FERMI LIMIT ON THE NEUTRINO FLUX FROM GAMMA-RAY BURSTS

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ABSTRACT

If gamma-ray bursts (GRBs) produce high-energy cosmic rays, neutrinos are expected to be generated in GRBs via photo-pion productions. However, we stress that the same process also generates electromagnetic (EM) emission induced by the secondary electrons and photons, and that the EM emission is expected to be correlated with neutrino flux. Using Fermi/Large Area Telescope results on gamma-ray flux from GRBs, the GRB neutrino emission is limited to be $<20$ GeV m$^{-2}$ per GRB event on average, which is independent of the unknown GRB proton luminosity. This neutrino limit suggests that IceCube, operating at full scale, requires stacking of more than 130 GRBs in order to detect one GRB muon neutrino.

Key words: acceleration of particles – elementary particles – gamma-ray burst: general

1. INTRODUCTION

The sources of high-energy, $>1$ PeV, cosmic rays (HECRs) are expected to produce high-energy neutrinos via photo-pion production. The detection of high-energy neutrinos will help identify the origin of HECRs. Gamma-ray bursts (GRBs) have long been proposed to be one of the strong candidates of extragalactic HECR sources (Waxman 1995), and are expected to produce high-energy neutrinos (Waxman & Bahcall 1997; Vietri 1998; Dermer & Atoyan 2003). Currently, IceCube, operating at full scale, is the most sensitive TeV-scale neutrino telescope and is believed to reach the level of GRB neutrino flux. The recent reported flux limits from IceCube in its uncompleted configuration have put stringent constraints on GRB neutrinos (Abbasi et al. 2010, 2011, 2012). Observations by IceCube in the full scale will soon provide even more stringent results.

Comparing the latest non-detection of GRB neutrinos by IceCube and the positive GRB neutrino prediction challenges the idea that GRBs are the source of HECRs (Abbasi et al. 2012). However, the predicted flux depends on some uncertainties in the GRB model. First, the neutrino flux is proportional to the proton luminosity from the GRB jet $L_p$, which is an unknown parameter. Second, the neutrino flux is proportional to the fraction of proton energy that is converted into pions, which further depends on other uncertain parameters, e.g., the bulk Lorentz factor of the jet, $\Gamma$, and the radius of the GRB emission regions, $R_{\text{em}}$ (Waxman & Bahcall 1997; Murase & Nagataki 2006). Given the fiducial values of these parameters, one can calculate the GRB neutrino flux, as done by Guetta et al. (2004) and Abbasi et al. (2010, 2011, 2012), but the flux is subject to the uncertainties. For example, if the ratio between energy in accelerated protons and electrons $f_p \equiv L_p/L_e$ is taken to be $f_p = 10$, then the predicted neutrino flux by Abbasi et al. (2012) and Zhang & Kumar (2012) challenges the current non-detection of neutrinos by IceCube, but, by using $f_p = 1$, even the photosphere model of GRBs, which has a small $R_{\text{em}}$ (hence large $f_p$), survives the current detection limit (Gao et al. 2012; see also Murase 2008 and Wang & Dai 2009). A systematic consideration of the parameter values makes a relatively more reasonable prediction (Baerwald et al. 2012), but the result still suffers the assumptions of parameters.

Here we investigate the neutrino production in GRBs and emphasize that the neutrino flux could be related to the electromagnetic (EM) one in the photo-pion processes (Becker et al. 2010). Then we derive a constraint on GRB neutrino flux based on the Fermi observations of GRB EM emission. As shown below, this normalization of GRB neutrino flux to gamma-ray emission does not suffer, in particular, the uncertainty of $L_p$. Unless otherwise specified, we will use the convention $Q_x \equiv Q/10^x$ and cgs units throughout this letter.

