SLAC-PUB-11954
astro-ph/0607104
July 2006

High Energy Neutrinos and Cosmic-Rays from Low-Luminosity Gamma-Ray Bursts?

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ABSTRACT

The recently discovered gamma-ray burst (GRB) 060218/SN 2006aj is classified as an X-ray Flash with very long duration driven possibly by a neutron star. Since GRB 060218 is very near ~ 140 Mpc and very dim, one-year observation by *Swift* suggests that the true rate of GRB 060218-like events might be very high so that such low luminosity GRBs (LL-GRBs) might form a different population of GRBs from the cosmological high luminosity GRBs (HL-GRBs). We found that the high energy neutrino background from such LL-GRBs could be comparable with or larger than that from HL-GRBs. If each neutrino event is detected by IceCube, later optical-infrared follow-up observations such as by Subaru could identify a Type Ibc supernova associated with LL-GRBs, even if gamma- and X-rays are not observed by *Swift*. This is in a sense a new window from neutrino astronomy, which might enable us to confirm the existence of LL-GRBs and to obtain information about their rate and origin. We also argue LL-GRBs as high energy gamma-ray and cosmic-ray sources.

Subject headings: gamma rays: bursts — acceleration of particles — elementary particles

1. Introduction

Gamma-ray bursts (GRBs) and supernovae (SNe) are most powerful phenomena in the universe. Theorists predicted that the former would result from the death of massive stars, and the association of long-duration GRBs with core-collapse supernovae (SNe of Type Ibc to be more specific) has been observed over the last decade (Colgate 1974; Woosley 1993). The first hint for such a connection came with the discovery of a nearby SN 1998bw (SN Ic) in the error circle of GRB 980425 (Galama et al. 1998; Iwamoto et al. 1998). The first spectroscopic identification of a SN Ic superposed on a GRB afterglow component was done in GRB 030329/SN 2003dh (Hjorth et al. 2003).

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Work supported in part by Department of Energy contract DE-AC02-76SF00515

Recently *Swift* discovered GRB 060218, which is the second nearest GRB identified to-date (Camapana et al. 2006; Cusumano et al. 2006; Mirabal & Halpern 2006; Sakamoto 2006). GRB 060218 is associated with SN 2006aj and provides another example of low luminosity GRBs. This event is 100 times less energetic and the duration is very long ~ 2000 s. A thermal component in the X-ray and UV-optical spectra was discovered and the size of the emitting black-body region is estimated to be $r_{\rm BB} \sim 6 \times (10^{11} - 10^{12})$ cm. This thermal component would be the shock break out from a stellar envelope or a dense wind, or from a hot cocoon surrounding the GRB ejecta (Ramirez-ruiz et al. 2002).

These GRB 060218-like events are phenomenologically peculiar events compared with the conventional bursts because these have lower isotropic luminosity and energy, simpler prompt light curves, and larger spectral time lags. Guetta et al. (2005) argued that no bright burst $z < 0.17$ should be observed by a HETE-like instruments within the next 20 years, assuming that GRB 060218-like bursts follow the logN-logP relationship of HL-GRBs. Therefore, this unexpected discovery of GRB 060218 can lead to the idea that they form a different new class of GRBs from the conventional HL-GRBs, although much uncertainty remains and we do not know what distinguishes such LL-GRBs from the conventional HL-GRBs. Under this assumption, Soderberg et al. (2006b) estimated the rate of LL-GRBs and found that they are ten times more common than conventional HL-GRBs, and Liang et al. (2006) obtained a similar LL-GRB rate. However, each origin of LL-GRBs could be different. Mazzali et al. (2006) suggested that GRB 980425 and GRB 031203 could be related with a black hole formation, while GRB 060218 could be driven by a neutron star. GRB 060218-like events might possibly be associated with the birth of magnetars. The origin of such LL-GRBs and whether these bursts are typical or not are open problems. However, LL-GRBs like GRB 060218 could provide enough energy for high energy cosmic-rays, neutrinos, and gamma-rays, if we assume such LL-GRBs are more common than HL-GRBs. The detection of such signals can be important, even though most LL-GRBs cannot be observed by *Swift* due to their low luminosities.

