Analysis of the Neutrino Burst from Supernova 1987A in the Large Magellanic Cloud

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We analyze the neutrino burst from the supernova 1987A detected by the Kamiokande II collaboration, and obtain the following results. (1) The total energy of antineutrinos is about 4.8×10^{52} ergs, which is consistent with theoretical predictions. If we take the simulation of Wilson and collaborators as the theoretical model, it corresponds to the models with the progenitor mass $15M_\odot$. (2) The first two neutrino events cannot correspond to the predicted initial neutronization burst from the energetics and the duration time. (3) The duration time of the burst suggests that the electron-neutrino mass < 26 eV. We also discuss implications on the explosion mechanism of the supernova.

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According to the theories of stellar evolution, neutron stars and/or black holes are formed by gravitational collapse of massive stars ($M > 8M_\odot$). Most of the gravitational energy released by the collapse ($\sim 3\times10^{53}$ ergs) is emitted as neutrinos. It has been argued that if neutrinos from the gravitational collapse of stars could be detected, it would give not only strong evidence of the scenario of the final stage of stellar evolution but also direct information on the mechanism of supernova explosion.[1]

On 23 February 1987, 7:35 UT the Kamioka nucleon-decay-experiment group (Kamiokande II Collaboration) detected the neutrino burst from the supernova 1987A which appeared in the Large Magellanic Cloud.[2] Independently, Castagnoli *et al.*[3] working in the Mont Blanc Tunnel claimed that the neutrino burst was detected on 23 February 1987, 02:52 UT, 5 h earlier than that of the Kamiokande II collaboration (see Ref. 2 for a discussion on the consistency between these two observations).

Soon after the discovery of the supernova 1987A, Bahcall, Dar, and Piran[4] presented the expected neutrino signals in terrestrial detectors.

In the present paper, we make an analysis of the observed burst systematically by comparing with theoretical predictions, mainly the numerical simulation of collapse by Wilson and collaborators.[5-7]

Total energy of antineutrinos and the progenitor mass.— In Fig. 1, the energies of eleven neutrinos detected by the Kamiokande II Collaboration are shown. The energy of neutrinos E is estimated from that of electrons E_e as $E=E_e+m_n-m_p$ on the assumption that all the events are $\bar\nu_e p \rightarrow e^+ n$, because the cross section of this reaction is almost one hundred times larger than that of the $\nu_e e$ scattering, and the directions of e^+ (or e^-) formed in the detector are random except the first and

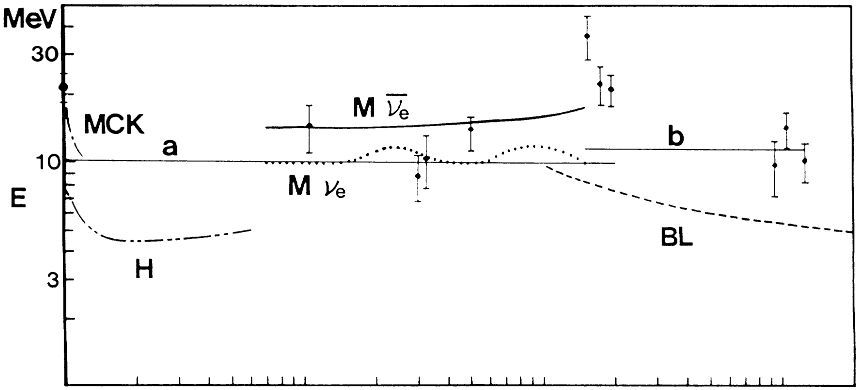

FIG. 1. The energies of eleven neutrinos detected by the Kamiokande II collaboration with error bars. The energies are derived by the assumption that all the events are caused by $\bar\nu_e p \rightarrow e^+ n$ process. The fine horizontal lines *a* and *b* represent the mean energy of the neutrino flux averaged in the respective ranges (see Table II). The mean energy of neutrinos predicted by various theories are also shown: MCK, Mazurek, Cooperstein, and Kahana (Ref. 10) (ν_e); H, Hillebrandt (Ref. 11) (ν_e); M ν_e, Mayle (Ref. 5) (ν_e); M $\bar\nu_e$, Mayle (Ref. 5) ($\bar\nu_e$); BL, Burrows and Lattimer (Ref. 15) (ν_e and $\bar\nu_e$). In order to display the first event (time=0 sec) on the logarithmic time scale, it was shifted artificially to the point 0.01 sec.

