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Neutrinos from SN1987A and Current Models of Stellar-Core Collapse

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The neutrino signatures obtained from extended hydrodynamic calculations of stellar-core collapse are described and compared with the data of Hirata *et al.* and Bionta *et al.* The comparisons suggest that SN1987A resulted from the collapse of a small core, and marginally suggest the delayed-shock mechanism.

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The detections by the Kamiokande II[1] and IMB (Irvine-Michigan-Brookhaven)[2] collaborations of neutrinos from the supernova, SN1987A,[3] in the Large Magellanic Cloud (LMC) have provided a unique opportunity for testing, among other things, the current stellar-core-collapse–type-II-supernova scenario. This scenario begins with the destabilization of the iron core of a massive star ($11M_\odot \le M \le 70M_\odot$) or the O+Ne+Mg core of a less-massive star ($8M_\odot \le M \le 11M_\odot$) when such a core exceeds the effective Chandrasekhar mass. During the ensuing collapse, the core divides into an approximately homologously collapsing inner core ($v \propto r$) and an outer core collapsing supersonically with a different velocity profile ($v \propto r^{-1/2}$).[4] In a mere fraction of a second the collapsing inner core reaches nuclear density and bounces as a result of the stiffness of supranuclear-density matter. The outer edge of the rebounding inner core acts like a spherical piston, launching a shock wave into the outer core. At this point the standard scenario admits two possibilities. The first is that the shock continues to propagate outward, withstanding the energy drains of nuclear dissociation and neutrino emission, and ejects the stellar envelope as a prompt type-II supernova.[5–7] The second is that the shock stalls, but is then revived after a pause of 0.1–0.5 s by energy deposition from the intense neutrino flux from the underlying neutrino-emission surface.[8,9] Neither alternative is well established, since numerical calculations with realistic neutrino transport have always found that the shock stalls,[10–15] yet only one group so far has performed the difficult numerical calculations modeling the revival of stalled shocks.[8,14,15]

In this Letter, results are presented of several core-collapse models which have been evolved for a total of $\simeq 1.6$ s (1.2–1.4 s after core bounce) for comparison with the Kamioka and IMB data. This evolution time is long enough to bridge the gap between initial-core-collapse calculations and the slow (10–20 s) cooling of a hot, compact proto-neutron-star, as recently calculated by Burrows and Lattimer.[16] Some investigators[17–20] have already pointed out that the number of neutrinos detected, their mean energy (10–15 MeV), and the total time period involved (seconds) is consistent with neutrinos diffusing out of a hot neutron star. Woosley, Wilson, and Mayle[21] have presented time-integrated antineutrino spectra of six stars of different masses that underwent gravitational collapse, and Mayle[22] has presented some additional results. Here we are interested in the details of the luminosity profiles and energy spectra of all neutrino types during the first several seconds after core collapse. General relativistic hydrodynamics coupled to multigroup transport of all neutrino types as described by Bruenn[11] was used to evolve these models. In an attempt to span currently accepted initial-core configurations, three models were evolved: model "$2M_\odot$ Fe" consisting of a $2M_\odot$ iron core of a $25M_\odot$ main-sequence star (representative of "warm," large cores); model "$1.35M_\odot$ Fe" consisting of a $1.35M_\odot$ core of a $12M_\odot$ main-sequence star (representative of a "cold," small core), and model "$1.35M_\odot$ Fe*" consisting of the same initial-core configuration as model "$1.35M_\odot$ Fe," but with highly suppressed electron capture during infall to produce a successful prompt shock. (The shock stalls in the other two models.) The initial-core models were those of Woosley and Weaver.[23] Because of some remaining uncertainties in the theory of stellar evolution (e.g., convection) the association of a given presupernova iron-core mass with a main-sequence star of specific mass is still uncertain. Thus, the $1.35M_\odot$ core might be appropriate to a $15M_\odot$ or even an $18M_\odot$ main-sequence star. I note finally that because my neutrino transport algorithm has not yet been given a generally covariant formulation, the neutrino luminosities and spectra used in computing the expected detection rates have been corrected for red shift and time dilation by using the value of the red-shift parameter at the location of the neutrino-emission surface.