In this letter, we study the possibility of the high energy cosmic-ray production and the successive neutrino production in LL-GRBs under the usual internal shock model.[1] Such neutrino bursts from HL-GRBs were predicted in the context of the standard scenario of GRBs assuming that ultra-high-energy cosmic rays (UHECRs) come from GRBs (Waxman & Bahcall 1997; Waxman & Bahcall 1999). Murase & Nagataki (2006a, 2006b) also investigated such emission from HL-GRBs and from flares, using the Monte Carlo simulation kit GEANT4 (Agostinelli et al. 2003). With the same method, we will calculate the high energy neutrino emission and the diffuse neutrino background from LL-GRBs. We will also discuss various implications of such LL-GRBs. Large neutrino detectors such as IceCube (Ahrens et al. 2004), ANTARES (Aslanides et al. 1999) and NESTOR (Grieder et al. 2001) are being constructed. In the near future, these detectors may detect high energy neutrino signals and give us more clues on testing our models and understanding

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[1] When we were completing the draft, we knew that a similar study was independently carried out by Gupta & Zhang (2006).

GRB phenomena.

2. THE MODEL

We suppose GRB 060218-like events as LL-GRBs in this letter. This burst has low luminosity $\sim (10^{46} - 10^{47})$ ergs/s, which is much smaller than that of usual HL-GRBs, which is typically $L_{\max} \sim (10^{51} - 10^{52})$ ergs/s. In this letter, we take $L_{\max} = 10^{47}$ ergs/s as a peak luminosity of LL-GRBs and fix $E_{\gamma,\mathrm{iso}} = L_{\max} \delta t N \sim 10^{49-50}$ ergs as the released radiation energy. Here δt is the variability time and N is the number of collisions. To explain the prompt emission, we assume the usual internal shock model in which the gamma-rays arise from the internal dissipation of ultra-relativistic jets, although there is another explanation (Dai et al. 2006). The typical collision radius will be expressed by commonly used relation, $r \approx 10^{15} (\Gamma/10)^2 (\delta t/150\,\mathrm{s})$ cm. Of course, this radius has to be smaller than the deceleration radius, $r < r_{\mathrm{BM}} \approx 4.4 \times 10^{16} (E_{\mathrm{kin},50}/n_0 (\Gamma/10)^2)^{1/3}$ cm. The observed lightcurve of GRB 060218 is simple and smooth, suggesting $\delta t \sim (10^2 - 10^3)$ s (Cusumano et al. 2006). But it is uncertain whether these parameters are typical or not (Fan et al. 2006). Hence, we take $r \sim (10^{14} - 10^{16})$ cm with $\Gamma \sim (10 - 100)$. These radii will be important for neutrino production (Murase & Nagataki 2006a). We also assume that the Lorentz factor of the internal shocks will be mildly relativistic, $\Gamma_{\mathrm{sh}} \approx (\sqrt{\Gamma_{\mathrm{f}}/\Gamma_{\mathrm{s}}} + \sqrt{\Gamma_{\mathrm{s}}/\Gamma_{\mathrm{f}}})/2 \sim$ a few. The typical values in the usual synchrotron model are obtained as follows. The minimum Lorentz factor of electrons is estimated by $\gamma_{e,\mathrm{m}} \approx \epsilon_e (m_p/m_e)(\Gamma_{\mathrm{sh}} - 1)$. Since the intensity of magnetic field is given by $B = 7.3 \times 10^2\ \mathrm{G} \epsilon_{B,-1}^{1/2} (\Gamma_{\mathrm{sh}}(\Gamma_{\mathrm{sh}} - 1)/2)^{1/2} L_{\mathrm{M},48}^{1/2} (\Gamma/10)^{-1} r_{15}^{-1}$, the observed break energy is, $E^{\mathrm{b}} = \hbar \gamma_{e,\mathrm{m}}^2 \Gamma e B / m_e c \sim 1\ \mathrm{keV} \epsilon_e^2 \epsilon_B^{1/2} (\Gamma_{\mathrm{sh}} - 1)^{5/2} (\Gamma_{\mathrm{sh}}/2)^{1/2} L_{\mathrm{M},48}^{1/2} r_{15}^{-1}$, where L_{M} is the outflow luminosity. This value is not so different from the observed peak energy of GRB 060218, $E^{\mathrm{b}} \sim$ keV. We expect LL-GRBs with the lower Lorentz factor release most energy in the X-ray band.

