9

NEUTRINO ASTROPHYSICS

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Here we report on how recent progress in understanding the physics of supernovae and several issues in the early universe and cosmology promise to lead to deeper insights into fundamental neutrino physics (e.g., neutrino masses and mixings) and *vice versa*. Recent and proposed experiments and theoretical studies which bear on our understanding of neutrino oscillations, neutrino masses, and other neutrino properties are discussed in this context. We also report on the progress of supernova modeling, and on the prospects for real time supernova neutrino detection. These topics represent a subset of the discussion issues which arose during the meetings of the Neutrino Astrophysics working group at the 1994 Snowmass Workshop.

1 General Remarks on Neutrinos, Supernovae, and Cosmology

Particle physicists and astrophysicists would very much like to know whether or not any of the neutrino species have rest masses. Indeed, positive evidence for the existence of non-vanishing neutrino masses may well be our first and (absent future definitive results from the proposed LHC and B-factories) perhaps our only indication of the requirement for physics beyond the Standard Model.

Furthermore, the question of neutrino masses ties in with another of the great mysteries of modern physics: the nature of the dark matter. From observations of the relic microwave background radiation and observational inference of the light element primordial abundances, we know that the photon-to-baryon number in our universe is of order $\sim 10^{10}$. On broad theoretical grounds (for example, assuming universality and that the Fermi constant is really constant !) we expect that the neutrino-to-baryon number should be quite similar. From this we can conclude immediately that even very small neutrino masses can be dynamically important for the evolution of the universe [1].

In fact, it would be highly significant for cosmology if the mass of any one neutrino flavor, or the sum of the masses for two or all three flavors, was found to lie in the range of about 1 eV to 100 eV [1]. If a neutrino contributes a fraction Ω_ν of the closure density of the universe it must have a mass $m_\nu \approx 92\Omega_\nu h^2$ eV, where h is the Hubble parameter in units of 100 km^{-1} sec^{-1} Mp^{-1}. Reasonable ranges for Ω_ν and h then give 1 eV to 92 eV as a cosmologically significant range. A neutrino with a mass is the higher end of this range, i.e., $10 \lesssim m_\nu \lesssim 92$ eV, could contribute significantly to the closure density of the Universe. The Cosmic Background Explorer (COBE [2]) observation of anisotropy in the microwave background, combined with observations at smaller scales, the distribution of galaxy streaming velocities, and the results of numerical large scale structure simulations *have been interpreted* as implying that there are two components of dark matter: i.e., hot (HDM) and cold dark matter (CDM) components, with $\Omega_{CDM} \sim 0.6$ and $\Omega_{HDM} \sim 0.3$. The hot dark matter (HDM) component in these models could be provided by a scheme in which the sum of the active light neutrino masses is about 5 - 7 eV [3]. Of course, there may be several other viable models for structure growth which meet the microwave background anisotropy constraints, yet do not invoke neutrino dark matter. Primarily, these would be models for a spatially "flat" universe with $\Omega_{CDM} \sim 0.3$ and vacuum energy density (in units of the closure density) $\lambda \sim 0.6$. Present data on the distribution and sizes of structure in the universe is inadequate to discriminate between these models. But it is with great hope that we note that future observations from the Keck and other large telescopes may give us a definitive answer on the evolution of small scale nonlinear structures with redshift around the epoch corresponding to redshift $z \approx 3$. These observations may or may not point to the need for neutrino dark matter.

However, despite the obvious cosmological and particle physics interest in massive neutrinos, there are very few terrestrial experimental means for measuring neutrino masses in the range of significance for neutrino hot dark matter. The electron neutrino mass is constrained by the tritium end point experiments to be less than about 7.2 eV. It is conceivable that ν_μ to ν_τ accelerator neutrino oscillation experiments, such as the NOMAD and CHORUS experiments at CERN and the E803 experiment at Fermilab, could be used to infer a mass in the

cosmologically interesting range for ν_μ or ν_τ. Likewise, the LSND neutrino oscillation experiment at Los Alamos conceivably could infer a cosmologically significant mass (or sum of masses) for the mu and/or electron neutrinos. However, to be successful, all of these laboratory experiments would depend on there being a fairly large (by the standards of, admittedly suspect, theoretical arguments) vacuum mixing between the neutrino flavors probed by each particular experiment. However, there are some astrophysical venues in which small mixing between the neutrino flavors could be amplified by coherent effects.

