Observatory for Multiflavor NeutrInos from Supernovae, has developed this concept into a proposal for the WIPP. OMNIS is being designed to observe about 2000 neutrino induced events from a SN at 8 kpc, the distance to the Galactic center. Some of these would be due to ν_e's and $\bar{\nu}_e$'s, but the majority ($\sim$ 90%) would be due to ν_μ's, $\bar{\nu}_\mu$'s, ν_τ's, and $\bar{\nu}_\tau$'s through neutral-current excitation, due to their release from the SN with higher mean energy (Qian et al. 1993) than the ν_e's and $\bar{\nu}_e$'s. This is in contrast to SuperK, for which nearly all of the events will be from $\bar{\nu}_e$'s via the charged-current interaction. SNO, in its heavy water mode, will observe some neutral-current events, but still a much smaller number than would be required for extracting good quantitative results from the data. In addition, OMNIS' fast timing capability (see below) would not be matched by SNO during all of its planned existence; this is important in several contexts, as will be described. Table 1 compares the typical event numbers from various world detectors, showing that OMNIS will complement existing detectors in its sensitivity to the ν_μ and ν_τ neutrinos and their antineutrinos.

Detector	Target Material	Fiducial Mass(Ton)	Target Element	Yield(ν_e)	Yield($\bar{\nu}_e$)	Yield(ν_μ+ν_τ +$\bar{\nu}_\mu$+$\bar{\nu}_\tau$)
SuperK	H_2O	32000	p, e, O	180	8300	50
LVD	H_2O	1200	p, e, C	14	540	30
SNO	H_2O	1600	p, e, O	16	520	6
SNO	D_2O	1000	d, e, O	190	180	300
OMNIS	Fe	10000	Fe	20	40	500
OMNIS	Pb	4000	Pb			
No osc.				160*	70*	1400*
$\nu_{\mu,\tau} \rightarrow \nu_e$ osc.				$\leq$4420*	40*	$\leq$ 640*
OMNIS	liq. sc.	xx	p, C	xx	xx	xx

Table 1: Yields of Events from an 8 kpc-Distant Supernova. *Assumes a single neutron detection efficiency of 35% in lead and 30% in iron.

Only by observing neutrinos of all flavors will it be possible to observe many of the phenomena associated with stellar astrophysics and neutrino physics that scientists want to study. One feature of the neutrinos that OMNIS would measure is their energy distribution. While this is not directly measurable for *individual* neutral current interactions (which is what would produce most of the signals observed in OMNIS), OMNIS would provide three different energy thresholds from which to infer the energy *distributions* of the neutrinos: two from the lead (one from one-neutron emission and the other from two-neutron emission) and one from iron.

Moreover, OMNIS will be able to achieve a short detection time, less than 100 μs. Given good enough statistics, this might allow OMNIS to observe short-time phenomena in the neutrino luminosities associated with stellar collapse, *e.g.*, collapse to a black hole. This level of timing might also allow measurement of neutrino masses to around 30 eV if the collapse did not go to a black hole, or a few eV if it did. Finally, the special sensitivity of the lead detector to the energy of the ν_e neutrinos would make it capable of observing $\nu_{\mu,\tau} \rightarrow \nu_e$ flavor oscillations. These phenomena are discussed in greater detail below.

2. Astrophysics from Observation of Supernova Neutrinos

2.1. Stellar Collapse Diagnosis

The observation of neutrinos from SNe provides a unique opportunity to understand the core-collapse process and the subsequent explosion of a massive star (Burrows 1990). The different flavor neutrinos are likely to contain different types of information. Specifically, the ν_e's should exhibit the "neutronization spike" that first signals the core collapse, shortly after the protoneutron star has formed, from the reaction

$$p + e^- \rightarrow n + \nu_e. \tag{1}$$

Since these neutrinos are produced when the (high-temperature-producing) shock wave produced at the core of the star passes through the ν_e neutrinosphere, neutrinos and antineutrinos of all flavors will also be produced by the reactions

$$e^+ + e^- \rightarrow \nu_j + \bar{\nu}_j \tag{2}$$

$$A* \rightarrow A + \nu_j + \bar{\nu}_j, \tag{3}$$

where the subscript j refers to e, μ, or τ. The collapse that precedes the neutronization spike is thought (Burrows 1990) to trap the neutrinos produced, keeping their energy within the collapsing core so as to increase the temperature to the maximum extent possible. This requires (because of large coherence effects on the cross sections for neutrinos on nuclei) that preexisting nuclei not be destroyed until the maximum density of the core has been reached, which imposes a limit on the entropy. Then, following the neutronization spike, neutrinos of all flavors are thought to be created in tens of milliseconds deep within the core of the star (Burrows 1990) by the processes of eqs. 2 and 3, their trapping stretches the time scale over which they are emitted to seconds. That this gross feature of the time structure is essentially correct was confirmed by the observations of SN 1987a (Hirata et al. 1987, Bionta et al. 1987).

