

HIGH ENERGY NEUTRINOS AND COSMIC-RAYS FROM LOW-LUMINOSITY GAMMA-RAY BURSTS?

KOHTA MURASE¹, KUNIHITO IOKA², SHIGEHIRO NAGATAKI^{1,3}, AND TAKASHI NAKAMURA²

ABSTRACT

The recently discovered gamma-ray burst (GRB) 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 rate of GRB 060218-like events might be very high so that such low luminosity GRBs (LL-GRBs) might form a different population from the cosmological high luminosity GRBs (HL-GRBs). We found that the high energy neutrino background from LL-GRBs could be comparable with that from HL-GRBs. If each neutrino event is detected by IceCube, later optical-infrared follow-up observations such as by Subaru and HST have possibilities to 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. 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).

Recently *Swift* discovered GRB 060218, which is the second nearest GRB identified to-date (Campana et al. 2006; Cusumano et al. 2006; Mirabal & Halpern 2006; Sakamoto 2006). GRB 060218 is associated with SN 2006aj and provides another example of LL-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 $r_{\text{BB}} \sim (5 \times 10^{11} - 10^{12})$ cm. It would come from the shock break out from a stellar envelope or a dense wind (Campana et al. 2006), or from a hot cocoon surrounding the GRB ejecta (Liang et al. 2006b; 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. (2004) 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 about ten times more common than conventional HL-GRBs, and Liang et al. (2006a) obtained a high LL-GRB rate similarly. 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.

If such LL-GRBs like GRB 060218 are more common than HL-GRBs, they would provide enough energy for high energy cosmic-rays, neutrinos, and gamma-rays. 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.⁴ 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 1998). 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 experimental data. With the same method, we study the high energy neutrino emission from LL-GRBs. We will also discuss various implications for 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 to understanding LL-GRBs and testing our model.

2. THE MODEL

We suppose GRB 060218-like events as LL-GRBs in this Letter. GRB 060218 has low luminosity $\sim 10^{46-47}$ ergs/s, which is much smaller than that of usual HL-GRBs, typically $L_{\text{max}} \sim 10^{51-52}$ ergs/s. Hereafter, we take $L_{\text{max}} = 10^{47}$ ergs/s as a peak luminosity of LL-GRBs and fix $E_{\gamma,\text{iso}} = L_{\text{max}} \delta t N \sim 10^{49-50}$ ergs as the released radiation energy. Here δt is the variability time and N is the number of collisions. To

¹ YITP, Kyoto University, Kyoto, 606-8502, Japan

² Department of Physics, Kyoto University, Kyoto 606-8502, Japan

³ KIPAC, Stanford University, Stanford, CA, 94309, USA

⁴ When we were completing the draft, we knew that a similar study was independently carried out by Gupta & Zhang (2006).

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, $r \approx 10^{15}(\Gamma/10)^2(\delta t/150\text{ s})$ cm. Of course, this radius has to be smaller than the deceleration radius, $r < r_{\text{BM}} \approx 4.4 \times 10^{16}(E_{\text{kin},50}/n_0(\Gamma/10)^2)^{1/3}$ cm. The observed light curve of GRB 060218 is simple and smooth, suggesting $\delta t \sim 10^{2-3}$ s (Cusumano et al. 2006). But it is uncertain whether these parameters are typical or not (Fan et al. 2006). Hence, we take $r \sim 10^{14-16}$ 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, $\Gamma_{\text{sh}} \approx (\sqrt{\Gamma_f/\Gamma_s} + \sqrt{\Gamma_s/\Gamma_f})/2 \sim$ a few. The typical values in the usual synchrotron model are obtained as follows. The minimum Lorentz factor of electrons is estimated by $\gamma_{e,\text{m}} \approx \epsilon_e(m_p/m_e)(\Gamma_{\text{sh}} - 1)$. Since the intensity of magnetic field is given by $B = 7.3 \times 10^2 G \epsilon_{B,-1}^{1/2} (\Gamma_{\text{sh}} - 1)/2)^{1/2} L_{\text{M},48}^{1/2} (\Gamma/10)^{-1} r_{15}^{-1}$, the observed break energy is, $E^b = \hbar \gamma_{e,\text{m}}^2 \Gamma e B / m_e c \sim 1 \text{ keV} \epsilon_e^2 \epsilon_B^{1/2} (\Gamma_{\text{sh}} - 1)^{5/2} (\Gamma_{\text{sh}}/2)^{1/2} L_{\text{M},48}^{1/2} r_{15}^{-1}$, where L_{M} is the outflow luminosity. This value is not so different from the observed peak energy of GRB 060218, $E^b \sim \text{keV}$.