Reconciliation of the observations of neutrinos from the sun in the Homestake, Gallex, SAGE, Kamiokande II, and (some day) the SNO detectors may well require matter-enhanced neutrino oscillation of some sort in the sun. This would *prove* that at least some of the neutrinos have mass. However, the neutrino mass scale that could be directly inferred from solar considerations would be only on the order of a millivolt, well below the $\sim 1\,\mathrm{eV}$ neutrino mass range of interest for the dark matter question.

But there is hope. We now know that the dynamics and heavy element nucleosynthesis of Type II Supernovae, and in fact nearly every aspect of the behavior of these events, is determined by the interplay of gravitation and neutrino emission and absorption. Very tiny amounts of lepton number violation from, for example, neutrino flavor oscillations, can cause dramatic alteration of supernova explosion models and/or the predicted heavy element nucleosynthesis yield in neutrino-heated ejecta from these objects. If we can understand the supernova explosion mechanism (arguably a very hard problem !) or the nucleosynthesis from neutrino-heated supernova ejecta (arguably an considerably easier problem), then we may gain insights into fundamental neutrino physics that we have otherwise only a poor chance of ever obtaining from laboratory experiments. Much of our discussion in the Neutrino Astrophysics working group centered broadly around these issues: supernova dynamics; nucleosynthesis from neutrino-heated supernova ejecta; and how various aspects of neutrino physics (masses and mixings, lepton number violating processes, majorons, etc.) bear on the first and second issues. In this vein, we now report on progress in understanding these issues and on prospects for direct supernova neutrino detection.

2 Neutrinos and Supernovae

The weak interaction (specifically, neutrino interactions) and gravitation are the twin engines of Type II Supernovae. The progenitors of these events are massive stars ($> 10\,\mathrm{M}_\odot$), which in less than 10 milion years evolve to form Chandrasekhar mass iron cores. The structure of such a core resembles that of a high mean molecular weight white dwarf. The iron cores of the supernova progenitor objects are destabilized by any of a combination of electron capture and associated neutrino energy and entropy losses, photo-disintegration rearrangement and general relativity. These cores subsequently collapse to nuclear density (or beyond) on a timescale of about $\sim 1\,\mathrm{s}$. The core collapse process is halted in a hydrodynamic "bounce," forming a quasi-static hot proto neutron star. The hydrodynamic bounce generates a shock wave, which begins to move out through the infalling material.

The entropy per baryon in the collapsing core is typically (in units of Boltzmann's constant k), $s/k \sim 1$, while the characteristic post-bounce (post shocked) entropy per baryon is $s/k \sim 10$. This large entropy jump across the shock front is quite significant, because it implies that low entropy material (mostly heavy nuclei) flowing through the shock will be photo-disintegrated into free nucleons and alpha particles. In turn, this is an endothermic process, which saps energy from the shock front, typically causing it to stall and evolve into a stationary accretion shock within about $t_{pb} \approx 0.1\,\mathrm{s}$ (here t_{pb} denotes the lapsed time *post core bounce*). We now believe that this stalled shock is revived or "re-heated" by neutrinos emitted from a neutrino sphere (near the edge of the hot proto neutron star). A small fraction of the neutrinos emitted from the neutrino sphere are captured or otherwise interact in the material behind the shock front to deposit energy and so raise the pressure behind the shock and thus do work on it [4]. Producing a shock with $\approx 10^{51}$ ergs of energy is sufficient to produce a Type II Supernova explosion. The shock re-heating process takes on the order of a few tenths of a second to half a second.

It is instructive to examine where the energy resides in this picture of how Type II Supernovae explode. In fact, essentially all the energy resides in the neutrinos. At the outset of core collapse, the strong and electromagnetic interactions are each in equilibrium and the baryons are thus in nuclear statistical equilibrium (NSE). However, initially the weak interaction is not in either thermal or chemical equilibrium. As the core collapses, electrons are captured on protons (most of which reside inside heavy nuclei), driving the material more neutron-rich. Early in the collapse process the neutrinos produced by electron capture escape. But as the density of the core rises, the neutrino mean free path becomes smaller than the size of the core, and the neutrinos become "trapped" and eventually thermalized. The total gravitational binding energy released by the core in collapsing from an iron "white dwarf" to a hot proto neutron star (at the bounce) is about 10^{52} ergs. All but about 10 percent of this energy resides in the thermalized neutrinos which are trapped inside the hot neutron star. The rest resides in the kinetic energy of the infalling material. At bounce this infall kinetic energy is converted

with fair efficiency into the initial energy of the outgoing shock ($\approx 10^{51}$ ergs).

