Features of Nucleosynthesis and Neutrino Emission from Collapsars

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Abstract

In this study we present two indicators that will reflect the difference between collapsars and normal collapse-driven supernovae. They are products of explosive nucleosynthesis and neutrino emission. In the collapsar model, it is natural to consider that the product of explosive nucleosynthesis depends on the zenith angle because the system becomes highly asymmetric in order to generate a fire ball. We also consider the detectability of the HNRs which is located nearby our Galaxy. As a result, the number of the HNRs is estimated to be $5 \times (10^2 - 10^{-3})$, whose chemical composition can be spatially resolved. Using the optimistic estimate, more HNRs will be found and it will be possible to discuss on the chemical composition statistically. As for the energy spectrums of neutrinos, they are not thermalized in a collapsar because the density of the accretion disk is much lower than that of a neutron star. The energy spectrums of (anti-)electron neutrinos from hypernovae will be mainly determined by the process of electron (positron) capture on free proton (neutron). It is also noted that high energy tail is not dumped in the case of hypernovae because the density of emitting region is low. Total energy of neutrino from hypernovae will depend on a lot of physical parameters such as total accreting mass and mass accretion rate, which are quite contrary to the situation of the normal collapse-driven supernovae. Therefore there will be a large variety of total neutrino's energies among collapsars. In the case of SN 1998bw, we think that the matter around the equatorial plane might be ejected from the system, which resulted in the formation of relatively weak jets and faint GRB 980425.

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I. INTRODUCTION

It will be a big progress that the fact that at least a part of the gamma-ray bursts (GRBs) comes from the hypernova (HN) explosions is being supported by the observations. It was reported for the first time that there seems to be a physical connection between GRB 980425 and SN 1998bw [1]. They discovered an optical transient within the BeppoSAX Wide Field Camera error box of GRB 980425. Then they reported that the optical transient can be interpreted to be the light curve of SN 1998bw. As for the explosion energy of SN 1998bw, it was estimated to be as high as \((20-50) \times 10^{51}\) erg as long as we believe the explosion is spherically symmetric [2,3]. This is the reason why SN 1998bw is called as a HN. The late afterglow of GRB 970228 also suggests the physical connection between GRB and HN [4]. It was shown that the optical light curve and spectrum of the late afterglow of GRB 970228 are well reproduced by those of SN 1998bw transformed to the redshift of GRB 970228. The afterglow of GRB 980326 is also believed to be the evidence for the GRB/HN connection due to the same reason [5].

If we believe that a part of the GRBs comes from the explosion of massive stars, the explosion must be a jet-induced one because spherical explosion model has a difficulty in avoiding the baryon contamination problem [4]. In fact, some observations on GRBs are interpreted as evidence for the jet-induced explosion. For example, the breaks in the rate of decline of several afterglows can be explained by the beaming effect [4]. The light curve and spectrum of SN 1998bw also seem to suggest a jet-induced explosion [8,9]. There are also some excellent numerical simulations on the jet-induced explosion of massive stars whose aim is to reproduce the fire ball [10–12], although the fire ball has not been reproduced yet.

Here we must note the following two points. (i) it is not determined that all of the GRBs come from HNe. (ii) the explosion energy of SN 1998bw may be small if the explosion is the jet-induced one. Taking these points into consideration, we can classify the relation of GRB, SN, and HN as shown in Figure 1. For example, region (a)/(d) means that HNe which didn’t/ did generate GRBs. We note that \(HN \cap SN = \emptyset\) by definition. Here we defined that SN is the explosion of a massive star whose total explosion energy is about \(10^{51}\) erg. HN is defined as the explosion of a massive star whose total explosion energy is significantly larger than \(10^{51}\) erg. As for the region (b), other systems such as the merging neutron stars [13] may belong to this region.

One of the most famous model to realize a GRB from a death of a massive star is the collapsar model [14,15]. The definition of the collapsar is written in [15] as a massive star whose iron core has collapsed to a black hole that is continuing to accrete at a very high rate. Woosley also pointed out that there will be two types for collapsars. One (type I collapsar) is that the central core immediately forms a black hole with an accretion disk. The other (type II collapsar) is that the central core forms a neutron star at first, but the neutron star collapses to be a black hole with an accretion disk due to the continuous fall back. In both types, a strong jet, which is required to produce a GRB, is generated around the polar region due to the pair-annihilation of neutrinos that come from the accretion disk and/or MHD processes. The remnants of a collapsar will belong to the regions (a), (b), (c), and (d) in Figure 1. When the explosion energy of a collapsar is small, it will be classified as SNR. When the hydrogen envelope exists, a collapsar can not produce a GRB.

