CONF/CP-100732

2996

RECEIVED
JAN 22 1999
OSTI

Cosmic Closure: Relating the Ultimate Fate of Massive Stars and the Ultimate Fate of the Universe

Anthony Mezzacappa
Physics Division, Oak Ridge National Laboratory
Building 6010, MS 6354, P.O. Box 2008
Oak Ridge, TN 37831-6354

Stephen W. Bruenn
Department of Physics, Florida Atlantic University
Boca Raton, FL 33431-0991

We give a brief overview of the status of core collapse supernova modeling, particularly as it pertains to predictions of neutrino signatures for the next galactic or near extragalactic supernova. We also consider the implications of neutrino mass for both the supernova mechanism and neutrino signature predictions.

1 Introduction

The possibility of connecting the ultimate fate of massive stars, i.e., their death through core collapse supernova explosions, and the ultimate fate of the Universe is an exciting one. Core collapse supernovae are powered by neutrinos. These astyrophysical events produce more than 10^{57} neutrinos per second, making them the most copious localized source of neutrinos in the Universe and an ideal laboratory for the exploration of neutrino physics. Moreover, given the prevalence of neutrinos in the Universe, owing to its early evolution, neutrino masses in the range $3-10$ eV would result in a significant neutrino contribution to the closure density and the Universe's ultimate fate. A nonzero neutrino mass also opens up the possibility of neutrino oscillations, which, as we will discuss, may have ramifications for the supernova mechanism and, as we will show, will certainly have ramifications for supernova neutrino signature predictions.

2 The Core Collapse Supernova Mechanism: A Status Report

Core collapse supernovae result when the iron core of a massive star becomes unstable late in the star's life, collapses gravitationally, at supernuclear densities becomes incompressible, rebounds, and generates a shock wave that ultimately propagates out through the core and the outer layers of the star to disrupt it in a core collapse supernova explosion. Unfortunately, because of dissociation and neutrino losses, the shock stalls to form an accretion shock.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Current supernova theory revolves around the idea that the stalled shock is revived by a "delayed shock mechanism" first discovered by Wilson[26] and fully developed by Bethe and Wilson[2]. In this mechanism, the stalled shock is revived by neutrino heating, i.e., by the absorption of electron neutrinos and antineutrinos by the dissociation-liberated protons and neutrons behind it.

Although the basic paradigm is believed to be in hand, simulations of core collapse supernovae have not consistently yielded explosions[3,27,15,8,16,21]. This disparity resulted in part from the fact that the delayed shock mechanism is extremely sensitive to approximations to the transport of the neutrinos responsible for shock revival, as they propagate from the radiating "neutrinospheres" below the shock to the shock itself. Until recently this transport has been approximated[3,27]. Recent results obtained with exact transport are very promising[19] and prove that different transport schemes do yield differences with consequences for the supernova mechanism. This decade has also seen the birth of multidimensional supernova modeling, which has demonstrated that multidimensional effects, such as convection below the neutrinospheres or the shock or both, may play a role in shock revival and the explosion mechanism[15,8,16]. However, these investigations are only in their infancy and the results have been mixed[21].

Convection below the neutrinospheres, if vigorous, may boost the neutrinosphere luminosities as hot matter is dredged from deeper regions in the stellar core[17]. Convection above the neutrinosphere and behind the stalled shock may boost the shock radius considerably, which would move the shock to a shallower point in the gravitational potential and to a lower preshock ram pressure, facilitating shock revival[8]. Convection below the neutrinospheres is arguably the most difficult to investigate numerically because the neutrinos and the matter are coupled in this region and, consequently, multidimensional simulations must include both multidimensional hydrodynamics and multidimensional neutrino transport. Thus, final conclusions regarding the extent of convection and its impact on the explosion mechanism, and the resolution of the disparate predictions of previous, less realistic simulations[15,8,16,17,22,21], must await next-generation simulations. These simulations will also be needed to more thoroughly investigate other effects such as rotation and magnetic field effects.