second events. For ease of analysis, we assume that the neutrino spectrum is a Fermi-Dirac distribution with temperature T and a vanishing chemical potential, $F(E,T)$; then the mean energy of the neutrino flux $\langle E\rangle$ is $3.15T$. The mean energy of detected neutrinos is given by

$$\bar{E}=\frac{\int_0^\infty E\sigma(E)f(E_e)F(E,T)dE}{\int_0^\infty \sigma(E)f(E_e)F(E,T)dE},$$

where $f(E_e)$ is the detection efficiency for positrons in the Kamiokande detector (2140-ton fiducial mass).[1] By using the above relation between $\bar{E}$ and T, we can calculate T and $\langle E\rangle$ from the observed value $\bar{E}$. Then we can get 4.8×10^{52} ergs as the integrated antineutrino energy of the burst from T and the number of events (11), where the distance to the supernova was assumed to be 50 kpc.[8] If the $\bar{\nu}_e$ energy is one-sixth of the total neutrino burst energy, the total neutrino energy becomes 2.9×10^{53} ergs, which falls nicely in the range of typical binding energies of neutron stars.

In Table I, we summarize the results of Wilson and collaborators[5-7] and the expected number of events in the Kamiokande detector.

The implication obtained by the comparison of Table I with the observations is that the progenitor mass of this supernova is smaller than or equal to $15M_\odot$ from the number of detected neutrinos. If the mass of progenitor were $25M_\odot$ or higher, the number of detected neutrino events would be higher than 25 ($\simeq 31-\sqrt{31}$, model M100A) or 31 ($\simeq 37-\sqrt{37}$, model M25B), if we take into account the statistical fluctuations, whereas the Kamiokande II Collaboration detected eleven events. We must, however, mention that the implication on the progenitor mass is considerably model dependent: First, the energy released by the gravitational collapse corresponds to the binding energy of the neutron star just born, which depends on the equation of state of the high-density matter.[9] Second, for the same main-sequence mass, stellar-evolution calculations by various authors at the present time give very different iron-core masses, on which the neutrino emission depends greatly.

TABLE I. Expected number of events in the Kamiokande detector from several simulations. Mode 1, $\nu_e e^-$ scattering; Mode 2, $\bar{\nu}_e$ capture by hydrogens. $\langle E\rangle$ is neutrino mean energy. The numbers in the model names are the mass of progenitor in solar-mass units ($M_\odot$). Models are taken from Ref. 5 (M), 15 (BL), 7 (MW), 11 (H), and 10 (MCK). The last four columns correspond to neutronization ν_e burst.

Model	Integrated luminosity (ergs)	$\langle E\rangle$ (MeV)	Mode	Flux (cm^{-2})	Count
M12C	3.0×10^{52}	10	1	6.2×10^{9}	0.29
	2.8×10^{52}	13	2	4.5×10^{9}	12
M15C	3.9×10^{52}	10	1	8.1×10^{9}	0.38
	3.5×10^{52}	13	2	5.6×10^{9}	15
M25C	1.6×10^{53}	10	1	3.3×10^{10}	1.5
	1.5×10^{53}	14	2	2.2×10^{10}	69
M25B	8.2×10^{52}	11	1	1.5×10^{10}	0.84
	8.0×10^{52}	14	2	1.2×10^{10}	37
M50A	8.6×10^{52}	10	1	1.8×10^{10}	0.83
	8.4×10^{52}	13	2	1.3×10^{10}	35
M100A	8.0×10^{52}	10	1	1.7×10^{10}	0.77
	8.3×10^{52}	12	2	1.4×10^{10}	31
BL	2.8×10^{52}	6	1	9.7×10^{9}	0.15
	2.3×10^{52}	6	2	8.0×10^{9}	2.1
MW8	3.5×10^{51}	10	1	7.3×10^{8}	0.034
H20	2.5×10^{51}	7.5	1	6.9×10^{8}	0.018
M25C	4.5×10^{51}	9	1	1.0×10^{9}	0.040
MCK	6.0×10^{50}	18	1	6.9×10^{7}	0.0074

Neutronization burst.—The result of the Kamiokande II Collaboration shows that the neutrino burst begins with two neutrino events which occurred within 107 msec. A more important fact is that the directions of electrons produced by the two neutrino events are respectively 18° ± 18° and 15° ± 27° from the counter direction of the Large Magellanic Cloud (LMC). The latter fact strongly suggests that these two events are induced by $\nu_e e^-$ scattering, because if they are antineutrinos, they are mainly absorbed by the charged-current interaction $\bar{\nu}_e p\rightarrow e^+ n$ and the direction of the emitted positrons becomes random. The probability that a positron is emitted within 20° in one event is 3%. Thus, the expected number is only 0.33 in eleven events. The possibility that these events are due to electron scattering by $\bar{\nu}_e$, ν_μ, or ν_τ is small because the scattering cross sections for these neutrinos are $\frac{1}{3}-\frac{1}{7}$ of that of $\nu_e e$ scattering.

