

Review Article

Gamma-Ray Bursts as Multienergy Neutrino Sources

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Received 23 December 2014; Accepted 23 March 2015

Academic Editor: Valery Nakariakov

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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 $\eta \equiv (L_{\text{jet}}/\dot{M}c^2)$. 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 $\langle\sigma_{\text{el}}v_{\text{rel}}\rangle \sim \sigma_{\text{pp}}c$, where the cross-section for pion production via pp -collision is $\sigma_{\text{pp}} \sim 3 \times 10^{-26} \text{ cm}^2$. When the scattering timescale $(n'_p \langle\sigma_{\text{el}}v_{\text{rel}}\rangle)^{-1}$ 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

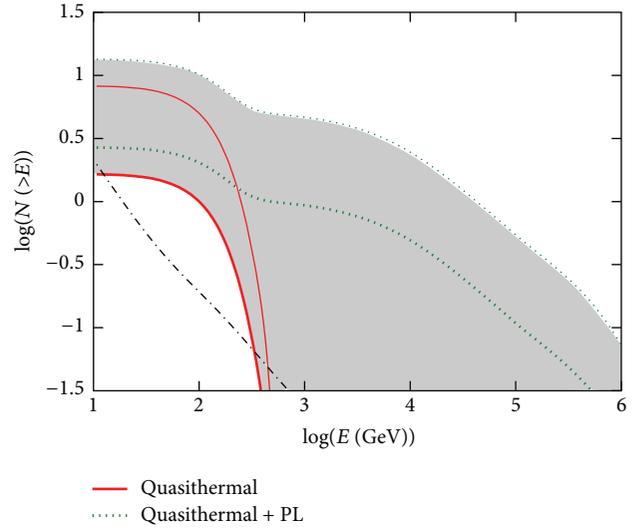


FIGURE 1: The expected number of subphotospheric $\nu_\mu + \bar{\nu}_\mu$ for 3250 GRB stacking analyses with DeepCore + IceCube from Murase et al. [45].

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).

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 $\xi \epsilon_p' / c e B'$ leads to

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

where $\xi > 1$ is the effective Bohm factor. According to the local GRB rate of $0.1\text{--}1 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (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

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

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), $\sigma_{p\gamma} \sim 5 \times 10^{-28} \text{ cm}^2$ for $200 \text{ MeV} < \epsilon'' < 400 \text{ MeV}$, 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

$$f_{p\gamma} \approx \frac{2K_\Delta \sigma_\Delta \Delta \bar{\epsilon}_\Delta}{1 + \alpha} \frac{L_\gamma^b}{\bar{\epsilon}_\Delta 4\pi R \Gamma^2 c \epsilon_\gamma^b} \left(\frac{\epsilon_p}{\epsilon_\gamma^b}\right)^{\beta-1}, \quad (5)$$

where $t'_{\text{dyn}} \approx r/\Gamma_j c$ is the dynamical time, $K_\Delta \sim 0.2$, $\bar{\epsilon}_\Delta \sim 0.3 \text{ GeV}$, $\Delta \bar{\epsilon}_\Delta \sim 0.2 \text{ GeV}$, L_γ^b is the luminosity at ϵ_γ^b , 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

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

For a low-energy portion ($\epsilon_p < \epsilon_p^b$), the photomeson production efficiency decreases as $t'_{p\gamma}{}^{-1} \propto \epsilon_p^{-(1+\beta)}$. 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])

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

where

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

and $N_\nu(\epsilon_\nu)$ (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 $\sim 10^{-11} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. 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,

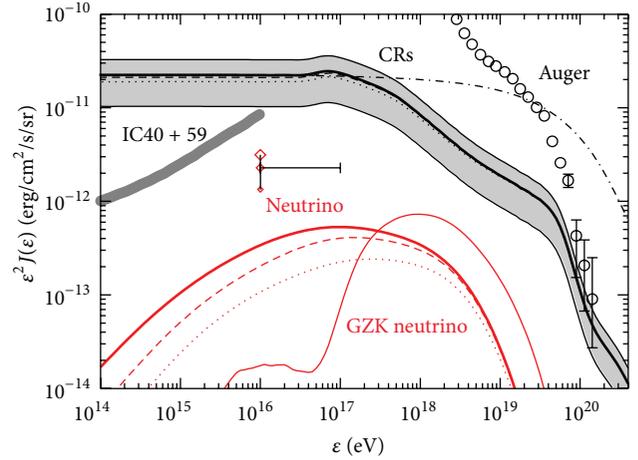


FIGURE 2: CR (black) and neutrino diffuse intensities in the model calculation in the work of Asano and Mészáros [95].

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, $E_{\text{iso}} \lesssim 10^{51}$ 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].

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

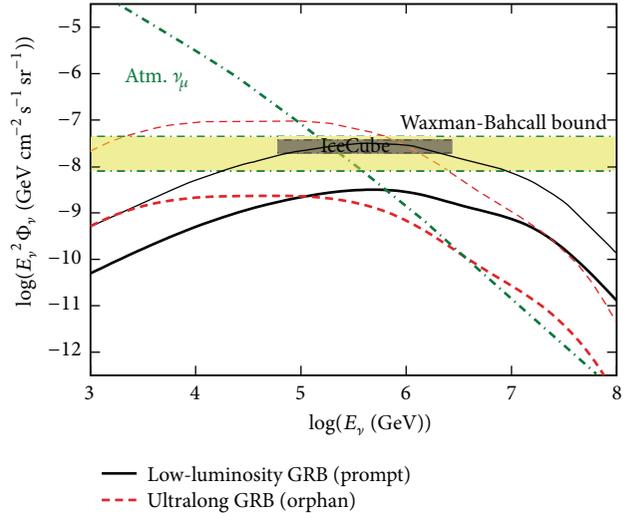


FIGURE 3: The neutrino background from LL GRBs in the works of Murase et al. [141] and Murase and Ioka [51]. The optimistic case agrees with the observed neutrino intensity reported by Aartsen et al. [11].