Here we note that there are no observations that support directly the scenario of col-
Lapsars. This situation is a contrast to that of the scenario of collapse-driven SN, which is supported by the detection of neutrinos at Kamiokande [16] and IMB [17]. Thus we present in this study two observable indicators that reflect the mechanism of collapsars. These observations will affirm the difference between collapsars and collapse-driven SN clearly. These are products of explosive nucleosynthesis and neutrino emission. We will discuss these essential features in the following sections. We also discuss the possibility of detection of such observations taking the event rate into consideration.

In section II, we consider the explosive nucleosynthesis in the collapsar model. The luminosity and spectrum of neutrino from collapsars are shown in section III. Summary and discussion are presented in section IV.

II. FEATURES OF REMNANTS OF COLLAPSARS

If we believe the collapsar model, the system is highly asymmetric in order to generate a fireball [10–12]. Thus it is natural to consider that the product of explosive nucleosynthesis depends on the zenith angle (see details below). So we consider its detectability in this section.

Here we must note that the asymmetric explosion can occur in the collapse-driven supernova as long as the effects of rotation and/or magnetic field are taken into consideration, e.g. see [18–20]. As a result, the products of explosive nucleosynthesis also depends on the zenith angle in such an asymmetric collapse-driven supernova [21,22]. This means that we can not distinguish well whether it is the remnant of a collapsar or of a rotating collapse-driven supernova when we find an asymmetric SNR. In order to avoid such a problem, we should search for the hypernova remnants (HNRs), whose explosion energy can not be attained by the scenario of delayed explosion for the collapse-driven supernova. Thus we consider the detectability of the HNRs in this section.

To tell the truth, the products of explosive nucleosynthesis in collapsars are not known exactly. There are many possibilities. For example, it is pointed out that $^{56}$Ni is synthesized by the wind blowing off the accretion disk in a type I collapsar as long as the disk viscosity is set to be high [11]. In their simulations, the outflow containing much of $^{56}$Ni is shown to be moving at 15 to 40 degrees off axis. However, the region where most of $^{56}$Ni is contained may be around the polar region in a type I collapsar. This is the result of the explosive nucleosynthesis behind the strong jet. This picture is like the situation which occurs in the jet-like explosion of collapse-driven supernova [22]. On the other hand, the chemical composition of the remnant of a type II collapsar may be spherically symmetric, because the launch of the jet is too late to cause the explosive nucleosynthesis [23].

Such a situation is a contrast to that about the explosive nucleosynthesis in SN. The results of numerical calculations on explosive nucleosynthesis in collapse-driven SNe are compared with the observations very carefully, e.g. see [21,22]. Thus, observations of the HNRs are necessary in order to determine which model is realistic and which model is unrealistic. Such observations may also give a light on the occurrence frequency of the type I collapsar relative to the type II collapsar.

Here we estimate the chance probability to find the nearby HNRs whose chemical composition can be resolved by the latest X-ray telescopes such as the ESA’s X-ray Multi-Mirror...
(XMM) and Chandra (AXAF) satellites whose spatial resolution is of order of 1 arcsec.

At first, we consider the event rate of HN in a Galaxy. If we consider the event rate of GRB is equal to that of HN, the estimated HN rate becomes \((10^{-6} - 10^{-8})\) yr\(^{-1}\) per Galaxy \([26, 28]\). If we take the beaming effect into account, the HN rate becomes larger than the observed GRB rate. On the other hand, the HN rate can be estimated to be \(\sim 10^{-3}\) yr\(^{-1}\) per Galaxy, when we assume that the slope of the initial mass function is -1.35 \([29]\), the maximum mass of a star is \(50M_\odot\) \([30]\), (10-30)\(M_\odot\) stars explodes as collapse-driven SNe \([24]\), (30-50)\(M_\odot\) stars explodes as HNe, and the collapse-driven SN event rate is \(10^{-2}\) yr\(^{-1}\) per Galaxy \([31]\). This will be an upper limit for the HN event rate because all of the massive stars in the range (30-50)\(M_\odot\) are assumed to explode as HNe. So we consider that the HN rate is in the range \((10^{-3} - 10^{-8})\) yr\(^{-1}\) per Galaxy.

