THE ASTROPHYSICAL JOURNAL, **318**:L63–L68, 1987 July 15

NEUTRINOS FROM SN 1987A

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Received 1987 April 6; accepted 1987 May 11

ABSTRACT

The detections by the Kamiokande II and IMB collaborations of the neutrinos from the supernova, SN 1987A, have provided the nuclear and neutrino astrophysics communities with an unprecedented opportunity to probe deeply into a collapsed core and watch the birth of a neutron star. We compare model calculations of the neutrino emissions following core collapse with these data and obtain reasonable agreement for the total energy, average neutrino energy, and burst duration. The simultaneous observation of both 10 MeV neutrinos and second, not millisecond, characteristic times indicates that the neutrinos do indeed *diffuse* out of the core. Furthermore, this is direct evidence that neither exotic particles nor nonstandard neutrino properties play a role. We have performed various statistical tests on these data and see no reason to evoke pulsing or oscillation at the source. Most, if not all, of the events in both detectors must have been from antielectron neutrino absorption, not electron neutrino scattering. We explore the consequences of these observations for supernova theory and derive a tentative upper limit to the electron neutrino mass of ~ 6.5 eV.

Subject headings: neutrinos — stars: collapsed — stars: evolution — stars: supernovae

I. INTRODUCTION

Theorists have long believed that neutrino, not photon, emission dominates the last phase of the evolution of massive stars ($M_* \geq 8\ M_\odot$) (Chiu 1964). The formation of such an iron (for $M_* \geq 11\ M_\odot$) or O-Ne-Mg (for $8\ M_\odot < M_* < 11\ M_\odot$) core that will become unstable and implode as the star dies is in many ways a direct consequence of the primacy of neutrino emission during the final quasi-static, burning stages. The collapse and supernova phase is thought to be accompanied by the most energetic neutrino burst of all as a neutron star (or black hole) is formed.

While there was indirect evidence for the prominent role of the neutrino in massive star evolution and neutron star formation, these neutrinos had never actually been observed. Recently, however, the Kamiokande II (Hirata *et al.* 1987) and the IMB (Bionta *et al.* 1987) collaborations reported the detection, at ostensibly the same time, of the neutrino burst from the supernova SN 1987A in the Large Magellanic Cloud (LMC). The eight neutrino events spread over 5.6 s in the IMB detector and the 11 neutrino events spread over 12.5 s in the Kamioka detector are a true milestone in neutrino astronomy. In this *Letter*, we extract some of the implications of this epochal detection and compare the standard model with these new data. We find that the standard model is verified to a surprising degree.

II. THE STANDARD MODEL

When the core, which is comprised of either iron-peak elements or O-Ne-Mg, reaches the effective Chandrasekhar mass ($M_C \approx 1.2$–$1.8\ M_\odot$; Woosley and Weaver 1986), through a combination of photodisintegration (Hoyle and Fowler 1964) and/or electron capture (Nomoto 1984), it collapses dynamically and pulls away from the rest of the star (Colgate and White 1966; Arnett 1967; Wilson 1971; Wilson 1985; Burrows and Lattimer 1985; Wilson *et al.* 1986; Woosley, Wilson, and Mayle 1986). Compression raises the electron Fermi energy above the electron capture thresholds and copious electron neutrino (ν_e) emission ensues. Concomitantly, however, the opacity of the core to neutrinos increases and beyond a density of $\sim 10^{12}$ g cm^{-3}, these neutrinos are trapped (Mazurek 1974; Sato 1975) in the flow. As a result, net neutronization ceases before nuclear densities are reached. Upon reaching nuclear densities, the subsonic inner core stiffens, rebounds, and drives a shock wave into the outer mantle. Either the shock overcomes the debilitating effects of nuclear dissociation and electron neutrino radiation after the breakout of the neutrinosphere to become a prompt Type II supernova (Colgate and Johnson 1960; Baron, Cooperstein, and Kahana 1985) or it stalls, only to be revived later after a short pause of between 0.1 and 1.0 s (Wilson 1985; Bethe and Wilson 1985). In either case, shortly after bounce, the residue is in hydrostatic equilibrium. It is hot, lepton-rich, and only marginally bound. Electron neutrino losses during the collapse amount to only $\sim 10^{51}$ ergs and those accompanying breakout to less than 10^{52} ergs (Burrows and Mazurek 1982). Most of the energy and leptons that must be radiated to form a neutron star, whose binding energy is 2–4×10^{53} ergs, has yet to be released.