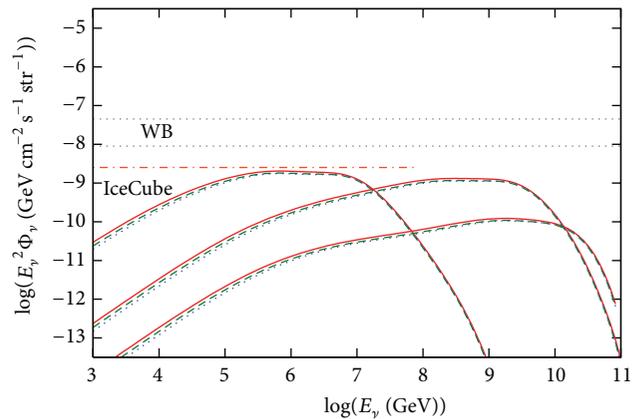


FIGURE 4: Afterglow neutrino fluxes shown by Murase [80].

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.

Acknowledgment

This paper is partially supported by Grants-in-Aid for Scientific Research no. 25400227 from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

References

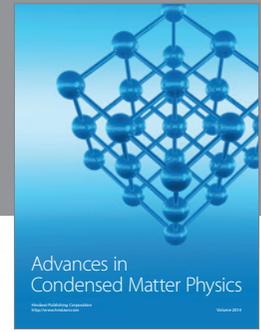
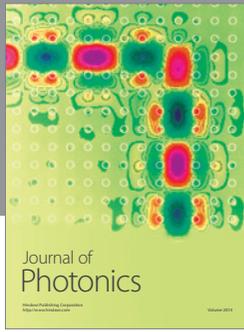
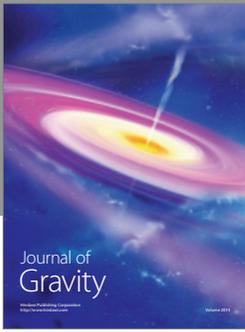
- [1] E. Waxman, "Cosmological Gamma-Ray Bursts and the Highest Energy Cosmic Rays," *Physical Review Letters*, vol. 75, no. 3, pp. 386–389, 1995.
- [2] M. Vietri, "The acceleration of ultra-high-energy cosmic rays in gamma-ray bursts," *Astrophysical Journal Letters*, vol. 453, no. 2, pp. 883–889, 1995.
- [3] B. Paczynski and G. Xu, "Neutrino bursts from gamma-ray bursts," *The Astrophysical Journal*, vol. 427, no. 2, pp. 708–713, 1994.
- [4] E. Waxman and J. Bahcall, "High energy neutrinos from cosmological gamma-ray burst fireballs," *Physical Review Letters*, vol. 78, no. 12, pp. 2292–2295, 1997.
- [5] C. D. Matzner, "Supernova hosts for gamma-ray burst jets: dynamical constraints," *Monthly Notices of the Royal Astronomical Society*, vol. 345, no. 2, pp. 575–589, 2003.
- [6] O. Bromberg, E. Nakar, T. Piran, and R. Sari, "The propagation of relativistic jets in external media," *Astrophysical Journal*, vol. 740, no. 2, article 100, 2011.
- [7] S. A. Colgate, "The prompt effects of supernovae," *Annals of the New York Academy of Sciences*, vol. 262, pp. 34–46, 1975.
- [8] R. I. Klein and R. A. Chevalier, "X-ray bursts from type II supernovae," *The Astrophysical Journal*, vol. 223, pp. L109–L112, 1978.
- [9] A. M. Soderberg, E. Berger, K. L. Page et al., "An extremely luminous X-ray outburst at the birth of a supernova," *Nature*, vol. 453, no. 7194, pp. 469–474, 2008.
- [10] M. G. Aartsen, R. Abbasi, Y. Abdou et al., "First observation of PeV-energy neutrinos with IceCube," *Physical Review Letters*, vol. 111, Article ID 021103, 2013.
- [11] M. G. Aartsen, R. Abbasi, and Y. Abdou, "Evidence for high-energy extraterrestrial neutrinos at the IceCube detector," *Science*, vol. 342, no. 6161, Article ID 1242856, 2013.
- [12] M. G. Aartsen, M. Ackermann, J. Adams et al., "Observation of high-energy astrophysical neutrinos in three years of icecube data," *Physical Review Letters*, vol. 113, Article ID 101101, 2014.
- [13] M. Aartsen, R. Abbasi, M. Ackermann et al., "Search for a diffuse flux of astrophysical muon neutrinos with the IceCube 59-string configuration," *Physical Review D*, vol. 89, no. 6, Article ID 062007, 19 pages, 2007.
- [14] E. Waxman and J. Bahcall, "High energy neutrinos from astrophysical sources: an upper bound," *Physical Review D*, vol. 59, no. 2, Article ID 023002, 8 pages, 1998.
- [15] K. Mannheim, R. J. Protheroe, and J. P. Rachen, "Cosmic ray bound for models of extragalactic neutrino production," *Physical Review D*, vol. 63, no. 2, Article ID 023003, 2001.
- [16] K. Murase and J. F. Beacom, "Neutrino background flux from sources of ultrahigh-energy cosmic-ray nuclei," *Physical Review D*, vol. 81, Article ID 123001, 2010.
- [17] U. F. Katz, "KM3NeT: towards a km3 Mediterranean neutrino telescope," *Nuclear Instruments and Methods in Physics Research A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 567, no. 2, pp. 457–461, 2006.
- [18] P. Allison, J. Auffenberg, R. Bard et al., "Design and initial performance of the Askaryan radio array prototype EeV neutrino detector at the south pole," *Astroparticle Physics*, vol. 35, no. 7, pp. 457–477, 2012.
- [19] S. W. Barwick, "ARIANNA: a new concept for UHE neutrino detection," *Journal of Physics: Conference Series*, vol. 60, pp. 276–283, 2007.
- [20] P. W. Gorham, P. Allison, S. W. Barwick et al., "The antarctic impulsive transient antenna ultra-high energy neutrino detector: design, performance, and sensitivity for the 2006–2007 balloon flight," *Astroparticle Physics*, vol. 32, no. 1, pp. 10–41, 2009.
- [21] P. W. Gorham, F. E. Baginski, P. Allison et al., "The ExaVolt antenna: a large-aperture, balloon-embedded antenna for ultra-high energy particle detection," *Astroparticle Physics*, vol. 35, no. 5, pp. 242–256, 2011.
- [22] I. Bartos, P. Brady, and S. Márka, "How gravitational-wave observations can shape the gamma-ray burst paradigm," *Classical and Quantum Gravity*, vol. 30, no. 12, Article ID 123001, 2013.
- [23] G. M. Harry, "Advanced LIGO: the next generation of gravitational wave detectors," *Classical and Quantum Gravity*, vol. 27, Article ID 084006, 2010.
- [24] F. Acernese, M. Agathos, K. Agatsuma et al., "Advanced virgo: a 2nd generation interferometric gravitational wave detector," *Classical and Quantum Gravity*, vol. 32, no. 2, Article ID 024001, 2014.

