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Review Article

Gamma-Ray Bursts as Multienergy Neutrino Sources

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We review theoretical models for nonelectromagnetic emission, mainly neutrinos and cosmic rays, from gamma-ray bursts (GRBs). In various stages of the relativistic jet propagation, cosmic-ray ion acceleration and subsequent neutrino emission are expected. GRBs are popular candidate sources of the highest-energy cosmic rays, and their prompt phase has been most widely discussed. IceCube nondetection of PeV neutrinos coincident with GRBs has put interesting constraints on the standard theoretical prediction. The GRB-UHECR hypothesis can critically be tested by future observations. We also emphasize the importance of searches for GeV-TeV neutrinos, which are expected in the precursor/orphan or prompt phase, and lower-energy neutrinos would be more guaranteed and their detections even allow us to probe physics inside a progenitor star. Not only classical GRBs but also low-power GRBs and transrelativistic supernovae can be promising sources of TeV-PeV neutrinos, and we briefly discuss implications for the cumulative neutrino background discovered by IceCube.

1. Introduction

The most luminous explosions in the universe, gamma-ray bursts (GRBs), are characterized by nonthermal photon emission in both the prompt and afterglow phases. In such extreme phenomena, nonleptonic emissions, such as cosmic rays and neutrinos, have been suggested. Waxman [1] and Vietri [2] pointed out GRBs as possible sources of ultrahigh-energy cosmic rays (UHECRs). Then, associated neutrino emission was predicted [3, 4].

The GRB jets have several candidate sites where nonthermal particles are accelerated. First, the energetic jet launched from the central engine may generate a jet's head-cocoon structure (e.g., [5, 6]) in the progenitor star. Then, the shock wave reaches the stellar surface (shock breakout, e.g., [7–9], for the supernova case), and the jet propagates in the interstellar medium (ISM) or the wind material from the progenitor. In the classical internal shock model, the prompt gamma-ray emission is attributed to internal shocks due to the inhomogeneity in the jet or the temporal variability of the engine activity. At $\sim 10^{16}$–10^{17} cm from the central engine, the jet starts deceleration via interactions with the external medium. The external shock in this stage corresponds to the afterglow observed at optical, X, and radio wavelengths. In those various stages of the jet evolution, we can expect particle acceleration, which may result in not only photon emission but also neutrino and cosmic-ray emissions.

In this paper, we review studies on neutrino and cosmic-ray emission from GRBs. The multimessenger astronomy is an important subject, the present day is just at the dawn of neutrino astrophysics, since IceCube recently detected astrophysical neutrinos [10–13]. The detected PeV neutrino flux is compatible with various upper bounds based on the UHECR production rate [14–16], which may suggest some connection between UHECRs and PeV neutrinos. In the next decade, the connection between neutrinos and high-energy celestial objects may be revealed by not only IceCube but also other neutrino detectors [17–21].

GRBs will be detected with also gravitational wave (GW) detectors [22] such as aLIGO [23], aVirgo [24], and KAGRA [25]. The promising candidate of short GRB sources especially is a binary neutron star merger, which is the primary target for GW detectors. The recent claim of detection of a "kilonova," infrared transient about ~10 days after the burst, from short GRB 130603B [26] is encouragingly consistent with the binary merger models, in which r-process nuclei produced in the neutron rich ejecta provide the infrared energy via their radioactive decays (e.g., [27, 28] and the references therein). Therefore, GW observations of GRBs will be one of the hottest research areas in the next decade. Taking into account qualitative difference between GW and neutrinos, we omit this topic in this paper. However, we should notice the importance of the future correlation study between GW and neutrino detectors (e.g., [29–33]).

2. GeV-TeV Neutrinos in the Precursor/Orphan Stage

In the most widely accepted scenario for long GRBs, a relativistic jet is launched from a black hole-accretion disk system in a core collapse of a massive star. Alternatively, the central engine may be a fast-rotating, highly magnetized neutron star. The classical fireball scenario [34] supposes that a radiation-dominated electron-positron pair plasma is formed just above the accretion disk. The accretion disk may emit copious thermal MeV neutrinos, which may generate the fireball via neutrino pair annihilation [35–37]. However, the contribution of the GRB thermal neutrinos would be negligible compared to the diffuse supernova neutrino background [38]. Here, we discuss high-energy neutrinos produced in the early stage of the fireball.