In addition to the requirements of more accurate transport and the continued exploration of multidimensional effects, there is the need for and further complications associated with improvements in the microphysics that is input to the one- and multidimensional simulations. Work by several groups has shown that we can expect changes in the core neutrino luminosities of order 50% owing to changes in the high-density neutrino opacities when nucleon–

nucleon correlations are taken into account[23,11,10,24], although feedbacks may reduce these changes considerably. Transport simulations have thusfar assumed that the neutrinos interact with free nucleons in the center of the core. In reality, nucleons at high density are correlated, and these correlations can reduce the neutrino opacities. Reductions in the opacities would tend to result in enhancements in the neutrino luminosities, and it might be expected that these enhancements will become important "late" in the postbounce evolution — after about 500 ms — when the proto-neutron star accretion rate falls off and the luminosity becomes dominated by the luminosity from the central core where nucleon correlations are important[11,10].

3 Implications for Neutrino Signature Predictions

The uncertainties associated with the development of convection in the proto-neutron star and the improvements in the high-density neutrino opacities, among other uncertainties associated with other phenomena, such as rotation, that have not beeen fully explored, have an impact on the ability of current models to make neutrino signature predictions.

Given a delayed shock scenario, the neutrino signatures can be compartmentalized into four phases: the infall, burst, accretion, and cooling phases. During the infall phase electron neutrinos are produced during core collapse by electron capture on the low-entropy preshocked material. This phase is not expected to yield a significant number of events in the detectors and will not be discussed here. The burst phase occurs as the shock wave passes the electron neutrinosphere, above which electron neutrinos freely escape from the core. These neutrinos are also produced by electron capture on the dissociation-liberated protons behind the shock. During the accretion phase the neutrino luminosities are dominated by the luminosity of matter accreted onto the surface of the proto-neutron star below the stalled shock, and it is during this phase that the explosion is initiated. The cooling phase follows the accretion phase and is characterized by the neutrino luminosities from a cooling, contracting proto-neutron star at the center of the explosion. Improvements in neutrino transport modeling might lead to significant changes in the signature predictions for the burst phase and the rise time and luminosity maxima for the three-flavor luminosities. Proto-neutron star convection, if vigorous, might lead to an enhancement in the neutrino luminosities and, consequently, neutrino signature predictions during and after the accretion phase, and neutrino opacity corrections might result in different signature predictions after the end of the accretion phase/beginning of the proto-neutron star cooling phase after the explosion has been initiated.

In light of the above discussion, it is clear that supernova models have not yet advanced to the stage where they can make exact quantitative predictions of neutrino signatures from core collapse supernovae. The question naturally arises: What can they predict?

4 Neutrino Signatures: The Massless Case

In Figures 1 and 2 we plot the neutrino luminosities and rms energies and the total event rates for Super-Kamiokande (Super-K) and SNO for our 11 and 25 $M_\odot$ models. These models were computed with hydrodynamics and multigroup flux-limited diffusion neutrino transport that were both fully general relativistic, in one dimension (spherical symmetry), and assume that the neutrinos are massless[6].

The event rate per flavor per reaction is computed by[4]

$$\frac{dN_{\rm d}}{dt} = \frac{N_{\rm p}}{4\pi R^2}\int_0^\infty d\epsilon \frac{dN_{58}(\epsilon,t)}{d\epsilon}\sigma(\epsilon)\eta(\epsilon) \quad (1)$$

where we have chosen electron antineutrino absorption on protons as an example and where $N_{\rm p}$ is the number of protons in the detector, R is the distance to the supernova, $dN_{58}/d\epsilon$ is the differential neutrino number luminosity in units of 10^{58}/MeV, $\sigma(\epsilon)$ is the cross section for neutrino absorption or scattering as a function of neutrino energy, and $\eta(\epsilon)$ is the detector efficiency.