Neutrino pair production occurs only about once in 10^{19} electron-positron annihilations, but still produces most of the neutrinos that cool the neutron star. It is also thought that the ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$ distributions would tend to have considerably higher mean energies ($\mathrm{E}(\nu_x) \approx 25$ MeV) than would the ν_e ($\mathrm{E}(\nu_e) \approx 11$ MeV) and $\bar{\nu}_e$ ($\mathrm{E}(\bar{\nu}_e) \approx 16$ MeV) distributions (Qian et al. 1993), since the μ- and τ-neutrinos interact with the nucleons in their stellar production environment only through the neutral-current interaction, whereas the ν_e's and $\bar{\nu}_e$'s interact also through the charged-current interaction. Thus the ν_e's and $\bar{\nu}_e$'s are trapped farther from the center of the star, which will be a cooler region, and will therefore produce the lower ν_e and $\bar{\nu}_e$ energies.

Recent studies, though, have focused on other possible reactions that affect both the numbers and the energies of the emitted neutrinos. Neutrino bremsstrahlung (Hannestad and Raffelt 1998)

$$n + n \rightarrow n + n + \nu_i + \bar{\nu}_i \tag{4}$$

could be important, but would probably only affect the numbers of low-energy neutrinos, while the "inelastic scattering process" (Hannestad and Raffelt 1998, Janka et al. 1996)

$$\nu + n + n \rightarrow \nu + n + n \tag{5}$$

would affect their energies. While the actual magnitudes of these effects are difficult to calculate (Hannestad and Raffelt 1998), their effect on the neutrino emission is expected to be small compared to that due to convection.

The energy distributions of the neutrinos can also indicate, at least in principle, whether those energies are distorted from a Fermi-Dirac distribution to one that is "pinched" at both the low- and high-energy ends by neutrino scattering (Totani et al. 1998) in the dense stellar core. The combined time and energy distributions from observations of supernova neutrinos will help to assess the validity of the description of the region outside the protoneutron star. Because the cross sections for neutrinos interacting with matter increase with energy, the neutrinos detected earlier might be expected to have lower energies, unless their masses are large enough to distort this relationship. Furthermore, convective motion and rotation (Burrows 1990, Mezzacappa et al. 1998, Totani et al. 1998) might be indicated by the time and energy information. If convective motion occurred, the thermal energy brought up to near the surface by convection would increase the luminosity and harden the neutrino spectra.

While it will be difficult to discriminate between all of the effects discussed above by observing the SN neutrinos, the two OMNIS converters, plus observation of both single- and two-neutron events in the lead converter, will provide important information about the evolution of the number, energy, and flavor of neutrinos with time. It will be important to observe the neutrino luminosities well beyond the peak, as that will test predictions of the evolution of their energies as well as allow the possible observation of late-time collapse to a black hole. Although the signals from the lead modules may combine neutrino yield, energy, and even oscillation information in complicated ways, the signals from the iron modules are rather insensitive to oscillations, so combination of the three profiles should at least allow identification of major effects. Moreover, the prospects for separating the various effects appear even more promising when data from all detectors are considered. OMNIS will provide three time profiles to add to the charged- and neutral-current profiles from SuperK and SNO when all three observatories are operational.

2.2. Collapse to a Black Hole

Observation of SN neutrinos would also allow observation of the formation of a black hole should such an event result from stellar collapse. If the collapse were delayed by even a significant fraction of a second from the time the first neutrinos were emitted, its signature would be striking; it would produce an abrupt termination of the neutrino luminosities (Burrows 1990). However, the termination would not necessarily occur at the same instant for all the luminosities (Baumgarte et al. 1996). Because the ν_μ's, $\bar{\nu}_\mu$'s, ν_τ's and $\bar{\nu}_\tau$'s interact differently with matter than do the ν_e's and $\bar{\nu}_e$'s, their neutrinospheres would probably not be at the same distance from the center of the collapsing star. While the termination time difference would be expected to be short, of order 1 millisecond (Beacom, Boyd, and Mezzacappa 2000, Baumgarte et al. 1996), it might carry information about the process of collapse to a black hole, or even of a measurement of the sizes of the neutrinospheres if a sufficient number of events could be obtained just prior to the luminosity terminations. While this would only be possible for a close supernova, the possibility of such event, along with the incredible scientific information that would be obtained from it, must be considered in building a supernova neutrino observatory. Even a late-time collapse to a black hole might provide a timing signal that could be used in measuring neutrino masses (see below).

