NEUTRINOS FROM GAMMA-RAY BURSTS: PROPAGATION OF COSMIC RAYS IN THEIR HOST GALAXIES

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ABSTRACT

Gamma-ray bursts (GRBs) are proposed as candidate sources of ultra-high-energy cosmic rays (UHECRs). We study the possibility that the PeV neutrinos recently observed by IceCube are produced by GRB cosmic rays interacting with the interstellar gas in the host galaxies. By studying the relation between the X-ray absorption column density $N_H$ and the surface star formation rate (SFR) of GRB host galaxies, we find that $N_H$ is a good indicator of the surface gas density of the host galaxies. Then we are able to calculate the neutrino production efficiency of CRs for GRBs with known $N_H$. We collect a sample of GRBs that have both measurements of $N_H$ and accurate gamma-ray fluence and attempt to calculate the accumulated neutrino flux based on the current knowledge about GRBs and their host galaxies. When the CR intensity produced by GRBs is normalized with the observed UHECR flux above $\sim 10^{19}$ eV, the accumulated neutrino flux at PeV energies is estimated to be about $(0.3 \pm 0.2) \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (per flavor) under the assumption that the GRB energy production rate follows the cosmic SFR and the favorable assumption about the CR diffusion coefficient. This flux is insufficient to account for the IceCube observations, but the estimate suffers from some assumptions in the calculation and thus we cannot rule out this scenario at present.

Key words: gamma-ray burst; general – neutrinos

1. INTRODUCTION

Gamma-ray bursts (GRBs) have been proposed as a potential origin of ultra-high-energy cosmic rays (UHECRs; e.g., Milgrom & Usov 1995; Vietri 1995; Waxman 1995). High-energy neutrinos are thought to be a useful tool for probing CR acceleration in GRBs, as they are predicted to be produced in dissipative processes (e.g., Waxman & Bahcall 1997; Guetta et al. 2004; Dermer & Atoyan 2006; Murase et al. 2006; Wang & Dai 2009). However, the search for high-energy neutrinos coinciding with GRBs using IceCube has failed to find any associated neutrinos so far (Abbasi et al. 2012; Aartsen et al. 2015). This non-detection has put stringent constraints on the neutrino production efficiency and fireball properties of GRBs (He et al. 2012; Gao et al. 2013; Zhang & Kumar 2013; Yacobi et al. 2014). Because the low neutrino flux could be simply due to a low efficiency in converting CRs to neutrinos, as expected in some GRB models with a large dissipation radius, one cannot rule out CR acceleration in GRBs using the non-detection of neutrinos.

CRs accelerated by GRBs will finally escape from the source and enter the interstellar space of the host galaxy. The proton–proton collisions between CRs and nuclei in the interstellar medium (ISM) will also produce high-energy neutrinos. Recently, the IceCube Collaboration reported the detection of extraterrestrial TeV–PeV neutrinos with a best-fit flux of $E_\nu^2\Phi_\nu = (0.95 \pm 0.3) \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ per flavor (Aartsen et al. 2014). Noting the coincidence between the IceCube neutrino flux and the Waxman–Bahcall bound ($\sim 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$) derived from the flux of UHECRs above $10^{19}$ eV, some authors suggest that IceCube neutrinos may be produced by the same source responsible for these UHECRs (Katz et al. 2013; Waxman 2013). As GRBs are one candidate source of UHECRs, one may wonder whether neutrinos resulting from CR collisions with the ISM in the host galaxy can explain the IceCube observations (Waxman 2013; Wang et al. 2014). In this paper, we study this interesting possibility by performing a calculation of the expected neutrino flux using knowledge about the properties of GRBs and their host galaxies.