The reactions considered for Super-K are

$$\begin{aligned} \bar{\nu}_{\rm e} + p &\longrightarrow e^+ + n \\ \bar{\nu}_{\rm e} +^{16} O &\longrightarrow e^+ +^{16} N \\ \nu_i + e^- &\longrightarrow \nu_i + e^- \end{aligned} \quad (2)$$

where $\nu_i = \nu_{\rm e}, \bar{\nu}_{\rm e}, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$. The reactions considered for SNO are

$$\begin{aligned} \nu_i + e^- &\longrightarrow \nu_i + e^- \\ \nu_i + d &\longrightarrow \nu_i + p + n \\ \nu_{\rm e} + d &\longrightarrow p + p + e^- \\ \bar{\nu}_{\rm e} + d &\longrightarrow n + n + e^+ \end{aligned} \quad (3)$$

The cross sections for these reactions are taken from Bruenn[5], Krauss et al.[18], and Ying et al.[28] The rate in Super-K is dominated by electron antineutrino absorption, for which the detector efficiency, which is really a function of the positron energy, can be computed accurately — the neutrino and positron energies in this case are nearly the same. For the other reactions, in particular, neutrino–electron scattering, the electron energy can take on a continuum of energies from the incident neutrino, up to the total neutrino energy. The results shown in Figures 1 and 2 assume that on average half the neutrino energy is imparted to the electron. For a more accurate treatment the response of the detector must be modeled by a separate Monte Carlo calculation[25].

The 11 $M_\odot$ model explodes by the *prompt* mechanism, i.e., the shock does not stall after it forms, and propagates directly out of the iron core (extreme values were chosen for the nuclear equation of state parameters to make this happen). The 25 $M_\odot$ model did not explode. What are the generic neutrino signature features we can identify? First, there is an electron neutrino burst in both models, which is followed by a sharp rise in the three-flavor neutrino luminosities. In the exploding model, this sharp rise is followed by a sharp drop as (a) the explosion develops, (b) the accretion luminosities drop off, and (c) the luminosities come to be dominated by the core luminosities. The protoneutron star then exhibits its characteristic exponential cooling behavior. In the 25 $M_\odot$ model, with no explosion the accretion is maintained, the three-flavor accretion luminosities remain high, and finally, after a few seconds, a black hole forms, followed by a sudden termination in luminosity. A 15 $M_\odot$ model in which a *delayed* explosion was *simulated* by lifting off the mantle at a chosen postbounce time exhibited characteristics of both the 11 and the 25 $M_\odot$ models, i.e., at the time the explosion is simulated, there is a sharp drop in both the ν_e and $\bar{\nu}_e$ luminosities and rms energies, as in the 11 $M_\odot$ model, whereas they are maintained at higher values by accretion prior to explosion, as in the 25 $M_\odot$ model (see also Burrows et al.[9] and Totani et al.[25]). Of course these "generic" features may be altered by neutrino oscillations, as we will see. For example, the electron neutrino burst may not be present in either model, although the other features would remain. (For more detail, see Bruenn and Mezzacappa[7].)

5 The Implications of Neutrino Mass

Given the evidence for neutrino oscillations from the Super-K atmospheric neutrino data[12] and the compelling explanation of the solar neutrino deficit in terms of neutrino oscillations, the case for neutrino mass, with all of its implications for the revision of fundamental particle physics and perhaps supernova