The standard model predicts that neutrinos of all species ($\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$), *not* just ν_e's, carry away the neutron

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TABLE 1

DATA FROM THE KAMIOKA AND IMB DETECTORS

Event	Time (s)	Electron Energy (MeV)	Angle with Respect to LMC
		Kamioka	
1	0.0[a]	20.0 ± 2.9	18° ± 18°
2	0.107	13.5 ± 3.2	15 ± 27
3	0.303	7.5 ± 2.0	108 ± 32
4	0.324	9.2 ± 2.7	70 ± 30
5	0.507	12.8 ± 2.9	135 ± 23
6[b]	0.686	6.3 ± 1.7	68 ± 77
7	1.541	35.4 ± 8.0	32 ± 16
8	1.728	21.0 ± 4.2	30 ± 18
9	1.915	19.8 ± 3.2	38 ± 22
10	9.219	8.6 ± 2.7	122 ± 30
11	10.433	13.0 ± 2.6	49 ± 26
12	12.439	8.9 ± 1.9	91 ± 39
		IMB	
1	0.0[a]	38 (±25%)	...[c]
2	0.42	37	...[c]
3	0.65	40	...[c]
4	1.15	35	...[c]
5	1.57	29	...[c]
6	2.69	37	...[c]
7	5.01	20	...[c]
8	5.59	24	...[c]

[a] Time for initial event set equal to zero.

[b] Excluded by Kamiokande II collaboration.

[c] Ambiguous.

star's binding energy in roughly equal amounts in, *not* milliseconds, but *seconds* (Sawyer and Soni 1979; Burrows, Mazurek, and Lattimer 1981; Burrows and Lattimer 1986) as these neutrinos *diffuse* out of the hot, opaque proto–neutron star. This time scale is set by the opacity of dense matter. The initial emission is dominated by the cooling and neutronization of the shocked outer core. This early phase lasts no more than half a second and blends into the long-term phase of diffusion from the inner core. As the neutrinos escape, they downscatter in energy. The average energy of the ν_e's and $\bar{\nu}_e$'s should be 10–20 MeV and that of the ν_μ's, $\bar{\nu}_\mu$'s, ν_τ's, and $\bar{\nu}_\tau$'s (hereafter "ν_μ's") should be 15–25 MeV (Bowers and Wilson 1982). It is *not* expected that 100 MeV neutrinos will be seen in great numbers, that ν_e's will dominate, or that the signal will last only milliseconds. It is expected that the $\bar{\nu}_e$'s, by their large absorption cross section on protons, will dominate the signal in water Cherenkov detectors.

III. THE DATA AND ENERGY ESTIMATES

Data from the Kamioka and IMB detectors are given in Table 1. The 11 Kamioka events are clustered in three bunches. Setting $t = 0.0$ as the time of the first event, the first bunch consists of five events between 0.0 and ~ 0.5 s; the second, of three events between 1.5 and 2.0 s; and the third, of three events between 9.0 and 12.5 s. The observed secondary electron energies as inferred from the emitted Cherenkov light range between 7.5 and 35.4 MeV, with errors of ~ 20%–25%. The Kamioka detection threshold is ~ 7 MeV. There is a hint of spectral softening with time in the first bunch, and perhaps in the second, though the paucity of data does not allow us to conclude much about the spectral evolution of the source. Event 6 is eliminated from consideration by the collaboration due to the small number of photomultiplier hits. Table 1 also includes the extrapolated angle of the initiating neutrino with respect to the LMC.

The eight IMB events arrived over an interval of 5.5 s, the first five within the first 2 s. The estimated neutrino energies ranged between 20 and 40 MeV, with errors of ~ 25%. These data show a statistically significant softening of the spectrum with time (Student's t significance ≈ 0.01). The IMB threshold is higher than Kamioka's and near 20 MeV. The first IMB event was clocked at UT February 23 0735:41.37, while the first Kamioka event was at UT February 23 0735:35 (±1 minute). The ambiguity in the Kamioka time is unfortunate, but the near simultaneity of both detections more than suggests that not only did each see the neutrino burst from SN 1987A, but that each saw it at the same time. Therefore, the two data sets are mutually confirming.