- [25] K. Somiya, “Detector configuration of KAGRA—the Japanese cryogenic gravitational-wave detector,” *Classical and Quantum Gravity*, vol. 29, no. 12, Article ID 124007, 2012.
- [26] N. R. Tanvir, A. J. Levan, A. S. Fruchter et al., “A ‘kilonova’ associated with the short-duration γ -ray burst GRB 130603B,” *Nature*, vol. 500, no. 7464, pp. 547–549, 2013.
- [27] L.-X. Li and B. Paczynski, “Transient events from neutron star mergers,” *The Astrophysical Journal*, vol. 507, no. 1, p. L59, 1998.
- [28] K. Hotokezaka, K. Kyutoku, M. Tanaka et al., “Progenitor models of the electromagnetic transient associated with the short gamma ray burst 130603B,” *The Astrophysical Journal*, vol. 778, no. 1, article L16, 2013.
- [29] V. van Elewyck, S. Ando, B. Baret et al., “Joint searches between gravitational-wave interferometers and high-energy neutrino telescopes: science reach and analysis strategies,” *International Journal of Modern Physics D*, vol. 18, no. 10, p. 1655, 2009.
- [30] I. Bartos, C. Finley, A. Corsi, and S. Márka, “Observational constraints on multimessenger sources of gravitational waves and high-energy neutrinos,” *Physical Review Letters*, vol. 107, no. 4, Article ID 251101, 2011.
- [31] B. Baret, I. Bartos, B. Bouhou et al., “Multimessenger science reach and analysis method for common sources of gravitational waves and high-energy neutrinos,” *Physical Review D*, vol. 85, Article ID 103004, 2012.
- [32] S. Ando, B. Baret, I. Bartos et al., “Colloquium: multimessenger astronomy with gravitational waves and high-energy neutrinos,” *Reviews of Modern Physics*, vol. 85, no. 4, pp. 1401–1420, 2013.
- [33] S. Adrián-Martínez, I. Al Samarai, A. Albert et al., “A first search for coincident gravitational waves and high energy neutrinos using LIGO, virgo and ANTARES data from 2007,” <http://arxiv.org/abs/1205.3018>.
- [34] M. J. Rees and P. Mészáros, “Relativistic fireballs: energy conversion and time-scales,” *Monthly Notices of the Royal Astronomical Society*, vol. 258, article 41P, 1992.
- [35] D. Eichler, M. Livio, T. Piran, and D. N. Schramm, “Nucleosynthesis, neutrino bursts and γ -rays from coalescing neutron stars,” *Nature*, vol. 340, no. 6229, pp. 126–128, 1989.
- [36] K. Asano and T. Fukuyama, “Relativistic effects on neutrino pair annihilation above a Kerr black hole with the accretion disk,” *The Astrophysical Journal*, vol. 546, no. 2, pp. 1019–1026, 2001.
- [37] I. Zalama and A. M. Beloborodov, “Neutrino heating near hyper-accreting black holes,” *Monthly Notices of the Royal Astronomical Society*, vol. 410, no. 4, pp. 2302–2308, 2011.
- [38] J. F. Beacom, “The diffuse supernova neutrino background,” *Annual Review of Nuclear and Particle Science*, vol. 60, no. 1, pp. 439–462, 2010.
- [39] J. N. Bahcall and P. Mészáros, “5–10 GeV neutrinos from gamma-ray burst fireballs,” *Physical Review Letters*, vol. 85, no. 7, pp. 1362–1365, 2000.
- [40] M. J. Rees and P. Mészáros, “Dissipative photosphere models of gamma-ray bursts and X-ray flashes,” *The Astrophysical Journal*, vol. 628, no. 2, p. 847, 2005.
- [41] G. Drenkhahn, “Acceleration of GRB outflows by Poynting flux dissipation,” *Astronomy and Astrophysics*, vol. 387, no. 2, pp. 714–724, 2002.
- [42] H. B. J. Koers and D. Giannios, “Neutron-rich gamma-ray burst flows: dynamics and particle creation in neutron-proton collisions,” *Astronomy & Astrophysics*, vol. 471, no. 2, pp. 395–408, 2007.
- [43] S. Gao and P. Mészáros, “Multi-GeV neutrino emission from magnetized gamma-ray bursts,” *Physical Review D*, vol. 85, Article ID 103009, 2012.
- [44] A. M. Beloborodov, “Collisional mechanism for gamma-ray burst emission,” *Monthly Notices of the Royal Astronomical Society*, vol. 407, no. 2, pp. 1033–1047, 2010.
- [45] K. Murase, K. Kashiyama, and P. Mészáros, “Subphotospheric neutrinos from gamma-ray bursts: the role of neutrons,” *Physical Review Letters*, vol. 111, no. 13, Article ID 131102, 2013.
- [46] I. Bartos, A. M. Beloborodov, K. Hurley, and S. Márka, “Detection prospects for GeV neutrinos from collisionally heated gamma-ray bursts with IceCube/DeepCore,” *Physical Review Letters*, vol. 110, no. 24, 2013.
- [47] K. Asano and P. Mészáros, “Photon and neutrino spectra of time-dependent photospheric models of gamma-ray bursts,” *Journal of Cosmology and Astroparticle Physics*, vol. 2013, no. 9, article 008, 2013.
- [48] P. Mészáros and E. Waxman, “TeV neutrinos from successful and choked gamma-ray bursts,” *Physical Review Letters*, vol. 87, Article ID 171102, 2001.
- [49] S. Razzaque, P. Mészáros, and E. Waxman, “Neutrino tomography of gamma ray bursts and massive stellar collapses,” *Physical Review D*, vol. 68, Article ID 083001, 2003.
- [50] S. Razzaque, P. Mészáros, and E. Waxman, “TeV neutrinos from core collapse supernovae and hypernovae,” *Physical Review Letters*, vol. 93, no. 18, Article ID 181101, 4 pages, 2004.
- [51] K. Murase and K. Ioka, “TeV-PeV neutrinos from low-power gamma-ray burst jets inside stars,” *Physical Review Letters*, vol. 111, Article ID 121102, 2013.
- [52] S. Ando and J. F. Beacom, “Revealing the supernova-gamma-ray burst connection with TeV neutrinos,” *Physical Review Letters*, vol. 95, Article ID 061103, 2005.
- [53] S. Horiuchi and S. Ando, “High-energy neutrinos from reverse shocks in choked and successful relativistic jets,” *Physical Review D*, vol. 77, Article ID 063007, 2008.
- [54] R. Enberg, M. H. Reno, and I. Sarcevic, “High energy neutrinos from charm in astrophysical sources,” *Physical Review D*, vol. 79, no. 5, Article ID 053006, 6 pages, 2009.
- [55] F. Iocco, K. Murase, S. Nagataki, and P. D. Serpico, “High-energy neutrino signals from the epoch of reionization,” *The Astrophysical Journal*, vol. 675, no. 2, pp. 937–945, 2008.
- [56] A. Levinson and O. Bromberg, “Relativistic photon mediated shocks,” *Physical Review Letters*, vol. 100, Article ID 131101, 2008.
- [57] E. V. Derishev, F. A. Aharonian, and V. V. Kocharovskiy, “Particle acceleration through multiple conversions from a charged into a neutral state and back,” *Physical Review D*, vol. 68, no. 4, Article ID 043003, 2003.
- [58] K. Kashiyama, K. Murase, and P. Mészáros, “Neutron-proton-conversion acceleration at subphotospheres of relativistic outflows,” *Physical Review Letters*, vol. 111, Article ID 131103, 2011.
- [59] I. Bartos, B. Dasgupta, and S. Márka, “Probing the structure of jet-driven core-collapse supernova and long gamma-ray burst progenitors with high-energy neutrinos,” *Physical Review D*, vol. 86, Article ID 083007, 2012.
- [60] O. Mena, I. Mocioiu, and S. Razzaque, “Oscillation effects on high-energy neutrino fluxes from astrophysical hidden sources,” *Physical Review D*, vol. 75, Article ID 063003, 2007.
- [61] S. Razzaque and A. Y. Smirnov, “Flavor conversion of cosmic neutrinos from hidden jets,” *Journal of High Energy Physics*, vol. 2010, no. 3, article 31, 2010.