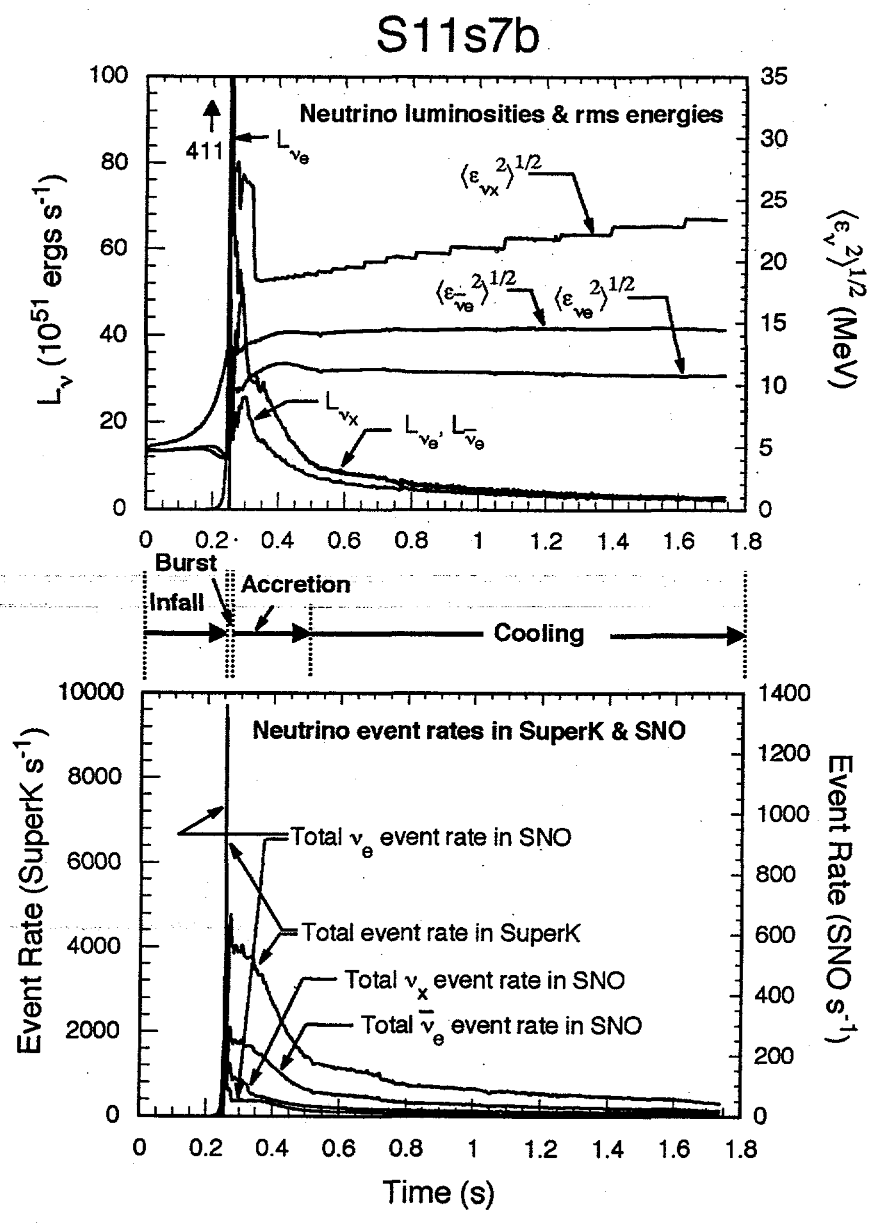

Figure 1: Three-flavor luminosities, rms energies, and event rates in Super-K and SNO as a function of time for our exploding 11 solar mass model.

