

The High-Energy Neutrino Background from Gamma-Ray Bursts

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Abstract. High-energy neutrinos from gamma-ray bursts (GRBs) have been expected in various scenarios. Many predictions for the prompt emission and afterglow emission were done in the pre-*Swift* era. In this paper, we see predictions of the high-energy neutrino emission in the *Swift* era. Recently, *Swift* has shown several novel phenomena such as flares, which allows new possibilities for the high-energy neutrino emission from GRBs. High-energy neutrino signals may be detected by future-coming large neutrino detectors such as IceCube and KM3Net. If detected, they are useful for revealing the nature of GRBs and connection between ultra-high-energy cosmic rays (UHECRs) and GRBs.

1. Introduction

Gamma-ray bursts (GRBs) are the most energetic phenomena in the universe. Their emission is usually explained by dissipation of kinetic energy of relativistic shells. In both of the internal shock model for the prompt emission and external shock model for the afterglow (AG), accelerated electrons in the (mildly) relativistic shocks are considered to radiate high-energy gamma rays. If relativistic shells contain baryons, not only electrons but also protons (and possibly heavy nuclei) will be accelerated in the both models. The cosmic rays accelerated up to very high energies exceed the photomeson production threshold, and produce pions and kaons via the photomeson production. Pions and kaons will decay to neutrinos as they cool down due to various cooling processes. We take into account these cooling processes in order to calculate neutrino spectra in detail. We also use Geant4 combined with experimental data to treat the photomeson production. The method is described in Murase [1]. Expected muon events from one burst are too few to be detected. Therefore, we will need many GRB events as the neutrino background, which can be calculated by assuming that the GRB rate traces the star formation rate for the given local GRB rate. By observing neutrinos simultaneously with gamma rays, various models of the neutrino emission from GRBs will be tested by future-coming neutrino observations.

2. The Expected High-Energy Neutrino Background

Waxman & Bahcall [2] predicted neutrino bursts under the internal shock model, assuming that ultra-high-energy cosmic rays (UHECRs) come from GRBs. Since the origin of UHECRs (above the ankle below the GZK cutoff) is still unknown, observations of neutrinos will be important in the sense that they enable us to test the GRB-UHECR hypothesis. Although many authors studied the neutrino emission under this model, most of the calculations were

based on the Δ -resonance approximation. We studied the neutrino emission in detail without this approximation, by exploiting the numerical method [1, 3]. We also introduced the nonthermal baryon loading factor $\xi_{\text{acc}} \equiv U_p/U_\gamma$. This is because the recently estimated local GRB rate requires the large nonthermal baryon loading factor for GRBs to explain observed UHECRs [3]. Even if GRBs are not main sources of UHECRs, high-energy neutrinos from GRBs may be detected by future-coming neutrino detectors such as IceCube. For example, $\xi_{\text{acc}} = 10$ leads to the detectable neutrino background flux, as long as collision radii are sufficiently small. Observations have been giving us useful insights into the amount of accelerated baryons [4, 5]. The high-energy neutrino emission is also expected in the afterglow phase. Waxman & Bahcall [6] predicted neutrino afterglows under the reverse shock model, while Dermer [7] did under the forward shock model. In the former model, strong infrared/optical flashes from short-lived reverse shocks are expected. However, recent observations have suggested the lack of such infrared/optical flashes. Several mechanisms for suppression of infrared/optical flashes are proposed. In terms of recent observational results, the high-energy neutrino emission from the reverse shock is discussed in detail by Murase [1]. Even if we can expect very-high-energy neutrinos in the afterglow phase, the expected background flux is usually low. Because cosmogenic neutrinos will mainly contribute to the very-high-energy neutrino background, the simultaneous observations with gamma rays are still required. In Fig.1, we show the pre-*Swift* era predictions of high-energy neutrinos.

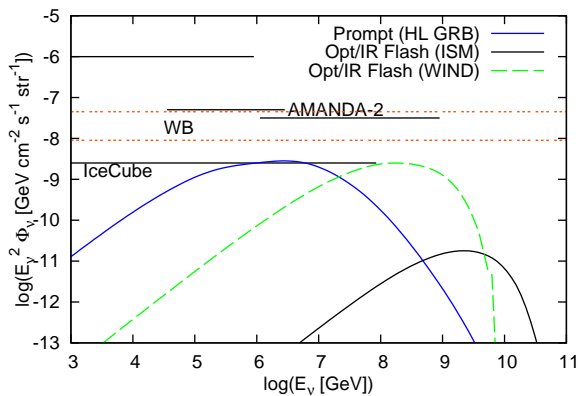


Figure 1. The predictions of the neutrino background in the pre-*Swift* era (where high-energy cosmic rays have the comparable energy to that of the prompt emission).

