NEUTRINO AND COSMIC-RAY RELEASE FROM GAMMA-RAY BURSTS: 
TIME-DEPENDENT SIMULATIONS

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ABSTRACT

We revisit the neutrino and ultra-high-energy cosmic-ray (UHECR) production from gamma-ray bursts (GRBs) with time-dependent simulations for the proton-induced cascades. This method can generate self-consistent photon, neutrino, and escaped neutron spectra. To obtain the integrated background spectra, we take into account the distributions of the burst luminosity and pulse duration timescale. A benchmark case with standard GRB luminosity function, a bulk Lorentz factor $\Gamma = 300$, and a proton to gamma-ray luminosity fraction $f_p = 10$ is consistent with both the neutrino upper limits and the observed UHECR intensity at $\sim 10^{20}$ eV, while requiring a different type of UHECR source at the ankle. For the benchmark case, the GRBs in the bright end of the luminosity function, which contribute most of the neutrinos, have their photon spectrum substantially distorted by secondary photons. Such bright GRBs are few in number, and reducing their $f_p$ eliminates the distortion and reduces the neutrino production. Even if we neglect the contribution of the brightest GRBs, the UHECR production rate at energies corresponding to the Greisen-Zatsepin-Kuzmin limit is almost unchanged. These nominal GRB models, especially with $L_{\gamma\nu} \lesssim 10^{53}$ erg s$^{-1}$, appear to meet the current constraints as far as being candidate UHECR sources above the ankle energy.

Key words: cosmic rays – gamma-ray burst: general – neutrinos – radiation mechanisms: non-thermal

1. INTRODUCTION

Since the pioneering study by Waxman & Bahcall (1997), the possibility of neutrino emission from gamma-ray bursts (GRBs) has been discussed by many authors (e.g., Murase & Nagataki 2006; Hüümer et al. 2012 and references therein) in the context of an ultra-high-energy cosmic-ray (UHECR) source (Waxman 1995; Vietri 1995). The IceCube team provided upper limits of an ultra-high-energy cosmic-ray (UHECR) source (Waxman 2006; Hüümer et al. 2012 and references therein) in the context possibility of neutrino emission from gamma-ray bursts (GRBs) of photopion production by accelerated protons (Asano et al. 2009a, 2010), the non-detection of neutrinos from the very low-luminosity GRBs (Murase & Nagataki 2006), or ultra-high-energy cosmic-ray (UHECR) (see, e.g., Baerwald et al. 2014). Two extreme models from alternative models, such as dissipative photospheres (Gao et al. 2012) or ICMART (Zhang & Kumar 2013), has also been discussed. In addition to these models, neutrinos from low-luminosity GRBs (Murase & Nagataki 2006), or ultra-long GRBs (Murase & Ioka 2013) etc., are also interesting as potential sources for the detection of cosmological PeV neutrinos with IceCube (Aartsen et al. 2013a).

However, the internal shock for GRBs is still the archetypal and most widely considered model for producing UHECRs. In this paper, we revisit the neutrino and UHECR production in the standard internal shock model, using our time-dependent method from Asano & Mészáros (2012; see also Asano & Mészáros 2011) to simulate the proton-induced cascade process. The advantages of our time-dependent code are (1) consistent spectra of photons and neutrinos and (2) a more realistic treatment for the neutron escape. As the number of secondary photons increases, the pion production efficiency is enhanced. This nonlinear process affects the amount of neutrons and the spectrum. Especially in cases where the protons experience multiple collisions with photons, strong cooling due to pion production occurs before neutrons escape, which leads to suppression of the UHECR amount. Although our code is based on a one-zone approximation, it allows for the time-dependent change of the size, densities, and other variables, and the effect of this on the gradual escape of neutral particles can be simulated.

In this paper, we take into account the distributions of the luminosity and the pulse width or variability timescale to obtain the neutrino and UHECR spectra, which are propagated from cosmological distances with a Monte Carlo approach. The exact UHECR escape mechanism is unknown, and this can significantly affect the resultant spectra of neutrinos and UHECR (see, e.g., Baerwald et al. 2014). Two extreme models for the UHECR escape, a pessimistic one and an optimistic one, are considered here.