- [62] Y. Farzan and A. Y. Smirnov, "Coherence and oscillations of cosmic neutrinos," *Nuclear Physics B*, vol. 805, no. 1-2, pp. 356–376, 2008.
- [63] P. Mehta and W. Winter, "Interplay of energy dependent astrophysical neutrino flavor ratios and new physics effects," *Journal of Cosmology and Astroparticle Physics*, vol. 2011, no. 3, article 41, 2011.
- [64] D. Wanderman and T. Piran, "The luminosity function and the rate of Swift's gamma-ray bursts," *Monthly Notices of the Royal Astronomical Society*, vol. 406, no. 3, pp. 1944–1958, 2010.
- [65] K. Murase, K. Ioka, S. Nagataki, and T. Nakamura, "High-energy cosmic-ray nuclei from high- and low-luminosity gamma-ray bursts and implications for multimessenger astronomy," *Physical Review D*, vol. 78, Article ID 023005, 2008.
- [66] S. D. Wick, C. D. Dermer, and A. Atoyan, "High-energy cosmic rays from gamma-ray bursts," *Astroparticle Physics*, vol. 21, no. 2, pp. 125–148, 2004.
- [67] A. Calvez, A. Kusenko, and S. Nagataki, "Role of galactic sources and magnetic fields in forming the observed energy-dependent composition of ultrahigh-energy cosmic rays," *Physical Review Letters*, vol. 105, Article ID 091101, 2010.
- [68] J. Miralda-Escudé and E. Waxman, "Signatures of the origin of high-energy cosmic rays in cosmological gamma-ray bursts," *Astrophysical Journal Letters*, vol. 462, no. 2, pp. L59–L62, 1996.
- [69] E. Waxman and J. Miralda-Escudé, "Images of bursting sources of high-energy cosmic rays: effects of magnetic fields," *Astrophysical Journal Letters*, vol. 472, no. 2, pp. L89–L92, 1996.
- [70] H. Takami and K. Murase, "The role of structured magnetic fields on constraining properties of transient sources of ultrahigh-energy cosmic rays," *The Astrophysical Journal*, vol. 748, no. 1, p. 9, 2012.
- [71] A. Aab, P. Abreu, M. Aglietta et al., "Searches for anisotropies in the arrival directions of the highest energy cosmic rays detected by the Pierre Auger observatory," <http://jp.arxiv.org/pdf/1411.6111v2>.
- [72] K. Murase and H. Takami, "Implications of ultra-high-energy cosmic rays for transient sources in the Auger era," *The Astrophysical Journal Letters*, vol. 690, no. 1, pp. L14–L17, 2009.
- [73] A. Aab, P. Abreu, M. Aglietta et al., "Depth of maximum of air-shower profiles at the Pierre Auger observatory. I. Measurements at energies above $10^{17.8}$ eV," *Physical Review D*, vol. 90, Article ID 122005, 2014.
- [74] A. Aab, P. Abreu, M. Aglietta et al., "Depth of maximum of air-shower profiles at the Pierre Auger observatory. I. Measurements at energies above $10^{17.8}$ eV," *Physical Review D*, vol. 90, no. 12, Article ID 122005, 25 pages, 2014.
- [75] R. U. Abbasi, M. Abe, T. Abu-Zayyad et al., "Study of ultra-high energy cosmic ray composition using telescope array's middle drum detector and surface array in hybrid mode," *Astroparticle Physics*, vol. 64, pp. 49–62, 2015.
- [76] B. D. Metzger, D. Giannios, and S. Horiuchi, "Heavy nuclei synthesized in gamma-ray burst outflows as the source of ultrahigh energy cosmic rays," *Monthly Notices of the Royal Astronomical Society*, vol. 415, no. 3, pp. 2495–2504, 2011.
- [77] X.-Y. Wang, S. Razzaque, and P. Mészáros, "On the origin and survival of ultra-high-energy cosmic-ray nuclei in gamma-ray bursts and hypernovae," *The Astrophysical Journal*, vol. 677, no. 1, pp. 432–440, 2008.