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 a Band spectrum. The photon spectrum in the comoving frame is expressed by, $dn/d\varepsilon = n_b(\varepsilon/\varepsilon^b)^{-\alpha}$ for $\varepsilon^{\text{min}} < \varepsilon < \varepsilon^b$ and $dn/d\varepsilon = n_b(\varepsilon/\varepsilon^b)^{-\beta}$ for $\varepsilon^b < \varepsilon < \varepsilon^{\text{max}}$, where we set $\varepsilon^{\text{min}} = 0.1$ eV because the synchrotron self-absorption will be crucial below this energy (Li & Song 2004) and $\varepsilon^{\text{max}} = 1$ MeV because the pair absorption will be crucial above this energy (Asano & Takahara 2003). Corresponding to the observed break energy of GRB 060218, $E^b = 4.9$ keV with the assumption of the relatively low Lorentz factor, we take $\varepsilon^b = 0.5$ 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 non-thermal protons is given by $dn_p/d\varepsilon_p \propto \varepsilon_p^{-2}$. By the condition $t_{\text{acc}} < t_p$, we can estimate the maximal energy of accelerated protons, where t_p is the total cooling time scale given by $t_p^{-1} \equiv t_{p\gamma}^{-1} + t_{\text{syn}}^{-1} + t_{\text{IC}}^{-1} + t_{\text{ad}}^{-1}$ and the acceleration time scale is given by $t_{\text{acc}} = \eta \varepsilon_p / e B c$. Especially, the two time scales t_{syn} (synchrotron cooling time) and $t_{\text{ad}} \approx t_{\text{dyn}}$ (dynamical time) are important in our cases. We can estimate the maximum proton energy by $E_{p,\text{max}} \approx \min[eBr/\eta, \sqrt{6\pi e/\sigma_T B\eta}(\Gamma m_p^2 c^2/m_e)]$ from the conditions, $t_{\text{acc}} < t_{\text{dyn}}$ and $t_{\text{acc}} < t_{\text{syn}}$. These two conditions equivalently lead to,

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

where we have used notations such as $E_p \equiv 10^{20} \text{ eV} E_{p,20}$.

These inequalities suggest that the only relatively more luminous/magnetized LL-GRBs with higher Lorentz factor (i.e., larger L_{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 $f_{p\gamma} \equiv t_{\text{dyn}}/t_{p\gamma}$ analytically using the Δ -resonance approximation (Murase & Nagataki 2006b; Waxman & Bahcall 1997) as,

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

where $E_p^b \simeq 0.5\bar{\varepsilon}_{\Delta} m_p c^2 \Gamma^2 / E^b$ 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 $r_{\text{BB}} = 10^{12}$ cm as the typical photon energy of the thermal component and the apparent emitting radius (Campana 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 $dn/d\varepsilon(\varepsilon) \approx dn_{\text{lab}}/d\varepsilon_{\text{lab}}(\varepsilon_{\text{lab}})$, where $dn_{\text{lab}}/d\varepsilon_{\text{lab}}$ is the photon distribution in the laboratory frame.