Although we have too less information about spectral features of LL-GRBs at present, we assume a similar spectral shape to that of HL-GRBs for our calculations and approximate it by the broken power-law instead of exploiting the synchrotron model. The photon spectrum in the comoving frame is expressed by, $dn/d\varepsilon = n_{\mathrm{b}} (\varepsilon/\varepsilon^{\mathrm{b}})^{-\alpha}$ for $\varepsilon^{\min} < \varepsilon < \varepsilon^{\mathrm{b}}$ and $dn/d\varepsilon = n_{\mathrm{b}} (\varepsilon/\varepsilon^{\mathrm{b}})^{-\beta}$ for $\varepsilon^{\mathrm{b}} < \varepsilon < \varepsilon^{\max}$, where we set $\varepsilon^{\min} = 0.1$ eV because the synchrotron self-absorption will be crucial below this energy (Li & Song 2004) and $\varepsilon^{\max} = 1$ MeV because the pair absorption will be crucial above this energy (Asano & Takahara 2003). Corresponding to the observed break energy of GRB 060218, $E^{\mathrm{b}} = 4.9$ keV with the assumption of the relatively low Lorentz factor, we take $\varepsilon^{\mathrm{b}} = 0.5$ keV in the comoving frame as a typical value throughout the letter. We also take $\alpha = 1$ and set $\beta = 2.2$ as photon indices. Note that we may have to wait for other GRB 060218-like events to know the reliable typical values.

We believe not only electrons but also protons will be accelerated. Although the detail of acceleration mechanisms is poorly known, we assume that the first-order Fermi acceleration mechanism works in GRBs and the distribution of nonthermal protons is given by $dn_p/d\varepsilon_p \propto \varepsilon_p^{-2}$. By the condition $t_{\rm acc} < t_p$, we can estimate the maximal energy of accelerated protons, where t_p is the total cooling time scale given by $t_p^{-1} \equiv t_{p\gamma}^{-1} + t_{\rm syn}^{-1} + t_{\rm IC}^{-1} + t_{\rm ad}^{-1}$ and the acceleration time scale is given by $t_{\rm acc} = \eta \varepsilon_p / eBc$. Especially, the two time scales $t_{\rm syn}$ (synchrotron cooling time) and $t_{\rm ad} \approx t_{\rm dyn}$ (dynamical time) are important in our cases. We can estimate the maximum proton energy by $E_{p,{\rm max}} \approx \min[eBr/\eta, \sqrt{6\pi e/\sigma_{\rm T} B \eta}(\Gamma m_p^2 c^2/m_e)]$ from the conditions, $t_{\rm acc} < t_{\rm dyn}$ and $t_{\rm acc} < t_{\rm syn}$. These two conditions equivalently lead to,

$$0.5\eta(\Gamma/10)E_{p,20} \lesssim L_{{\rm M},48}^{1/2}\epsilon_{B,-1}^{1/2}\left(\frac{\Gamma_{\rm sh}(\Gamma_{\rm sh}-1)}{2}\right)^{1/2} \lesssim 0.55\eta^{-1} r_{15} (\Gamma/10)^3 E_{p,20}^{-2}, \tag{1}$$

where we have used notations such as $E_p \equiv 10^{20}\,{\rm eV} E_{p,20}$. These inequalities suggest that the only relatively more luminous/magnetized LL-GRBs with higher Lorentz factor (i.e., larger $L_{\rm M}$ and/or ϵ_B, and higher Γ) will have possibilities to explain the observed flux of UHECRs.

We consider neutrinos from the decay of pions generated by photomeson productions. The photomeson time scale is $t_{p\gamma}$. Let us evaluate $f_{p\gamma} \equiv t_{\rm dyn}/t_{p\gamma}$ analytically using the Δ-resonance approximation (Murase & Nagataki 2006b) as,

$$f_{p\gamma} \simeq 0.06 \frac{L_{{\rm max},47}}{r_{15}(\Gamma/10)^2 E_{5\,{\rm keV}}^{\rm b}} \begin{cases} (E_p/E_p^{\rm b})^{\beta-1} & (E_p < E_p^{\rm b}) \\ (E_p/E_p^{\rm b})^{\alpha-1} & (E_p^{\rm b} < E_p) \end{cases} \tag{2}$$

where $E_p^{\rm b} \simeq 0.5 \bar{\varepsilon}_\Delta m_p c^2 \Gamma^2 / E^{\rm b}$ is the proton break energy. Here, $\bar{\varepsilon}_\Delta$ is around 0.3 GeV. From Eq. (2), we can conclude that a moderate fraction of high energy accelerated protons will be converted into neutrinos.