As Table 1 indicates, most of the events do not point back toward the LMC. This fact implies that most, possibly all, were not $\nu_e - e^-$ scattering events, but were $\bar{\nu}_e$ absorption events. Relativistic kinematics confines $\nu_e - e^-$ scattering to the forward cone. The cross section for the $\bar{\nu}_e p \rightarrow e^+ n$ reaction at ~ 10 MeV is ~ 100 times that for $\nu_e - e^-$ scattering and ~ 700 times that for $\nu_\mu - e^-$ scattering. The large number of high-angle Kamioka events confirms the prediction of the standard model that $\bar{\nu}_e$'s should dominate the signal. Not only would one ν_μ detection be unlikely, more than one ν_e would be suspect, but not impossible, given the statistics. Hirata *et al.* (1987) and Arafune and Fukugita (1987) have argued that the small angles for events 1 and 2 strongly suggest that both are scattering events, and they identify them with prompt neutronization neutrinos, emitted in the first 100 ms. A neutronization burst of ~ 10^{53} ergs in 100 ms is not expected. According to the Kolmogorov-Smirnov (KS) test, the data are not inconsistent with the hypothesis that all 11 events are isotropically distributed. If Davis (1987) does not see an anomalously large number of argon decays, then even if the first two events were ν_e's, they probably do not reflect an anomalously large and sharp ν_e burst at the source, but must be a consequence of small number statistics.

Both the Kamioka and the IMB data allow us to determine the average energy of the emitted neutrinos, the effective temperature of the source, and the total energy emitted in $\bar{\nu}_e$'s ($E_{\bar{\nu}_e}$). The total energy radiated in neutrinos of all species (E_T) can thereby be estimated and compared to theoretical expectations for the binding energy of the residual neutron star. The higher threshold of the IMB detector means that it samples only the high-energy tail of the spectrum and will provide estimates of lower reliability. However, the small number of events and imperfect energy resolution in both detectors introduce large uncertainties in the calculations.

To arrive at energy estimates, we assume that the $\bar{\nu}_e$ source spectrum does not evolve appreciably with time and is Fermi-Dirac with zero chemical potential. Theory suggests that the effective temperature changes during the critical seconds by no more than 50%, and that the time-integrated spectra have a Fermi-Dirac shape (Mayle, Wilson, and Schramm 1987). In working back from the detected events to the source, we must correct for the energy dependence of the $\bar{\nu}_e p$ cross section ($\sim \varepsilon_\nu^2$), the energy dependence of the detection efficiency, and the detection threshold, all of which distort the signal. We employ two different methods, one integral, the other discrete, to derive the source characteristics. If the spectrum were Fermi-Dirac and we had enough events, both methods would be equivalent.

In method I, the average energy of the source $\bar{\nu}_e$'s is

$$\langle \varepsilon \rangle_s = \frac{\int_0^\infty \varepsilon^3 f\, d\varepsilon}{\int_0^\infty \varepsilon^2 f\, d\varepsilon} = \frac{F_3(0)}{F_2(0)} T = 3.15T, \tag{1}$$

where f is the Fermi distribution function, T is the effective temperature, and F_i is the standard Fermi integral. On the other hand, the average energy of the detected neutrinos, $\langle \varepsilon \rangle_d$, is weighted by the cross section and the detection efficiency, $W(\varepsilon)$. We obtain

$$\langle \varepsilon \rangle_d = \frac{\sum_i \varepsilon_i}{N_d} = \frac{\int_H^\infty \varepsilon^5 f W(\varepsilon)\, d\varepsilon}{\int_H^\infty \varepsilon^4 f W(\varepsilon)\, d\varepsilon} = T \frac{G_5(H/T)}{G_4(H/T)}, \tag{2}$$

where H is the energy threshold, ε_i is the energy of the ith detected $\bar{\nu}_e$, the G_i's are threshold-truncated modified Fermi integrals, and N_d is the total number of detected $\bar{\nu}_e$'s. For Kamioka and IMB, we fit the published efficiencies with $1 - e^{-(\varepsilon/10)^{2.5}}$ and $1 - 3e^{-\varepsilon/16}$, respectively, where ε in these formulae is in MeV. Note that equation (2) is an implicit function for T and that it must be solved iteratively. Therefore, in method I, we find that the total $\bar{\nu}_e$ energy fluence from SN 1987A is