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 $\delta t \sim 150$ s. In our calculations, we include various cooling processes of pions (synchrotron cooling, IC cooling, adiabatic cooling) similarly to Murase & Nagataki (2006a, 2006b). These cooling processes are important for neutrino spectra (Rachen & Meszaros 1998; Waxman & Bahcall 1997). A diffuse neutrino background under the standard Λ CDM cosmology ($\Omega_m = 0.3, \Omega_\Lambda = 0.7; H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$) is calculated by using Eq. (15) of Murase & Nagataki (2006a), where we set $z_{\text{max}} = 11$. Assuming that the long GRB rate traces the starformation rate (SFR), we exploit the SF2 model of Porciani & Madau (2001) combined with the normalization of geometrically corrected overall HL-GRB rates $R_{\text{HL}}(0)$ 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 corrected overall GRB rate, $R_{\text{LL}}(0) = 230 \text{ Gpc}^{-3} \text{ yr}^{-1}$. Liang et al. (2006a) also had a high value, $\rho_{\text{LL}}(0) = 550 \text{ Gpc}^{-3} \text{ yr}^{-1}$. (Note that the true rate $R_{\text{LL}}(0)$ is almost the same as the apparent one $\rho_{\text{LL}}(0)$ for LL-GRBs because we are assuming GRB 060218-like spherical bursts.) 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 $\sim 4800 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (and the larger value is ruled out with a confidence level of $\sim 90\%$) (Soderberg et al. 2006a). The high rate might be realized if LL-GRBs are related with the birth of magnetars and the fraction of SNe Ibc that produce magnetars is comparable with that of SNe II, i.e., $\sim 10\%$.

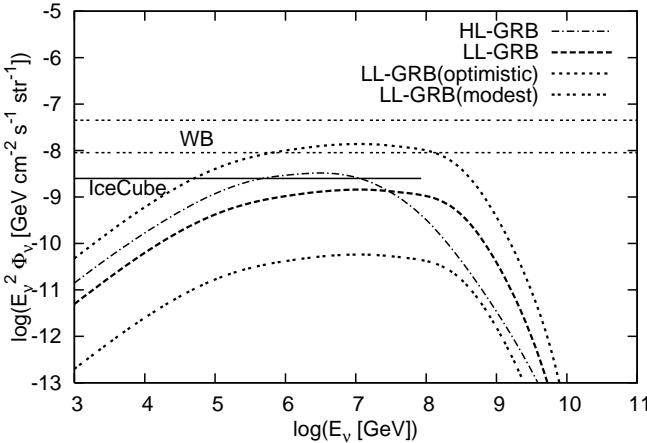


FIG. 1.— The neutrino background from GRBs for $\xi_{\text{acc}} = 10$ and $\xi_B = 1$. LL-GRB: $r = 9 \times 10^{14}$ cm and $\Gamma = 10$ with the local rate $\sim 500 \text{ Gpc}^{-3} \text{ yr}^{-1}$ obtained by Liang et al. (2006a). LL-GRB (optimistic): $r = 9 \times 10^{14}$ cm and $\Gamma = 10$ with the most optimistic local rate $\sim 4800 \text{ Gpc}^{-3} \text{ yr}^{-1}$. LL-GRB (modest): $r = 9 \times 10^{14}$ cm and $\Gamma = 10$ with the modest local rate $\sim 20 \text{ Gpc}^{-3} \text{ yr}^{-1}$. HL-GRB: taken from (Murase & Nagataki 2006a) with $E_{\gamma, \text{iso}}/N = 2 \times 10^{51}$ ergs, $r = 10^{13-14.5}$ cm and $\Gamma = 300$. WB: Waxman-Bahcall bounds (Waxman & Bahcall 1998). ξ_B and ξ_{acc} are the ratio of energy density, $\xi_B \equiv U_B/U_\gamma$ and $\xi_{\text{acc}} \equiv U_p/U_\gamma$, respectively. For the fast cooling case and the acceleration efficiency ~ 1 , we have $\xi_B \sim (\epsilon_B/\epsilon_e)$ and $\xi_{\text{acc}} \sim 1/\epsilon_e$.

