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New prospects for high-energy neutrinos from gamma-ray bursts(*)

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Summary. — High-energy neutrinos from Gamma-Ray Bursts (GRBs) have been expected since the pre-*Swift* era. Such signals may be detected by future large neutrino detectors such as IceCube. Recently *Swift* has shown several novel phenomena. We suggest the new prospects for high-energy neutrino emission in the *Swift* era. Expected signals, if detected, are useful for revealing of the nature of GRBs.

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PACS `95.85.Ry` – Neutrino, muon, pion, and other elementary particles; cosmic rays.

1. – Introduction

Gamma-Ray Bursts (GRBs) are the most energetic explosions in the universe. Their emission is usually explained by dissipation of kinetic energy of relativistic shells. In both the internal shock model for the prompt emission and external shock model for the afterglow, accelerated electrons in the relativistic shocks radiate high-energy gamma-rays. In both models, not only electrons but also protons will be accelerated. If so, very high-energy cosmic rays can produce pions by photomeson production, which lead to high-energy neutrinos. Waxman and Bahcall [1] predicted neutrino bursts under the internal shock model, assuming that ultra-high-energy cosmic rays come from GRBs. We also studied neutrino emission in detail without their assumption [2]. Now, the future neutrino detectors such as IceCube are being constructed. Neutrino signals, if detected, give very meaningful implications for the nature of GRBs and the astrophysical acceleration sites.

The *Swift* satellite was launched to solve several outstanding questions in the pre-*Swift* era. *Swift* has presented indeed very fruitful results until now. The recently discovered XRF 060218 is the second nearest GRB associated a supernova, which has Low-Luminosity (LL) and thermal components, and possibly implies the existence of a different population from conventional High-Luminosity (HL) GRBs. In addition, many *Swift* bursts have flares in the early afterglow phase. Flares are also energetic and imply the late activities of the central engine. Recently we suggested the possibilities of high-energy neutrino emission from flares [2] and LL GRBs [3]. Such high-energy neutrino signals predicted in the *Swift* era are also useful for revealing the nature of GRBs.

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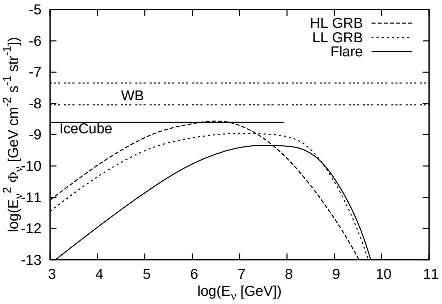

Fig. 1. – Diffuse neutrino background from GRBs. HL GRB (the dashed line): $E_{\gamma,\mathrm{iso}}/N = 10^{51}\,\mathrm{ergs}$, $r = 10^{13-14.5}\,\mathrm{cm}$, $\Gamma = 10^{2.5}$, $\xi_B = 1$, and $\xi_{\mathrm{acc}} = 10$; $N_\mu \sim 10$ events/y. LL-GRB (the dotted line): $L_{\max} = 10^{47}\,\mathrm{ergs/s}$, $r = 9 \times 10^{14}\,\mathrm{cm}$, $\Gamma = 10$, $\xi_B = 1$, $\xi_{\mathrm{acc}} = 10$, and $\rho_{\mathrm{LL}}(0) = 700\,\mathrm{Gpc}^{-3}\,\mathrm{y}^{-1}$; $N_\mu \sim 5$ events/y. Far-ultraviolet flare (the solid line): $L_{\max} = 10^{48}\,\mathrm{ergs/s}$, $r = 10^{15.3}\,\mathrm{cm}$, $\Gamma = 15$, $\xi_B = 1$, $\xi_{\mathrm{acc}} = 10$, and $f_{\mathrm{F}} = 1/10$; $N_\mu \sim 1$ events/y. We assume the SF3 model with $\Omega_{\mathrm{M}} = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 71\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, and $z_{\max} = 11$.

2. – High-energy neutrinos produced by photomeson production

Protons accelerated up to sufficiently high energy can produce pions through photomeson production. High-energy pions will decay as they cool down due to various cooling processes, and generate neutrinos. We can obtain neutrino spectra by the method using Geant4 with experimental data, which is the same as in Murase and Nagataki [2] but quantitatively improved. We assume the internal shock model for the prompt emission of both HL GRBs and LL GRBs, and the late internal shock model for flares. Expected muon events from each burst under each scenario are too few to detect. Therefore, we will need many GRB events. We can evaluate the neutrino background assuming that the GRB rate traces the star formation rate with the local GRB rate. For details, see Murase and Nagataki [2]. We show the results for each scenario in fig. 1. HL GRBs have luminosity $L \sim 10^{51}\,\mathrm{ergs\,s^{-1}}$ and duration $T \sim 10\,\mathrm{s}$. On the other hand, we assume $L \sim 10^{47}\,\mathrm{ergs\,s^{-1}}$ and $T \sim 100$–$1000\,\mathrm{s}$ for LL GRBs, and $L \sim 10^{48-49}\,\mathrm{ergs\,s^{-1}}$ and $T \sim 100\,\mathrm{s}$ for flares. The typical pion production efficiency is ~ 0.1–1 for HL GRBs, ~ 0.01–0.1 for LL GRBs, and ~ 1 for flares. In the case of flares, high efficiency is expected so that the highest-energy cosmic rays will be depleted and neutrino production is efficient. The local long GRB rate is typically $\sim 1\,\mathrm{Gpc^{-3}\,y^{-1}}$ for HL GRBs. On the other hand, it might be higher ~ 100–$1000\,\mathrm{Gpc^{-3}\,y^{-1}}$ for LL GRBs. The high rate of LL GRBs could compensate their lower luminosity. In HL GRBs and flares, neutrino signals will be correlated with the prompt emission and the early afterglow phase, respectively. But we cannot expect such correlations for most LL GRBs. Note that the contribution to the very high energy background from flares and LL GRBs could dominate that from HL GRBs due to the lower magnetic field strength.

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