One key unknown factor that determines the neutrino flux from GRB host galaxies is the pion production efficiency, i.e., the energy loss of CR protons into pions due to collisions with the ISM of the host galaxy. CRs interact with the ISM along their path before escape, so this efficiency relates to the gas column density that CRs traversed. As CRs are transported outward by galactic winds, the gas surface density $\Sigma_g$ represents an averaged column density of matter that CRs traversed. However, for most GRBs, we do not have measurements of $\Sigma_g$ at the GRB explosion site as GRB hosts are hardly spatially resolved. We note that the X-ray absorption column density $N_H$, inferred from the X-ray observations of the prompt and afterglow emission, has a similar role, but $N_H$ reflects the column density along the line of sight (rather than the averaged gas column density). Moreover, the value of $N_H$ is derived assuming solar metallicity for the absorbing gas, while GRBs seem to occur preferentially in low-metallicity galaxies (Stanek et al. 2006; Prieto et al. 2008). The X-ray absorption, as measured with Swift/XRT observations, mainly takes place through inner shell electrons of metals, thus it is linked to the metallicity of the ISM in the host galaxies. If GRB host galaxies have lower metallicity, the true absorbing gas column density should be higher than the quoted values obtained from fitting X-ray afterglows, considering this metallicity difference. We thus study how well $N_H$ can trace the gas surface density $\Sigma_g$ in Section 2. We find that $N_H$ is well correlated with the surface star formation rate (SFR; $\Sigma_{SFR}$) of the host galaxies. Then taking into account the Kennicutt–Schmidt law, which relates the surface gas density and the
surface SFR (Kennicutt 1998), we obtain a relation between $N_H$ and $\Sigma_{SFR}$. Once $\Sigma_{SFR}$ is known for each GRB, we can calculate the neutrino production efficiency and further calculate the accumulated neutrino flux from all GRB host galaxies (Section 3).

2. THE RELATIONS BETWEEN $N_H$ AND $\Sigma_{SFR}$

Because we have very few measurements of $\Sigma_{SFR}$, but have measurements of $N_H$ for many GRBs, we study whether $N_H$ is correlated with $\Sigma_{SFR}$ and acts as an indicator of the gas surface density. We collect the GRB hosts that have spatially resolved observations from the literature (Fruchter et al. 2006; Savaglio et al. 2009; Svensson et al. 2010), which are given in Table 1. The total SFR and 80% light radius of these hosts $R_{80}$ are obtained in these observations. By comparing the 80% light radius and half-light radius of some GRB hosts that are spatially resolved (Fruchter et al. 2006; Kelly et al. 2014), we find that $R_{80}$ $\approx$ 2$R_{50}$. Converting the 80% light radius to the half-light radius $R_{50}$ with $R_{80}$ = 2$R_{50}$, we calculate the surface SFRs $\Sigma_{SFR}$. With a sample of 18 GRBs that have both measurements of $N_H$ from the XRT data of Swift observations and $\Sigma_{SFR}$ of their host galaxies, we then study the relation between $N_H$ and $\Sigma_{SFR}$. Through the ordinary least-squares (OLS) bisector fitting (Isobe et al. 1990), we find that

$$\Sigma_{SFR} = 10^{-1.89^{\pm}0.27} \left( \frac{N_H}{10^{21} \text{cm}^{-2}} \right)^{1.42^{\pm}0.25} M_{\odot} \text{yr}^{-1} \text{kpc}^{-2} \quad (1)$$

with a correlation coefficient of $r = 0.756$ and a null hypothesis probability of $p = 7.09 \times 10^{-4}$, indicating a good correlation. The result of the fit is shown in the left panel of Figure 1. Considering the Kennicutt–Schmidt law between the surface SFR and the surface density of molecular plus atomic gas (Kennicutt 1998), i.e.,

$$\Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4} \left( \frac{\Sigma}{1 M_{\odot} \text{pc}^{-2}} \right)^{1.4^{\pm}0.15} M_{\odot} \text{yr}^{-1} \text{kpc}^{-2}, \quad (2)$$