2. SIMULATIONS

The details of our numerical code used to simulate the photon and neutrino emission is discussed in Asano & Mészáros (2012). Here, as a benchmark case, we fix the bulk Lorentz factor at $\Gamma = 300$. We consider GRBs with isotropic-equivalent luminosities $L_{\gamma\nu}$ greater than $10^{50}$ erg s$^{-1}$. The luminosity function per logarithmic interval is taken from Wanderman & Piran (2010), as $\phi(L) \propto L^{-0.17}$ below $L_{\gamma\nu} = 10^{52.5}$ erg s$^{-1}$, and $\phi(L) \propto L^{-1.44}$ above that. Following this function, we divide the luminosity into nine intervals, as shown in Figure 1. Another important parameter for the neutrino emission is the initial shock radius $R_0$ at which the proton injection starts. This radius, $R_0$, is related to the variability timescale as $\delta t = R_0/(2c\Gamma^2)$. As output, our time-dependent code provides the light curve for one shell with the Doppler and curvature effects. We changed $R_0$ from $10^{14}$ to $10^{16}$ cm, which corresponds to $R_0/(2c\Gamma^2) = 0.019$–1.9 s.
The obtained light curves show a sharp rise and long tail (Asano 
& Mészáros 2011), with the rise timescale being slightly shorter
than the above simple estimate. According to our results, the
radii, $R_0$, are allocated to nine timescale bins as shown in
Figure 1. Nakar & Piran (2002) showed that the pulse width
follows a log-normal distribution with the parameters $\mu = 0.065$
($\delta t \simeq 1$ s) and $\sigma = 0.77$. The pulse width is wider than
the rise timescale we need. In the study of Bhat (2013), the
minimum variability timescale is typically 0.25 s. Therefore,
taking into account the cosmological redshift effect, we shift
the distribution peak in Nakar & Piran (2002) to $\delta t = 0.1$ s
with the same $\sigma$ to obtain the rise timescale distribution.
In Figure 1, the histogram for the $\delta t$-distribution assumed is shown
with a log-normal distribution.

Given $L_{iso}$ and $R_0$, the initial photon energy density in the
shell frame is written as $L_{iso}/4\pi c R_0^2 \Gamma^2$. The magnetic energy
density is assumed to be 10% of the photon energy density. In
this paper, we omit simulating the primary photon production
because the emission mechanism is not well understood due
to several competing models. The photon spectrum is simply
assumed to be the conventional Band function, whose spectral
peak energy $\varepsilon_p$ satisfies the $\varepsilon_p - L_{iso}$ relation (Yonetoku et al.
2004). We express this as $\varepsilon_p = 10^{-22.49} L_{iso}^{0.49} \text{ keV}$ following
Nava et al. (2012), where $L_{iso}$ is in cgs unit. The photon indices
are fixed as $\alpha = -1.0$ and $\beta = -2.25$. The shell width in
the comoving frame is taken as $W' = R_0/\Gamma$, which gives us the
total photon energy from one pulse $E_{ph}$. To satisfy the typical
total energy of the burst $E_{iso}$, we need multiple pulses for one
burst. We estimate the average pulse numbers using an $E_{iso}$-$L_{iso}$
based on the sample in Ghirlanda et al. (2012) (see below). We
inject protons of total energy $f_p E_{ph}$ in a timescale $W'/c$ at a
constant rate. Hereafter, we adopt $f_p = 10$ as a benchmark
case. The proton number spectrum at injection is assumed to be
$\propto \varepsilon^{-2} \exp(-\varepsilon/\varepsilon_{max})$, where the maximum proton energy $\varepsilon_{max}$
is calculated with the Bohm limit assumption, taking into account
the cooling due to synchrotron and photons production.

Our time-dependent code follows the cascade processes in
the shell as far as $R = 30 R_0$. The primary photons and
the secondary photons/neutrinos gradually escape from the
shell.