The bulk Lorentz factor of the fireball evolves with radius R as $\Gamma \sim R/R_0$, where R_0 is the initial size of the fireball. The acceleration saturates at $R \sim \eta R_0$, where $\eta \equiv (L_{\rm jet}/\dot{M}c^2)$. At the base of the fireball, a significant fraction of baryons may be in the form of neutrons. Initially p and n components are tightly coupled via nuclear elastic scattering with the cross-section of $\langle \sigma_{\rm el} v_{\rm rel} \rangle \sim \sigma_{\rm pp} c$, where the cross-section for pion production via pp-collision is $\sigma_{\rm pp} \sim 3 \times 10^{-26}\,{\rm cm}^2$. When the scattering timescale $(n'_p \langle \sigma_{\rm el} v_{\rm rel} \rangle)^{-1}$ becomes longer than the dynamical timescale $R/(c\Gamma)$, p and n components decouple. Defining the density ratio $f_n \equiv n'_n/n'_p$, the proton density in the comoving frame can be written as

$$n'_p = \frac{1}{1+f_n} \frac{\dot{M}}{4\pi R^2 m_p c\Gamma}. \quad (1)$$

If the decouple occurs during the acceleration period, only the p component can be accelerated by the radiation pressure. Then, the relative velocity between p and n flows can be high enough to produce pions via np collision. Then, we can expect neutrino emissions at an energy of a few GeV from pion and muon decays [39, 40]. If the decouple occurs later, internal shocks should also play a role in dissipation. If we adopt the Poynting flux dissipation model as an alternative acceleration mechanism, the jet may initially evolve as $\Gamma \sim (R/R_0)^{1/3}$ [41], depending on the dissipation mechanism. Koers and Giannios [42] and Gao and Mészáros [43] calculated the neutrino flux for such models.

This compound-flow model has been considered in the context of the photospheric scenario for prompt emission, in which the origin of gamma-ray photons is mainly thermal rather than synchrotron. The injection of secondary electron-positron pairs via inelastic np collisions leads to a nonthermal component in the photon spectrum [44]. Such models inevitably predict quasithermal neutrino emission in the 10–100 GeV range [45–47]. However, detecting neutrinos from a single GRB is challenging. Murase et al. [45] showed that ~10 yr stacking analyses will be needed to find quasithermal neutrino signatures (see Figure 1).

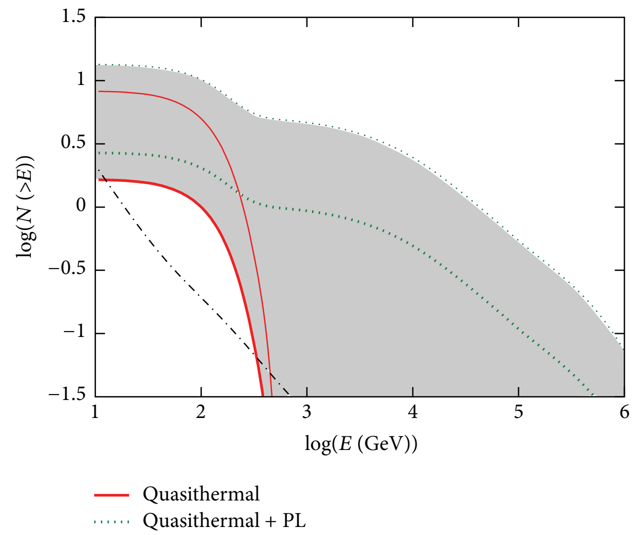

Figure 1: The expected number of subphotospheric $\nu_\mu + \bar{\nu}_\mu$ for 3250 GRB stacking analyses with DeepCore + IceCube from Murase et al. [45].

The jet inside a progenitor star can be the site where precursor and orphan neutrinos are produced [48–51]. A significant fraction of the jets originated from core collapse of massive stars may fail to break through the stellar envelope. The shock-accelerated protons can produce pions via interactions with thermal photons and thermal nucleons. If cosmic-ray acceleration occurs in the high density plasma, cooling effects of pions can strongly limit neutrino energies, and contributions from kaons can be dominant at higher energies [52–54]. Neutrinos from choked jets can also be expected for massive progenitors in the first generation of stars (Pop. III stars [55]).