- [78] S. Horiuchi, K. Murase, K. Ioka, and P. Mészáros, "The survival of nuclei in jets associated with core-collapse supernovae and gamma-ray bursts," *The Astrophysical Journal*, vol. 753, no. 1, p. 69, 2012.
- [79] K. Murase and S. Nagataki, "High energy neutrino emission and neutrino background from gamma-ray bursts in the internal shock model," *Physical Review D*, vol. 73, no. 6, Article ID 063002, 14 pages, 2006.
- [80] K. Murase, "High energy neutrino early afterglows from gamma-ray bursts revisited," *Physical Review D*, vol. 76, Article ID 123001, 2007.
- [81] J. P. Rachen and P. Mészáros, "Photohadronic neutrinos from transients in astrophysical sources," *Physical Review D*, vol. 58, Article ID 123005, 1998.
- [82] C. D. Dermer and A. Atoyan, "High-energy neutrinos from gamma ray bursts," *Physical Review Letters*, vol. 91, Article ID 071102, 2011.
- [83] D. Guetta, D. Hooper, J. Alvarez-Muñiz, F. Halzen, and E. Reuveni, "Neutrinos from individual gamma-ray bursts in the BATSE catalog," *Astroparticle Physics*, vol. 20, no. 4, pp. 429–455, 2004.
- [84] K. Asano, "Cooling of accelerated nucleons and neutrino emission in gamma-ray bursts," *Astrophysical Journal Letters*, vol. 623, no. 2, pp. 967–972, 2005.
- [85] K. Asano and S. Nagataki, "Very high energy neutrinos originating from Kaons in gamma-ray bursts," *The Astrophysical Journal Letters*, vol. 640, no. 1, p. L9, 2006.
- [86] P. Baerwald, S. Hummer, and W. Winter, "Magnetic field and flavor effects on the gamma-ray burst neutrino flux," *Physical Review D*, vol. 83, Article ID 067303, 2011.
- [87] M. Ahlers, M. C. Gonzalez-Garcia, and F. Halzen, "GRBs on probation: testing the UHE CR paradigm with IceCube," *Astroparticle Physics*, vol. 35, no. 2, pp. 87–94, 2011.
- [88] R. Abbasi, Y. Abdou, T. Abu-Zayyad et al., "An absence of neutrinos associated with cosmic-ray acceleration in γ -ray bursts," *Nature*, vol. 484, pp. 351–354, 2012.
- [89] Z. Li, "Note on the normalization of predicted gamma-ray burst neutrino flux," *Physical Review D*, vol. 85, no. 2, Article ID 027301, 3 pages, 2012.
- [90] S. Hümmer, P. Baerwald, and W. Winter, "Neutrino emission from gamma-ray burst fireballs, revised," *Physical Review Letters*, vol. 108, no. 23, Article ID 231101, 5 pages, 2012.
- [91] H.-N. He, R.-Y. Liu, X.-Y. Wang, S. Nagataki, K. Murase, and Z.-G. Dai, "Icecube nondetection of gamma-ray bursts: constraints on the fireball properties," *Astrophysical Journal*, vol. 752, no. 1, article 29, 2012.
- [92] R.-Y. Liu and X.-Y. Wang, "Diffuse PeV neutrinos from gamma-ray bursts," *The Astrophysical Journal*, vol. 766, no. 2, article 73, 2013.
- [93] M. Ackermann, M. Ajello, K. Asano et al., "Fermi-LAT observations of the gamma-ray burst GRB 130427A," *Science*, vol. 343, no. 6166, pp. 42–47, 2013.
- [94] S. Gao, K. Kashiyama, and P. Mészáros, "On the neutrino non-detection of GRB 130427A," *Astrophysical Journal Letters*, vol. 772, no. 1, article L4, 2013.
- [95] K. Asano and P. Mészáros, "Neutrino and cosmic-ray release from gamma-ray bursts: time-dependent simulations," *The Astrophysical Journal*, vol. 785, no. 1, p. 54, 2014.
- [96] P. Baerwald, M. Bustamante, and W. Winter, "Are gamma-ray bursts the sources of ultra-high energy cosmic rays?" *Astroparticle Physics*, vol. 62, p. 66, 2015.
- [97] M. Bustamante, P. Baerwald, K. Murase, and W. Winter, "Neutrino and cosmic-ray emission from multiple internal shocks in gamma-ray bursts," <http://arxiv.org/abs/1409.2874>.