At first glance, it seems natural to consider that these two neutrino events are due to the initial neutronization burst which is predicted by numerical simulations.[5-7,10-12] This peak is formed by the electron capture by protons and nuclei when the shock wave goes out of the neutrino sphere. The duration time of this peak in the $15M_\odot$ model is 7 msec.[4] (The value of the duration time is, however, different depending on authors, for example, 0.5 msec,[12] 1 msec,[10] 5 msec.[11]) However, as shown in Table I, the number of events in the Kamiokande detector expected from theories is much smaller than the observed number of 2. Moreover, the observed duration time of this peak, 107 msec, is also ten times longer than theoretically predicted ones. If we assume that the two neutrino events are caused by ν_e, the total energy becomes 1.9×10^{53} ergs as shown in Table II. This energy is almost one-half the typical binding energy of neutron stars and almost ten times greater than the energy of degenerate neutrino energy in the core, $\sim 2\times 10^{52}$ ergs. We may, therefore, conclude that the two neutrino events do not correspond to the neutronization burst, and this conclusion does not depend on the details of the model.

TABLE II. Integrated luminosity of $\bar{\nu}_e$ calculated from observed data. $\bar{E}$ is the neutrino mean energy of the observed events, T is neutrino temperature, and $\langle E \rangle$ is the mean energy of the neutrino flux.

Time (sec)	Event number	$\bar{E}$ (MeV)	T (MeV)	$\langle E \rangle$ (MeV)	Integrated luminosity (ergs)
0.000–0.107	2	18.1	3.2	10.0	7.2×10^{51}
	2[a]	16.5	3.5	11.1	1.9×10^{53}
0.000–1.915	8	18.7	3.3	10.4	2.7×10^{52}
0.000–12.439	11	16.7	2.8	8.9	4.8×10^{52}
1.541–12.439	6	19.1	3.4	10.7	1.9×10^{52}

[a] Assumed to be $\nu_e e^-$ scattering with scattering angles of 0°.

Time profile of the burst.— In the standard scenario of gravitational collapse, electron neutrinos which could not escape in the early stage of collapse are trapped and degenerate in the core.[13] In the late stage after the core bounce, they diffuse out slowly.[14,15] In this period, every type of neutrinos is emitted by thermal process and most of the energy released by the gravitational collapse is lost in this period. The time scale of diffusion is of the order of 1–10 sec. The result of the Kamiokande II Collaboration shows that although eight events are concentrated within the first 2 sec, the neutrino burst continues for about 12 sec, which is consistent with the above prediction.[14,15]

An interesting phenomenon of the time profile of the observed neutrino burst is that the neutrino events are bunched into three clusters: the first five events (0–0.507 sec), the next three events (1.541–1.728 sec), and the last three events (9.219–12.439 sec). As is well known, the simulation of Wilson and collaborators shows that oscillations of neutrino luminosity occur, which are caused by intermittent mass accretion onto the core. However, the amplitude of the oscillation is too small to explain the observed oscillation. In particular, the amplitude of the oscillation of $\bar{\nu}_e$ is about 40% for $100M_\odot$, 20% for $25M_\odot$, and no oscillation for $M < 15M_\odot$. If the observed bunch structure of neutrino events is real, although it is not clear by the effect of statistical fluctuations, we must look for an unknown mechanism in order to explain this phenomenon.

Time evolution of the neutrino energy.— At present, the most important and controversial question in supernova theory is whether the explosion is driven by the neutrinos diffused out from the core at the late time after the bounce. Wilson[16] showed in his simulation that the energy is deposited in the region behind the shock by neutrinos leaving the neutrino sphere, thereby strengthening the shock and allowing it to propagate into the stellar envelope. On the other hand, Hillebrandt[11] calculated the collapse by using an initial model similar to that of Wilson and collaborators, and showed that accretion shock never revives by such neutrino deposition mechanism.