The combined signals from OMNIS and SuperK might even determine the mechanism by which collapse occurred. Baumgarte et al. 1996 showed that the deleptonization of the neutron star might produce a phase transition in the nascent neutron star, which could soften its equation of state enough to result in its collapse to a black hole. On the other hand, the collapse to a black hole could also result from matter infalling on the neutron star so as to raise its mass in excess of the Chandrasekar limit (Fryer, Benz, and Herant 1996). The neutrino signatures predicted for the two cases are strikingly different. In the former case, the $\nu_\mu+\bar{\nu}_\mu+\nu_\tau+\bar{\nu}_\tau$ and $\bar{\nu}_e$ luminosities remain relatively flat as they approach their respective black hole cutoffs, whereas the ν_e luminosity decreases by a factor of three during the last 100 ms. In the latter case, all the luminosities would be expected to remain flat up to their cutoff point. Furthermore, the relative intensities of the different flavors are also different between the two collapse scenarios. These qualitative differences should allow discrimination between these modes of collapse.

2.3. Frequency of Supernova and Black Hole Formation

An important aspect of SN neutrino detection is the frequency at which Galactic SNe occur. The observational record suggests that the rate inferred from various astronomical arguments is much too low. Several recent papers have discussed the Galactic SN rate (see discussion in Beacom, Boyd, and Mezzacappa 2000). The observed rate suggests roughly 8 core collapse SNe in the past 2000 years. However, this is essentially the number out to an observable distance of about 4 kpc, representing the local 5-6% sample of the Galaxy; taking this into account leads to an estimate of about 7 per century for the whole Galaxy. Thus the typical interval for our Galaxy could be as small as 15 years, although the uncertainty on this value is large.

Although the possibility of collapse to a black hole would provide some stunning science, the frequency of such events must also be addressed. Unfortunately, it is also not well known. The ratio of black hole formation to neutron star formation has been estimated (see discussion in Beacom, Boyd, and Mezzacappa 2000) to be as low as 1:4 to as high as 9:1. While this enormous range of results is not very informative as to what the rate of black hole formation is, the values do suggest that black hole formation is at least not a much rarer event than neutron star formation.

3. Neutrino Physics Motivation

Another type of information that might be obtained from SN neutrinos concerns the masses of the neutrinos. Although the recent results from SuperKamiokande (Fukuda et al. 1998) strongly suggest that at least some neutrinos have nonzero mass, the new results do not indicate the mass values, or even how many neutrinos are involved in the observed oscillations. Thus any measurements of neutrino mass at a level that would affect their time of flight from the SN to a terrestrial detector is of fundamental significance.

Such an opportunity exists with OMNIS. The difference in arrival time of two (unmixed) neutrino flavors, one of small mass and the other with a much larger mass is

$$\Delta t(s) = 1.6[R/8kpc][m(\nu)/50eV]^2[25MeV/E(\nu)]^2 \tag{6}$$

where m(ν) is the rest mass energy of the more massive neutrino in eV/c^2 and E(ν) is its energy in MeV. Thus a light neutrino and one with a mass of 50 eV/c^2, assuming they were emitted simultaneously from a SN 8 kpc distant from earth, would be separated in time by 2 s (after traveling for 33,000 years!). However, the situation is not as clean as this, as neutrinos of both flavors would have energy distributions, and their intrinsic time distributions may be 1-2 seconds wide. Furthermore, oscillations might smear the distributions. This has been studied for SuperK and SNO (Beacom and Vogel 1996). Very good statistics would be necessary to observe the separate mass distributions, or would require some mechanism to discriminate between the neutrino flavors. However, the rise-times of the distributions might be able to provide (Beacom 2000), depending on the statistics, a timing signal from OMNIS at the several ms level which, when compared with the $\bar{\nu}_e$ signal from SuperK, would provide a mass measurement to roughly 30 eV/c^2. However, in the event of collapse to a black hole, comparison of the OMNIS and SuperK timing signals (Beacom, Boyd, and Mezzacappa 2000) might allow a mass measurement at a level of a few eV/c^2. Note that this value would be of great importance to cosmology (Cosmologyref).

Matter enhanced neutrino flavor transformations have been hypothesized to be a solution of the solar neutrino problem (Bahcall 1989). The recent results from SuperK (Fukuda et al. 1998) have lent considerable support to the concept of oscillations, although those observed by the latter facility are not necessarily consistent with those from the solar neutrino experiments (Hampel et al. 1996, Abdurashitov et al. 1994). None the less, the possibility of detecting oscillations from SN neutrinos is of great interest.