However, particle acceleration postulated in choked jets and subphotospheric GRB emission models is inefficient in high-power jets [51]. The high radiation pressure inside the progenitors deforms the shock structure [56], where the shock transition layer becomes thicker than the collisionless mean-free path of particles, so that particles cannot be efficiently accelerated to very high energies. Murase and Ioka [51] derives radiation constraints on high-energy neutrino production, taking into account the fact that the jet is collimated and becomes cylindrical rather than conical. Although high-power GRB jets cannot be good neutrino emitters, interestingly, it is shown that low-power GRB jets are more promising sources of TeV neutrinos. Low-power jets are more difficult to penetrate the star, so that “choked jets” or “failed GRBs” may be better neutrino sources. If the fraction of the choked GRBs is high enough, this greatly enhances the neutrino background flux compared to the estimate according to only the observed GRB rate [51].

Then, can we still expect nonthermal neutrinos from high-power GRBs? An interesting idea to overcome this difficulty is to invoke the neutron-proton-converter (NPC) acceleration mechanism [57, 58], and Murase et al. [45] pointed out that this mechanism naturally occurs in GRB jets as long as neutrons are loaded. When compound flows cause internal shocks, neutrons from the upstream can easily cross the shock transition layer and may be converted again into protons in the downstream. Then, such protons are easily isotropized by magnetic fields, and some of them can go back to the upstream as neutrons. Kashiyama et al. [58] first performed numerical simulations and showed that a good fraction of the incoming neutron energy is converted into high-energy nucleons. Since the neutrino-nucleon cross-section increases as energy, the NPC acceleration mechanism enhances the detectability of neutrinos.

Detections of high-energy neutrinos produced in jets inside a star will bring to us precious information about the progenitor stars from the energy-dependent onset time of the neutrinos and cutoff energy in the neutrino spectrum [59]. One would be able to study neutrino oscillation including matter effects [60, 61], and flavor measurements could allow us to probe magnetic fields [62] or other new physics effects such as neutrino decay or quantum decoherence [63].

3. PeV Neutrinos and UHECRs in the Prompt Emission Stage

The internal shock in the prompt emission stage is one of the candidates of UHECR acceleration site. Using the conventional energy fraction parameters ϵ_e and ϵ_B, the magnetic field in the jet frame is written as

$$B' = \sqrt{\frac{2\epsilon_B L_\gamma}{\epsilon_e c R^2 \Gamma^2}} \sim 10^5 \left(\frac{\epsilon_e}{0.5}\right)^{-1/2} \left(\frac{\epsilon_B}{0.1}\right)^{1/2} \left(\frac{\Gamma}{300}\right)^{-1} \left(\frac{R}{10^{13}\,\text{cm}}\right)^{-1} \cdot \left(\frac{L_\gamma}{10^{52}\,\text{erg s}^{-1}}\right)^{1/2} \text{G}. \quad (2)$$

Although synchrotron cooling often limits the maximum energy of accelerated protons, if not, equating the dynamical timescale and acceleration timescale $\xi\varepsilon'_p/ceB'$ leads to

$$\varepsilon_{p,\max} \sim 4\times 10^{20}\xi^{-1} \left(\frac{\epsilon_e}{0.5}\right)^{-1/2} \left(\frac{\epsilon_B}{0.1}\right)^{1/2} \left(\frac{\Gamma}{300}\right)^{-1} \cdot \left(\frac{L_\gamma}{10^{52}\,\text{erg s}^{-1}}\right)^{1/2} \text{eV}, \quad (3)$$

where $\xi > 1$ is the effective Bohm factor. According to the local GRB rate of 0.1–1 $\text{Gpc}^{-3}\,\text{yr}^{-1}$ (e.g., [64]), the required energy of accelerated protons to explain local UHECR flux (integrated from the minimum proton energy to the maximum proton energy) is 10–100 times the gamma-ray energy released in the prompt phase (e.g., [65]). Although the GRB rate in our Galaxy may be very low, a possible past GRB could contribute to the observed flux and composition of cosmic rays [66, 67]. However, the required baryon loading factor has to be quite large.