- [98] W. Winter, J. B. Tjus, and S. R. Klein, "Impact of secondary acceleration on the neutrino spectra in gamma-ray bursts," *Astronomy & Astrophysics*, vol. 569, article A58, II pages, 2014.
- [99] M. Petropoulou, D. Giannios, and S. Dimitrakoudis, "Implications of a PeV neutrino spectral cut-off in gamma-ray burst models," *Monthly Notices of the Royal Astronomical Society*, vol. 445, no. 1, pp. 570–580, 2014.
- [100] N. Globus, D. Allard, R. Mochkovitch, and E. Parizot, "UHECR acceleration at GRB internal shocks," <http://arxiv.org/abs/1409.1271>.
- [101] M. G. Aartsen, M. Ackermann, J. Adams et al., "Search for prompt neutrino emission from gamma-ray bursts with Ice-Cube," <http://arxiv.org/abs/1412.6510>.
- [102] M. Vietri, "GeV photons from ultrahigh energy cosmic rays accelerated in gamma ray bursts," *Physical Review Letters*, vol. 78, no. 23, pp. 4328–4331, 1997.
- [103] M. Bottcher and C. D. Dermer, "High-energy gamma rays from ultra-high-energy cosmic-ray protons in gamma-ray bursts," *The Astrophysical Journal*, vol. 499, no. 2, article L131, 1998.
- [104] T. Totani, "TeV burst of gamma-ray bursts and ultra-high-energy cosmic rays," *The Astrophysical Journal*, vol. 509, no. 2, pp. L81–L84, 1998.
- [105] K. Asano and F. Takahara, "Photon emission in a cascade from relativistic protons initiated by residual thermal photons in gamma-ray bursts," *Publications of the Astronomical Society of Japan*, vol. 55, no. 2, pp. 433–444, 2003.
- [106] C. D. Dermer and A. Atoyan, "Ultra-high energy cosmic rays, cascade gamma rays, and high-energy neutrinos from gamma-ray bursts," *New Journal of Physics*, vol. 8, article 122, 2006.
- [107] K. Asano and S. Inoue, "Prompt GeV-TeV emission of gamma-ray bursts due to high-energy protons, muons, and electron-positron pairs," *The Astrophysical Journal*, vol. 671, no. 1, pp. 645–655, 2007.
- [108] N. Gupta and B. Zhang, "Prompt emission of high-energy photons from gamma ray bursts," *Monthly Notices of the Royal Astronomical Society*, vol. 380, no. 1, pp. 78–92, 2007.
- [109] A. A. Abdo, M. Ackermann, M. Ajello et al., "A limit on the variation of the speed of light arising from quantum gravity effects," *Nature*, vol. 462, pp. 331–334, 2009.
- [110] A. A. Abdo, M. Ackermann, M. Ajello et al., "FERMI observations of GRB 090902B: a distinct spectral component in the prompt and delayed emission," *The Astrophysical Journal*, vol. 706, no. 1, article L138, 2009.
- [111] M. Ackermann, K. Asano, W. B. Atwood et al., "Fermi observations of GRB 090510: a short hard gamma-ray burst with an additional, hard power-law component from 10 keV to GeV energies," *The Astrophysical Journal*, vol. 716, no. 2, pp. 1178–1190, 2010.
- [112] M. Ackermann, M. Ajello, K. Asano et al., "Detection of a spectral break in the extra hard component of GRB 090926A," *The Astrophysical Journal*, vol. 729, no. 2, p. 114, 2011.
- [113] K. Toma, X.-F. Wu, and P. Mészáros, "An up-scattered cocoon emission model of gamma-ray burst high-energy lags," *The Astrophysical Journal*, vol. 707, no. 2, article 1404, 2009.
- [114] K. Toma, X.-F. Wu, and P. Mészáros, "Photosphere-internal shock model of gamma-ray bursts: case studies of Fermi/LAT bursts," *Monthly Notices of the Royal Astronomical Society*, vol. 415, no. 2, pp. 1663–1680, 2011.
- [115] A. Corsi, D. Guetta, and L. Piro, "GeV emission from short gamma-ray bursts: the case of GRB 081024B," *Astronomy and Astrophysics*, vol. 524, no. 4, article 92, 2010.