2. EM AND NEUTRINO CORRELATION

If HECRs are generated in GRB outflows, then they interact with the intense MeV photon field and produce charged pions. The charged pions decay via the primary mode, $\pi^\pm \rightarrow \mu^\pm + \nu_\mu$, and muons further decay via $\mu \rightarrow e + \nu_e + \nu_\mu$. The final neutrino flavor ratio in the source is $\Phi_\nu = \Phi_\nu^0 : \Phi_\nu^\mu : \Phi_\nu^\tau = 1:2:0$, but, due to neutrino oscillation, the flavor ratio observed in the distance is $\Phi_\nu = \Phi_\nu^0 : \Phi_\nu^\mu : \Phi_\nu^\tau \approx 1:1:1$ (Particle Data Group 2004). The final products induced by one charged pion decay are therefore four leptons, each equally sharing the original pion energy, $E_\pi$, implying that the neutrino flux may be normalized to and constrained by the observed gamma-ray flux.

The secondary electrons and positrons (electrons hereafter for simplicity) may easily convert their energy into gamma rays by radiation processes, e.g., synchrotron and inverse Compton (IC) radiations. Thus, there should be a straightforward relation between the muon neutrino flux and the gamma-ray flux induced by the secondary electrons,

$$F_\nu \approx E_\pi^{\alpha_\nu},$$

implying that the neutrino flux may be normalized to and constrained by the observed gamma-ray flux.

The secondary electrons are very energetic and cool rapidly by synchrotron radiation since the IC cooling suffers a strong Klein–Nishina effect. Let us calculate the synchrotron photon energy. For a flat proton distribution with index $p \approx 2$ ($E_p^2dE_p/dE_\pi \propto E_\pi^{-p-1}$), and a typical GRB spectrum of a broken power law with low- and high-energy photon indices, $\alpha_\gamma = 1$ and $\beta_\gamma = 2$, respectively, the generated pions also show a flat spectrum at $E_\pi \gtrsim E_{\pi,b} = 0.2E_{p,b}$. Here $E_{p,b}$ is the energy
The energy ratio between the $\pi^+$-induced electrons and $\pi^0$-induced photons is $F_{\pi^+}/F_{\pi^0} \approx (1/4) \log((4/3)E_{\mu,c}/E_{\pi,c})/(1/2) \log(\epsilon_{\max}/\epsilon_{\pi,b})$. The 1/4 factor arises because electrons carry one-fourth of the $\pi^\pm$ energy, and 1/2 because the energy ratio of $\pi^0$ to $\pi^\pm$ is $\Phi_{\pi^0}/\Phi_{\pi^\pm} \approx 1/2$ by the numerical calculation of photo-pion production in GRBs (Hümmer et al. 2010). The $f$ factor is then calculated as $f < F_{\pi^0}/(F_{\pi^+} + F_{\pi^0}) \approx (1 + F_{\pi^0}/F_{\pi^+})^{-1}$. This is an upper limit because the leptonic contribution to gamma-ray emission is neglected. Inserting the typical values of $E_{\mu,c}, E_{\pi,b}, \epsilon_{\max}$, and $\epsilon_{\pi,b}$, one gets $f < 0.1$. This number is sensitive to $\Gamma$ (but weakly depends on other parameters); for $\Gamma$ varying from $10^2$ to $10^3$ it ranges from approximately 0.02 to 0.2. If the leptonic component is dominant, the electron energy will be transferred to EM cascade radiation.

The detailed calculation of the EM cascade emission induced by the photon-production in GRBs has been carried out numerically (Dermer & Atöyan 2006; Asano et al. 2009, 2010; Murase et al. 2012) to explain the extra spectral components observed in certain GRBs. The main difference here is that we...
Table 1
The Values of Factor $g$

| Parameter Values | $g$  |
|------------------|-----|
| $\Gamma = 100, 300, 600, 1000$ | 0.15, 0.42, 0.04, 0.58 |
| $L/\text{erg s}^{-1} = 10^{31}, 10^{35.5}, 10^{52.5}, 10^{55}$ | 0.08, 0.23, 0.42, 0.26 |
| $\Delta t/\text{s} = 10^{-2}, 10^{-2.5}, 10^{-15}, 10^{-1}$ | 0.48, 0.26, 0.19, 0.06 |
| $\epsilon_{b}/\text{MeV} = 0.1, 0.3, 3$ | 0.80, 0.24, 0.20 |
| $\epsilon_{b}/\epsilon_{e} = 0.1, 0.3, 3$ | 0.31, 0.36, 0.36 |