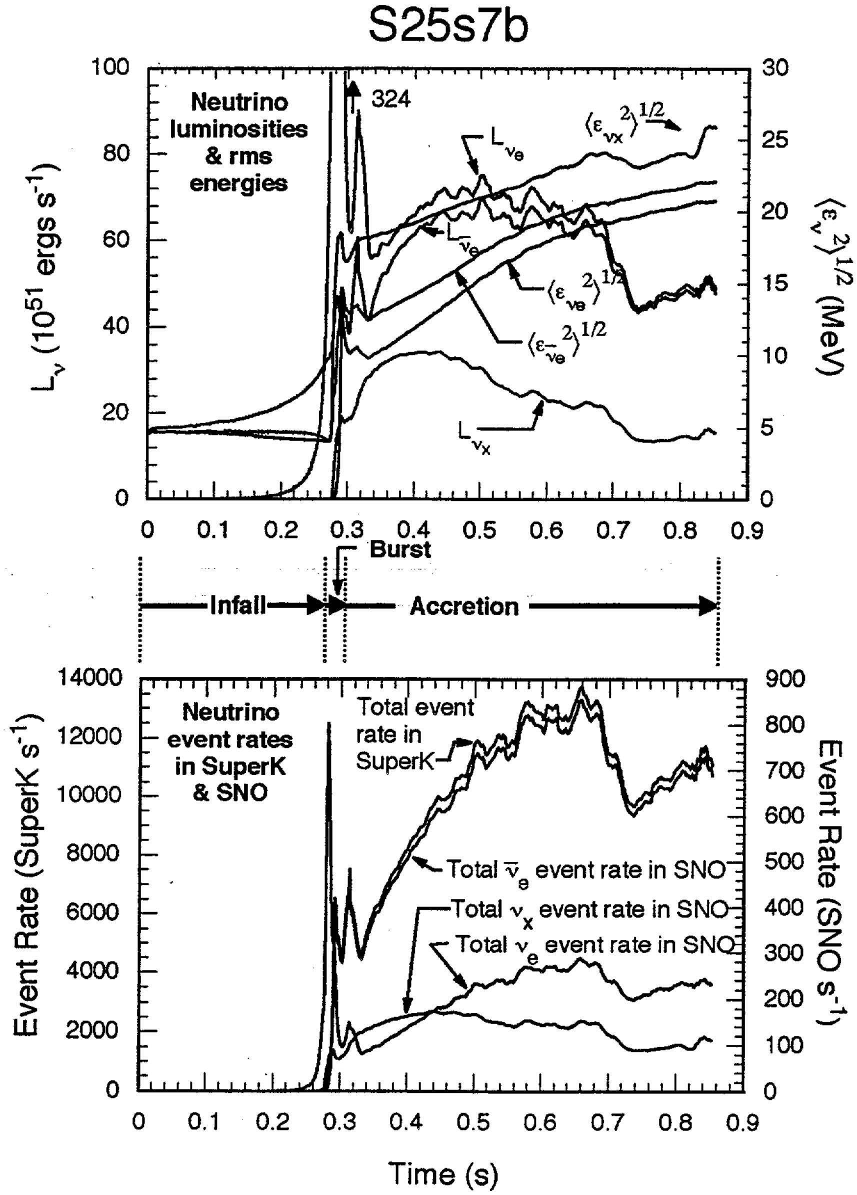

Figure 2: Three-flavor luminosities, rms energies, and event rates in Super-K and SNO as a function of time for our nonexploding 25 solar mass model.

theory, is mounting. The implications for supernova theory are twofold: We must be concerned about the impact of neutrino masses on (1) the neutrino signatures and (2) the explosion mechanism.

The muon and tau neutrinos interact only via neutral currents and, therefore, decouple at higher density and temperature in the proto-neutron star. As a result, they have harder spectra. (The differences in the neutrinosphere temperatures for the different flavors are expected to be reduced when nucleon–nucleon correlations are introduced into the models [14].) If oscillations between tau and electron neutrinos occur, the shock heating rate would be boosted by converting tau neutrinos, which are not absorbed by nucleons, to electron neutrinos, which are, while at the same time converting the softer-spectra electron neutrinos to tau neutrinos. Because the absorption cross section depends on the square of the neutrino energy, both the probability of absorption as well as the energy absorbed are increased when the neutrino spectra are hardened. Of course, this is benefitial only when the oscillations occur below the gain radius, otherwise the transformation occurs farther out where it becomes useless for shock revival.

For comparison, we follow Fuller et al.[13] and assume a neutrino mass hierarchy that follows the lepton mass hierarchy, i.e., where $m_{\nu_\tau} >> m_{\nu_\mu} > m_{\nu_e}$. In particular, we chose the tau neutrino mass to be 25 eV, the electron neutrino mass to be 0 eV, $m^2_{\nu_\tau} - m^2_{\nu_\mu} = 625$ eV^2, and $m^2_{\nu_\mu} - m^2_{\nu_e} = 6 \times 10^{-6}$ eV^2. We also chose the vacuum mixing angles to be $\theta_{\rm V} = 10^{-3}$ for ν_τ–ν_e oscillations (within the range considered by Fuller et al.) and $\sin^2 2\theta_{\rm V} = 6 \times 10^{-3}$ for ν_μ–ν_e oscillations. The latter choices for the mass difference and vacuum mixing angle were motivated by the small-mixing-angle solution to the solar neutrino problem. The ν_μ–ν_e oscillations would occur in the low-density outer layers of the star and would not have an impact on generating the explosion. However, because they would occcur between the source (the proto-neutron star) and the detector, they must be included to assess their effects on the neutrino signatures.