At about $t_{pb} \approx 0.1$ s after core bounce we have a hot proto neutron star with a radius of about ~ 45 km, and a dead shock at a radius of at least several hundred kilometers. The neutrinos trapped inside the neutron star have mean free paths which are very small (centimeters near the center of the star). These neutrinos diffuse out of the core with a typical diffusion timescale of 10 to 15 seconds. We can approximate each neutrino species as decoupling from a characteristic neutrino sphere located near the edge of the neutron star, where the density gradient is very steep. Above the neutrino sphere(s) , the neutrinos stream nearly freely, with the material in this region being essentially transparent to neutrinos. The energy spectra for each of the neutrino species at their respective neutrino spheres are roughly Fermi-Dirac black body with near zero chemical potential.

In fact, the mu and tau neutrinos and their antiparticles decouple deepest inside the neutron star (their neutrino sphere has a smaller radius than the neutrino sphere for either the ν_e or $\bar{\nu}_e$), since these species have no charged current contributions to their opacity, while the ν_e or $\bar{\nu}_e$ do. The charged current contributions to the opacities for the ν_e or $\bar{\nu}_e$ come from electron scattering and the charged current absorption processes on free nucleons,

$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^- \qquad (1a)$$

$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+. \qquad (1b)$$

In fact, since the material of the neutron star has a neutron excess, the ν_e have a larger opacity contribution from the process in Eq. (1a) than do the $\bar{\nu}_e$ from the process in (1b). As a result, the mu and tau neutrino sphere lies deeper than the neutrino sphere for $\bar{\nu}_e$, which in turn lies deeper than the neutrino sphere for the ν_e. Since the temperature of the material and neutrinos tends to decrease with increasing radius inside the neutron star, generically the average energies of the neutrino species at their respective neutrino spheres and in the region above the neutron star will satisfy $\bar{E}_{\nu_{\tau(\mu)}} = \bar{E}_{\bar{\nu}_{\tau(\mu)}} > \bar{E}_{\bar{\nu}_e} > \bar{E}_{\nu_e}$, so long as there are no significant neutrino flavor transformations.

After bounce, the hot proto neutron star will radiate neutrinos (and hence net lepton number) from its surface and so will quasi-statically contract, releasing $\sim 10^{53}$ ergs of gravitational binding energy as the star shrinks in radius to ~ 10 km over a timescale set, of course, by the neutrino diffusion timescale of about 10 s to 20 s. The neutrino luminosities are about the same for each neutrino species and range from about 10^{52} ergs s^{-1} immediately after bounce to roughly 10^{51} ergs s^{-1} after about 10 or 20 seconds. During this time the average energies of each neutrino species increases, while the disparity between the ν_e and $\bar{\nu}_e$ average energies grows.

From this general overview of the Type II supernova explosion process we can identify three relatively distinct epochs:

1. the collapse or infall epoch with $s/k \sim 1$;
2. the shock re-heating epoch at $t_{pb} \approx 0.1$ s to ~ 1 s where the characteristic entropy per baryon is $s/k \sim 50$;
3. the "hot bubble" r-Process epoch at $t_{pb} \sim 3$ s to ~ 15 s, where $s/k \sim 200$ or more.

The high entropy in the hot bubble/r-Process epoch is a result of the cumulative neutrino heating of the (by this time low density) plasma above the neutron star by the processes in Eqs (1a) and (1b) and by other neutrino interactions.

Let us at this point make some simple generalizations about our overview of the supernova explosion process. First note that there are two numbers of overwhelming signifigance in this picture: the mass of the neutron star; and the neutrino diffusion timescale. These quantities determine the essential features of the supernova and they are, in turn, expected to be known reasonably accurately. The mass of the neutron star must be very close to the mass of the initial iron core (~ 1.4 M$_\odot$), the Chandrasekhar mass. The neutrino diffusion timescale depends on the assumption of universality of the weak interaction, the standard model of the weak interaction, and the saturation density of nuclear matter (i.e., the characteristic density of a neutron star). So really it is the Chandrasekhar mass and the saturation density of nuclear matter which are the only ***non weak interaction*** quantities which are important in the supernova! This is the principal reason why supernovae are potentially such wonderful probes of the weak interactions and neutrino physics. Of course, do we really know what the density of matter is in the neutron star, or equivalently do we really know the equation of state of matter at high density? And how accurately do we know the initial iron core mass? Furthermore, how accurately do we need to know the answers to either of these questions before we can begin to use supernova nucleosynthesis and dynamics to constrain weak interaction physics? The neutrino astrophysics working group discussed these issues in some detail.