In order to know the chemical composition of the ejecta, HNR must be so young that the remnant is not composed mainly by the inter-stellar medium (ISM) but by the HN ejecta. Here we consider the Fe distribution in the remnant because the main products of explosive nucleosynthesis, \(^{56}\)Ni, decays to Fe. We can estimate the shock radius, \(R_s\), at which the amount of Fe from the ejecta becomes equal to that from ISM in the remnant as follows:

\[
R_s = 1.6 \times 10 \left( \frac{M_{Fe}}{0.7 M_\odot} \right)^{1/3} \left( \frac{1 \text{cm}^{-3}}{n} \right)^{1/3} \left( \frac{1.36}{\mu} \right)^{1/3} \text{[pc]}, \tag{1}
\]

where \(M_{Fe}\), \(n\), \(\mu\) are the amount of Fe from the ejecta, mean ambient hydrogen density, and mean atomic weight of cosmic material per H atom \([32]\). Here we assumed that the mass fraction of Fe in the ISM is equal to that in the solar system abundances \([33]\). On the other hand, the shock radius in the adiabatic phase can be written as follows \([34]\):

\[
R_s = 7.9 \left( \frac{E_{exp}}{10^{52} \text{erg}} \right)^{1/5} \left( \frac{1 \text{cm}^{-3}}{n} \right)^{1/5} \left( \frac{t}{10^3 \text{yr}} \right)^{2/5} \text{[pc]}, \tag{2}
\]

where \(E_{exp}\) and \(t\) are total explosion energy and age of the remnant, respectively. In the case of SN 1998bw, \(M_{Fe}\) is estimated to be \(0.7M_\odot\) \([3]\). If we consider that this is the standard case with HN, \(t\) has to be less than the following value:

\[
t \leq 6.4 \times 10^3 \left( \frac{n}{1 \text{cm}^{-3}} \right)^{1/2} \left( \frac{10^{52} \text{erg}}{E_{exp}} \right)^{1/2} \left( \frac{R_s}{16 \text{pc}} \right)^{5/2} \text{[yr]}. \tag{3}
\]

That is, roughly speaking, the HNR whose age is less than \(10^4\) yr must be searched for in order to know the chemical composition of the ejecta. As for the limit of the distance from the Earth to the target, it must be nearer than 3 Mpc in order to resolve the asymmetry of the chemical composition of the ejecta as long as the spatial resolution of the X-ray telescope is 1 arcsec.

Since there are 55 galaxies within 3 Mpc from our Galaxy \([35]\), the number of the HNRs is estimated to be \(5 \times (10^2 - 10^{-3})\), whose chemical composition can be spatially resolved. \((10^{-3} - 10^{-8})\) yr\(^{-1}\) per Galaxy and \(10^4\) yr are adopted for the HN event rate and the age of the oldest HNR, respectively. Using the optimistic estimate, the HNRs will be found more and we will be able to discuss on the chemical composition statistically.

Here we consider the report of Wang \([36]\) on NGC 5471B and MF83 in M101. They reported that NGC 5471B and MF83 may be the HNRs since they require explosion energies
comparable to the energies frequently associated with GRBs. Since the distance of M101 from our Galaxy is about $7.2 \pm 0.4$ Mpc \cite{37}, it seems difficult to observe the distribution of the chemical composition of the remnants at a present state. However, we can say that the HNR event rate seems larger than the lower estimate for the GRB rate if these are really HNRs. Although other interpretations are possible for these highly luminous X-ray sources \cite{38}, search for the hypernova remnants nearby our Galaxy has a potential to reveal the mechanism of the GRB.

III. NEUTRINO EMISSION FROM COLLAPSARS

The second important feature of collapsars is that no neutron star but an accretion disk around the black hole is formed. One of the most probable heating source for the jet formation is believed to be the $\nu\bar{\nu}$ annihilation emitted from the accretion disk \cite{11}. On the other hand, neutrinos are emitted from only the surface of a neutron star in SN explosion. In this section we discuss the differences of the energy spectrum of the emitted neutrinos between the collapse-driven SN and the collapsar.

In the case of SN, the energy spectrum of neutrinos is approximately represented by the thermal distribution, because the mean free path of neutrinos is much shorter than the radius of the neutron star \cite{39}. Strictly compared to the perfect Fermi-Dirac distribution with zero chemical potential, however, the high energy phase space is less populated \cite{10,11}. This is because the high energy tail is dumped due to much larger opacities ($\propto \epsilon_n^2$). In addition, it is well-known that the total energy of neutrinos is determined by only the gravitational binding energy of the neutron star \cite{39}.