The neutrino emission produced by model $2M_\odot$ Fe is shown in Figs. 1–3. The neutrino emission from the other two models is qualitatively similar, but important quantitative differences exist which will be discussed below. The sharp initial rise in the luminosity (Fig. 1) of all neutrino types at $t = 0.36$ s signals the emergence of the shock, with the narrow ν_e spike arising from rapid electron capture on the thermally dissociated free protons behind the shock. About 4.5×10^{51} ergs are radiated in $\simeq 15$ ms by this ν_e spike, which is far too small (and narrow) to account for the first two events in the

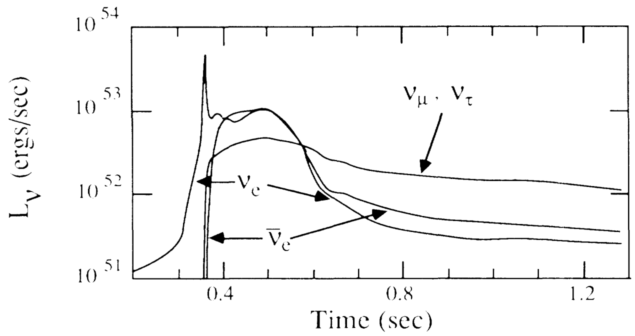

FIG. 1. Luminosity of model $2M_\odot$ Fe as a function of time in ν_e's, $\bar{\nu}_e$'s, and each member of the ν_μ-ν_τ family.

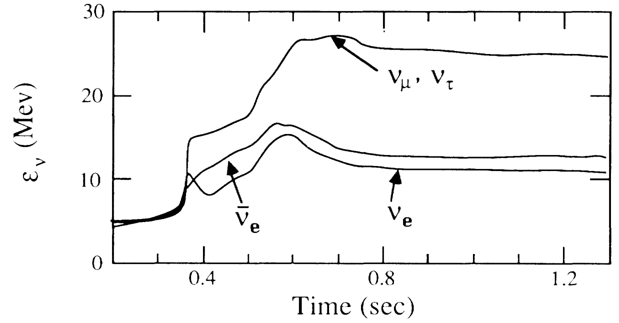

FIG. 2. Average energy of the radiated neutrinos as a function of time for model $2M_\odot$ Fe.

Kamioka detector. (These two events point back to the LMC, suggesting ν_e-electron scattering in the detector. But $\bar{\nu}_e+p \rightarrow n+e^+$, which produces isotropic events, is much more probable, and one or possibly both alignments may simply reflect small-number statistics.)

Of great importance for the data comparisons is the 0.2-s plateau in the $\bar{\nu}_e$ luminosity which follows the emergence of the shock and during which a detectable amount of $\bar{\nu}_e$'s ($\simeq 2\times 10^{52}$ ergs) is radiated. This radiation comes from the hot, shocked outer core in the following manner. It begins immediately after shock emergence with the establishment of a hot ($T_e \simeq 4.3$ MeV) $\bar{\nu}_e$-emission surface ($\bar{\nu}_e$ sphere) of radius 85 km. The shocked matter interior to this $\bar{\nu}_e$ sphere, comprising a mass ΔM of $0.609 M_\odot$ and a thermal energy of $\Delta U \approx \Delta M k\langle T\rangle/m_p \approx 10^{52}$ ergs, undergoes a Kelvin-Helmholtz contraction in a time $\Delta U/4\pi R^2(\frac{7}{8})\sigma T_e^4 \approx 0.2$ s. This reduces the radius of the $\bar{\nu}_e$ sphere to 25.4 km, after which it decreases very slowly. An application of the virial theorem and the radiation-diffusion equation to this contracting matter gives $T \propto \rho^{1/3}$ and $L \propto RT^4/\kappa\rho$, respectively. With the neutrino opacity κ varying as $\epsilon_\nu^2 \propto T^2$, we expect from these simple considerations that $L \propto R^2$. This, in fact, accounts quite well for the overall decline in the $\bar{\nu}_e$ luminosity during this phase, but not for the persistence of high luminosity throughout most of this pulse. The latter is due to the inflow of shocked matter through the $\bar{\nu}_e$ sphere. Since the $\bar{\nu}_e$ production rate per baryon for matter in β-kinetic equilibrium (a good approximation for this inflowing matter shortly after being shocked) goes as ρ to a power of $\simeq \frac{5}{3}$, this matter radiates $\bar{\nu}_e$'s most strongly after falling to the vicinity of the $\bar{\nu}_e$ sphere, rather than immediately upon being shocked. The $\bar{\nu}_e$ luminosity profile of the pulse correlates with the mass flow rate of the shocked matter through the $\bar{\nu}_e$ sphere. Except for the initial ν_e luminosity spike, the evolution of the ν_e luminosity following shock emergence is similar to that just described for the $\bar{\nu}_e$ luminosity.