Note. The other parameters not mentioned are taken to be the typical values: $\Gamma = 300$, $L = 10^{52}$ erg s$^{-1}$, $\Delta t = 10^{-2}$ s, $\epsilon_{b} = 1$ MeV, and $\epsilon_{b}/\epsilon_{e} = 1$, for which $g = 0.42$.

estimate in general the contribution of hadronic components in GRBs.

3. FERMI LIMIT ON NEUTRINO FLUX

The Fermi Gamma-ray Space Telescope provided a new opportunity to observe GRBs, especially the GeV scale. We constrain the GRB neutrino flux by Fermi observations.

The Fermi satellite has two instruments: the Gamma-ray Burst Monitor (GBM), which has a wide field of view (FOV) and is sensitive to MeV scale emission, and LAT, a narrower FOV and is sensitive to GeV emission, i.e., from 0.1 to 300 GeV. The LAT has detected roughly 8% of the GBM-triggered GRBs that occurred within the LAT FOV. For these LAT-bright GRBs, the analysis by Zheng et al. (2012) has shown (their Table 2) the photon fluence (i.e., time-integrated photon flux) of each LAT-detected GRB in the 0.1–300 GeV range. We then obtain the average photon fluence for one GRB, $F_{\gamma, \text{det}} = 108$ photons m$^{-2}$. Since there are few photons detected above a few tens of GeV, the photon number in the 0.1–10 GeV range is practically equal to that in the 0.1–300 GeV range. For the LAT-dark GRBs, the upper limits of LAT detection are given first by Guetta et al. (2011) and Beniamini et al. (2011), but here we use the results from the Fermi team. In their recent paper (Ackermann et al. 2012), the Fermi team analyzed the LAT-dark GRBs in a roughly 3 yr operation, which are the other 92% of GBM-triggered GRBs that are in the LAT FOV. The upper limits to the gamma-ray flux in the 0.1–10 GeV range for each GRB has been listed in their Table 1. We use the upper limits in the last column to calculate the average upper limit of all of these LAT-dark events, $\phi_{\text{dark}} = 34.6$ photons m$^{-2}$ (0.1–10 GeV range). Regarding $\phi_{\text{bright}}$ as the upper limits of the bright GRBs, we can calculate the average upper limit of all GRBs, including both bright and dark GRBs, as $\phi_{\text{limit}} = 8\% \times \phi_{\text{bright}} + 92\% \times \phi_{\text{dark}} = 40$ photons m$^{-2}$ in 0.1–10 GeV range. Assuming a flat photon spectrum, $\epsilon^{2}d\nu_{\gamma}/d\epsilon \propto \epsilon^{-2}$ for $\gamma = 2$, the average limit to the energy fluence per GRB is $F_{\gamma, \text{limit}} = 20$ GeV m$^{-2}$ in the 0.1–10 GeV range. For softer photon spectrum with $\gamma = 3$, the limit becomes $F_{\gamma, \text{limit}} = 8.5$ GeV m$^{-2}$, smaller by a factor of 2.3, whereas for harder spectrum with $\gamma = 1.5$, $F_{\gamma, \text{limit}} = 75$ GeV m$^{-2}$, larger by 3.7. Given the correlation between the neutrino flux and gamma-ray flux, the average neutrino fluence per GRB is

$$F_{\nu_{\mu}} = \langle f/g \rangle F_{\gamma, \text{lim}} = 20(f/g) \text{ GeV m}^{-2}. \quad (3)$$

Note that $\langle f/g \rangle \lesssim 1$ is estimated in the previous section.