Next, we consider the contribution to the neutrino flux from a thermal photon component. The discovery of the thermal component in GRB 060218 will provide additional photon flows. This photon flow has a possibility to produce more neutrinos by interaction with protons accelerated in internal shocks. We take $kT = 0.15$ keV and $r_{\rm BB} = 10^{12}$ cm as the typical photon energy of the thermal component and the apparent emitting radius (Camapana et al. 2006), respectively. Just for simplicity, we assume the photon density drops as $\propto r^{-2}$ and approximate it by the isotropic distribution with $dn/d\varepsilon(\varepsilon) \approx dn_{\rm lab}/d\varepsilon_{\rm lab}(\varepsilon_{\rm lab})$, where $dn_{\rm lab}/d\varepsilon_{\rm lab}$ is the photon distribution in the laboratory frame. From the Δ-resonance approximation, we can expect that the typical energy of neutrinos produced by additional photons is $\sim (0.1-1)$ EeV.

3. Results and Discussions

We calculate neutrino spectra for some parameter sets and will show the case where the width of shells $\Delta \approx (r/2\Gamma^2) = 4.5 \times 10^{12}$ cm, according to $\delta t = 150$ s. A diffuse neutrino background under the standard ΛCDM cosmology ($\Omega_{\rm m} = 0.3, \Omega_\Lambda = 0.7; H_0 = 71\,{\rm km\,s^{-1}\,Mpc^{-1}}$) is calculated by the following expression,

$$\Phi_\nu = \frac{c}{4\pi H_0}\int_{z_{\rm min}}^{z_{\rm max}} dz\, R_{\rm GRB}(z) \frac{dN_\nu((1+z)E_\nu)}{dE_\nu}$$

$$\times \frac{1}{(1+z)\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}} \tag{3}$$

where we set $z_{\rm max} = 11$. Assuming that the long GRB rate traces the starformation rate (SFR), we use the SF2 model of Porciani & Madau (2001) combined with the normalization of geometrically corrected overall HL-GRB rates $R_{\rm HL}(0)$ obtained by Guetta et al. (2005) for HL-GRBs. The local LL-GRB rate is very uncertain for now. Soderberg et al. (2006b) obtained the geometrically uncorrected local GRB rate, $\rho_{\rm LL}(0) = 700\,{\rm Gpc}^{-3}{\rm yr}^{-1}$. Liang et al. (2006) had a similar value. However, too large rates will be impossible due to constraints by observations of SNe Ibc. Soderberg et al. (2006a) argued that at most $\sim 10\,\%$ of SNe Ibc are associated with off-beam LL-GRBs based on their late-time radio observations of 68 local SNe Ibc. Hence, the most optimistic value allowed from the local SNe Ibc rate will be around $\sim 4800\,{\rm Gpc}^{-3}{\rm yr}^{-1}$ (Cappellaro et al. 1999; Marzke et al. 1998; Soderberg et al. 2006a). The high rate of LL-GRBs might be realized if LL-GRBs are related with the birth of magnetars and the fraction of SNe Ibc that produce magentars is comparable with that of SNe II, i.e., $\sim 10\%$.

Although we calculate numerically, we can estimate the diffuse neutrino flux from LL-GRBs approximately by the following analytical expression (Murase & Nagataki 2006b),

$$\begin{aligned} E_\nu^2 \Phi_\nu &\sim \frac{c}{4\pi H_0}\frac{1}{4}{\rm min}[1, f_{p\gamma}] E_p^2 \frac{dN_p}{dE_p} R_{\rm LL}(0) f_z \\ &\simeq 1.4\times 10^{-9}{\rm GeV cm^{-2} s^{-1} str^{-1}} \left(\frac{\xi_{\rm acc}}{10}\right) E_{\rm LL,50} \\ &\times \left(\frac{f_{p\gamma}}{0.05}\right)\left(\frac{R_{\rm LL}(0)}{1000\,{\rm Gpc^{-3} yr^{-1}}}\right)\left(\frac{f_z}{3}\right), \end{aligned} \tag{4}$$