On the other hand, the energy spectrums of neutrinos are not dumped in collapsars, because the nucleon density of the accretion disk is much lower than that of a neutron star \cite{42}. Namely the energy spectrums of neutrinos emitted from collapsars are entirely proportional to the emission rates. Then the total energy of neutrinos could depend on a lot of physical parameters such as the total accreting mass $M$, the mass accretion rate $\dot{M}$, and so on. Therefore there will be a variety of total energies of the emitted neutrino for collapsars. MacFadyen and Woosley \cite{11} have shown that the accretion disk in a collapsar can be described well by the analytic solution derived by Popham et al. \cite{42}. According to their analytic solution, the neutrinos are mainly emitted from the region where $T = (1-10)$ MeV and $\rho = (10^9-10^{10})$ g cm$^{-3}$.

If we assume that the density and the temperature are constant in the neutrino emitting region \cite{42}, we can estimate the energy spectrum of the emitted neutrinos from the accretion disk. For $n + e^+ \rightarrow p + \bar{\nu}_e$, the spectrum of $\bar{\nu}_e$ in unit time, unit volume, and unit energy is represented by

$$\frac{d^2n_{\bar{\nu}_e}^{en}}{dtdE_{\bar{\nu}_e}}(E_{\bar{\nu}_e}) = \frac{G_F^2}{2\pi^3} (1 + 3\tilde{C}_A^2) n_n E_{\bar{\nu}_e}^2 \sqrt{(E_{\bar{\nu}_e}^2 - m_e^2)(E_{\bar{\nu}_e} - Q)} \frac{1}{e^{(E_{\bar{\nu}_e} - Q)/T} + 1},$$

where $E_{\bar{\nu}_e}$ is energy of $\bar{\nu}_e$, $T$ is temperature, $G_F$ is Fermi coupling constant, $\tilde{C}_A \simeq 1.37$ is normalized by the experimental value of neutron lifetime $\tau_n \simeq 887.6$ s \cite{13}, $n_n$ is number density of neutron, $Q \simeq 1.29$ MeV, and $m_e$ is electron mass. For $e^- + e^- \rightarrow \nu_e + \bar{\nu}_e$, we obtain
\[ \frac{d^2 n_{\nu_e}^{e^+e^-}}{dtdE_{\nu_e}}(E_{\nu_e}) = \frac{C_V^2}{9\pi^4}(C_V^2 + C_A^2)E_{\nu_e}^3\frac{1}{T} + \frac{1}{T^4} \int_{m_e/T}^{\infty} \frac{(e^2 - (m_e/T)^2)^{3/2}}{e^2 + 1} de, \]

where \( C_V = 1/2 + 2\sin^2\theta_W, C_A = 1/2, \) and \( \sin^2\theta_W \simeq 0.231 \) is Weinberg angle \[43\], and we assume \( E_{\nu_e} \gg T \).

In Figure 2(a) we plot the obtained spectrum of \( \nu_e \) emitted from the accretion disk \( (d^2n_{\nu_e}/dtdE_{\nu_e}) \equiv d^2n_{\nu_e}^{eN}/dtdE_{\nu_e} + d^2n_{\nu_e}^{e+e^-}/dtdE_{\nu_e} \) in unit time, unit volume, and unit energy. It should be noted that the high energy tail is not dumped at all because the nucleon density of the accretion disk is much lower than that of a neutron star and the mean free path is much longer. This is remarkable feature only for collapsars.

The luminosity of \( \nu_e \) can be obtained by integrating the spectrum as \( \dot{q} \equiv \int dE_{\nu_e} E_{\nu_e} d^2n_{\nu_e}/dtdE_{\nu_e}. \) Then we obtain \( \dot{q}e_N \simeq 4.6 \times 10^{33} \rho_{10} T_{11}^6 X_{\text{nuc}} \text{erg cm}^{-3} \text{s}^{-1} \) and \( \dot{q}^{e+e^-} \simeq 2.4 \times 10^{33} T_{11}^6 \text{erg cm}^{-3} \text{s}^{-1}, \) where \( \rho_{10} = \rho/10^{10} \text{g cm}^{-3}, T_{11} = T/10^{11} \text{K}, \) and \( X_{\text{nuc}} \) is the mass fraction of nucleons. \( X_{\text{nuc}} \) is given by \( X_{\text{nuc}} = 30.97 \rho_{10}^{-3/4} T_{10}^{-9/8} \exp(-0.6096/T_{10}), \) where \( X_{\text{nuc}} \leq 1 \[44\].