At Snowmass, T. A. Weaver and S. E. Woosley discusssed uncertainties in the initial models for core collapse and the outstanding issues that need to be resolved for the future. We concluded that our understanding of the infall epoch at this point is reasonably good, though uncertainties in electron capture, beta decay, and other weak processes (as discussed by M. Aufderheide, G. Fuller, and T. Ressel) remain. D. Swesty and J. Lattimer presented their views on the effects of kaon condensation

and/or a transition from nucleons and mesons to quark soup in the de-leptonizing proto neutron star. This latter issue is quite important, because it bears on the question of whether or not black hole remnants might be left by Type II supernovae. In turn, it may tie in with the expected gravitational radiation signature for supernovae. All of these issues will clearly be subjects of intense research in this and the next millenium!

Stirling Colgate presented a beautiful picture of the "convective engine " which obtains in the shock re-heating epoch [5]. In fact, as the material above the neutron star is heated by neutrino interactions a negative entropy gradient develops which is necessarily convectively unstable. Thus, convection *must* accompany neutrino heating during this epoch. Colgate described his recent calculations with Herant and Benz (see also the work of Miller and Wilson), and showed how convection at this epoch neatly transports energy from the region immediately above the neutrino sphere to the region of the shock - effectively pumping neutrino energy into shock energy! With this insight into the role of convection, we know that the re-heated shock will have the requisite energy to produce the Type II Supernova display. We no longer have a nagging uncertainty regarding how the shock gets re-heated. But there are still plenty of other uncertainties surrounding this epoch.

For example, we would very much like to have a better understanding of how neutrinos are transported through the neutrino sphere. Additionally, we need to know what the neutrino energy distribution functions above the neutrino should be. These issues bear on the neutrino luminosity, the neutrino heating rate , and the nucleosynthesis from the neutrino-heated ejecta from the shock re-heating epoch. There are many technical issues in the numerical treatment of neutrino transport in the vicinity of the neutrino sphere. In this region, neutrinos go from optically thick to optically thin in a quite short length scale. At the Snowmass meeting, D. Swesty gave a very good overview of these issues. There was not a great deal of discussion about convection through the neutrino sphere (the so called "salt finger instability") in our working group, though the resolution of this problem may be important for the issues outlined above. Furthermore, the "bubbling" and "boiling" of the material near the neutrino sphere engendered by convection may be a very important source of gravitational radiation in a frequency range in which LIGO may be sensitive (see the references to A. Burrows talk in the report of the Gravitational Radiation working group in these proceedings).

In the course of our working group sessions, R. Sawyer brought up a potentially important issue regarding the possible renormalization of the effective weak coupling constant as a result of matter effects in the neutron star. Sawyer argued that weak intreaction rates of neutrinos on nucleons (as in Eqs (1a) and (1b)) would be reduced by these matter effects. This clearly could be important for our picture of both the shock re-heating epoch and the hot bubble epoch, if these renormalization effects are still significant even at densities characteristic of those of the neutrino spheres at this epoch (less than one percent of nuclear matter density).

In our meeting, S. E. Woosley, Y. Z. Qian, and G. M. Fuller talked about the nucleosynthesis from the neutrino-heated ejecta originating in the hot bubble epoch. In a stunning development in the last two years Woosley and his collaborators have shown that neutrino-heated ejecta from this epoch is an excellent site for the rapid neutron capture process (r-Process) of nucleosynthesis [6]. Most of the elements with masses greater than 100 were created in this process. Subsequently, Y. Z. Qian and G. M. Fuller and their collaborators [7] showed that this r-process nucleosynthesis may be an excellent probe of the mixing of ν_e with either ν_μ or ν_τ (or the mixing of $\bar{\nu}_e$ with either $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$), when one or more of these species has a cosmologically significant mass. The sensitivity of r-Process nucleosynthesis to matter-enhanced neutrino oscillations follows from three points:

1. r-Process nucleosynthesis is sensitive to the ratio of neutrons to protons in the hot bubble and there must be a fair excess of neutrons to get an acceptable abundance pattern;

2. the neutron to proton ratio in the hot bubble is determined by the competition between the reactions in Eqs (1a) and (1b);

3. transformation of, for example, ν_τ into ν_e will result in driving the material less neutron-rich as a result of the average energy hierarchy of the neutrino species outlined above.

This is a subject of intense current research, because the stakes are high. Essentially, the gist of this work is that the known abundance distribution of the heavy elements may provide clues to (or constraints on) the existence of neutrino dark matter and the mixing parameters of the neutrino species!

Finally, it is clear from the above overview of the Type II Supernova explosion process that *any* aspect of the weak interaction that results in lepton number violation can potentially alter our picture of the explosion process. It would be unwarranted bravado to assume that we know everything there is to know about the weak interactions. For example, if neutrinos have masses, how do they acquire them. If physics beyond the standard model is invoked to build these masses then it is legitimate to ask what effect this altered weak physics will have on our picture of the supernova process. In the course of the meetings of our working group, G. Gelmini gave a review of extensions of the stardard model in the weak sector. G.