The resonance region for each type of oscillation was found using the resonance condition[1]

$$\sqrt{2}\mathrm{G_F} n_e = \Delta_{\rm V} \cos 2\theta_{\rm V} \tag{4}$$

where $G_{\rm F}$ is the Fermi constant, n_e is the electron density in our model, and

$$\Delta_{\rm V} = |\Delta m^2/2E| \tag{5}$$

The Landau–Zener jump probability is then[1]

$$P_{\text{jump}} = e^{-\pi^2(\Delta r/L_{M,\text{res}})/2} \tag{6}$$

where

$$\frac{\Delta r}{L_{\text{M,res}}} = \frac{\Delta m^2 c^3 \sin^2 2\theta_{\text{V}} / \cos 2\theta_{\text{V}}}{hE|n_e^{-1} dn_e/dr|} \tag{7}$$

In equation (5), the logarithmic gradient in the electron density is evaluated at the resonance radius defined by equation (5). For small vacuum mixing angles, the flavor survival probability is approximately equal to the jump probability.

Plotted in Figures 3 and 4 are the predicted neutrino signatures for Super-K and SNO for our 15 $M_\odot$ model and both the zero neutrino mass and the nonzero neutrino mass (with oscillations) cases. It is evident that there are qualitative differences between the two. For example, when neutrino oscillations are included, the electron neutrino burst is converted to tau neutrinos, and because of their nonzero mass, the "burst" is delayed and significantly broadened in time. (For more detail, see Mezzacappa and Bruenn[20].)

Because our stalled supernova shock reaches a maximum radius only between 100–200 km, m_τ would have to be of order 150 eV before the resonance region is interior to the gain region. For our $m_\tau = 25$ eV neutrinos, the oscillations occur well outside the heating region and therefore have no impact on initiating an explosion, although their effects on the neutrino signatures are significant, as we have shown.

In contrast, the Fuller et al. calculations, which used an exploding model, estimated that neutrino oscillations were important for the explosion energetics. The difference arises because in their analysis the shock is already at 500 km and the resonance regions are within the shock heating region. This raises an important point: In order for neutrino oscillations to aid in *initiating* an explosion, the oscillations would have to occur deep within the core, as we have shown, which, for MSW oscillations, would imply that there must be a large mass difference between the tau and the muon neutrinos. Of course, other oscillation scenarios are possible and one cannot conclude that this must be the case. In any event, even if oscillations do not play a role in initiating the explosion, they may play a role in ensuring that the explosion *energy* is sufficiently high.