where $E_{\rm LL}$ is the geometrically corrected radiated energy of LL-GRBs, f_z is the correction factor for the possible contribution from high redshift sources, and we have estimated $\varepsilon_{p,{\rm max}} \sim 10^9$ GeV. Our numerical results are shown in Fig. 1. From these results, we can estimate the number of muon events N_μ due to muon-neutrinos above TeV energy by using the detection probability, $P(E_\nu) = 7\times 10^{-5}(E_\nu/10^{4.5}\,{\rm GeV})^\beta$, where $\beta = 1.35$ for $E_\nu < 10^{4.5}\,{\rm GeV}$ and $\beta = 0.55$ for $E_\nu > 10^{4.5}\,{\rm GeV}$ (Ioka et al. 2005; Razzaque et al. 2004), and a geometrical detector area of $A_{\rm det} = 1{\rm km}^2$. From Fig. 1, we can obtain $N_\mu = 9.3$ events/yr for the local rate obtained by Soderberg et al. (2006b) and $N_\mu = 64$ events/yr for the most optimistic local rate. The neutrino backgrounds from LL-GRBs are comparable with or larger than that from HL-GRBs (shown by HL-GRB in Fig. 1), $N_\mu = 17$ events/yr (Murase & Nagataki 2006a).

Unfortunately, neutrino signals from LL-GRBs are dark in the sense that most of such neutrinos from LL-GRBs will not correlate with the prompt emission. Only for very nearby bursts, we might be able to expect their correlations and it needs operations over a few years. The BAT detector on the *Swift* satellite has the sensitivity to detect the bursts $\gtrsim 10^{-8}$ ergs/s. Hence, we can expect correlated events only when $d_{\rm L} \lesssim 300$ Mpc for bursts with $L_{\rm max} \sim 10^{47}$ ergs/s. The expected correlated muon events are $N_\mu = 1$ event per 8 years for the Soderberg et al. (2006b) local rate and $N_\mu = 1.6$ events per 2 years for the most optimistic local rate.

However, SNe Ibc associated with LL-GRBs could be detected by optical-infrared follow-ups triggered by a neutrino event. The angular resolution of IceCube for neutrinos is about 1 degree or so, which can be searched with wide-field cameras such as Suprime-Cam on the Subaru telescope (whose field-of-view is 0.5 degrees) up to $z \sim 1.2$. With the SN lightcurves ~ 10 days after the burst, we can pin down the burst time within a few days, during which the atmospheric neutrino background within 1 degree would be small, i.e., $\lesssim 0.1$ events/day for above TeV energy neutrinos and less for higher energy threshold (Ando & Beacom 2005). Therefore, we can in principle detect LL-GRB neutrino events associated with SNe Ibc, even though X/γ-rays are not observed by *Swift*. The expected number of muon events is $N_\mu = 3.4$ events/yr for LL-GRBs within $z \sim 1.2$, with $r = 9 \times 10^{14}$ cm, $\Gamma = 10$, and $\rho_{\rm LL}(0) = 700\,{\rm Gpc}^{-3}{\rm yr}^{-1}$. Of course, such a follow-up with SNe detections will be difficult and it is severer to distinguish SNe Ibc from SNe Ia at higher redshift. Nevertheless, it is worthwhile to develop this kind of possibility of high energy neutrino astronomy not only for finding far SNe Ibc but also for revealing their origins. Note also that each event is low luminous, so we are not likely to detect doublet events from LL-GRBs except for very nearby bursts with observable X/γ-rays.

Even in the case of the prompt emission from HL-GRBs, we can not expect neutrino events from one burst, unless the source is nearby or energetic. Similarly, we can expect high energy neutrinos from one LL-GRB only if the burst is nearby or energetic. However, we might observe the very nearby events unexpectedly in future. In Fig. 2, we show an example of the observed neutrino spectra from the source at 10 Mpc. The expected muon events from neutrinos above TeV energy are $N_\mu = 1.1$ events in the case of $\Gamma = 10$ in Fig. 2. If we can detect such an event, we will be able to obtain some information on $\xi_{\rm acc}$, ξ_B, the photon density, the duration of bursts, and so on. More closer bursts can provide more neutrinos and we can detect ~ 10 events for a burst with $\sim 3\,$Mpc. In Fig. 2, we also show the contribution from the thermal target photon. The GRB 060218-like bursts have possibilities to provide us $N_\mu = 0.2$ events originating from the interaction between nonthermal protons and the thermal photon flow. This result depends on the photon density and hence on the temperature of the black body region. Note, the case of $\Gamma = 20$ in Fig. 2 would not be plausible because the magnetic field strength of this case seems too small to explain the prompt emission by the standard model.