$$E_{\bar{\nu}_e} = 0.77 \times 10^{52} \left(\frac{D}{50\ \mathrm{kpc}} \right)^2 \left(\frac{1}{M} \right) \times \left[\frac{F_3(0)\, G_5(H/T)}{G_4^2(H/T)} \right] \left[\frac{10\ \mathrm{MeV}}{\langle \varepsilon \rangle_d} \right] N_d \ \mathrm{ergs}, \tag{3}$$

where D is the distance to the LMC and M is the fiducial mass of the detector in kilotonnes.

Method II involves predominantly sums, instead of integrals, and allows one to gauge the contribution of each event to the results directly. In this method,

$$\langle \varepsilon \rangle_s = \frac{F_3(0)\, G_2'(H/T)}{F_2(0)\, G_3'(H/T)} \frac{\sum_i (1/\varepsilon_i W_i)}{\sum_i (1/\varepsilon_i^2 W_i)}. \tag{4}$$

Equations (1) and (4) are combined and iterated to obtain T. The total $\bar{\nu}_e$ energy is

$$E_{\bar{\nu}_e} = 0.77 \times 10^{52} \left(\frac{D}{50\ \mathrm{kpc}} \right)^2 \left(\frac{1}{M} \right) \times \left[\frac{F_3(0)}{G_3'(H/T)} \right] \left[\sum_i \frac{10\ \mathrm{MeV}}{\varepsilon_i W_i} \right] \mathrm{ergs}, \tag{5}$$

where the G_i''s are threshold-truncated Fermi integrals with the weights excluded, and the sums are over the data points above the chosen threshold. The numbers derived from Kamioka and IMB by both of these methods, after iterating to obtain a consistent T, are given in Table 2. The errors quoted in Table 2 include only the errors in the electron energies (Table 1) and are therefore understated. Fiducial masses of 2140 and 5000 kilotonnes have been assumed for Kamioka and IMB, respectively. For rigor's sake, the numbers in Table 2 have been corrected for the deviations of the true $\bar{\nu}_e$ absorption cross section from the ε_ν^2 dependence assumed in equations (2)–(5). Furthermore, cognizance has been taken of the difference between the observed electron energy and the incident antineutrino energy.

Table 2 shows that for the Kamioka data, $\langle \varepsilon \rangle_s$ for the antineutrino is 8–9 MeV, $E_{\bar{\nu}_e}$ is 5–9 $\times 10^{52}$ ergs, and T_{eff} is 2.5–3.0 MeV. If the last three Kamioka points are excluded, T_{eff} is ~ 3.2 MeV. The total energy radiated in neutrinos of all species (E_T) is therefore estimated to be $\sim 6 \times E_{\bar{\nu}_e} \approx 3$–5 $\times 10^{53}$ ergs. These estimates scale with the square of the distance to the LMC. If this distance is 10% closer than we have assumed, there could be as much as a 10^{53} ergs downward correction in E_T. The $\langle \varepsilon \rangle_s$'s derived from the IMB data are systematically higher, while the corresponding $E_{\bar{\nu}_e}$'s are systematically lower than the above. These differences may reflect deviations from the simple spectrum assumed. Simple averages of the IMB and Kamioka energies in Table 2 may yield more accurate estimates. Be that as it may, these numbers are close to what is expected in the standard model of neutron star formation. That the average energy is ~ 10 MeV, not ~ 100 MeV or 0.1 MeV, implies that we understand the basics of the neutrino transport theory that has never before been directly tested. A total energy of some multiple of 10^{53} ergs implies that indeed it is the neutrinos, not exotic particles, that carry away the bulk of the neutron star's binding energy. Furthermore, an energy of 3×10^{53} ergs forces the residue's gravitational mass to be at least 1.4 $M_\odot$ to be consistent with the realistic equations of state (Arnett and Bowers 1977). This limit is weak due to the ambiguity in the derived total energy (E_T), but a conclusion that the residual gravitational mass is greater than 1.2 $M_\odot$ seems robust. The absence of very high energy events in the data rules out the large magnetic moment for the ν_e that has been evoked to explain the solar neutrino problem (Okun, Voloshin, and Vysotsky 1986). The overlap of the Kamioka and IMB predictions, while not perfect, suggests that these two data sets are crudely consistent from the point of view of spectrum and total energy, though a factor of ~ 2 discrepancy may exist. This is not surprising, since they sample different spectral bands, and the data are subject to large statistical fluctuations.