The emission surface of the ν_μ's and ν_τ's and their antiparticles is at a smaller radius (59 km immediately following shock emergence) since the transport mean free paths for these neutrinos are about $\frac{5}{3}$ that of the $\bar{\nu}_e$'s. Since the ν_μ and ν_τ production rates are only $\simeq 0.002$ times their scattering rates for the prevailing conditions, the ν_μ's and ν_τ's are produced well within their emission surfaces. Their luminosities do not decrease as much as the ν_e's or the $\bar{\nu}_e$'s during the contraction of the shocked outer core, and they emerge from the core with considerably higher energies.

Figures 2 and 3 indicate that the $\bar{\nu}_e$ spectrum hardens and then softens slightly during the pulse, as does the ν_e spectrum. The simple considerations above which gave $L \propto R^2$ also suggest that the effective temperature $T_e \approx$ const. The change in the mean $\bar{\nu}_e$ energy comes instead from the change in entropy of the shocked matter accreting onto the $\bar{\nu}_e$ sphere. When the accretion rate tapers off and the rapid contraction of the shocked outer core has been completed, the core settles down to a prolonged period of diffusive neutrino loss during which the luminosities and spectra of all neutrino types change slowly. The computations were terminated during this phase.

The most interesting result of these computations as regards comparisons with the Kamioka and IMB data is shown in Fig. 4, and is the fact that the $\bar{\nu}_e$ luminosity integrated over the duration of the $\bar{\nu}_e$ pulse is quite

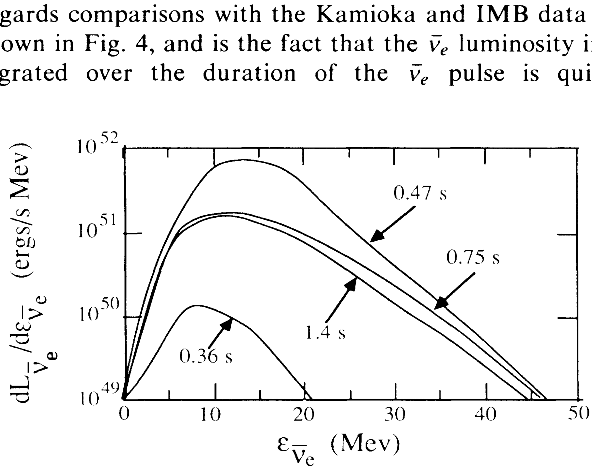

FIG. 3. Luminosity spectra of the radiated $\bar{\nu}_e$'s at various times during the calculation of model $2M_\odot$ Fe.

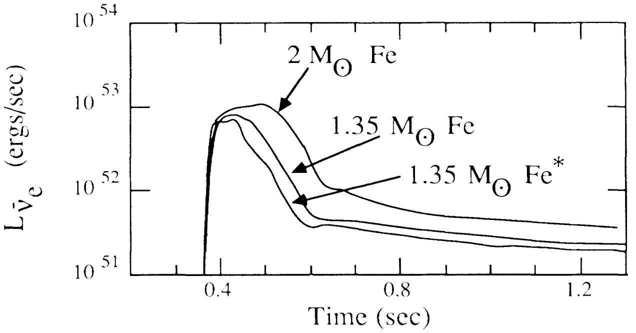

FIG. 4. Luminosities in $\bar{\nu}_e$'s as a function of time for models $2M_\odot$ Fe, $1.35M_\odot$ Fe, and $1.35M_\odot$ Fe*.