M. Fuller reviewed how aspects of the supernova problem might depend on such extensions. It became clear from our discussions that any extension of the Higgs sector to include majoron-like Goldstone bosons which couple only to neutrinos has the potential to drastically alter the infall epoch of the supernova (usually in ways which mitigate against ever getting an explosion!).

In any case, the supernova environment is a potentially wonderful neutrino physics laboratory. If we can decipher heavy element nucleosynthesis, we may learn important clues to the neutrino mass and mixing puzzle. Alternatively, terrestrial neutrino detectors proposed for the future may give us a complementary set of insights into such physics, if we would be so lucky a to have a Type II Supernova go off in our galaxy.

3 Supernova Neutrino Observation: Now and in the Future

The issue of whether or not neutrinos have masses is clearly important for astrophysics and cosmology. Unfortunately, as described above, terrestrial experimental probes of neutrino mass, especially the ν_μ and ν_τ masses, remain problematic. Astrophysical considerations may represent the best hope for inferring neutrino masses and mixings. In this section, we examine how proposed neutral-current-based supernova neutrino burst detectors, in conjunction with the next generation water Cerenkov detectors, could use a galactic supernova event to measure (or place costraints on) the ν_μ and/or ν_τ masses if they are in excess of 5 eV. Such measurements would have important implications for our understanding of particle physics, cosmology, and the solar neutrino problem, and would be complementary to constraints derived from proposed laboratory vacuum oscillation experiments.

Conceivably, the longest baseline neutrino beam will be from a supernova. In order to exploit this source, we will need a complement of detectors on Earth to cover the possible time of flight difference for a massive neutrino (ie., 10 eV) or to study the neutrino flavor transformatiom resulting from either the MSW effect occuring in the supernova or vacuum oscillations occuring in flight. Three detectors which can contribute to the study of neutrino interactions from supernovas are Super Kamiokande, ICARUS and SNO [8].

The Super Kamiokonde detector is a scaled up version (40 Ktons) of the Kamioka detector, which with the IMB detector gave the first neutrino detection from a supernova, SN1987A [9]. We note that this detector will be very sensitive to the $\bar{\nu}_e + p \rightarrow e^+ + n$ reaction and therefore to the $\bar{\nu}_e$ flux. This detector is under construction and should be operational in 1996. The ICARUS detector at the Gran Sasso is still in the development stage. The detector is a large liquid Argon calorimeter and it should provide some important information on the ν_e signal from a galactic supernova. The Sudbury Neutrino Observatory (SNO) detector will consist of 1.6 Ktons of D_20 and should also be ready in 1996. This detector is sensitive to the neutral current breakup of deuterium $\nu_x + d \rightarrow n + p + \nu_x$

At Snowmass there was a lively discussion of the future of supernova neutrino detection. There were presentations on ICARUS, SNO, and the Supernova Burst Observatory (SNBO), as well as discussions of the prospects for obtaining real time coincidences between neutrino detectors and other detectors such as gravity wave detectors [8].

The major physics issues that were discussed revolved around the determination of neutrino masses and/or mixing from the expected neutrino signal from a core collapse supernova event in our galaxy. However, a major problem in this field remains the unknown SNII rate in our galaxy. Furthermore, the feasibility of constructing a supernova detector large enough to be sensitive to extragalactic sources is an issue which, although not settled, must engender pessimism at this point. Let us now turn to some of the specific issues in the field of supernova neutrino detection. Some of this part of the report is adapted from some of our previous work [11].

3.1 Measurement of Neutrino Mass

Perhaps the most straight forward and obvious signature of a massive neutrino would come from the lenghtening in flight time from a distant supernova. For example, the flight time difference between ν_τ and $\nu_e(\bar{\nu}_e)$ in seconds is

$$\Delta t = 0.514 R_{10\ kpc}[(E_{\nu_\tau}/m_{\nu_\tau})^2 - (E_{\nu_e}/m_{\nu_e})^2] \text{ sec}$$

where m_{ν_τ} is in eV, E_{ν_τ} is the neutrino energy in MeV and $R_{10\ kpc}$ is the distance to the supernova in units of 10 kpc. A finite neutrino mass would alter the neutrino spectra in characteristic ways which could result in broadening and flattening of the observed signal.