4. NEUTRINO DETECTION RATE

Besides the normalization of neutrino flux, the neutrino spectral form is still required in order to calculate the neutrino detection rate by experiments such as IceCube. For a GRB spectrum with photon indices $\alpha_{\gamma}$ and $\beta_{\gamma}$, and for a flat proton distribution with $p = 2$, the GRB neutrino spectrum generated by the $p\gamma$ interactions can be approximated as $dn_{\nu}/d\epsilon \propto \epsilon^{-\alpha_{\gamma}}$ at $\epsilon < \epsilon_{1}$, $dn_{\nu}/d\epsilon \propto \epsilon^{-\beta_{\gamma}}$ at $\epsilon_{1} < \epsilon < \epsilon_{2}$, and $dn_{\nu}/d\epsilon \propto \epsilon^{-\gamma}$ at $\epsilon_{2} < \epsilon$ (for simplicity, we take $\epsilon_{1} \equiv \epsilon_{b}$ hereafter), where the spectral indices are $\alpha_{\gamma} = 3 - \beta_{\gamma}$, $\beta_{\gamma} = 3 - \alpha_{\gamma}$, and $\gamma = \beta_{\gamma} + 2$, and the break energies are $\epsilon_{1} = E_{\nu,b}/4$ and $\epsilon_{2} = E_{\mu,c}/3$. The normalization of the neutrino flux is obtained by the requirement $\int_{0}^{\epsilon} \epsilon^{2}dn_{\nu}/d\epsilon d\epsilon = \langle f/g \rangle F_{\gamma, \text{lim}}$. For a typical GRB spectrum with $\alpha_{\gamma} = 1$ and $\beta_{\gamma} = 2$, the specific neutrino flux at $\epsilon = \epsilon_{1}$ is $dn_{\nu}/d\epsilon (\epsilon = \epsilon_{1}) = (\langle f/g \rangle F_{\gamma, \text{lim}}/\epsilon_{1}) \langle 3/2 \rangle + \log(\epsilon_{2}/\epsilon_{1})$. Note that the broken power-law form is a good approximation to the spectral profile of GRB muon neutrinos from a full numerical calculation with the effect of neutrino mixing (see, e.g., Baerwald et al. 2012). Given the effective area of the neutrino experiment, the average neutrino number that can be detected in one GRB can be calculated as $N_{\text{det}} = \int_{0}^{\epsilon_{1}} A_{\text{eff}}(d\nu_{\mu}/d\epsilon) d\epsilon$. For the neutrino spectrum with $F_{\nu_{\mu}} < 20(f/g) \text{GeV m}^{-2}$, $\epsilon_{1} = 7 \times 10^{14}$ eV, and $\epsilon_{2} = 10^{16}$ eV, the detection rate by the IceCube 40-string configuration (using the effective area averaged over neutrino incident angles) is $N_{\text{Ice40}}^{\text{det}} = 2.5 \times 10^{-3} \langle f/g \rangle$ (for $\gamma = 2$) per GRB, so more than $N_{\text{Ice40}}^{\text{det}} = 400(f/g)^{-1}$ GRBs are required in the stacking analysis in order to detect one GRB muon neutrino. For the full-scale IceCube with a larger effective area $A_{\text{Ice40}}^{\text{eff}} \approx 3 \times 10^{43}$ (Karle et al. 2010), and for $\langle f/g \rangle < 0.1$ and $\langle g \rangle > 0.1$, one needs to stack $>130$ GRBs to detect one GRB muon neutrino (or $>40$ and $>310$ for $\gamma = 1.5$ and 3, respectively).

5. CONCLUSION AND DISCUSSION

We show in the $p\gamma$ processes that there is a correlation between the generated EM (electrons and photons) and neutrino fluxes (see also Baerwald & Guetta 2012). The EM radiation typically cascades down to a GeV scale before escaping from the GRB emission region. Using the Fermi/LAT observations, the average neutrino flux per GRB is constrained to be below 20 GeV m$^{-2}$, implying that IceCube needs $>400$ GRBs to detect one muon neutrino in its 40-string configuration. This suggests that the GRB samples analyzed by the IceCube collaboration in Abbasi et al. (2012) may not be large enough. As for the full-scale IceCube, the stacking of $>130$ GRBs is required.