As is clear from the above relations, the luminosity of neutrinos from collapsars depends sensitively on the temperature. Therefore if the configuration of the accretion disk is modified by the change of the environment such as the mass accretion rate, mass of the progenitor, and the mass of the black hole, then the total luminosity and energy of neutrino from collapsars will be changed drastically. These points are entirely different from the normal collapse-driven SN because the total energy of neutrinos from SN is determined only by the gravitational binding energy of the central neutron star. The event numbers of \( \bar{\nu}_e \) from HN expected at Super-Kamiokande is represented by

\[ \frac{dR}{dE_{e^+}} = \frac{V_A N_p}{4\pi D^2} \sigma_{p\bar{\nu}_e}(E_{e^+}) \frac{d^2n_{\bar{\nu}_e}}{dtdE_{\bar{\nu}_e}}(E_{e^+}) \Delta t, \]

where \( E_{e^+} = E_{\nu_e} - Q \) is the energy of the positron which is scattered through \( p + \nu_e \rightarrow n + e^+ \) in the detector, \( \sigma_{p\bar{\nu}_e} = \frac{C_V^2}{2\pi^2}(1 + 3C_A^2)E_{e^+}\sqrt{E_{e^+}^2 - m_e^2} \) is the cross section of the process, \( V_A \) is the volume of the emitting region in accretion disk, \( N_p \simeq 1.5 \times 10^{35} \) is the number of proton in Super-Kamiokande, \( D \) is the distance from the earth to the collapsar, \( \Delta t \simeq M/\dot{M} \) is the duration of the emission. In Figure 2(b), we show the plot of the event number adopting an representative parameter set \[12\]. We can find that the neutrino emission from a collapsar can be observed at Super-Kamiokande as long as it is located within \( \sim 3 \text{ Mpc} \) from the earth.

As for the estimate of the detection rate at Super-Kamiokande becomes as follows:

\[ P \sim 5 \times (10^{-2} - 10^{-7}) \text{ [yr}^{-1}], \]

where the same way of estimation is done as in section \[1\]. That is, \( (10^{-3} - 10^{-8}) \text{ yr}^{-1} \) per Galaxy and 55 are adopted for the HN event rate and the number of galaxies within 3 Mpc from our Galaxy. Using the optimistic event rate \( \sim 5 \times 10^{-2} \) per year, the detection probability of the collapsars can be as large as that of the collapse-driven SN.

**IV. SUMMARY AND DISCUSSION**
In this study, characteristic products of nucleosynthesis and neutrino emission have been proposed as two indicators that will reflect the features of the collapsars. We consider the detectability of the HNRs because we cannot distinguish well whether it is the remnant of a collapsar or of a rotating collapse-driven supernova when we find an asymmetric SNR. As a result, the number of the HNRs is estimated to be \( 5 \times (10^2 - 10^{-3}) \), whose chemical composition can be spatially resolved. Using the optimistic estimate, more HNRs will be found and it will be possible to discuss on the chemical composition statistically. Due to such observations, we will be able to determine which model is realistic and which model is unrealistic. Such observations may also give a light on the occurrence frequency of the type I collapsar relative to the type II collapsar. Moreover, we can say that the HNR event rate seems larger than the lower estimate for the GRB rate if NGC 5471B and MF83 in M101 are really HNRs. Although other interpretations are possible for these highly luminous X-ray sources \[38\], search for the hypernova remnants nearby our Galaxy has a potential to reveal the mechanism of the GRB.

Strictly speaking, there will be a little difference between the SNRs of collapsars and those of collapse-driven supernovae. We think that an extreme jet-induced explosion like collapsars will not happen in the case of SN. This is because almost all of the matter has to be ejected in order not to leave a black hole but to leave a neutron star at the center. That is, matter around the equatorial plane has to be also ejected, which will be observed as ‘jet-like’ explosion like SN 1987A \[22\]. On the other hand, an extreme jet-induced explosion is required in order to make fire balls for the model of the jet-induced HN. So, even if the matter around the equatorial plane is ejected due to some reasons in the case of HN too, the degree of jet-induced explosion will be very large and chemical composition will depend strongly on the zenith angle in the case of the type I collapsar.