Thus, neutrino masses might be obtained by comparing the observed neutrino signal with the signal expected from supernova models. Tables 1 and 2 give, respectively, information on supernova neutrino detection methods and estimates of the number of events expected from a galactic supernova at 10 kpc. Since water Cerenkov detectors such as Super Kamiokande are relatively insensitive to ν_μ and ν_τ, they are unlikely to measure cosmologically significant neutrino masses for these flavors. This is perhaps more likely for the neutral-current-based detectors being build at present, like the Sudbury Neutrino Observatory (SNO). The event rates for different neutrino reactions in SNO from a supernova explosion at 10 kpc are shown in Table 3.

Recently there has been real progress in supernova simulations giving an explosion as outlined in section

Table 1: Supernova neutrino detection methods in the 1990s. Adapted from Ref. [11].

Reactions	$\bar{\nu}_e p \rightarrow e^+ n$	$\nu_x e \rightarrow \nu_x e$	$\nu_x N \rightarrow \nu_x N$	$\nu_x N \rightarrow \nu_x N^* \rightarrow n$
Cross section	Large (KII,SK,IMB,LVD)	Small $\sim E_\nu^2$ (ICARUS)	Large for coherent process	large at high E_{ν_x} SNO/SNBO
Neutrino energy estimate	Yes $E_{\nu_e} \sim E_e$	Partial $E_{\nu_x} \sim f(E_e)$	No	No Threshold may set E_{ν_x}
ν direction	No	Yes	No	No
Time information	Yes	Yes	Yes	Yes
Down time speculations	$\gtrsim 10\%$	$\sim 30\%$	?	Could be small
Maximun detector size	2×10^5 ton (H_2O) LENA $\gtrsim 10^4$ ton liq. scint (LVD)	$\sim 2 \times 10^5$ ton (H_2O) or $\sim 10^3$ ton Cryogenic (ICARUS)	? Kilograms No detector proposed	$\sim 10^5 - 10^7$ ton of NaCl (SNBO) or $\sim 10^3$ ton D_2O (SNO)
Backgrounds	Small if e^+ and n capture detected; OK for H_2O galactic signal	Small if directionally used to reject background	?	Depends on radioactivity of material

Table 2: Events expected from a galactic supernova in future supernova ν detectors at 10 kpc. Adapted from Ref. [11].

	Comparison of future supernova ν detectors					
Process	$\bar{\nu}_e p \rightarrow e^+ n$ $\bar{\nu}_e d \rightarrow ppe$	$\bar{\nu}_e e \rightarrow \bar{\nu}_e e$	$\bar{\nu}_x e \rightarrow \bar{\nu}_x e$ $x = \mu, \tau$	$\nu_e N \rightarrow N^* \nu_e$ $\rightarrow n$	$\nu_x N \rightarrow N^* \nu_x$ $\rightarrow n$	ν_e prompt
ICARUS		~ 140	25			4
SNO (1.6 kT)	~ 435	3	21	~ 117	~ 200	5–20
LVD (1.8 kT):scint	~ 342					
MACRO (1.kT):scint	~ 220					
Kamiokande II (3 kT)	~ 355	~ 1				
Super Kam (40 kT)	~ 5310	~ 17				~ 5
SNBO (100 kT)	100			~ 100	10000	
Comments	Measure t_ν $E_\nu \sim E_e$ No direction	t_ν E_ν estimated from E_e Θ_ν measured		t_ν only No E_ν! No Θ_ν		$\Delta\tau \simeq 10$ ms

Table 3: SNO events Rates (10 kpc supernova). Adapted from Ref. [11].

Reaction	Target medium	Events in ν_e burst per kton	Events in cooling phase per kton
$\nu_e + d \rightarrow p + p + e^-$	D_2O	10	33
$\nu_x + e^- \rightarrow \nu_x + e^-$	D_2O/H_2O	1	16
$\nu_x + d \rightarrow \nu_x + p + n$ ($n^{35}Cl \rightarrow {}^{36}Cl + \gamma$)	D_2O	6	760
$\bar{\nu}_e + d \rightarrow n + n + e^+$	D_2O	0	20
$\bar{\nu}_e + p \rightarrow n + e^-$	H_2O	0	120