4 Since our goal is to estimate the functional relation between $N_H$ and $\Sigma_{SFR}$, and it is not clear which variable is causative. Therefore, the OLS bisector fitting which treats the variables symmetrically should be used, according to Isobe et al. (1990).
we get
\[ \Sigma_g = (2.1 \pm 1.0) \times 10^{21} \left( \frac{N_H}{10^{21} \text{cm}^{-2}} \right)^{0.10 \pm 0.21} \text{m}_\text{H} \text{cm}^{-2}, \quad (3) \]

where \( m_\text{H} \) is the mass of the hydrogen atom. The roughly linear relation between \( \Sigma_g \) and \( N_H \) suggests that \( N_H \) is a good indicator of the gas surface density \( \Sigma_g \). Note that \( N_H \) is derived assuming solar metallicity for the absorbing gas. Since GRB host galaxies usually have lower metallicity, the true absorbing gas column density should be corrected by the metallicity effect. The coefficient \( 2.1 \pm 1.0 \) may reflect such a correction.

We also study whether \( N_H \) is correlated with the total SFRs of the host galaxies. We collect 35 GRBs in total that have measurements of \( N_H \) and total SFRs, which are also listed in Table 1. Through the OLS bisector fitting of the data of \( N_H \) and SFR, we find that
\[ \text{SFR} = 10^{-0.63 \pm 0.23} \left( \frac{N_H}{10^{21} \text{cm}^{-2}} \right)^{1.55 \pm 0.26} M_\odot \text{yr}^{-1}, \quad (4) \]

with a correlation coefficient of \( r = 0.5576 \) and a null hypothesis probability of \( p = 0.0014 \), which indicates a tight positive correlation. The result of the fitting is shown in the right panel of Figure 1. With this relation, we can infer the SFR of GRB hosts with \( N_H \) for each GRB in our sample, which will be used to compute the galactic wind velocity in Section 3.1.

3. NEUTRINO FLUX FROM GRB HOST GALAXIES

3.1. The Pion Production Efficiency

The GRB accelerated CR protons travel through the host galaxy and produce high-energy neutrinos via proton–proton (pp) collisions with its ISM. The collisions produce charged pions, which decay to neutrinos \( (\pi^+ \rightarrow \nu_\mu \bar{\nu}_\mu \nu_e e^+ \), \( \pi^- \rightarrow \bar{\nu}_\mu \nu_\mu \bar{\nu}_e e^- \)). Meanwhile, CRs can escape out of the galaxy through diffusion or galactic wind advection. These two competing processes (i.e., collision and escape) regulate the efficiency of the pion production of CRs, which can be described by \( f_c = 1 - \exp(-t_\text{esc}/t_\text{loss}) \), where \( t_\text{loss} \) is the energy-loss time of CRs via (pp) collisions and \( t_\text{esc} \) is the escape time of CRs. The pp collision energy-loss time is
\[ t_\text{loss} = (\kappa_\text{in} \sigma_\text{pp} c)^{-1} = \left( \kappa_\text{in} \sigma_\text{pp} c / L \right)^{-1}, \]

where \( \kappa_\text{in} \approx 0.5 \) is the inelasticity, \( n \) is the gas number density, and \( L \) is the scale height of the gaseous disk of the galaxy. \( \sigma_\text{pp} \) is the pp collision inelastic cross-section, which slightly increases with the proton energy, given by \( \sigma_\text{pp} = \left( 34.3 + 1.88L + 0.25L^2 \right) \left[ 1 - \left( \frac{1.22 \times 10^{-6}}{E_p / 1 \text{ GeV}} \right)^{1.2} \right] \text{mb} \) where \( L = \log \left( E_p / 1 \text{ TeV} \right) \) (Kelner et al. 2006). Thus, the collision energy-loss time is
\[ t_\text{loss} = 5.4 \times 10^6 \text{ yr} \frac{1}{500 \text{ pc}} \left( \frac{N_g}{0.01 \text{ g cm}^{-2}} \right)^{-1} \left( \frac{\sigma_\text{pp}}{100 \text{ mb}} \right)^{-1}. \]