It is also noted that the mass accretion rate becomes low if the matter around the equatorial plane is ejected from collapsars. This will result in the decline of the total energy of neutrinos emitted from the accretion disk. As a result, total explosion energy may become small in that case. It is reported that the explosion energy of GRB 980425, which is said to be associated with SN 1998bw, is quite lower than that of the usual GRBs \[1\]. In the case of SN 1998bw, we think that the matter around the equatorial plane might be ejected from the system, which resulted in the formation of relatively weak jets and faint GRB 980425. This means that SN 1998bw and GRB 980425 may be classified in the region (e) in Figure \[\] . Of course, this picture requires that the system of SN 1998bw and GRB 980425 is highly asymmetric, because the total explosion energy of SN 1998bw is estimated to be \((20-50) \times 10^{51} \) when spherical explosion is assumed \[23\].

As for the (anti-)electron neutrino emission from the collapsars, its energy spectrum is mainly determined by the emission rate due to electron (positron) capture on proton (neutron). As the temperature becomes higher, contribution of the process of electron-positron pair annihilation can not be negligible. It is also noted that high energy tail is not dumped in the case of the collapsar because the density of emitting region is low. These features on energy spectrum are quite different from that of SN.

Total energy of neutrino depends on many physical quantum such as total accreting mass and mass accretion rate. It is noted the emission rate due to the electron capture on proton is proportional to \( T^6 \). So a little change in temperature results in great change in the neutrino flux. That is why there will be a variety of total luminosity of neutrino among
collapsars, which is in striking contrast to the case of SN. As for the event rate, the detection probability of the collapsar can be as large as that of the collapse-driven SN if we use the optimistic event rate $\sim 5 \times 10^{-2}$ per year at Super-Kamiokande.

Finally, we stress again that these features on nucleosynthesis and neutrinos will reveal the mechanism of GRB quite well. We hope the increase of further observations in the near future.