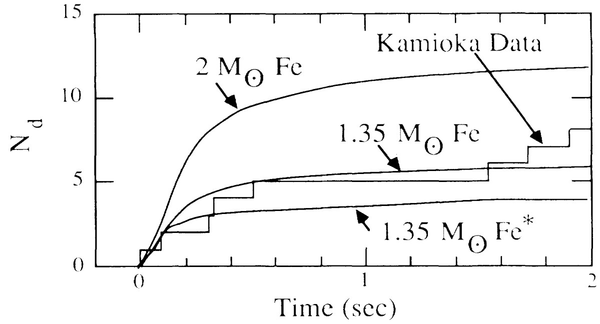

FIG. 5. Comparisons of the expected integrated event rates in the Kamioka detector for the three models with the Kamioka data.

different for the different models. Figures 5 and 6 compare the predicted integrated detections $N_d(t)$ for the three models with the integrated Kamioka and IMB detections, respectively. $N_d(t)$ for each model was computed by

$$N_d(t)=\frac{N_p}{4\pi R^2}\int_0^t dt\int_0^\infty d\epsilon\frac{dN_{58}(\epsilon,t)}{d\epsilon}\sigma(\epsilon)\eta(\epsilon)=\left[\frac{56\text{ kpc}}{R}\right]^2\int_0^t dt\int_0^\infty d\epsilon\frac{dN_{58}(\epsilon,t)}{d\epsilon}\epsilon^2\times\begin{cases}0.34\eta_{\text{K}}(\epsilon) & \text{(Kamioka)}\\ 0.79\eta_{\text{IMB}}(\epsilon) & \text{(IMB)}\end{cases}, \tag{1}$$

where R is the distance to the LMC (kpc stands for kiloparsecs), N_p is the number of protons in the detector, $dN_{58}(\epsilon,t)/d\epsilon$ is the differential number luminosity of $\bar{\nu}_e$'s in units of 10^{58} per MeV, $\sigma(\epsilon)$ is the cross section for $\bar{\nu}_e$ absorption on protons, and $\eta_{\text{K}}(\epsilon)$ and $\eta_{\text{IMB}}(\epsilon)$ are the detection efficiencies of the Kamioka and IMB detectors, respectively, which were taken from the published data. From Figs. 5 and 6 it is apparent that model $1.35M_\odot$ Fe best fits the data, although model $1.35M_\odot$ Fe* is not ruled out with high confidence. The large initial rise in $N_d(t)$ expected for model $2M_\odot$ Fe, on the other hand, is not seen in the data.

The $\bar{\nu}_e$ pulse that follows shock emergence arises from the shocked matter in the outer core, as discussed above, and is therefore proportional to the mass of this shocked matter. The lack of a prominent initial rise in the Kamioka and IMB data for $N_d(t)$ suggests that the mass of the shocked outer core of SN1987A was small. Simple hydrostatic considerations dictate that large stellar cores ($\simeq 2M_\odot$) must be warm (entropy $\simeq 1.5$ K/baryon). On infall, such cores undergo rapid electron capture on the few times 10^{-3} free-proton mass fraction,[24] and this results in considerable deleptonization.[25,26] The consequence is a small-inner–large-outer-core configuration at bounce. The passage of the shock then raises a significant fraction of this large outer core to high entropies. (This is true whether or not the shock stalls.) The small shocked outer core of SN1987A therefore suggests the collapse of a small core.

A supernova explosion produced by a prompt hydrodynamical shock must arise from a core configuration at bounce consisting of a large-inner-core–small-outer-core ratio. This configuration is needed for the production of a strong shock, and to ensure that the shock does not weaken too much while propagating through the outer core as it dissociates nuclei and suffers neutrino losses. Only cores that are small ($M \simeq 1.35M_\odot$) and cold (entropy $\simeq 0.5$ K/baryon) before collapse are possible candidates for this supernova mechanism.[7] When account is taken of the ejected matter which does not radiate many neutrinos, numerical simulations (Baron[27] and the present model $1.35M_\odot$ Fe*) show that only a few tenths of a solar mass is involved in radiating the $\bar{\nu}_e$ pulse. Supernova explosions produced by this prompt-shock mechanism would therefore radiate a rather small $\bar{\nu}_e$ pulse, as shown in Fig. 4 for model $1.35M_\odot$ Fe*, and a rapid rise in the initial detection signal would not be expected. On the other hand, a very strong shock arising from a soft-supranuclear equation of state[7] might produce a prompt explosion despite a slightly larger outer core.