IV. TIMING AND MODELS

Figure 1 depicts the integrated number of events in both the Kamioka and IMB detectors versus time, where for both data sets $t = 0.0$ s is the time of the first event. The histogram presents the data in 0.25 s bins. The average energies, total energy, and hence, the total integrated signal of neutron star formation will depend on the residue's mass, the neutron star

TABLE 2

DERIVED TEMPERATURES (T), AVERAGE $\bar{\nu}_e$ ENERGY ($\langle \varepsilon \rangle_s$), AND TOTAL $\bar{\nu}_e$ ENERGY ($E_{\bar{\nu}_e}$)

	KAMIOKA			IMB		
METHOD	T (MeV)	$\langle \varepsilon \rangle_s$ (MeV)	$E_{\bar{\nu}_e}$ (10^{51} ergs)	T (MeV)	$\langle \varepsilon_s \rangle$ (MeV)	$E_{\bar{\nu}_e}$ (10^{51} ergs)
I	2.72 ± 0.26	8.57 ± 0.82	75^{-14}_{+36}	4.48 ± 0.74	14.1 ± 1.9	34^{-14}_{+41}
II	2.81 ± 0.07	8.86 ± 0.22	57^{-3}_{+2}	$4.45^{+0.70}_{-0.53}$	$14.0^{+2.2}_{-1.67}$	29^{-10}_{+6}

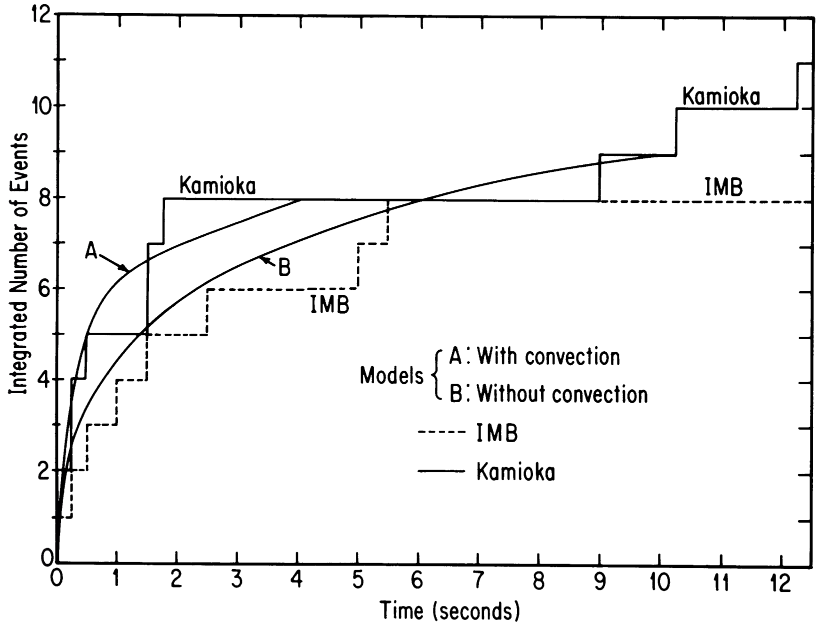

FIG. 1.—The integrated Kamioka and IMB data are plotted against time in 0.25 s bins. Superposed are the results of two model calculations of the expected integrated signal, normalized to the Kamioka data at the end of each calculation. Model A includes convection and covers 4 s after bounce. Model B does not include convection, employs a stiffer equation of state, and covers 10 s after bounce. Each calculation is for a core whose baryon mass is 1.4 $M_{\odot}$. The detected signals are bracketed by the theoretical absolute signals of Models A and B.