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REFERENCES

[1] T.J. Galama, P.M. Vreeswijk, J. van Paradijs, C. Kouveliotou, T. Augusteijn, H. Bohnhardt, J.P. Brewer, V. Doublier et al., Nature 395 (1998) 670.
[2] K. Iwamoto, P.A. Mazzali, K. Nomoto, H. Umeda, T. Nakamura, F. Patat, I.J. Danziger, T.R. Young, T. Suzuki, T. Shigeyama, et al., Nature 395 (1998) 672.
[3] S.E. Woosley, R.G. Eastman, B.P. Schmidt, Astrophys. J. 516 (1999) 788.
[4] D.E. Reichart, Astrophys. J. 521 (1999) 111.
[5] J.S. Bloom, S.R. Kulkarni, S.G. Djorgovski, A.C. Eichelberger et al., Nature 401 (1999) 453.
[6] M.J. Rees, P. Mészáros, Mon. Not. R. Astron. Soc. 258 (1992) 41.
[7] S.R. Kulkarni, S.G. Djorgovski, S.C. Odewahn, J.S. Bloom, R.R. Gal, C.D. Koersko, F.A. Harrison, L.M. Lubin et al., Nature 398 (1999) 389.
[8] P. Höflich, J.C. Wheeler, L. Wang, Astrophys. J. 521 (1999) 179.
[9] K. Nomoto, private communication.
[10] A.M. Khokhlov, P.A. Höflich, E.S. Oran, J.C. Wheeler, L. Wang, A.Y. Chcthelkanova, Astrophys. J. 524 (1999) 107.
[11] A.I. MacFadyen, S.E. Woosley, Astrophys. J. 524 (1999) 262.
[12] M.A. Aloy, E. Müller, J.M. Ibáñez, J.M. Martí, A. MacFadyen, Astrophys. J. Lett. 531 (2000) L119.
[13] M. Ruffert, H.-Th. Janka, Aston. Astrophys. 344 (1999) 573.
[14] S.E. Woosley, Astrophys. J. 405 (1993) 273.
[15] S.E. Woosley, astro-ph/9912484.
[16] K.S. Hirata, T. Kajita, M. Koshiba, M. Nakahata, Y. Oyama, N. Sato, A. Suzuki, M. Takita, Y. Totsuka, T. Kifune, T. Suda, K. Takahashi, T. Tanimori, K. Miyano, M. Yamada et al., Phys. Rev. D 38 (1988) 448.
[17] J. Matthews, in Proceedings of the 4th George Mason Astrophysics Workshop, ‘Supernova 1987A in the Large Magellanic Cloud’, Cambridge, New York, Cambridge University Press, 1988, p.151.
[18] E. Müller, M. Rozyczka, W. Hillebrandt, Aston. Astrophys. 81 (1980) 288.
[19] E.M.D. Symbalisty, Astrophys. J. 285 (1984) 729.
[20] S. Yamada, K. Sato, Astrophys. J. 434 (1994) 268.
[21] S. Nagataki, M. Hashimoto, K. Sato, S. Yamada, Astrophys. J. 486 (1997) 1026.
[22] S. Nagataki, Astrophys. J. Suppl., 127, 141
[23] A.I. MacFadyen, S.E. Woosley, A. Heger, astro-ph/9910034.
[24] M. Hashimoto, Prog. Theor. Phys. 94 (1995) 663.
[25] S.E. Woosley, T.A. Weaver, Astrophys. J. Suppl. 101 (1995) 181.
[26] E. Cohen, T. Piran, Astrophys. J. Lett. 444 (1995) L25.
[27] T. Totani, Astrophys. J. Lett. 486 (1997) L71.
[28] R.A.M.J. Wijers, J.S. Bloom, J.N. Bagla, P. Natarajan, Mon. Not. R. Astron. Soc. 294 (1998) L13.
[29] E.E. Salpeter, Astrophys. J. 121 (1955) 161.
[30] T. Tsujimoto, K. Nomoto, Y. Yoshii, M. Hashimoto, S. Yanagida, F.-K. Thielemann, Mon. Not. R. Astron. Soc. 277 (1995) 945.
[31] S. van den Bergh, G.A. Tammann, Ann. Rev. Astron. Astrophys. 29 (1991) 363.
[32] C.W. Allen, Astrophysical Quantities 3rd edition, London: Athlone, 1973.
[33] E. Anderse, N. Grevesse, Geochim. Cosmochim. Acta, 53, (1989) 197.
[34] L.I. Sedov, Similarity, Dimensional Methods in Mechanics, New York: Academic Press, 1959.
[35] R.B. Tully, Nearby Galaxies Catalog, Cambridge, Cambridge Univ. Press, 1988.
[36] L. Wang, Astrophys. J. Lett. 517 (1999) L27.
[37] P.B. Stetson et al., Astrophys. J. 508 (1998) 491.
[38] Y-H. Chu, C.-H.R. Chen, S.P. Lai, astro-ph/9909091.
[39] H.A. Bethe, Rev. Mod. Phys. 62 (1990) 801.
[40] H.-T. Janka, W. Hillebrandt, Aston. Astrophys. 224 (1989) 49.
[41] E.S. Myra, A. Burrows, Astrophys. J. 364 (1990) 222.
[42] R. Popham, S.E. Woosley, C. Fryer, Astrophys. J. 518 (1999) 356.
[43] Caso et al., Particle Data Group, Euro. Phys. J. C 3 (1998) 1.
[44] Y.Z. Qian, S.E. Woosley, Astrophys. J. 471 (1996) 331.
FIG. 1. Classification of the relation of GRB, SN, and HN. Here we defined that SN is the explosion of a massive star whose total explosion energy is about $10^{51}$ erg. HN is defined as the explosion of a massive star whose total explosion energy is significantly larger than $10^{51}$ erg. As for the region (b), other systems such as the merging neutron stars (Ruffert & Janka 1999) may belong to this region.
Fig. 2. (a) Energy spectrums of $\bar{\nu}_e$ from collapsars. (b) Event numbers expected at Super-Kamiokande. Solid line represents the total energy spectrum. Dashed line represents the contribution from $n + e^+ \rightarrow p + \nu_e$. Dotted line represents the contribution from $e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e$. The temperature, the nuclear density, and the volume of the emitting region are set to be 5 MeV, $10^{10}$ g cm$^{-3}$, and $6.5 \times 10^{20}$ cm$^3$, respectively (Popham et al. 1999). The distance, the total accreting mass, and the mass accretion rate are set to be 3 Mpc, $30 M_\odot$, and $0.1 M_\odot$ s$^{-1}$, respectively. Then the total event number which is obtained by $dE_{e^+}$ integration is $\sim 15$. 