HL-GRBs may be the main sources of UHECRs (Waxman 1995). In the internal shocks of HL-GRBs, the optical thickness for the photomeson production can be smaller than unity especially at larger radii $r \gtrsim 10^{14} (E_{\gamma,{\rm iso}}/N 10^{51}\,{\rm ergs})^{1/2}$ cm and the UHECRs can be produced in such regions. In the case of LL-GRBs, it is more difficult to accelerate protons up to ultra-high energy due to the lowness of their luminosities because it would need the fine tuning (see Eq. 1). Hence, it seems unlikely to explain UHECRs by LL-GRBs, although we have to know about their properties such as their luminosity function. Even if the acceleration to $\sim 10^{20}$ eV is difficult, the energy budget of LL-GRBs could be large enough to explain UHECRs ($\sim 10^{44}\,{\rm ergs}\,{\rm Mpc}^{-3}\,{\rm yr}^{-1}$), because the cosmic-ray production rate per Mpc^3 volume is estimated by,

$$E_p^2 \frac{d\dot{N}_p}{dE_p^2} \sim 5 \times 10^{43}\,\mathrm{ergs\,Mpc^{-3}\,yr^{-1}} \left(\frac{\xi_{\mathrm{acc}}}{10}\right) N L_{\mathrm{max},47} r_{15} \left(\frac{\Gamma}{10}\right)^{-2} \left(\frac{\rho_{\mathrm{LL}}(0)}{1000\,\mathrm{Gpc^{-3}\,yr^{-1}}}\right). \qquad (5)$$

Therefore, when the maximum proton energy exceeds $10^{18.5}$ eV, the neutrino flux should be constrained by the observed flux of UHECRs, even if LL-GRBs cannot explain all UHECRs. This implies that we have possibilities to constrain the LL-GRB rate by the observation of UHECRs.

High energy neutrino emission cannot avoid high energy gamma-ray emission through the neutral pion decay. Such high gamma-rays would cascade in the source and/or in microwave and infrared background (Dermer & Atoyan 2004; Razzaque et al. 2004). The latter emission will lead to the delayed emission. The detailed calculation is needed to calculate the expected spectra and it is beyond the scope of this letter. However, the detection of such high energy emission is also difficult except for very nearby bursts such as cases shown in Fig.2 where we can expect neutrino signals. For enough nearby events, high energy gamma-rays could be detected by GLAST and/or the BAT detector on the Swift satellite.

The origin of the thermal component of GRB 060218 is a mystery. One of possibilities is a supernova shock break out. If there is a shock break out, the shock may become collisionless, and electrons and protons may be accelerated there, so that neutrinos could be produced through the pp interaction (Waxman & Loeb 2001). But the amount of such neutrinos will not be so large because the available energy for nonthermal protons would be smaller than the rest energy of the shell, $\sim 5 \times 10^{-7} M_{\odot} c^2$ (Camapana et al. 2006). In addition, we have not discussed the neutrinos produced by protons accelerated in the star (Mészáros & Waxman 2001; Razzaque et al. 2003; Ando & Beacom 2005). Protons might be accelerated by internal shocks inside the stellar envelope and outflows may not penetrate the star (failed GRBs). In such cases, accelerated protons can produce $\sim$ TeV neutrinos mainly by pp interactions and may provide other detectable neutrino signals that become clues on the connection between GRBs and SNe.

So far, we have not taken account of neutrino oscillations, that are needed for more precise predictions. The produced neutrinos will be almost equally distributed among flavors as a result of vacuum neutrino oscillations (Waxman & Bahcall 1997).

In this letter, we have discussed a possibility that LL-GRBs could produce UHECRs and detectable high energy neutrinos. Because the possible higher rate of LL-GRBs can cover the relatively lower energy of them, we can expect that the diffuse neutrino flux is similar to that of HL-GRBs. Of course, the results depend on several unknown parameters such as the bulk Lorentz factor, and it is necessary to get more information by future observations in order to achieve more realistic predictions. If parameters we have adopted are typical, we might obtain some independent information such as the LL-GRB rate from neutrino observations. It is difficult to identify each neutrino signal with the LL-GRBs, in contrast to the case of HL-GRBs. But, if our model is valid, such neutrinos could be useful as one of indicators of far SNe Ibc.

K.M. and S.N. thank M. Doi and N. Tominaga for helpful advices. K.M. also thanks K. Toma and N. Kawanaka. This work is supported in part by by Grants-in-Aid for Scientific Research of the Japanese Ministry of Education, Culture, Sports, Science, and Technology 18740147 (K.I.).