If cosmological GRBs are sources of UHECRs, the arrival time is energy-dependent owing to intergalactic and galactic magnetic fields, so that individual sources could show a narrow spectral feature, depending on the apparent source number density [68–70]. Although a point source or striking anisotropy in the arrival directions of UHECRs has not been found yet [71], the UHECR constraints are still consistent with the GRB-UHECR scenario [70, 72].

Results of the Pierre Auger Collaboration claimed on depths of shower maximum for UHECRs suggest an increasing fraction of heavy nuclei [73, 74], while the data of the Telescope Array Team can still be interpreted as a proton dominated composition [75]. If the GRB jet is magnetically dominated, heavy nuclei may be synthesized because of its low entropy [76]. The survival of UHE nuclei in emission regions has been shown to be possible [65, 77, 78].

The timescale of photomeson production is calculated by

$$t'^{-1}_{p\gamma} = \frac{c}{2}\int d\varepsilon' \int_{-1}^{1} d\mu' \left(1-\mu'\right) n'_\gamma\left(\varepsilon'\right)\sigma_{p\gamma}K_{p\gamma}, \quad (4)$$

where μ is the cosine of the photon incident angle and $K_{p\gamma}$ is the proton inelasticity. If we adopt the rectangular approximation for pion production around the Δ-resonance (however see [79] for importance of multipion production), $\sigma_{p\gamma} \sim 5\times10^{-28}\,\text{cm}^2$ for 200 MeV $< \varepsilon'' <$ 400 MeV, where ε'' is the photon energy in the proton rest frame. the photomeson production efficiency $f_{p\gamma} \equiv t'_{\text{dyn}}/t'_{p\gamma}$ is estimated to be

$$f_{p\gamma} \simeq \frac{2K_\Delta\sigma_\Delta}{1+\alpha}\frac{\Delta\bar{\varepsilon}_\Delta}{\bar{\varepsilon}_\Delta}\frac{L^b_\gamma}{4\pi R\Gamma^2 c\varepsilon^b_\gamma}\left(\frac{\varepsilon_p}{\varepsilon^b_p}\right)^{\beta-1}, \quad (5)$$

where $t'_{\text{dyn}} \approx r/\Gamma_j c$ is the dynamical time, $K_\Delta \sim 0.2$, $\bar{\varepsilon}_\Delta \sim 0.3$ GeV, $\Delta\bar{\varepsilon}_\Delta \sim 0.2$ GeV, L^b_γ is the luminosity at ε^b_γ, β is the photon index, R is the emission radius, and Γ is the bulk Lorentz factor of jets. The typical neutrino energy is given by

$$\varepsilon^b_\nu \sim 0.02\Gamma_j^2 m_p c^2 \bar{\varepsilon}_\Delta \left[\varepsilon^b_\gamma\right]^{-1}. \quad (6)$$

For a low-energy portion ($\varepsilon_p < \varepsilon^b_p$), the photomeson production efficiency decreases as $t'^{-1}_{p\gamma} \propto \varepsilon'^{-(1+\beta)}_p$. For a high-energy portion, if $\beta \sim 1$, the timescale does not depend on proton energy.

The cumulative neutrino background intensity is obtained by integrating the comoving GRB rate, $R_{\text{GRB}}(z)$, into (e.g., [80])

$$\Phi_\nu\left(E_\nu\right) = \frac{c}{4\pi}\int_0^{z_{\max}} dz\,(1+z)\,R_{\text{GRB}}(z)\,N_\nu\left((1+z)\,E_\nu\right)\left|\frac{dt}{dz}\right|, \quad (7)$$

where

$$\left|\frac{dt}{dz}\right| = \frac{1}{(1+z)\,H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}, \quad (8)$$

and $N_\nu(\varepsilon_\nu)$ (neutrinos GeV^{-1}) is the average neutrino spectrum per burst.