- [116] K. Asano and P. Mészáros, "Spectral-temporal simulations of internal dissipation models of gamma-ray bursts," *The Astrophysical Journal*, vol. 739, no. 2, p. 103, 2011.
- [117] A. M. Beloborodov, R. Hascoët, and I. Vurm, "On the origin of GeV emission in gamma-ray bursts," *The Astrophysical Journal*, vol. 788, no. 1, article 36, 2014.
- [118] G. Ghisellini, G. Ghirlanda, L. Nava, and A. Celotti, "GeV emission from gamma-ray bursts: a radiative fireball?" *Monthly Notices of the Royal Astronomical Society*, vol. 403, no. 2, pp. 926–937, 2010.
- [119] P. Kumar and R. Barniol Duran, "External forward shock origin of high-energy emission for three gamma-ray bursts detected by Fermi," *Monthly Notices of the Royal Astronomical Society*, vol. 409, no. 1, pp. 226–236, 2010.
- [120] K. Murase, K. Toma, R. Yamazaki, S. Nagataki, and K. Ioka, "High-energy emission as a test of the prior emission model for gamma-ray burst afterglows," *Monthly Notices of the Royal Astronomical Society: Letters*, vol. 402, no. 1, pp. L54–L58, 2010.
- [121] K. Asano, S. Guiriec, and P. Mészáros, "Hadronic models for the extra spectral component in the short GRB 090510," *Astrophysical Journal Letters*, vol. 705, no. 2, pp. L191–L194, 2009.
- [122] K. Asano, S. Inoue, and P. Mészáros, "Prompt X-ray and optical excess emission due to hadronic cascades in gamma-ray bursts," *Astrophysical Journal Letters*, vol. 725, no. 2, pp. L121–L125, 2010.
- [123] S. Razzaque, C. D. Dermer, and J. D. Finke, "Synchrotron radiation from ultra-high energy protons and the fermi observations of GRB 080916C," *The Open Astronomy Journal*, vol. 3, pp. 150–155, 2010.
- [124] K. Asano, S. Inoue, and P. Mészáros, "Prompt high-energy emission from proton-dominated gamma-ray bursts," *The Astrophysical Journal*, vol. 699, no. 2, article 953, 2009.
- [125] P. Beniamini, D. Guetta, E. Nakar, and T. Piran, "Limits on the GeV emission from gamma-ray bursts," *Monthly Notices of the Royal Astronomical Society*, vol. 416, no. 4, pp. 3089–3097, 2011.
- [126] M. Ackermann, M. Ajello, L. Baldini et al., "Constraining the high-energy emission from gamma-ray bursts with Fermi," *The Astrophysical Journal*, vol. 754, no. 2, article 121, 2012.
- [127] L. Yacobi, D. Guetta, and E. Behar, "Constraints on the hadronic content of gamma ray bursts," *The Astrophysical Journal*, vol. 793, no. 1, p. 48, 2014.
- [128] K. Asano and T. Terasawa, "Slow heating model of gamma-ray burst: photon spectrum and delayed emission," *Astrophysical Journal Letters*, vol. 705, no. 2, pp. 1714–1720, 2009.
- [129] K. Murase, K. Asano, T. Terasawa, and P. Mészáros, "The role of stochastic acceleration in the prompt emission of gamma-ray bursts: application to hadronic injection," *The Astrophysical Journal*, vol. 746, no. 2, article 164, 2012.
- [130] M. Petropoulou, S. Dimitrakoudis, A. Mastichiadis, and D. Giannios, "Hadronic supercriticality as a trigger for γ -ray burst emission," *Monthly Notices of the Royal Astronomical Society*, vol. 444, no. 3, pp. 2186–2199, 2014.
- [131] P. Mészáros and M. J. Rees, "Steep slopes and preferred breaks in gamma-ray burst spectra: the role of photospheres and comptonization," *Astrophysical Journal Letters*, vol. 530, no. 1, pp. 292–298, 2000.
- [132] D. Giannios, "Prompt emission spectra from the photosphere of a GRB," *Astronomy & Astrophysics*, vol. 457, no. 3, pp. 763–770, 2006.
- [133] A. Pe'è, P. Mészáros, and M. J. Rees, "The observable effects of a photospheric component on GRB and XRF prompt emission spectrum," *The Astrophysical Journal*, vol. 642, no. 2, p. 995, 2006.