equation of state, the neutrino cross sections in degenerate neutron matter, and the convection scheme. We can fit the data in Figure 1 after the fact with judicious choices, but, since there has been some confusion in the community about the expected duration of the signal, we feel that it is more instructive to compare the characteristic shapes of the signal evolution with time. In this spirit, we superposed on Figure 1 predicted integral signals for two different model calculations for a baryon mass of 1.4 $M_{\odot}$ that have been normalized to the Kamioka data at the end of each calculation. A paper with detailed fits to the data is in preparation. A discussion of the calculational method employed can be found in Burrows and Lattimer (1986) and Burrows (1987*a*). Model A incorporates convection, a soft equation of state, and was continued for 4 s. The only differences between Model A and the calculation presented by Burrows (1987*a*) are in the longer duration of the former and in the assumption in Model A that the $\bar{\nu}_e$ and ν_e emissions after prompt neutronization are equal. Though this should be a good approximation, clearly the $\bar{\nu}_e$ transport calculation must be improved. Model B is without convection, incorporates a stiffer equation of state, and was continued for 10 s. A good fit to the evolution of the theoretical integrated signals is given by the equation

$$I = S(1 - e^{-t/\tau(t)}); \qquad \tau(t) = \tau_0 + \alpha t^q, \tag{6}$$

where S is the total signal and $\tau(t)$ is the running time constant that increases with time. For Model A, $\tau_0 = 0.3$ s, $\alpha = 2.0$, and $q = 0.82$. For Model B, $\tau_0 = 0.3$ s, $\alpha = 1.48$, and $q = 0.5$. S (observed) is bracketed by the S's of Models A and B.

Surprisingly, as Figure 1 shows, the models fit the data. We cannot as yet use these data to identify the effects of convection, for the generic evolution of the signals is reproduced by either model. However, the rapid rise of the Kamioka signal does suggest a significant enhancement in the luminosity over and above that associated with models without convection. The theoretical prediction that much of the signal comes in the first second, but that it continues for many seconds thereafter, is borne out by both the Kamioka and the IMB results. Both the "long" duration of the signal and the low average neutrino energies ($\ll$ 100 MeV) are explained by the diffusive, not impulsive, loss of neutrinos that downscatter as they slowly escape from the proto–neutron star. Figure 1 suggests that the bunching observed by Kamioka is a consequence of small-number statistics and that there is no evidence of significant pulsing at the source (Sato and Suzuki 1987). Significantly, if the two data sets are aligned as in Figure 1, the IMB data partially fill the gaps between Kamioka bunches. Note that any pulsing of the Wilson type (Mayle 1985) could not have been distinguished by these detectors. Furthermore, if a black hole had formed, the signal would have died within tenths of milliseconds. Black hole birth would not be accompanied by a burst of neutrinos at late times (Hillebrandt *et al.* 1987). The suggestion that Kamioka bunch three is a result of episodic mass accretion begs the question of why IMB did not register it. While not impossible, such a scenario seems unnecessary.

The number of events detected by Kamioka implies, after correction for efficiency and threshold, that the number of events (N_D) at 1 kpc in a perfect water Cherenkov detector of mass 1 kilotonne would have been $\sim 2 \times 10^4$. N_D is a detector-independent measure of the strength of the source. Models A and B, without normalization, give for $N_D \sim 3 \times 10^4$ and 1.2×10^4 respectively. A realistic range for N_D is 1×10^4–4×10^4 for the broad range of binding energies, masses, and mixing-length parameters possible. This implies that the models can reproduce the *actual* integrated signals as well.

We performed a K-S test to determine if the two data sets come from different distributions. If we cannot prove this, then we can argue that the two sets of data complement each other and that the source need not be pulsed. It is important to note that the zero time of the Kamioka data is not known to within about ± 1 minute. We find the significance level with zero relative time shift between the two data sets is 0.93. The time shift has to be greater than ± 1.5 s to obtain a significance level below 0.05. We conclude it is unlikely that the two data sets are representative of different parent distributions, and that the true relative time shift between them is less than 1.5 s.

We also performed K-S tests on each set of data, comparing each to an exponentially decaying signal. The test signal was characterized by a time constant, τ, in the range 0.5–3 s. On the basis of these tests, we cannot conclude that the bunching of the Kamioka data is significant.