Several authors have estimated the cumulative neutrino flux from GRBs [79, 81–87]. The IceCube Collaboration has put interesting constraints on theoretical predictions [88]. However, their theoretical model used for interpretations has several caveats that do not exist in earlier theoretical papers (e.g., [79, 86]). The predicted flux based on the original paper [4] is actually lower than that shown by Abbasi et al. [88]. Note that this difference does not arise from astrophysical uncertainty, so it should be properly taken into account [89–92]. As a result, only optimistic models such as the ones with large baryon loading factors have been ruled out by observations. Furthermore, nondetections of neutrinos from the nearby bright burst GRB 130427A [93] severely constrain the neutrino production efficiency [94].

In addition, several sophisticated developments have been made (e.g., [92, 95–100]). Asano and Mészáros [95] carried out time-dependent numerical simulations of hadronic cascades for a wide range of parameter sets, adopting the luminosity function in the work of Wanderman and Piran [64] and a log-normal distribution of variability timescale ($\delta t \sim R/\Gamma^2 c$). The diffuse neutrino intensity is well below the experimental limit by IceCube indicated by Abbasi et al. [88] (see Figure 2) and the latest result shown by Aartsen et al. [101], while UHECRs released by GRBs contribute to only above $10^{19.5}$ eV in this parameter set. The neutrino production efficiency should be suppressed by larger Γ or smaller f_p at least for bright GRBs. We should also notice that, depending on models, the neutrino intensity can be dominated by contributions from a few very bright GRBs, while most UHECRs are released from relatively less luminous GRBs. Bustamante et al. [97] performed simulations of internal shocks and first calculated neutrino, gamma-ray, and UHECR emission from multiple emission regions. They took into account all the detailed microphysics, including multipion production and neutrino mixing. They found that the neutrino emission is dominated by contributions around the photosphere, while UHECRs and gamma rays come from larger radii. Interestingly, it is shown that the minimum diffuse neutrino is pretty robust, which is $\sim 10^{-11}$ GeV cm^{-2} s^{-1} sr^{-1}. This implies that, in the internal shock model, the GRB-UHECR hypothesis can be more robustly tested by next-generation neutrino detectors.

Large nonthermal baryon loading factors have been challenged by gamma rays as well as neutrinos. If protons are efficiently accelerated in the prompt phase as assumed in the above models, electromagnetic cascades triggered by pionic gamma rays and/or proton synchrotron emission may generate GeV-TeV photons [102–108]. Actually *Fermi* has found extra spectral components in the GeV energy range, which are possible signatures of the hadronic cascades [109–112]. However, other interpretations exist, including leptonic models [113–117] and early afterglow models [118–120]. In hadronic models, the required energy of protons to agree with the observed GeV flux is 10–100 times the gamma-ray energy itself [121–123], which is consistent with the GRB-UHECR scenario. If all GRBs have such a large proton luminosity,

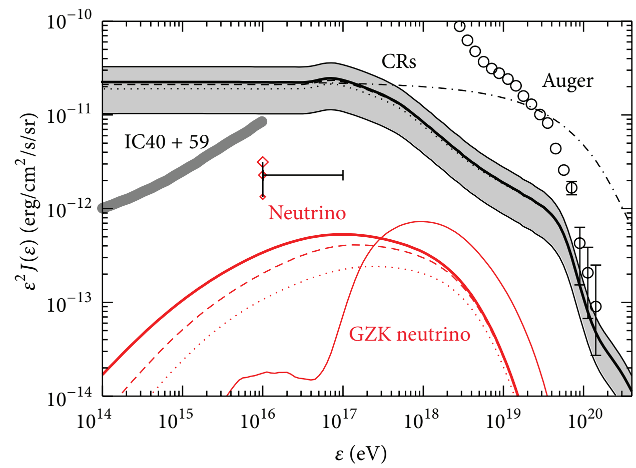

Figure 2: CR (black) and neutrino diffuse intensities in the model calculation in the work of Asano and Mészáros [95].

hadronic cascade emission should overwhelm the original leptonic component and distort the gamma-ray spectrum [124]. Most GRBs do not have strong evidence of the extra spectral components in the GeV range [125, 126], which implies that the neutrino production efficiency should not be high either [127].