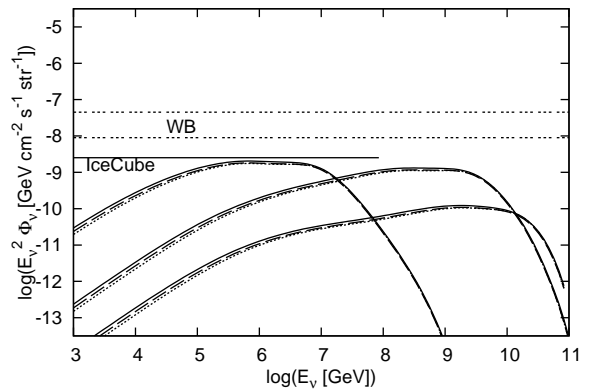


Figure 2. The optimistic predictions of the neutrino background from early afterglows in the *Swift* era. Curves are Late Prompt, AG (WIND) and AG (ISM) from top to bottom.

The *Swift* satellite was launched to solve several outstanding questions in the pre-*Swift* era. *Swift* has presented indeed very fruitful results until now. First, one of the novel results is the discovery of XRF 060218. Motivated by the discovery of this nearby event associated a supernova, which had the low luminosity (LL), some recent studies have suggested the existence of a different population from conventional high luminosity (HL) GRBs. If true, such a population may give the significant contribution to the observed ultra-high-energy cosmic ray flux and neutrino background flux. Murase et al. [8] first suggested that LL GRBs could be the origin of UHECRs. Even though it may be difficult for protons to be accelerated above $\sim 10^{20}$ eV, heavy nuclei could achieve such energies. The LLGRB-UHECR hypothesis can be tested by future-coming neutrino observations [8]. Second, *Swift* discovered the existence of the mysterious shallow decay emission in the early afterglow phase. Although various interpretations have been proposed, its origin is not conclusive yet. Implications to the neutrino background, based on the late prompt emission model and reverse shock model, are described in Murase [1] (see Fig.

2). Third, many *Swift* bursts have flares in the early afterglow phase. Flares are also energetic, and they imply the late activities of the central engine. They have lower peak energies and are expected to have lower Lorentz factors, which leads to the more efficient neutrino production. We showed the high-energy neutrino emission from flares can be important [9]. In Figs. 3 and 4, we compare results from several scenarios described above. HL GRBs have luminosity $L \sim 10^{51}$ ergs s^{-1} and duration $T \sim 10$ s. On the other hand, we assume $L \sim 10^{47}$ ergs s^{-1} and $T \sim 100 - 1000$ s for LL GRBs, and $L \sim 10^{48-49}$ ergs s^{-1} and $T \sim 100$ s for the late prompt emission such as flares (Late Prompt). The typical pion production efficiency is $\sim 0.1 - 1$ for HL GRBs, $\sim 0.01 - 0.1$ for LL GRBs, and ~ 1 for Late Prompt. In the case of Late Prompt, the 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 ~ 1 Gpc $^{-3}$ yr $^{-1}$ for HL GRBs. On the other hand, it might be higher $\sim 100 - 1000$ Gpc $^{-3}$ yr $^{-1}$ for LL GRBs. The high rate of LL GRBs could compensate their lower luminosity. In HL GRBs and Late Prompt, 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 because they are dim. Note that the contribution to the very high energy background from Late Prompt and LL GRBs could dominate that from HL GRBs due to their lower magnetic field strength. Although neutrino afterglows from the external shock can be important in the very high energies, fiducial parameter sets (as shown in Fig. 3) predict the insufficient background flux for detection by IceCube. High-energy neutrinos will be the very evidence of the acceleration of baryons in GRBs. The described models will be tested by IceCube and KM3Net. Once neutrino signals are detected, we can obtain useful information on physics of GRBs.

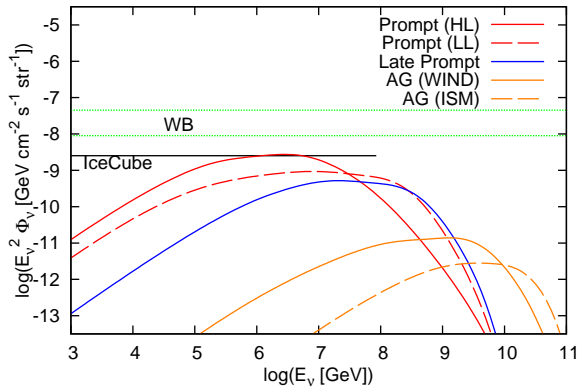


Figure 3. The fiducial predictions of the neutrino background from GRBs in the *Swift* era [1].

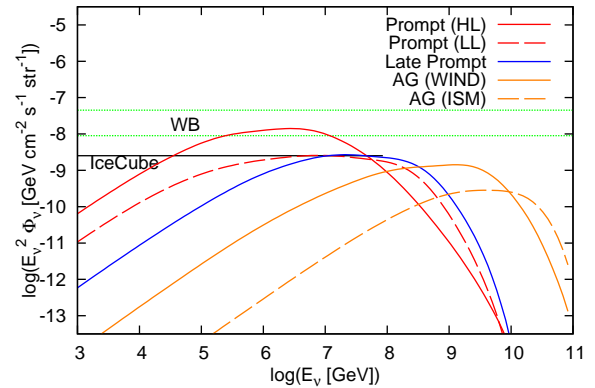


Figure 4. The optimistic predictions of the neutrino background from GRBs in the *Swift* era [1].

References

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