The derivation of neutrino flux using the EM–neutrino correlation is less dependent on the uncertainties in GRB models. In particular, unlike the previous calculations, the approach here is completely independent of the poorly known $L_{p}$ (or $f_{p}$). Yet the derivation here is not parameter-free. The location $\epsilon_{\gamma}$ where EM cascade radiation significantly piles up strongly depends on $\Gamma$. However, based on the theory of internal shock model for GRBs, a robust bound $10^{2} < \Gamma < 10^{7}$ is obtained. Moreover,
the escape of photons. And that the untriggered GRB contribution is not important, the electron to photon ratio is given by $f_p$. It is derived that the protons with energy $E_{p,b}$ typically lose a fraction $f_{p,b} < 0.2$ of its energy by $p\gamma$ interactions (Waxman & Bahcall 1997), and that the luminosity ratio of neutrinos to protons is (Li 2012)

$$L_{\nu_{\mu}} / L_p \approx 1 / 8 f_{\pi,b} \log (\frac{E_{\nu_{\mu}} / E_{\pi,b}}{E_{\nu_{\max},b} / E_{\pi,b}}) \sim f_{p,b} / 40.$$  

with $E_{\nu_{\max},b}$ ($E_{\pi,min}$) being the maximum (minimum) energy of accelerated protons. The proton to electron ratio is given by $f_p = L_p / L_{\gamma,\nu_{\mu}} = (L_p / L_{\nu_{\mu}})(F_{\nu_{\mu}} / F_{\gamma,\nu_{\mu}}) < 13(F_{\gamma,\nu_{\mu}} / 3 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1})^{-1}(f_{p,b} / 0.2)^{-1}$, where $F_{\gamma,\nu_{\mu}}$ is the average fluence of the GBM-detected GRBs in the MeV domain. On the other hand, the wide energy range observations by Fermi have made a more straightforward constraint on $f_p$. Fermi shows that the flux ratio of LAT to GBM is typically $L_{\gamma,\nu_{\mu}} / L_p < 10^{-1}$ (Abdo et al. 2009). Given $L_{\nu_{\mu}} / L_{\gamma,\nu_{\mu}} \approx f_p / g < 1$, we have $F_{\gamma,\nu_{\mu}} / 3 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \lesssim 20 f_{p,b} (0.2)^{-1}$, similar to the above constraint derived from the neutrino limit. Surely, both constraints depend on the uncertain $f_{p,b}$. It has been noted that $f_p > 10$ is required to explain the observed UHECRs as GRB origin (Wick et al. 2004; Ahlers et al. 2011; Eichler et al. 2010). Combining the neutrino (or gamma-ray) and UHECR constraints, the allowed range of $f_p$ is then quite small.

There may be some caveats that the neutrino limit in this paper can be avoided in some cases. First, we used the GeV scale, 0.1 to a few hundred GeV, flux to constrain the neutrino flux, but it could be that the cutoff photon energy is much larger, e.g., $\epsilon_{\gamma\gamma} \gg 100$ GeV, so the observations in $<100$ GeV range do not hold. Second, if, for unknown reasons, the generated secondary electrons, i.e., induced by the charged pion decay or $\gamma\gamma$ pair production, do not radiate at all, the EM–neutrino correlation would not exist. Finally, it is worth noting that neutrinos may be delayed or anticipated with respect to the GRB photons (see, e.g., Amelino-Camelia et al. 2013). In this case, the IceCube analysis should be performed in a larger window of time.

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**Note added in proof.** The IceCube non-detection of neutrinos from the recent low-redshift LAT-detected GRB 130427a (http://gcn.gsfc.nasa.gov/gcn3/14520.gcn3) is consistent with the EM-neutrino correlation. The LAT fluence of $\sim 10^{-4}$ erg cm$^{-2}$ only implies a muonic neutrino event number of about <0.4 in IceCube.

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