There are alternative models of the prompt emission, in which hadronic cascades play a crucial role. The leptonic stochastic acceleration model (e.g., [128]) assumes a narrow energy distribution of electrons due to the balance of acceleration and cooling. While such an energy distribution can naturally reproduce the hard spectral index in the low-energy portion, a high-energy component is needed to be explained. Murase et al. [129] considered hadronic cascade processes as an efficient electron injection mechanism, and the synchrotron spectrum is shown to be very hard. The combination of thermal and synchrotron spectra can explain spectra of various GRBs. In the model of Petropoulou et al. [130], the secondary photons produced via hadronic cascades are scattered by secondary electron-positron pairs. This comptonization makes a band-like spectrum. Such models always accompany some neutrino emission, so that constraints by IceCube should be taken into account.

Although the internal shock model can reproduce the observed light curves and gamma-ray spectra qualitatively, there are several quantitative difficulties such as the emission efficiency, low-energy spectral index, and the narrow distribution of the spectral peak energies. An alternative model is the dissipative photosphere model [44, 47, 131–135], in which some fraction of the jet energy is dissipated into nonthermal electrons near the photosphere. In such models, the dissipation radius, where particle acceleration is expected, is much smaller than that in the internal shock model. As a result, the $p\gamma$ and pp efficiency becomes higher, while the cooling effect on pions/muons softens the neutrino spectrum [136, 137]. For Poynting flux dominated jets, they have a relatively larger photosphere and magnetic field. Such differences in model characteristics lead to some variety in neutrino spectra [65, 91, 138, 139].

TeV gamma-ray observations in the CTA era will also be relevant. If CTA detects a GRB, its huge photon statistics provide dedicated light curves. The correlation study between TeV and MeV light curves allows us to determine the emission mechanism of GeV-TeV photons. If the GeV-TeV photons are secondary photons from hadronic cascades, GeV-TeV light curves will correlate with MeV gamma-ray variability but would show broader pulse profiles reflecting the longer timescale of the photomeson production than the electron cooling [140].

The dominant contributions to the UHECRs and cumulative neutrino background may come from another population of GRBs, such as low-luminosity GRBs (LL GRBs [142–144]). Though the gamma-ray energy, $E_{iso} \lesssim 10^{51}$ erg, is much lower, its higher event rate makes LL GRBs candidate sources of UHECRs and neutrinos [65, 141, 145, 146]. As shown in Figure 3, one of the model spectra in the works of Murase et al. [141] and Murase and Ioka [51] is interestingly close to the observed diffuse PeV neutrino intensity ($\sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} [11]).

So far, all LL GRBs are accompanied by broad-line-type Ic supernovae with mildly relativistic ejecta [147, 148]. The UHECR production and neutrinos from such a mildly relativistic shock [65, 149] and shock breakout [58] have been discussed as well. The shock breakout model of Kashiyama et al. [58] predicts TeV gamma rays as well as high-energy neutrinos, so future TeV gamma-ray observations such as CTA will be important although the detection possibility with CTA may be $<\sim 0.1$ yr^{-1} [150, 151].

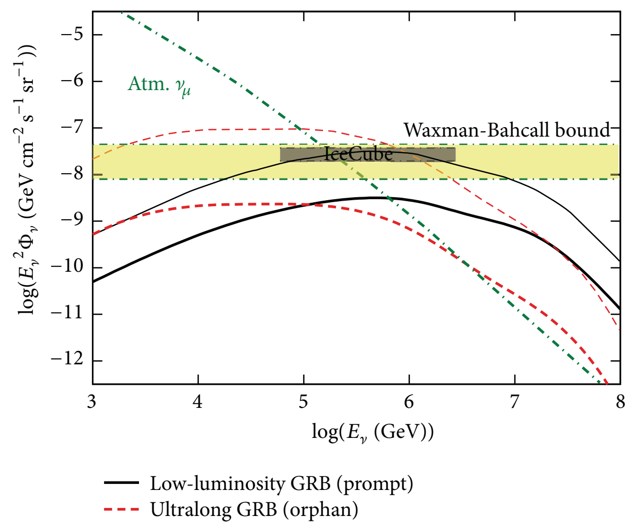

FIGURE 3: The neutrino background from LL GRBs in the works of Murase et al. [141] and Murase and Ioka [51]. The optimistic case agrees with the observed neutrino intensity reported by Aartsen et al. [11].