The CRs escape from the GRB host galaxy in two ways. One is advective transportation by the galactic wind. Galactic-scale gaseous winds are ubiquitous in star-forming galaxies at all cosmic epochs (Heckman et al. 1990; Pettini et al. 2001; Shapley et al. 2003). Such winds can be driven by stellar winds, supernova explosions, or other processes. It is found that, for luminous and ultraluminous infrared galaxies at low redshifts, the winds from more luminous starbursts have higher speeds, roughly as \( v_\text{w} \propto \text{SFR}^{0.25} \) with \( k \) being in the range of 0.25–0.35 (Martin 2005; Rupke et al. 2005; Arribas et al. 2014). A similar trend is found for star-forming galaxies at \( z \sim 1 \) (Weiner et al. 2009), i.e.,
\[ v_\text{w} \approx 175 \left( \frac{\text{SFR}}{1 M_\odot \text{yr}^{-1}} \right)^{0.3}, \]

with the error in \( v_\text{w} \) being 35%. This type of relation between the velocity of the outflowing material and the SFR is expected if the mechanical energy is supplied by stellar winds and supernova explosions. Thus, one can calculate \( v_\text{w} \) for each GRB host with measured \( N_H \) with the help of Equations (4) and (5). Taking \( v_\text{w} = 500 \text{ km s}^{-1} \) as the reference value for GRB host galaxies, the advective escape time is \( t_\text{adv} = L/v_\text{w} = 9 \times 10^5 \text{ yr} \frac{1}{500 \text{ pc}} \left( \frac{v_\text{w}}{500 \text{ km s}^{-1}} \right)^{-1}. \)

The other way that CRs escape is through diffusion, i.e., CRs are scattered off small-scale magnetic field inhomogeneities randomly and diffuse out of the host galaxy. The diffusion time is estimated to be \( t_\text{diff} = L^2 / 4D \), where \( D = D_0 (E/E_0) \delta \) is the diffusion coefficient, and \( D_0 \) and \( E_0 = 3 \text{ GeV} \) are normalization factors. Since little is known about the diffusion coefficient in GRB host galaxies, in the calculation we allow lower diffusion coefficients than that of our Galaxy, which is \( D_0 = 10^{28} \text{ cm}^2 \text{s}^{-1} \). The energy dependence of the diffusion coefficient is also unknown and \( \delta = 0–1 \) depending on the spectrum of interstellar magnetic turbulence. We assume two cases. One is the commonly used value \( \delta = 0.5 \), based on the measurement of the CR confinement time in our Galaxy (Engelmann et al. 1990; Webber et al. 2003). Another choice is...
\( \delta = 0.3 \), assuming a Kolmogorov-type turbulence, where the diffusive escape time is \( t_{\text{diff}} = 10^4 \text{ yr} \left( \frac{l}{500 \text{ pc}} \right)^2 \left( \frac{D_0}{10^3 \text{ cm}^3 \text{ s}^{-1}} \right)^{-1} \left( \frac{\varepsilon_p}{60 \text{ GeV}} \right)^{-0.3} \), with \( \varepsilon_p \approx 25(1 + z)\varepsilon_{\gamma} \).

Combining the advective and diffusive escape timescales, the total escape time is \( t_{\text{esc}} = t_{\text{diff}} + t_{\text{adv}} \). When the difference between \( t_{\text{loss}} \) and \( t_{\text{adv}} \) is large, \( t_{\text{esc}} \approx t_{\text{loss}} \). Note that when \( t_{\text{adv}} \ll t_{\text{diff}} \), which holds for low-energy CRs and small values of \( D_0 \), the pion production efficiency is independent of \( l \) and is given by

\[
\varepsilon_{\pi} \simeq 0.17 \left( \frac{\sum_{\nu} \nu}{0.01 \text{ g cm}^{-2}} \right) \left( \frac{v_{\nu}}{500 \text{ km s}^{-1}} \right)^{-1} \left( \frac{\varepsilon_{\gamma}}{100 \text{ mb}} \right). \tag{6}
\]

The dependence of \( \varepsilon_{\pi} \) on CR energy has a break at the energy where \( t_{\text{adv}} = t_{\text{diff}} \). Below the break energy, \( \varepsilon_{\pi} \) slightly increases with energy due to the pp collision inelastic cross-section, while above the break \( \varepsilon_{\pi} \) decreases as \( \varepsilon_{\pi}^{-\delta} \), leading to a steeper neutrino spectrum.