In total, we carried out 81 runs, changing $R_0$ and $L_{iso}$ to
simulate the emission from one shell. The emission from a
burst arises from multiple shells. Here, we simply multiply the
average number of pulses for one burst. For the cosmic-ray (CR)
release, we consider two extreme cases: the neutron conversion
model and the sudden release model. The neutron conversion
model is the most pessimistic model, in which only neutrons
can escape from the shell. In the sudden release model, all
protons and neutrons in the shell are released at $R = 3 R_0$
which is the most optimistic case for CR production; while
artificial, we consider it as a limiting case. The realistic CR
escape may be between those two extreme cases. Figure 2 shows
examples of the time-integrated spectra of photons, neutrinos,
and neutrons released from one shell. The photon spectrum for
$L_{iso} = 10^{54}$ erg s$^{-1}$ is dominated by the secondary photons, originating
from proton cascades. In this “proton-dominated”
case (Asano et al. 2009b), the GeV flux is brighter than the
MeV flux, and the low-energy spectrum is soft and curved, with
the photon index changing from $\sim -1.8$ to $-1.6$. Such photon
signatures have not been identified as common properties for
luminous GRBs. From this viewpoint, we emphasize that the
benchmark case of $\Gamma = 300$ and $f_p = 10$ seems to be ruled out
for bursts brighter than $L_{iso} = 10^{54}$ erg s$^{-1}$. However, we keep
this assumption temporarily and re-discuss this problem further
below.

The neutrino spectra in Figure 2 show complex changes in
luminosity. This is partially because of the importance of the
proton/neutron cooling and synchrotron cooling of muons/pions,
which grow with luminosity. Note that the neutrino
spectrum is a summation of both the muon- and pion-decay
contributions.

3. UHECRS AND NEUTRINO BACKGROUND

Based on the results in the previous section, we calculate the
cumulative contributions of GRBs over redshifts of $z \leq 5$ to the

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3 Other authors define proton energy in terms of electron energy, $f_p E_e$, which is equivalent to our definition for fast cooling electrons.
UHECR and neutrino fluxes. We estimate the average number of pulses per burst from a relation between $E_{\text{iso}}$ and the peak $L_{\text{iso}}$. For this purpose, we use the same relation as assumed in Kakuwa et al. (2012):

$$\log_{10} \left( \frac{E_{\text{iso}}}{10^{55} \text{ erg}} \right) = 0.56 + 1.1 \log_{10} \left( \frac{L_{\text{iso}}}{10^{52} \text{ erg s}^{-1}} \right),$$

(1)

which is obtained from the GRB sample in Ghirlanda et al. (2012). The GRB rate per comoving volume is also taken from Wanderman & Piran (2010), $R_{\text{GRB}}(z) \propto (1 + z)^{2.1}$ for $z \leq 3.0$ and $\propto (1 + z)^{3.4}$ for $z > 3.0$, with the local GRB rate of $1.3 \text{ Gpc}^{-3} \text{ yr}^{-1}$ above $10^{50} \text{ erg s}^{-1}$. Wanderman & Piran (2010) found no evidence of a luminosity evolution, so we do not consider evolution here. For the cosmological parameters we adopted $h = 0.7$, $\Omega = 0.3$, and $\Lambda = 0.7$.

The probability distributions for $\delta t$ and $L_{\text{iso}}$, together with the average pulse number, give us the average neutrino (UHECR) spectrum $N_{\nu}(\epsilon)$ ($N_{\text{CR}}(\epsilon)$) for one GRB. For simplicity, we neglect the dispersions in the $E_{\text{iso}}$–$L_{\text{iso}}$ and Yonetoku relations. We calculate the spectral intensity of the neutrino (UHECR) background in the standard way (see, e.g., Berezhizskiy et al. 2006; Ahlers et al. 2011). For the CR propagation, we take into account the energy loss due to the Bethe–Heitler pair production and photopion production. We adopt the model of Kneiske et al. (2004) for the extra galactic background light. The calculation method is basically the same Monte Carlo method as that for the cascade calculation inside the GRB shell.