To better gauge the temporal behavior suggested by the data, we carried out maximum-likelihood and least-squares analyses. The maximum-likelihood test for an exponentially decreasing signal is particularly simple: the best value for the time constant is just the mean value of the arrival times, with a mean error of $\tau/\sqrt{N}$, where N is the number of events considered. For the Kamioka data, considering in turn all 12, the first nine, and finally only the first five events, we find $\tau = 3.27 \pm 0.94$, 0.79 ± 0.26, and 0.25 ± 0.11 s, respectively. For the IMB data, considering in turn all eight and the first five events, we find $\tau = 2.14 \pm 0.75$ and 0.76 ± 0.34 s, respectively. A least-squares analysis for the Kamioka bins gives 1.7, 0.65, and 0.28 s, respectively. The fact that τ increases with the length of the signal sampled shows that the rate of decay is slowing with time, as predicted by the standard model and equation (6).

V. ELECTRON NEUTRINO MASS LIMIT

If the neutrino has a mass, a spectrum of energies implies a spectrum of speeds. A delta function pulse of neutrinos with a variety of energies would disperse as it travels the large distance between the LMC and Earth. The delay time is easily derived to be

$$\Delta t \approx 2.5\left(\frac{m}{10\text{ eV}}\right)^2\left[\frac{10\text{ MeV}}{E_\nu}\right]^2 \text{ s}, \qquad (7)$$

for an assumed distance to the LMC of 50 kpc. Therefore, the observed spread of arrival times might constrain the neutrino mass. We see no compelling need on the basis of these data to evoke a mass for the electron neutrino. We feel, however, that we can derive an upper limit.

Under the assumption that all the Kamioka and IMB events are either $\bar{\nu}_e$'s or ν_e's, we first note that there is no mass for which the Kamioka data, all 11 events, with their energy spread could have been emitted from SN 1987A over an interval of less than ~ 12 s. Even if we were to ignore the last Kamioka bunch, an emission duration of less than 2 s cannot be sanctioned.

We can exclude bunch two when deriving a mass limit, since these neutrinos, due to their higher energies, would have experienced substantially smaller delays than those in bunch one. For a given neutrino mass, we can extrapolate from the observed "light curve" to the "light curve" at the source using equation (7) (Arnett and Rosner 1987). In this way, we see that as the assumed neutrino mass increases, bunch one first focuses in time a little and then starts its characteristic and irreversible "defocusing." If the neutrino mass is large (10 eV), the source duration for bunch one is large (~ 2 s). A large mass implies not only a larger time interval for the event, but also a hardening of the spectrum with time at the source. This is the opposite of what is expected. How probable is it that not only did the sample we detected harden systematically in energy at the source, but that the distance to the LMC, the source timing, and the spectrum conspired to focus the first bunch into the relatively short interval of 0.5 s at Earth? If we say that the first bunch can have focused itself by no more than a factor of 2, from ~ 1 s to 0.5 s, we derive an upper limit to the electron neutrino mass of ~ 6.5 eV, subject to electron energy errors. This number is at odds with the ITEP result (Boris *et al.* 1985). A more systematic derivation of a mass limit is in press (Burrows 1987*b*).

VI. CONCLUSION

We have compared model calculations with the Kamioka and IMB data from SN 1987A and find reasonable agreement. The estimate of the total energy (E_T) radiated has large errors but is roughly consistent with the expectation that some multiple of 10^{53} ergs in neutrino emission accompanies the birth of neutron stars. Both the average detected energy of ~ 10 MeV and the long duration of the burst attest to the *diffusion*, not streaming, of the neutrinos out of the core. These data do not indicate in any obvious way by which mechanism, prompt or delayed, the supernova actually exploded. However, it is encouraging to note that emissions in the first second seemed sufficient for the long-term mechanism, should it have been required. The Kamioka and IMB data are more or less in accord with one another, but a discrepancy of a factor of 2 cannot be ruled out. However, since the two detectors sample different parts of the spectrum, there is no reason to believe that the simple constant Fermi-Dirac spectrum assumption and the problems of small-number statistics are not to blame. While we cannot rule out the possibility that a black hole formed, we consider such an outcome unlikely. The neutrino emissions from neutron star and black hole formation are similar, since the black hole must first go through a neutron star phase. However, it is hard to reconcile seeing neutrinos after many seconds (12 s in Kamioka and 5 s in IMB) with the expectation that if a black hole forms, it probably forms from a massive collapsed core ($M > 1.7\ M_{\odot}$). Such a core should experience rapid accretion over the relativistic limit within only a few seconds (Wilson *et al.* 1986). The relativistic instability terminates neutrino emission.