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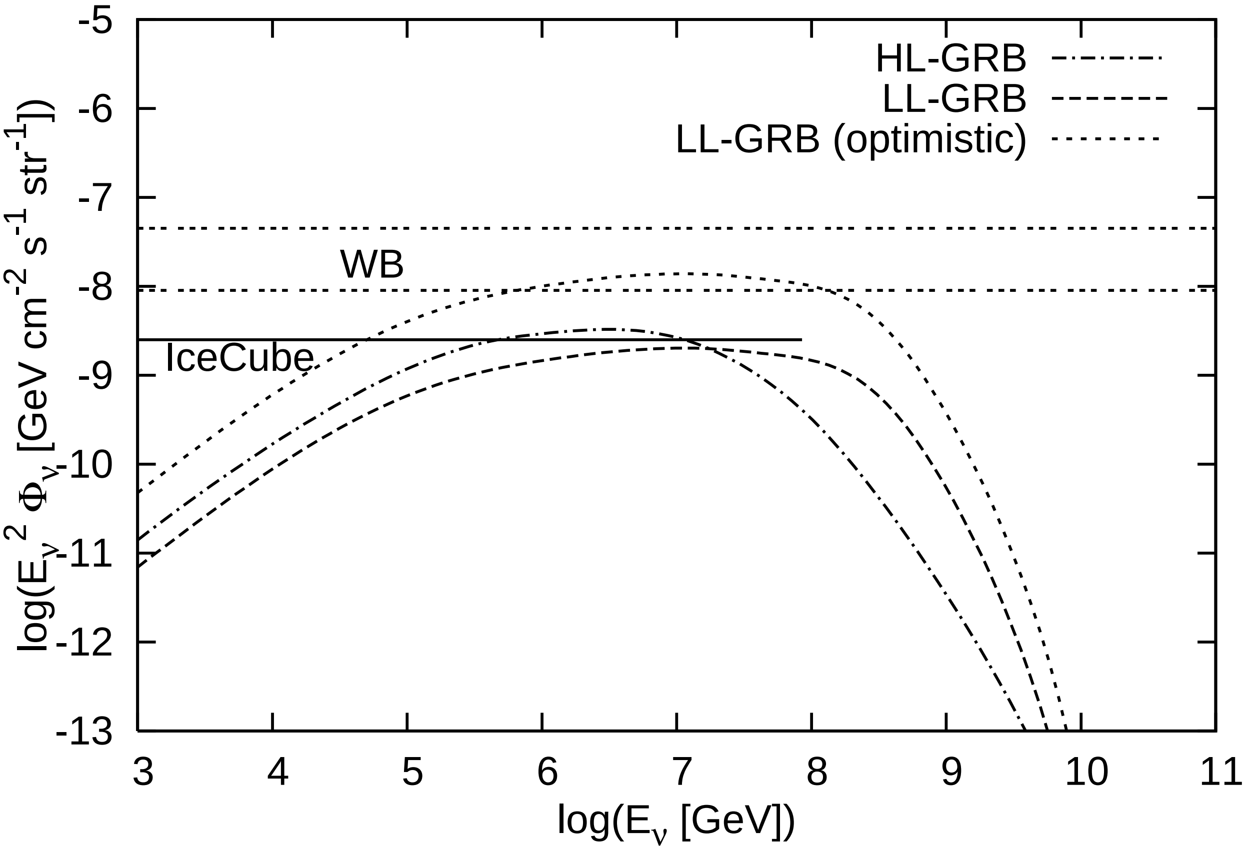

Fig. 1.— The neutrino background from GRBs for $\xi_{\rm acc} = 10$ and $\xi_B = 1$. LL-GRB: $r = 9 \times 10^{14}$ cm and $\Gamma = 10$ with the local rate $\sim 700\,{\rm Gpc}^{-3}{\rm yr}^{-1}$ obtained by Soderberg et al. (2006b). LL-GRB (optimistic): $r = 9{\times}10^{14}$ cm and $\Gamma = 10$ with the most optimistic local rate $\sim 4800\,{\rm Gpc}^{-3}{\rm yr}^{-1}$. HL-GRB: taken from (Murase & Nagataki 2006a) with $E_{\gamma,{\rm iso}}/N = 2 \times 10^{51}$ ergs, $r = (10^{13} - 10^{14.5})$ cm and $\Gamma = 300$. WB: Waxman-Bahcall bounds (Waxman & Bahcall 1999). ξ_B and $\xi_{\rm acc}$ are the ratio of energy density, $\xi_B \equiv U_B/U_\gamma$ and $\xi_{\rm acc} \equiv U_p/U_\gamma$, respectively. For the fast cooling case and the acceleration efficiency ~ 1, we have $\xi_B \sim (\epsilon_B/\epsilon_e)$ and $\xi_{\rm acc} \sim 1/\epsilon_e$.