The modules of a lead detector will provide events in which one or two neutrons can be emitted, with the latter events having a higher threshold than the former. Thus the two-neutron events would be expected to constitute a small fraction of the total. However, if oscillations such as $\nu_\mu \rightarrow \nu_e$ or $\nu_\tau \rightarrow \nu_e$ occurred, this would not necessarily be the case. The ν_μ's and ν_τ's have higher mean energy in the standard model, so that oscillations of this type would produce ν_e's of considerably higher energy (25 MeV) than would be produced without the oscillations (11 MeV). This, in turn, would increase neutron production in the lead from charged-current interactions (Fuller, Haxton, and McLaughlin 1999, Kolbe, Langanke, and Martinez-Pinedo 1999), but not in iron. The gain in absolute yield is estimated to be a factor of 4 in the lead. However, the two-neutron events will be enhanced much more, by an estimated factor of 40 if full oscillations of the type described here occur. The relative numbers of single and two-neutron events, with and without mixing, are summarized in Fig. 2. Fig. 3 shows the MSW and vacuum mixing boundaries covered by OMNIS in terms of the usual mixing parameters $\Delta(\mathrm{m}^2)$ and $\sin^2 2\theta$.

4. Event Producing Reactions in Lead and Iron

OMNIS is being designed to obtain around 2000 events from the next Galactic SN (assumed at 8 kpc), predominately through neutral current interactions of the higher energy μ- and τ-neutrinos and their antineutrinos. OMNIS is expected to be housed at the Center for Applied Repository and Underground Science, CARUS, near Carlsbad, NM. OMNIS will observe SN neutrinos by detecting the secondary neutrons produced when the neutrinos interact with "converters" (Cline et al. 1990, Cline et al 1994, Smith 1997). Lead and iron converters have been found to have a relatively high neutron production efficiency (Fuller, Haxton, and McLaughlin 1999, Woosley et al. 1990; Kolbe, Langanke, and Martinez-Pinedo 1999). Both lead and iron produce neutrons from neutral-current interactions

$$\nu_j + (N, Z) \rightarrow \nu_j' + (N, Z)^* \rightarrow (N-1, Z) + \ n \tag{7}$$

Iron's high threshold (11.20 MeV) for neutron emission and lack of sensitivity to charged-current processes makes it insensitive to the (lower energy) ν_e's and $\bar{\nu}_e$'s; its yields are due only to ν_μ's, $\bar{\nu}_\mu$'s, ν_τ's and $\bar{\nu}_\tau$'s. Lead, however, has a considerably lower threshold (7.37 MeV) for neutron production from neutral-current interactions. In addition, it can produce neutrons from charged-current interactions via

$$\nu_e + {}^{208}Pb \rightarrow e^- + {}^{208}Bi^* \rightarrow n + {}^{207}Bi, \tag{8}$$

with a threshold of 9.77 MeV. Finally, it can produce events in which two neutrons are emitted; the threshold for this process is 14.11 MeV. Thus use of modules of different nuclei provides discrimination between the yields of ν_e's and $\bar{\nu}_e$'s and those of the ν_μ's, $\bar{\nu}_\mu$'s, ν_τ's and $\bar{\nu}_\tau$'s. The yield predictions (Fuller, Haxton, and McLaughlin 1999, Kolbe, Langanke, and Martinez-Pinedo 1999) are summarized in Table 1.

The scintillator used to detect the neutrinos will also produce some neutrons, which will result in identifiable events. These come almost entirely from the following reaction:

$$\bar{\nu}_e + p \rightarrow n + e^+ \tag{9}$$

The yield from this reaction adds to those from the lead and iron; they are included in Table I.

5. Summary

It is clear that much is to be learned from detecting μ- and τ-neutrinos, in addition to $\bar{\nu}_e$-neutrinos, from a SN. Such events would allow for diagnosing core collapse and, possibly, black hole formation, in addition to the measurement of neutrino masses and mixing. The 2000 events for which OMNIS is being designed would thus provide information complementary to that from Super-Kamiokande. The two-neutron signal from OMNIS' lead would also provide a signature of mixing between ν_e's and ν_μ's or ν_τ's. Finally, OMNIS' fast timing capability would lead to some unique potential observations such as black hole cutoff detection and possibly to neutrino mass measurement at the few eV/c^2 level. Thus the signal characteristics, size, and fast timing capability of a detector such as OMNIS are essential to obtain the new astrophysics and neutrino physics information sought.

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