### 3.2. Calibration of CR Flux from GRBs

The Fermi/GBM detection rate of GRBs is about 250 per yr (Paciesas 2012), and the total gamma-ray (10–1000 keV) fluence of GRBs detected in 1 yr is \( 2 \times 10^{-3} \text{ erg cm}^{-2} \). The GBM field of view (FOV) is roughly \( f_{\text{GBM}} = 2 \pi \) steradians, so the total all-sky flux of gamma-rays in 10–1000 keV is \( f_{\gamma} = 4 \times 10^{-3} \text{ erg cm}^{-2} \). Then the energy production rate of gamma-rays in the energy range of 10–1000 keV is estimated to be \( W_{\gamma}(z = 0) = \varepsilon_{\gamma} f_{\gamma} / c = 5 \times 10^{12} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \), where \( H \) is the Hubble constant and \( \xi \) is a factor accounting for the source density evolution with redshift (Eichler et al. 2010). According to the estimate of Katz et al. (2009), the present-day differential energy production rate of UHECRs above 30 EeV is \( \varepsilon_{\gamma} d\Phi_{\gamma}/d\varepsilon_{\gamma}(z = 0) = (0.45 \pm 0.15) (\alpha - 1) \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \), where \( \alpha \) is the power-law index of the CR spectrum. We assume \( \alpha = 2 \) as suggested by Fermi data. We define \( \eta_{\gamma} \) as the ratio between the differential energy production rate of UHECRs and the energy production rate of gamma-rays in 10–1000 keV. If GRBs are the source of UHECRs above 30 EeV, \( \eta_{\gamma} = \left( \varepsilon_{\gamma} d\Phi_{\gamma}/d\varepsilon_{\gamma} \right)/W_{\gamma}(10–1000 \text{ keV}) = 9 \pm 3 \), assuming \( \xi = 0.5 \) (Eichler et al. 2011).

### 3.3. The Neutrino Flux

We collect a sample of GRBs that have both measurements of \( N_{\text{H}} \) and gamma-ray fluence. As the energy coverage of Swift/BAT is small, we choose GRBs that are detected by Fermi/GBM to get more accurate values of the gamma-ray fluence. There are 45 GRBs in total that have measurements of both \( N_{\text{H}} \) and gamma-ray fluence, as shown in Table 2. For each GRB, the (single-flavor) neutrino flux is estimated to be

\[
\varepsilon_{\nu}^2 \Phi_{\nu} = \frac{1}{6} f_\nu \varepsilon_{\nu}^2 \Phi_{\nu} = \frac{1}{6} \varepsilon_{\nu}^2 \Phi_{\nu}, \tag{7}
\]

where \( \varepsilon_{\nu}^2 \Phi_{\nu} \) is the differential energy flux of CR protons and \( F_{\gamma} \) is the gamma-ray fluence of this GRB. The accumulated truth produced by all GRBs in the universe is

\[
\varepsilon_{\nu}^2 \Phi_{\nu} = \frac{1}{N} \sum_i \varepsilon_{\nu}^2 \Phi_{\nu,i} R_{\text{GRB}} (4\pi)^{-1} \tag{8}
\]

where \( i \) represents the \( i \)-th GRB in our sample, \( N \) is the total number of GRBs in our sample, and \( R_{\text{GRB}} = 500 \text{ yr}^{-1} \) is the
neutrino flux produced by GRB CRs alone cannot explain the IceCube observations if other assumptions used in our calculation are correct.