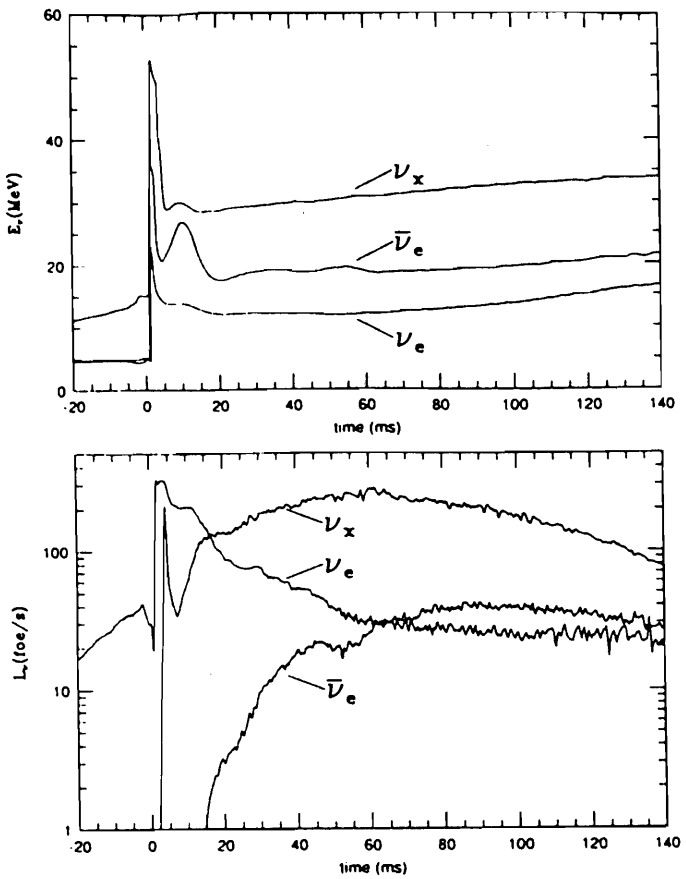


Figure 1: Neutrino luminosity and mean energy as a function of time for the 25 solar mass progenitor. Time 0 corresponds to the bounce of the core. Adapted from Ref. [13].

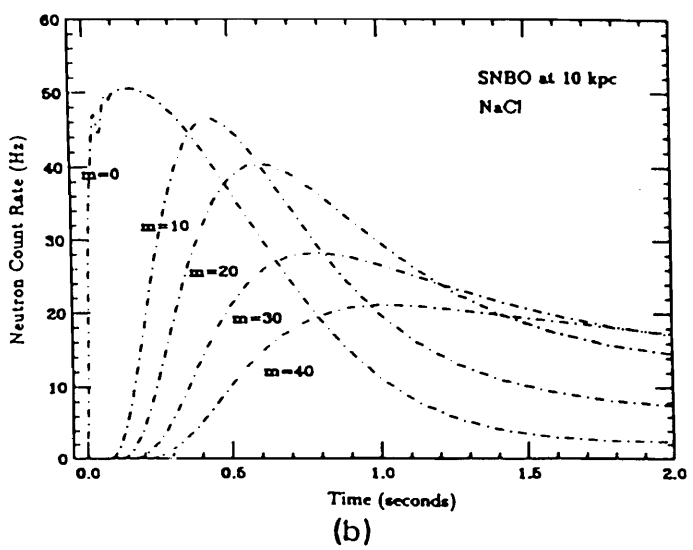
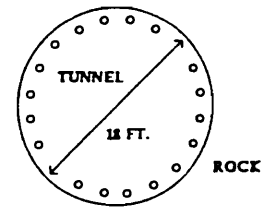


Figure 2: Effects of a massive ν_μ or ν_τ on the signal rate for a NaCl medium for different neutrino masses.

The Super Neutrino Burst Observatory Concept

1) GOAL: To measure τ neutrino mass
   - direct unambiguous measurement -
2) METHOD: Use time of flight from Galactic SN
3) DETECTOR: Rock ($\nu + A \rightarrow \nu' + A' + n$)
   (threshold exists since n is initially bound)
4) ENERGY: Average ν_τ energy is about 3/2 average ($\nu_e, \bar{\nu}_e$) energy



5) COUNTS: More than 10^4 counts expected from Galactic SN
   Use "inexpensive" neutron detectors - and
   detectors requiring little direct maintenance
6) FROM CALCULATIONS:
   $\langle E_{\nu_e} \rangle = 12\text{MeV}$ $\langle E_{\bar{\nu}_e} \rangle = 15\text{MeV}$ $\langle E_{\nu_{\mu,\tau}} \rangle = 25\text{MeV}$
7) RISE TIME: $L_{\bar{\nu}_e}$ and $L_{\nu_{\mu,\tau}}$ rise rapidly at
   almost the same time (about 0.1sec)
8) FIRST PREDICTION: Take model output for spectra and $L_{\bar{\nu}_e}$
   and $L_{\nu_{\mu,\tau}}$ and feed into detector response
   to predict first 0.35 seconds of detection
9) MEASUREMENT DATA: Use KamiokandeII data for supernova
   in Milky Way to measure $L_{\bar{\nu}_e}$ rise time
10) LIMITS: Compare ν_μ and/or ν_τ signal to find limits on m_{ν_μ} and/or m_{ν_τ}

LLNL Cal. for SNBO Detector:
No. of Counts = $2 \times 10^4 \frac{V}{R^2}$ with V in meters^3, R in Mpc;
For Milky Way R = 0.01 Mpc; Let V = 10^4 meters^3
Then No. of Counts = 2×10^4

Figure 3: Sketch of some of the principal concepts for SNBO.