Although we calculate numerically, we can estimate the diffuse neutrino flux from LL-GRBs approximately by the following analytical expression (Murase & Nagataki 2006b; Waxman & Bahcall 1998),

$$\begin{aligned} E_\nu^2 \Phi_\nu &\sim \frac{c}{4\pi H_0} \frac{1}{4} \min[1, f_{p\gamma}] E_p^2 \frac{dN_p}{dE_p} R_{\text{LL}}(0) f_z \\ &\simeq 7 \times 10^{-10} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ str}^{-1} \left(\frac{\xi_{\text{acc}}}{10} \right) E_{\text{LL},50} \\ &\quad \times \left(\frac{f_{p\gamma}}{0.05} \right) \left(\frac{R_{\text{LL}}(0)}{500 \text{ Gpc}^{-3} \text{ yr}^{-1}} \right) \left(\frac{f_z}{3} \right), \end{aligned} \quad (3)$$

where E_{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 used $\varepsilon_{p,\text{max}} \sim 10^9$ 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 Eq. (18) of Ioka et al. (2005) as the detection probability and a geometrical detector area of $A_{\text{det}} = 1 \text{ km}^2$. From Fig. 1, we can obtain $N_\mu = 6.6$ events/yr for $\rho_{\text{LL}}(0) = 500 \text{ Gpc}^{-3} \text{ yr}^{-1}$ and $N_\mu = 64$ events/yr for the most optimistic local rate. We also show the modest case where the local rate of LL-GRBs is comparable to the geometrically corrected local rate of HL-GRBs, $R_{\text{HL}}(0) \sim 20 \text{ Gpc}^{-3} \text{ yr}^{-1}$. In this case, we can find $N_\mu = 0.3$ events/yr. The neutrino backgrounds from LL-GRBs have possibilities to be comparable with that from HL-GRBs, $N_\mu = 17$ events/yr (Murase & Nagataki 2006a).

Unfortunately, neutrino signals from LL-GRBs are dark in the sense that most signals will not correlate with the prompt emission. Only for very nearby bursts, we might be able to expect their correlations and it will need many-years operations. The BAT detector on *Swift* has the sensitivity to detect the bursts $\gtrsim 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$. Hence, we can expect correlated events only when $d_L \lesssim 300$ Mpc for bursts with $L_{\text{max}} \sim 10^{47}$ ergs/s. The expected correlated muon events are

$N_\mu \sim 1$ events per 11 years for $\rho_{\text{LL}}(0) = 500 \text{ Gpc}^{-3} \text{ yr}^{-1}$.

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 $z \sim 1.2$. In the field-of-view we would find ~ 10 SNe and ~ 1 SNe Ibc that exploded within ~ 1 month. With the SN light curves ~ 10 days after the burst, we can pin down the burst time within ~ 1 day or so, 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). In addition, SNe Ibc could be specified by using telescopes such as HST. 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 $N_\mu = 2.4$ events/yr for LL-GRBs within $z \sim 1.2$, with $r = 9 \times 10^{14}$ cm, $\Gamma = 10$, and $\rho_{\text{LL}}(0) = 500 \text{ Gpc}^{-3} \text{ yr}^{-1}$. 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 associated with LL-GRBs but also for revealing their origins.

We can expect high energy neutrinos from one LL-GRB only if the burst is nearby or energetic, similarly to the case of HL-GRBs. 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 ξ_{acc} , ξ_B , the photon density, the duration of bursts, and so on. In Fig. 2, we also show the contribution from the thermal target photon. The GRB 060218-like bursts could provide us $N_\mu = 0.2$ events originating from the interaction between nonthermal protons and the thermal photon flow. This result depends on the temperature of the black body region.