Model $1.35M_\odot$ Fe, which gives the neutrino signature expected from a delayed-shock supernova initiated by the collapse of a small core, best fits the initial rise in the

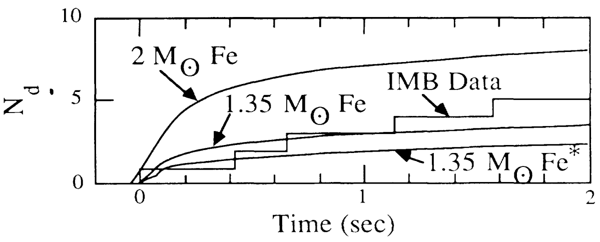

FIG. 6. Comparisons of the expected integrated event rates in the IMB detector for the three models with the IMB data.

Kamioka data for $N_d(t)$. This conclusion must be regarded with caution, however, because of the small number of detection events involved, the possibility mentioned above that a very strong shock could survive a larger outer core, and because convection can enhance the initial neutrino luminosity of a core.[28] Without the availability of detailed core-collapse calculations with convection, it appears difficult at the moment to distinguish the expected $\bar{\nu}_e$ pulse produced by a very small shocked outer core with convection from that produced by a larger shocked outer core with less effective convection or without convection at all.

When the computations were terminated (at 1.6 s), the luminosities and spectra of all neutrino types were changing slowly. The subsequent expected integrated detections of the models can be estimated by a simple extrapolation assuming constant luminosities and spectra after 1.6 s. For model $1.35M_\odot$ Fe at 1.6 s, the total luminosity L_{tot} is 3.2×10^{52} ergs/s, the total radiated energy E_{tot} is 8.2×10^{52} ergs, the gravitational potential energy Ω is 2.4×10^{53} ergs, and the predicted detection rates are 0.51 and 0.49 s^{-1} for Kamioka and IMB, respectively. I therefore predict significant neutrino emission for an additional time $t \simeq (\Omega - E_{\text{tot}})/L_{\text{tot}} = 5$ s with 2–3 more detections in each detector. This should be compared with 5 additional detections by Kamioka over a period of 10.8 s, and 3 additional detections by IMB over a period of 4 s. The extrapolation for model $1.35M_\odot$ Fe* gives an additional pulse duration similar to that of model $1.35M_\odot$ Fe and 85% of the predicted additional detections. For model $2M_\odot$ Fe I predict an additional pulse duration of 4 s and about 5–6 additional detections in each detector. The extrapolations of all three models give pulse durations and integrated deletions "in the same ballpark" as the data. I note that the last three Kamioka detections came after a hiatus of 7.3 s and may therefore represent a phenomenon other than neutron-star cooling. If these are excluded, the lower-mass models again best fit the data.

A comparison was made between the above extrapolations of my results and the time-integrated $\bar{\nu}_e$ spectra given in Fig. 1 of Woosley, Wilson, and Mayle,[21] obtained by similar extrapolations of their results. The agreement between my models $1.35M_\odot$ Fe and $1.35M_\odot$ Fe* and their model $15M_\odot$, and between my model $2M_\odot$ Fe and their model $25M_\odot$ is quite good as regards the total energy radiated by the $\bar{\nu}_e$'s, but the peaks in my $\bar{\nu}_e$ spectra are a few megaelectronvolts lower than theirs (e.g., compare my Fig. 3 with their Fig. 1).

I wish to thank S. Woosley for pointing out that a specific core configuration cannot at this time be associated with any certainty with a main-sequence progenitor of definite mass, E. Myra for pointing out that the prompt-shock mechanism may not require quite so small an outer core as I had supposed, and my wife for some of the data reductions and for critical readings of this manuscript. This work was supported in part by National Science Foundation Grant No. AST-8408432.

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