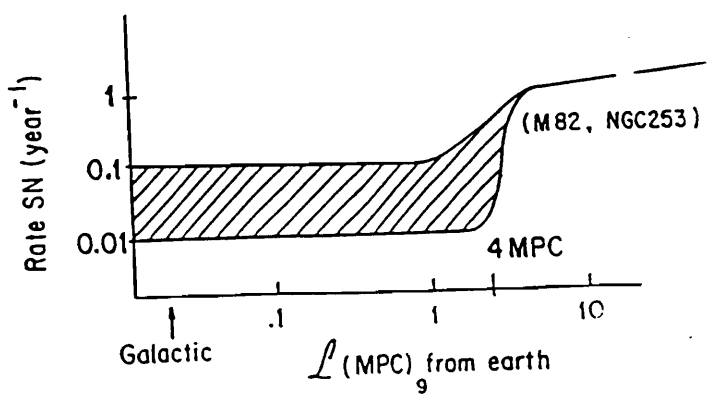


Figure 4: Estimated rate for Supernova explosions as a function of the distance from the Earth.

II. These calculations give interesting predictions for the neutrino spectra as a function of time, as shown in Fig. 1. Detectors like Super Kamiokande and the proposed Supernova Neutrino Burst Observatory(SNBO) may be able to detect such effects. Particularly, the SNBO detector may be of crucial importance for this study [10]. Using these various detectors it should be possible to detect a finite neutrino mass as shown in Fig. 2 [11].

3.2 Impact of Low Energy Neutrino Experiments

Recent measurements of the neutral current processes on nuclei at low energy (20- 50 MeV) by the KARMAN [8] group give additional confidence for the rate estimates for supernova observatories. This group has measured the process $\nu +^{12} C \rightarrow \nu +^{12} C^*$, and found very good agreement with theoretical predictions. They have also measured the charged current processes $\nu_e +^{12} C \rightarrow e^- +^{12} N(gs)$. Reactions like $\nu_e +^{12} C \rightarrow e^- +^{12} N^*$ most likely have been observed as well.

3.3 Ideal Supernova Observatories

The major problem of supernova neutrino detection is the uncertain period of time between supernova explosions in this galaxy. In addition, complementary detectors should be active when the supernova goes off. The comparison of signals from different detectors for the same supernova event should enable us to learn the maximum information about the explosion process and neutrino properties. Some of the requirements of such an ideal supernova observatory include:

- Long operating time, greater than the interval between expected observable supernova explosions (20 years for extra galactic and 60 years for galactic supernovas).
- Effective masses of the detector ranging from Ktons to a Megaton, depending on whether one is aiming at detecting signals from a galactic or an extragalactic supernova.
- capabilities to separate $\bar{\nu}_e, \nu_e$ and $\nu_\mu + \nu_\tau$ interactions
- Some directional ability to be able to point back to the supernova
- The ability to be in coincidence with Gravity Wave detectors

Lacking an ideal observatory, the SNBO group has been studying ideas for a very large detector [10]. Ideally, the SNBO detector should be a neutral current detector able to tag neutrino flavor, with an adequate event rate to be able to meausure m_{ν_μ}. Fig. 3 gives a schematic sketch of some of the more detailed steps needed in the development of SNBO. We have located a possible site for the observatory near Carlsbad N.M., the WIPP site. We have studied the radioactive background at this site (measured by the OSU group) and find it acceptable for a galactic supernova detector.

With a detector like SNBO, where up to 10^4 counts would be recorded, it should be possible to detect the supernova within 100 ms of its start, and to alert the WWW to "Supernova in Progress". The real issue in supernova neutrino detection is the long time needed to operate the detector between supernova explosions in the galaxy, longer than most underground detectors have operated for. One possibility is to build a large enough detector to "see" extra galactic supernovas. Fig. 4 shows the possible rate with distance from our galaxy, as estimated by E. Becklin [12]. A 10^7 ton detector may observe a supernova each year, though the feasibility of such a detector is questionable at this point. Nevertheless, aiming for such a rate must be the long term goal of the SNBO prototype study!

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