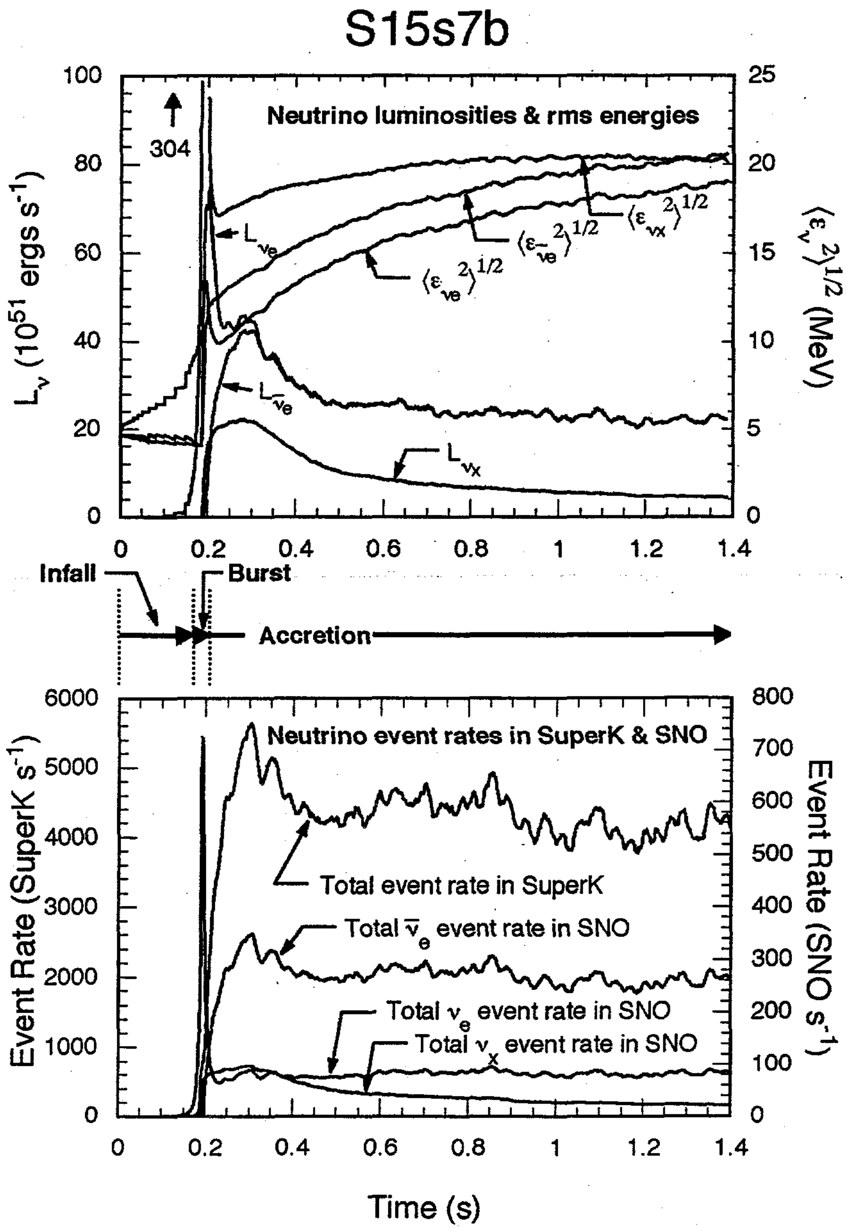

Figure 3: Neutrino luminosities, rms energies, and predicted event rates in Super-K and SNO for our 15 solar mass model with no mixing.