Figures 3 and 4 show the resultant spectra for the neutron conversion model and the sudden release model, respectively. In both models, the neutrino intensities are well below the upper limit of Abbasi et al. (2012), owing to the relatively long average $\delta t$ and the inclusion of time-dependent effects. The results are syntheses of the neutrino emission for various luminosities, variabilities, and redshifts. Therefore, the spectral shapes are curved and have no clear break, but they are roughly consistent with the results in He et al. (2012). Although the CR spectral shapes are significantly different in the neutron escape and sudden release models, the intensities around the highest energy range (~$10^{20} \text{ eV}$) are similar. Even for the conservative assumptions in the benchmark models, GRBs appear able to contribute significantly to the higher energy CR flux. However, the intensities at the ankle region (~$10^{18.5} \text{ eV}$) are far below the observed ones, requiring different sources.

In Figures 3 and 4 we also plot the diffuse spectra, neglecting the contribution of GRBs in the highest luminosity-bin of Figure 1 (~$10^{54} \text{ erg s}^{-1}$). As discussed in the previous section, the photon spectrum for such luminous GRBs is inconsistent with observations. At least for these luminous GRBs, consistency with the photon (and UHECR as well as neutrino) observations might be achieved if the pion production is somehow reduced, e.g., by decreasing $f_\pi$ or increasing $\Gamma$. This would also agree with the non-detection of neutrinos from the very bright burst, GRB 130427A (Gao et al. 2013). The number fraction of bursts in the highest luminosity-bin is only 0.085%. Nevertheless, ignoring this bin, the neutrino intensity in the low-energy region is significantly suppressed (see the dashed lines), while the highest energy CR spectrum is almost unchanged. If we additionally ignore the contribution of one more luminosity-bin at ~$10^{53.5} \text{ erg s}^{-1}$ (0.45% in the number fraction), the neutrino background in the energy range constrained by IceCube is even further suppressed (dotted lines). In other words, current neutrino limits may have constrained the emission from only a small fraction of bright GRBs, as also suggested by He et al. (2012) and Adrian-Martinez et al. (2013, e.g., their Figure 3(b)).

As is well known, the neutrino production efficiency is sensitive to the bulk Lorentz factor $\Gamma$. If the average of $\Gamma$ is an increasing function of $L_{\text{iso}}$ or $E_{\text{iso}}$, as discussed in He et al. (2012), the neutrino production would be suppressed even for a higher $L_{\text{iso}}$. This is consistent with the subtraction of the most

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**Figure 3.** CR (black) and neutrino (red, $\nu_\mu$ and $\bar{\nu}_\mu$ after oscillation) diffuse intensities for the neutron conversion model. The gray shaded area for CRs indicates the uncertainty in the local GRB rate. The thin dash-dotted line is the CR spectrum without the effects of photomeson production and Bethe–Heitler pair production. The data for the UHECR intensity (circles) is from Schulz (2013). The dashed (dotted) lines are the spectra without the contribution of GRBs of $L_{\text{iso}} \geq 10^{54}$ ($\geq 10^{53.5}$) erg s$^{-1}$. The cosmicogenic neutrino spectrum produced via the GZK process is also shown as the thin red line. The thick gray line is the neutrino upper limits in Abbasi et al. (2012), which are functions of the neutrino break energy, assuming a spectral shape with $\propto \epsilon^{-1}$ below and $\propto \epsilon^{-3}$ above. While this can be regarded as the approximate differential upper limits, our results have no distinct break in the spectra. For reference, we also plot the integrated energy fluxes (diamonds) for the three results with uncertainty in break energies of $10^{16}$–$10^{17} \text{ eV}$.

**Figure 4.** Same as Figure 3 but for the sudden release model.
luminous GRBs that we discussed above. If the less luminous GRBs ($L_{\text{iso}} \lesssim 10^{53}$ erg s$^{-1}$) have properties similar to those of the benchmark model, they can contribute significantly as UHECR sources at $\sim 10^{20}$ eV, as shown in Figures 3 and 4. Such relatively low-luminosity GRBs may in principle have larger $f_p$ without infringing the same energy budget constraints that affect the brightest GRBs. Thus, in principle, if $f_p \gtrsim 100$ for bursts of $L_{\text{iso}} \lesssim 10^{53}$ erg s$^{-1}$ in the sudden release model, such GRBs could be dominant UHECR sources above the ankle energy (Baerwald et al. 2014).