When a supernova occurs in our Galaxy, it will speak one hundred times more eloquently than SN 1987A. We hope that when it does, the experiments of that age will be on line to hear it.

The authors wish to thank W. D. Arnett, E. Baron, H. Bethe, G. Brown, M. Cherry, J. Cooperstein, M. Goldhaber, C. Hogan, K. Lande, P. Rosen, R. Shrock, S. Woosley, and A. Yahil for stimulating and useful discussions. We offer our special thanks to the Kamiokande II and IMB collaborations for being on-line on February 23. This research was supported in part by the U.S.D.O.E. under grant DE-FG02-87ER40317.A000.

REFERENCES

Arafune, J., and Fukugita, M. 1987, preprint.
Arnett, W. D. 1967, *Canadian J. Phys.*, **45**, 1621.
Arnett, W. D., and Bowers, R. L. 1977, *Ap. J. Suppl.*, **33**, 415.
Arnett, W. D., and Rosner, J. L. 1987, *Phys. Rev. Letters*, submitted.
Baron, E., Cooperstein, J., and Kahana, S. 1985, *Phys. Rev. Letters*, **55**, 126.
Bethe, H., and Wilson, J. R. 1985, *Ap. J.*, **295**, 14.
Bionta, R. M., *et al.* 1987, *Phys. Rev. Letters*, **58**, 1494.
Boris, S. D., *et al.* 1985, *Soviet Phys.—JETP Letters*, **42**, 130.
Bowers, R. L., and Wilson, J. R. 1982, *Ap. J. Suppl.*, **50**, 115.
Burrows, A. 1987*a*, *Ap. J.* (*Letters*), **318**, L57.
———. 1987*b*, *Proc. of Telemark IV: Neutrino Masses and Neutrino Astrophysics* (Philadelphia: World Scientific), in press.
Burrows, A., and Lattimer, J. M. 1985, *Ap. J.* (*Letters*), **299**, L19.
———. 1986, *Ap. J.*, **307**, 178.
Burrows, A., and Mazurek, T. J. 1982, *Ap. J.*, **259**, 330.
Burrows, A., Mazurek, T. J., and Lattimer, J. M. 1981, *Ap. J.*, **251**, 325.
Chiu, H. Y. 1964, *Ann. Phys.*, **26**, 364.
Colgate, S. A., and Johnson, H. J. 1960, *Phys. Rev. Letters*, **5**, 235.
Colgate, S. A., and White, R. H. 1966, *Ap. J.*, **143**, 626.
Davis, R., Jr., 1987, private communication.
Hillebrandt, W., *et al.* 1987, preprint.
Hirata, K., *et al.* 1987, *Phys. Rev. Letters*, **58**, 1490.
Hoyle, F., and Fowler, W. 1964, *Ap. J. Suppl.*, **9**, 201.
Mayle, R. 1985, Ph.D. dissertation, UC Berkeley.
Mayle, R., Wilson, J. R. and Schramm, D. N. 1987, *Ap. J.*, **318**, 288.
Mazurek, T. J. 1974, *Nature*, **252**, 287.
Nomoto, K. 1984, *Ap. J.*, **277**, 791.
Okun, L. B., Voloshin, M. B., and Vysotsky, M. I. 1986, preprint.
Sato, K. 1975, *Prog. Theor. Phys.*, **54**, 1325.
Sato, K., and Suzuki, H. 1987, *Phys. Rev. Letters*, submitted.
Sawyer, R. F., and Soni, A. 1979, *Ap. J.*, **230**, 859.
Wilson, J. R. 1971, *Ap. J.*, **163**, 290.
———. 1985, in *Numerical Astrophysics*, ed. J. Centrella, J. LeBlanc, and R. Bowers (Boston: Jones and Bartlett), p. 422.
Wilson, J. R., Mayle, R., Woosley, S. E., and Weaver, T. A. 1986, *Ann. NY Acad. Sci.*, **470**, 267.
Woosley, S. E., and Weaver, T. A. 1986, in *Radiation Hydrodynamics in Stars and Compact Objects*, ed. D. Mihalas and K.-H. A. Winkler (Berlin: Springer-Verlag), p. 91.
Woosley, S. E., Wilson, J. R., and Mayle, R. 1986, *Ap. J.*, **302**, 19.

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