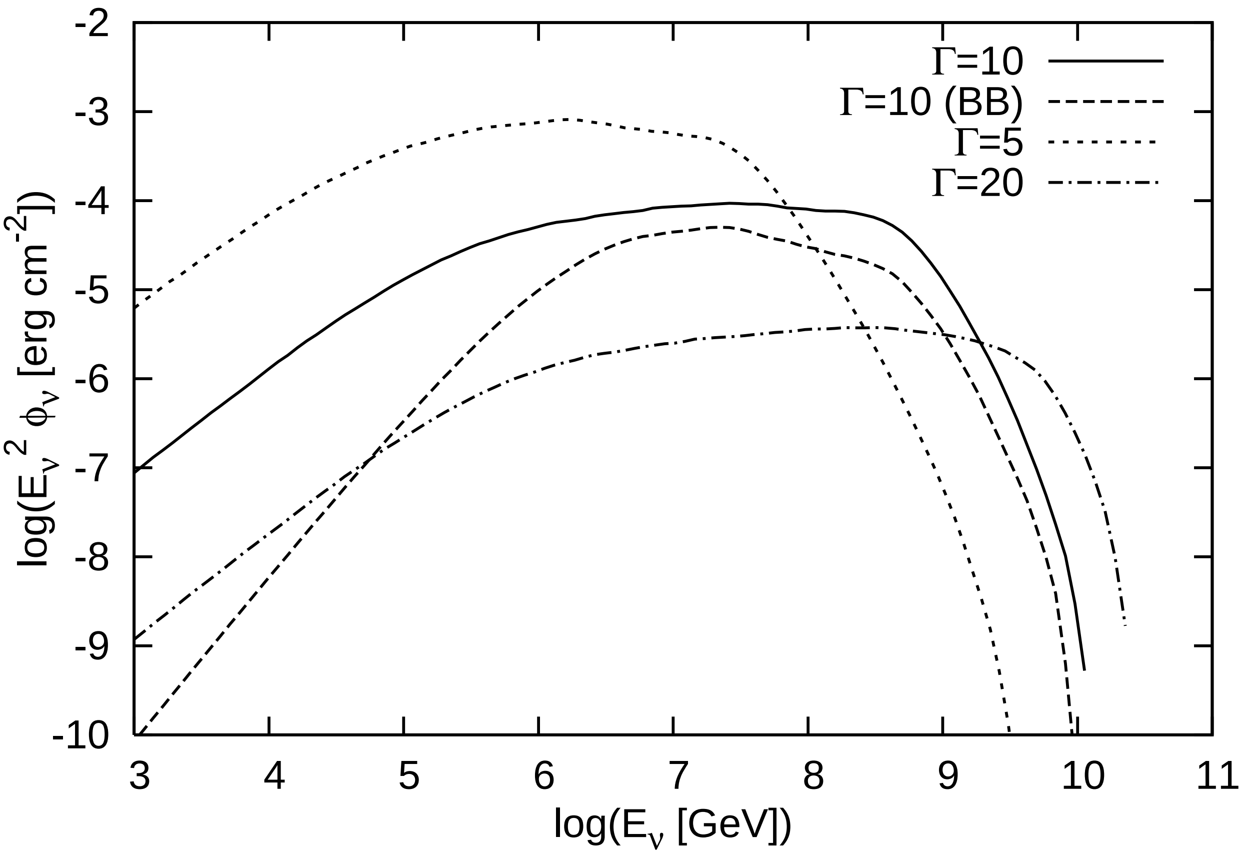

Fig. 2.— The observed muon-neutrino ($\nu_\mu + \bar{\nu}_\mu$) spectra for one very nearby GRB event at 10 Mpc. Solid line: $r = 9 \times 10^{14}$ cm and $\Gamma = 10$. Dashed line: the contribution from the blackbody target photon with $r = 9 \times 10^{14}$ cm and $\Gamma = 10$. Dotted line: $r = 2.25 \times 10^{14}$ cm and $\Gamma = 5$. Dot-dashed line: $r = 3.6 \times 10^{15}$ cm and $\Gamma = 20$. In all cases $\xi_B = 1$ and $\xi_{\rm acc} = 10$ (see the caption of Fig.1).