In the calculation of the accumulated neutrino flux, we only considered those GRBs that triggered the Fermi/GBM detector (i.e., adopting $R_{\text{GRB}} = 500 \, \text{yr}^{-1}$). There are dim GRBs that do not trigger the detector and their total gamma-ray fluence may even be larger than that of the triggered ones according to the simulation results in Liu & Wang (2013). These untriggered GRBs may also produce diffuse neutrinos as triggered GRBs. However, one should note that considering the contribution by untriggered GRBs would not change our result about the accumulated neutrino flux because the CR-to-gamma-ray ratio $\eta_\gamma$ needs to be re-calibrated accordingly and thus the accumulated neutrino flux remains unchanged.

There could be an exceptional case, i.e., if some dim GRBs do not accelerate protons to energy $10^{19} \, \text{eV}$ (although nuclei can still be accelerated to ultra high energies), but they can still contribute to PeV neutrinos with CRs of $\gtrsim 100 \, \text{PeV}$. Note also that this does not exclude the possibility that low-luminosity GRBs themselves are responsible for their origin (e.g., Murase & Ioka 2013; Bhattacharya et al. 2014).

4. DISCUSSIONS AND CONCLUSIONS

The above calculation has some uncertainties in the following aspects. First, the estimate of the energy production rate of gamma-rays $W$, has an uncertainty (e.g., Dermer 2012). Note that the factor $\xi = 0.5$ is obtained by assuming that the GRB rate follows the cosmic SFR of Porciani & Madau (2001) or that of Hopkins & Beacom (2006). If GRB density evolves faster than the cosmic SFR, $\xi$ is smaller and then $\eta_\gamma$ is larger. Second, the estimate of the UHECR energy budget has an uncertainty. The value can be a bit larger if one uses the Telescope Array or HiRes data. Third, the power-law index $\alpha$ could be softer than 2, in which case the energy budget of CRs at 100 PeV could be larger. Thus, given these uncertainties, the neutrino flux in the optimistic case could reach the IceCube observed value.

On the other hand, if one considers that GRB host galaxies that are not detected by optical observations are possibly smaller galaxies, such as dwarf galaxies, the pion production efficiency may be smaller and thus the neutrino flux contributed by these galaxies also would be smaller. Also, as shown by Equation (6), the pion production efficiency depends on the speeds of the galactic winds. The properties of the galactic winds in GRB host galaxies have not been well explored. X-ray observations of starburst galactic winds, such as M82, usually give higher speeds than that inferred from the optical observations (Strickland & Heckman 2009). If the galactic wind speeds of GRB hosts are proven to be faster, the neutrino flux produced by GRB hosts would decrease. The pion production efficiency also depends on the diffusive coefficient. If $D_0$ is larger than $10^{27} \, \text{cm}^2 \, \text{s}^{-1}$ (for example, $D_0 = 10^{28} \, \text{cm}^2 \, \text{s}^{-1}$ for our Galaxy), the accumulated neutrino flux would be lower than $10^{-9} \, \text{GeV cm}^{-2} \, \text{yr}^{-1} \, \text{sr}^{-1}$ at 1 PeV, as shown in Figure 3.

In summary, we calculated the neutrino flux produced by CRs accelerated by GRBs while they are propagating in the host galaxies based on our current knowledge about GRB and their host galaxies. These CRs collide with nuclei of the ISM and produce neutrinos before they escape out of the galaxy.
When the flux of CRs produced by GRBs is normalized with the observed flux of UHECRs above ~10^19 eV, the accumulated neutrino flux is (0.3 ± 0.2) × 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} per flavor under the usual assumptions about the GRB properties and favorable assumptions about the CR diffusion coefficient. The estimate, however, has uncertainty due to the uncertainty in our current knowledge of GRBs and their host galaxies and the accumulated neutrino flux could reach the observed value by IceCube in the optimistic case, so we cannot rule out this scenario at present.

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