- [134] K. Ioka, K. Murase, K. Toma, S. Nagataki, and T. Nakamura, “Unstable GRB photospheres and e^{\pm} annihilation lines,” *The Astrophysical Journal*, vol. 670, no. 2, pp. L77–L80, 2007.
- [135] D. Lazzati and M. C. Begelman, “Non-thermal emission from the photospheres of gamma-ray burst outflows. I. high-frequency tails,” *The Astrophysical Journal Letters*, vol. 725, no. 1, pp. 1137–1145, 2010.
- [136] K. Murase, “Prompt high-energy neutrinos from gamma-ray bursts in photospheric and synchrotron self-Compton scenarios,” *Physical Review D*, vol. 78, no. 10, Article ID 101302, 5 pages, 2008.
- [137] X.-Y. Wang and Z.-G. Dai, “Prompt TeV neutrinos from the dissipative photospheres of gamma-ray bursts,” *The Astrophysical Journal Letters*, vol. 691, p. L67, 2009.
- [138] S. Gao, K. Asano, and P. Mészáros, “High energy neutrinos from dissipative photospheric models of gamma ray bursts,” *Journal of Cosmology and Astroparticle Physics*, vol. 2012, no. 11, article 58, 2012.
- [139] B. Zhang and P. Kumar, “Model-dependent high-energy neutrino flux from gamma-ray bursts,” *Physical Review Letters*, vol. 110, no. 12, Article ID 121101, 5 pages, 2013.
- [140] K. Asano and P. Mészáros, “Delayed onset of high-energy emissions in leptonic and hadronic models of gamma-ray bursts,” *The Astrophysical Journal*, vol. 757, no. 2, p. 115, 2012.
- [141] K. Murase, K. Ioka, S. Nagataki, and T. Nakamura, “High-energy neutrinos and cosmic rays from low-luminosity gamma-ray bursts?” *The Astrophysical Journal Letters*, vol. 651, no. 1, p. L5, 2006.
- [142] A. M. Soderberg, S. R. Kulkarni, E. Nakar et al., “Relativistic ejecta from X-ray flash XRF 060218 and the rate of cosmic explosions,” *Nature*, vol. 442, no. 7106, pp. 1014–1017, 2006.
- [143] K. Toma, K. Ioka, T. Sakamoto, and T. Nakamura, “Low-luminosity GRB 060218: a collapsar jet from a neutron star, leaving a magnetar as a remnant?” *Astrophysical Journal*, vol. 659, no. 2 I, pp. 1420–1430, 2007.
- [144] E. Liang, B. Zhang, F. Virgili, and Z. G. Dai, “Low-luminosity gamma-ray bursts as a unique population: luminosity function, local rate, and beaming factor,” *The Astrophysical Journal*, vol. 662, no. 2, pp. 1111–1118, 2007.
- [145] N. Gupta and B. Zhang, “Neutrino spectra from low and high luminosity populations of gamma ray bursts,” *Astroparticle Physics*, vol. 27, no. 5, pp. 386–391, 2007.
- [146] R.-Y. Liu, X.-Y. Wang, and Z.-G. Dai, “Nearby low-luminosity gamma-ray bursts as the sources of ultra-high-energy cosmic rays revisited,” *Monthly Notices of the Royal Astronomical Society*, vol. 418, no. 2, pp. 1382–1391, 2011.
- [147] A. M. Soderberg, S. Chakraborti, G. Pignata et al., “A relativistic type Ibc supernova without a detected γ -ray burst,” *Nature*, vol. 463, no. 7280, pp. 513–515, 2010.
- [148] N. Smith, S. B. Cenko, N. Butler et al., “SN 2010jp (PTF10aaxi): a jet in a type II supernova,” *Monthly Notices of the Royal Astronomical Society*, vol. 420, no. 2, pp. 1135–1144, 2012.
- [149] X.-Y. Wang, S. Razzaque, P. Mészáros, and Z.-G. Dai, “High-energy cosmic rays and neutrinos from semirelativistic hypernovae,” *Physical Review D*, vol. 76, Article ID 083009, 2007.
- [150] J. Kakuwa, K. Murase, K. Toma, S. Inoue, R. Yamazaki, and K. Ioka, “Prospects for detecting gamma-ray bursts at very high energies with the Cherenkov Telescope Array,” *Monthly Notices of the Royal Astronomical Society*, vol. 425, no. 1, pp. 514–526, 2012.
- [151] S. Inoue, J. Granot, P. T. O’Brien et al., “Gamma-ray burst science in the era of the Cherenkov telescope array,” *Astroparticle Physics*, vol. 43, pp. 252–275, 2012.
- [152] C. D. Dermer, “Neutrino, neutron, and cosmic-ray production in the external shock model of gamma-ray bursts,” *Astrophysical Journal Letters*, vol. 574, no. 1, pp. 65–87, 2002.
- [153] Z. G. Dai and T. Lu, “Neutrino afterglows and progenitors of gamma-ray bursts,” *The Astrophysical Journal*, vol. 551, no. 1, article 249, 2001.
- [154] S. Razzaque, “Long-lived PeV-EeV neutrinos from gamma-ray burst blastwave,” *Physical Review D*, vol. 88, no. 10, Article ID 103003, 11 pages, 2013.
- [155] L. Sironi, A. Spitkovsky, and J. Arons, “The maximum energy of accelerated particles in relativistic collisionless shocks,” *The Astrophysical Journal*, vol. 771, no. 1, article 54, 2013.
- [156] E. Waxman and J. N. Bahcall, “Neutrino afterglow from gamma-ray bursts: $\sim 10^{18}$ eV,” *Astrophysical Journal Letters*, vol. 541, article 707, 2000.
- [157] X.-Y. Wang, Z. Li, and P. Mészáros, “GeV-TeV and X-ray flares from gamma-ray bursts,” *The Astrophysical Journal*, vol. 641, pp. L89–L92, 2006.
- [158] K. Murase and S. Nagataki, “High energy neutrino flashes from far-ultraviolet and X-ray flares in gamma-ray bursts,” *Physical Review Letters*, vol. 97, Article ID 051101, 2006.



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