4. DISCUSSION

We have considered a generic internal shock model of GRBs with an observationally motivated distribution of luminosities and variability timescales. The benchmark case with Lorentz factor, $\Gamma = 300$, and proton load, $f_p = 10$, is consistent with both the neutrino upper limits by IceCube and the observed UHECR intensity at $\sim 10^{20}$ eV. However, the photon spectrum for very bright GRBs with $L_{\text{iso}} \sim 10^{54}$ erg s$^{-1}$ seems inconsistent with observations. A lower $f_p$ or higher $\Gamma$ would be required for such luminous GRBs, which would further reduce their neutrino contribution. However, even if we neglect the contribution of the brightest GRBs in the benchmark case, the predicted UHECR intensity at $\sim 10^{20}$ eV is almost unchanged. For relatively less luminous GRBs, the luminosity function and $E_{\text{iso}}$–$L_{\text{iso}}$ relation may have a large uncertainty. In terms of the energy budget, a larger proton loading such as $f_p = 100$ can be allowed for such less luminous GRBs. Therefore, internal shock models of GRBs, especially those with $L_{\text{iso}} \lesssim 10^{53}$ erg s$^{-1}$, are compatible with the observational constraints so far, and can be UHECR source candidates above the ankle energy.

Our calculation of the GRB internal shock explicitly accounts for the time-dependent effects of the shock region expansion. This differs from previous GRB internal shock neutrino and UHECR calculations, including, e.g., Baerwald et al. (2014). However, despite differing in method, our results are broadly compatible with theirs, once these differences are taken into account. While we have explicitly incorporated the distributions in luminosity and variability, Baerwald et al. (2014) have performed separate calculations for a range of those parameters. They considered several models for the redshift evolution, while we have taken the Wanderman & Piran (2010) distribution as representative. Two other differences are that secondary photon production is taken into account in our model, which enhances the pion production, and our time-dependent code provides an improved neutron escape treatment. The latter can lead to appreciable differences especially in cases where the protons experience multiple collisions with photons, which lead to strong cooling due to pion production before neutrons escape. Multiple collisions are treated approximately in their scheme, while they are included explicitly in our time-dependent scheme. Our choice of a magnetic to photon energy fraction of 10% versus theirs of unity, and our stronger cooling due to secondary photons, leads to a larger ratio of prompt neutrinos to Greisen-Zatsepin-Kuzmin (GZK) neutrino compared to that in Baerwald et al. (2014). They considered a neutron escape and a leakage dominated model for CR escape, while we considered a time-dependent neutron escape and an extreme sudden release model. In the leakage dominated model, the highest energy CRs escape freely, while lower energy CRs also escape according to an escape probability that is proportional to the energy. In agreement with Baerwald et al. (2014), we find that the less luminous bursts are less constrained. However, the inclusion in our calculation of the time-dependence of the shocked shells as they expand enhances the neutrino and CR escape, reducing the neutrino production. Thus, for accelerated protons, in our case the same models appear less constrained even for standard parameters.

We note that the diffuse PeV neutrino flux detected by IceCube (Aartsen et al. 2013a) cannot be reproduced by the GRB internal shock models discussed here. On the other hand, these models are not constrained by the diffuse PeV–E$^{-2}$ model-independent IceCube limits (Aartsen et al. 2013b), which are an order of magnitude above our predicted flux in this energy range.

The present calculations suggest that the current IceCube TeV neutrino limits mainly constrain the small fraction of the bright end GRBs, as far as their potential role as UHECR sources. However, the observed gamma-ray spectra for such bright GRBs, in the context of internal shock models of UHECR, suggest that these bright bursts must then have an inefficient neutrino production. It may be natural to consider that luminous GRBs have larger $\Gamma$, as suggested by Fermi observations (Abdo et al. 2009c). In this case, the current non-detection of neutrinos would be a natural consequence.

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