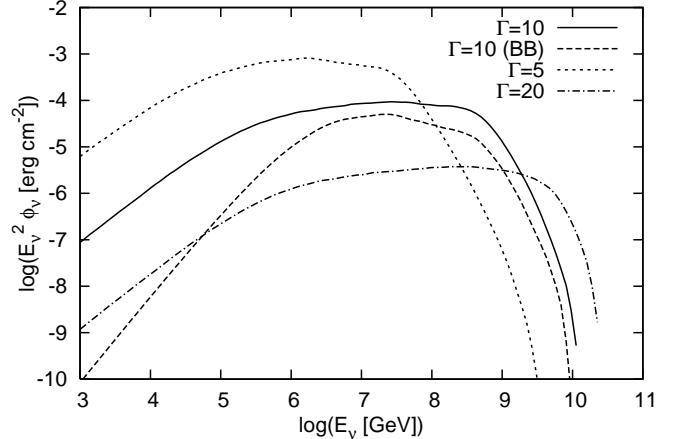


FIG. 2.— The observed muon-neutrino ($\nu_\mu + \bar{\nu}_\mu$) spectra for one very nearby GRB event at 10 Mpc. Solid line: $r = 9 \times 10^{14}$ cm and $\Gamma = 10$. Dashed line: the contribution from the blackbody target photon with $r = 9 \times 10^{14}$ cm and $\Gamma = 10$. Dotted line: $r = 2.25 \times 10^{14}$ cm and $\Gamma = 5$. Dot-dashed line: $r = 3.6 \times 10^{15}$ cm and $\Gamma = 20$. In all cases $\xi_B = 1$ and $\xi_{\text{acc}} = 10$ (see the caption of Fig.1). Note, the case of $\Gamma = 20$ would not be plausible because the magnetic field strength seems too small to explain the prompt emission by the standard model.

HL-GRBs may be the main sources of UHECRs (Waxman 1995). The optical thickness for the photomeson production can be smaller than unity especially at larger radii $r \gtrsim 10^{14} (E_{\gamma,\text{iso}}/N10^{51} \text{ ergs})^{1/2}$ cm in the internal shocks of HL-GRBs and UHECRs can be produced in such regions. In the case of LL-GRBs, it seems more difficult to accelerate protons up to ultra-high energy due to the lowness of their luminosities and it would need some fine tuning (see Eq. 1), 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 ($\sim 10^{44} \text{ ergs Mpc}^{-3} \text{ yr}^{-1}$) because the cosmic-ray production rate per Mpc³ is estimated by,

$$E_p^2 \frac{d\dot{N}_p}{dE_p^2} \sim 2.5 \times 10^{43} \text{ ergs Mpc}^{-3} \text{ yr}^{-1} \left(\frac{\xi_{\text{acc}}}{10} \right) \\ \times NL_{\max,47} r_{15} \left(\frac{\Gamma}{10} \right)^{-2} \left(\frac{\rho_{\text{LL}}(0)}{500 \text{ Gpc}^{-3} \text{ yr}^{-1}} \right). \quad (4)$$

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 physical parameters of LL-GRBs 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 detailed calculation is needed to calculate the expected spectra. However, the detection of such high energy emission by GLAST and/or the BAT detector on

Swift would be difficult except for nearby and/or energetic bursts similarly to the cases of neutrinos.

If there is a shock break out which might be the origin of the mysterious thermal component, the shock may become collisionless, and protons may be accelerated there as well as electrons, so that neutrinos could be produced through the pp interaction (Waxman & Loeb 2001). In addition, protons accelerated by internal shocks inside the stellar envelope could produce detectable \sim TeV neutrinos mainly by pp interactions (Mészáros & Waxman 2001; Razzaque et al. 2003; Ando & Beacom 2005). These other neutrino signals might become clues on the connection between GRBs and SNe.

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 could be comparable with that of HL-GRBs. Of course, the results depend on several unknown parameters such as the bulk Lorentz factor, and future observations are needed for more realistic predictions. If parameters we have adopted are typical, expected neutrino signals may not only give us independent information but could also be useful as one of indicators of far SNe Ibc and may contribute to revealing their mysterious origin. One of possibilities is the birth of magnetars (Soderberg et al. 2006b). Possibly, metallicity might play a crucial role (Stanek et al. 2006).

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