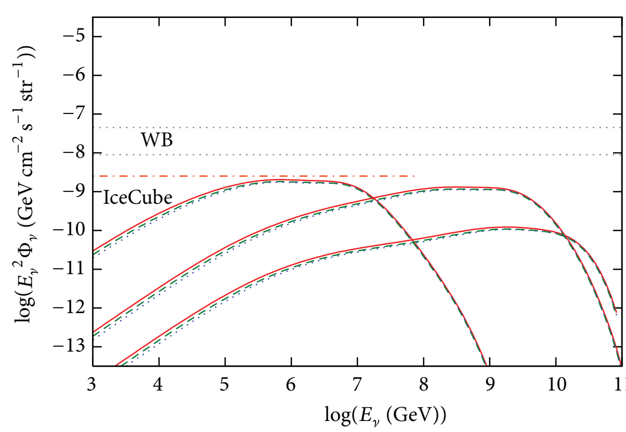

FIGURE 4: Afterglow neutrino fluxes shown by Murase [80].

4. EeV Neutrinos and UHECRs in the Afterglow Phase

Afterglow emission is caused by external shocks propagating the ISM or wind material. The external-forward shock has been considered as the site of UHECR and EeV neutrino production [152–154]. The long-lasting GeV emissions from several GRBs detected with *Fermi* can be interpreted as afterglows [118, 119], in which a significant fraction of the bulk energy is dissipated into electrons, unless only a fraction of the particles are injected into nonthermal acceleration. Note that the spectral peak is in the EeV range; this model cannot explain the cumulative neutrino background detected by IceCube. We should also notice the theoretical difficulty of particle acceleration to ultrahigh energies at the forward shock (see, e.g., [155] and the references therein). The relativistic shock often becomes superluminal, where particle acceleration is inefficient at very high energies. It has been thought that UHECRs cannot be generated by the shock acceleration mechanism at the forward shock, but other possibilities such as stochastic acceleration have also been invoked [152].

On the other hand, the external-reverse shock has been one of the good sites of UHECR production and EeV neutrino production, since it is mildly relativistic or nonrelativistic [156]. The low photon density in the afterglow phase typically implies a moderate efficiency of photomeson production. The afterglow picture is now rich in the *Swift* era, and many models have been proposed. UHECRs accelerated at the reverse shock can interact with photons produced by both forward and reverse shocks. Murase [80] investigated various possibilities and showed that it is possible to detect EeV neutrinos by next-generation neutrino detectors such as Askaryan Radio Array (see Figure 4).

In addition, afterglow emission may include components coming from internal dissipation. A famous example is X-ray flare emission. Although high-energy gamma-ray emission from flares is typically discussed in view of leptonic models [157], it is possible to expect hadronic emission as well [158]. Since the photomeson production efficiency is likely to be higher than that in the prompt phase, neutrinos coincident with flares and afterglow emission (caused by internal dissipation) can be as much important as prompt neutrino emission [80, 158].

5. Summary

The multimessenger era of GRBs is now coming. In particular, the IceCube Collaboration has discovered high-energy neutrinos, and neutrino astrophysics has now started. Although GRB neutrinos have not been found yet, detecting GRB neutrinos is still one of the appealing possibilities to identify neutrino sources. Even with nondetections, the latest constraints are important to test the connection between GRBs and UHECRs. Gamma-ray observations by *Fermi* have also provided complementary information, and CTA may enable us to detect TeV gamma rays from GRBs with high statistics.

CTA should also be powerful to study afterglow mechanisms. So far, there has been no indication of hadronic emission in the afterglow phase, but it is possible to expect associated UHECR and EeV neutrino emission. Searches for extremely high-energy neutrinos from afterglows will also be improved in the future; next-generation detectors such as Askaryan Radio Array may enable us to test the GRB-UHECR hypothesis even in afterglow models.

In addition, GeV-TeV neutrino detections are also promising, and analyses for such low-energy neutrinos from choked jets and GRBs before jet breakouts should be important to reveal the jet physics and relationship between GRBs and supernovae. In this case, gamma rays cannot escape directly, so neutrinos provide us with a unique opportunity.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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