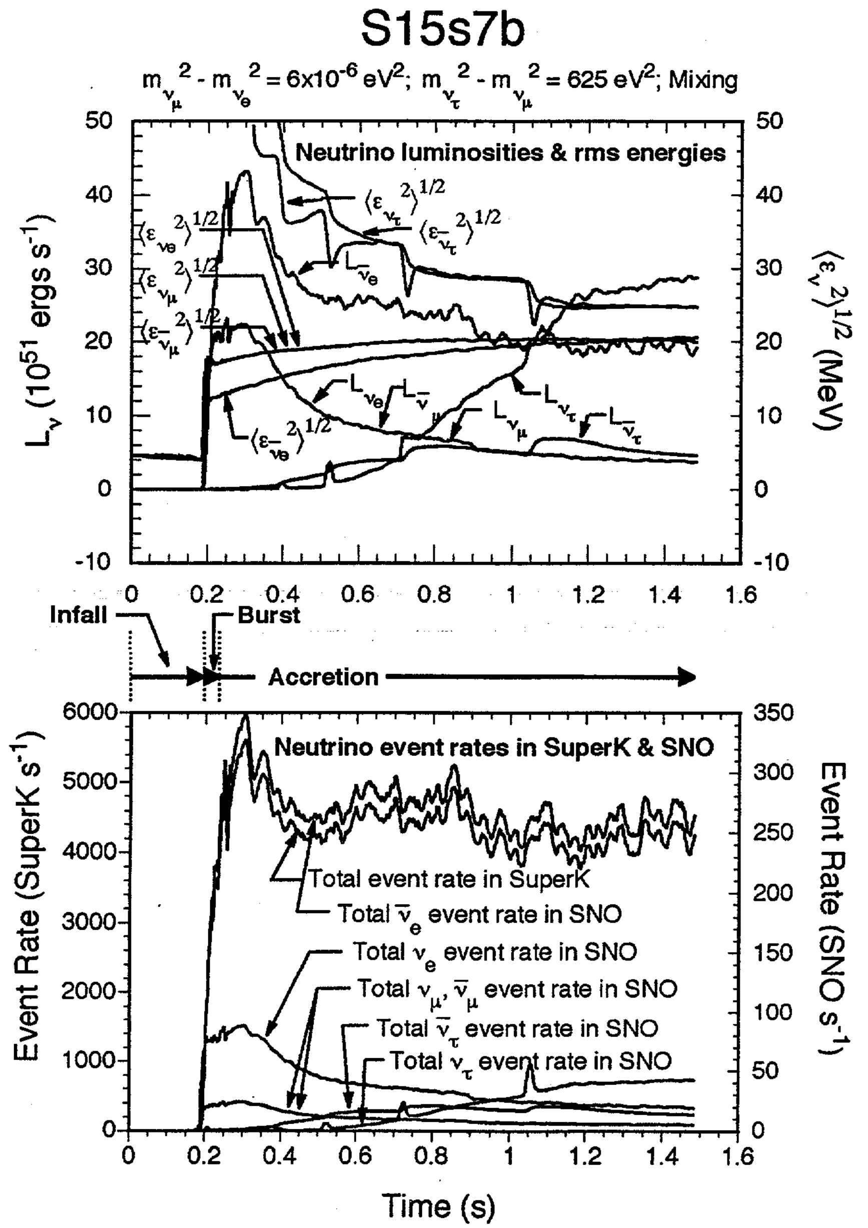

Figure 4: Neutrino luminosities, rms energies, and the predicted event rates in Super-K and SNO for our 15 solar mass model with mixing.

17. W. Keil, H.-Th. Janka, & E. Müller, *Ap.J.* **473**, L111 (1996).
18. L.M. Krauss, P. Romanelli, D. Schramm, & R. Lehrer, *Nucl. Phys.* **380**, 507 (1992).
19. O.E.B. Messer, A. Mezzacappa, S.W. Bruenn, & M.W. Guidry, *Ap.J.* **507**, 353 (1998).
20. A. Mezzacappa & S.W. Bruenn, *Ap.J.*, submitted (1998).
21. A. Mezzacappa, A.C. Calder, S.W. Bruenn, J.M. Blondin, M.W. Guidry, M.R. Strayer, & A.S. Umar, *Ap.J.* **495**, 911 (1998).
22. A. Mezzacappa, A.C. Calder, S.W. Bruenn, J.M. Blondin, M.W. Guidry, M.R. Strayer, & A.S. Umar, *Ap.J.* **493**, 848 (1998).
23. S. Reddy, M. Prakash, & J.M. Lattimer, *Phys. Rev.* **D58**, 013009 (1997).
24. S. Reddy, M. Prakash, & J.M. Lattimer, & J.A. Pons, *Phys. Rev.*, submitted (1998).
25. T. Totani, K. Sato, H.E. Dalhed, & J.R. Wilson, *Ap.J.* **496**, 216 (1998).
26. J.R. Wilson, in *Numerical Astrophysics*, eds. J.M. Centrella, J.M. LeBlanc, & R.L. Bowers (Boston: Jones and Bartlett Publishers, Inc.), p. 422 (1985).
27. J.R. Wilson & R.W. Mayle, *Phys. Rep.* **227**, 97 (1993).
28. S. Ying, W.C. Haxton, & E.M. Henley, *Phys. Rev.* **C45**, 1982 (1992).