The essential difference between these simulations is that the neutrino-sphere temperatures are very different from each other. In the calculation (M15C) of Wilson and collaborators, the temperature is about 4 MeV, while in Hillebrandt's calculation, it is 2 MeV, which is smaller than the former by a factor of 2. The mean energy of emitted neutrinos in the Hillebrandt calculation is about 5 MeV, which is also lower by a factor of 2. The revival of the shock does not occur in Hillebrandt's simulation, because the degree of neutrino deposition depends sensitively on the neutrino energy.

The Kamiokande II Collaboration result seems to support the calculation of Wilson and collaborators, because the mean energy of $\bar{\nu}_e$ up to 2 sec is 10.4 MeV. Although this value is a little lower than the prediction of Wilson and collaborators, 13 MeV ($12M_\odot$ and $15M_\odot$), we would say that both are qualitatively compatible.

Because Wilson and collaborators performed their calculations only up to 1.5 sec, we cannot compare them with the last five events (from the eighth to twelfth events). Recently, however, Burrows and Lattimer[15] calculated the cooling of neutron stars just born. According to their calculation, the mean energy of $\bar{\nu}_e$ becomes lower than 6 MeV after 7 sec from the birth of neutron star. We cannot, however, compare their results directly with the results of the Kamiokande II Collaboration, because they made use of an appropriate initial model independently of the hydrodynamical calculation. In spite of this ambiguity, we superimposed the time evolution of the mean energy of neutrinos obtained by them in Fig. 1, by assuming that their initial model corresponds to the model 1 sec after the core bounce. This is because accretion of matter on the core stops 1 sec after the core bounce, according to the result of Wilson and collaborators. The curve of Burrows and Lattimer (BL) runs in the region about 6 MeV lower than the mean energy of six neutrinos, which is displayed by the horizontal line b (see also Table II). According to their cooling calculation, the expected number of events is 2.1, as shown in Table I, which is about one-third of the observed number of events. These facts imply that the core or the neutron star just born does not cool so rapidly as suggested by them.

One way out of this conflict would be to consider that this amount of energy ($\simeq 1.9\times 10^{52}$ ergs) was released by unknown mechanism 10 sec after the core bounce. Phase transition to quark matter or a pion-condensed state in the core might be a possible mechanism, because the phase transition induces contraction of the core, by which gravitational energy is released. We may also conjecture mass accretion onto the core if we consider the explosion nonspherical from the effects of angular momentum and the magnetic field of stars.

Neutrino mass.— If neutrinos have nonvanishing mass, the arrival time of the neutrino burst is dispersed.[17] The typical duration of the delayed burst from the LMC supernova can be estimated as[17]

$$\left(\frac{R}{10\ \mathrm{kpc}}\right)\left(\frac{m}{10\ \mathrm{eV}}\right)^{2}\left(\frac{\langle E\rangle}{10\ \mathrm{MeV}}\right)^{-2}\ \mathrm{sec},$$

where the distance of the LMC is $R=50$ kpc, and the mean energy of eleven neutrinos is $\langle E\rangle=16.7$ MeV. From the condition that this duration Δ must be smaller than the observed duration of burst, 12.4 sec, we obtain an upper limit on the mass, $m<26$ eV.

Finally, we would like to mention the necessity of further theoretical investigation. In this paper, we made analysis by using the data that appeared in Mayle's thesis,[5] because it contains detailed information on the spectra and time profiles. However, the calculations of Mayle, Wilson, and Schramm terminate at 1.5 sec after the core bounce. At this time, electron neutrinos have not diffused out and the lepton-to-baryon ratio Y_L is still greater than 0.3. This suggests strongly the importance of a detailed investigation of the late-time cooling of supernova cores such as Ref. 15.

Note added.—After this paper was submitted, Bionta *et al.*[18] reported that eight neutrino events were detected. We calculated the expected neutrino events by using the results of the simulation of Wilson and collaborators. The result is 6.4 events for M12C, 8.0 events for M15C, 24 events for M25B, and 44 events for M25C. This also implies the progenitor mass might be less than $15M_\odot$, if we adopt the results of their simulation.

Very recently, Burrows and Lattimer[19] and Burrows[20] calculated the neutrino luminosity and the mean energy of neutrinos from the supernova core, taking into account the convection in it. They showed that the luminosity and the mean energy of neutrinos increase considerably by this effect. It is very interesting that the mean energy of neutrinos obtained by them, $\simeq 10$ MeV in the period of the first 1 sec, nicely fits that of neutrinos observed by the Kamiokande II Collaboration (see Fig. 1).

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