TeV–PeV NEUTRINO OSCILLATION OF LOW-LUMINOSITY GAMMA-RAY BURSTS

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ABSTRACT

There is evidence that long-duration gamma-ray bursts (GRBs) originate from the core collapse of massive stars. When a jet punctures through the progenitor envelope, high-energy neutrinos can be produced by the reverse shock formed at the jet head. It is suggested that low-luminosity GRBs are possible candidates of this high-energy neutrino precursor up to \textasciitilde PeV scales. Before leaving the progenitor, these high-energy neutrinos must oscillate from one flavor to another with the matter effect in the envelope. Under the assumption of a power-law stellar envelope density profile $\rho \propto r^{-\alpha}$ with an index $\alpha$, we study the properties of TeV–PeV neutrino oscillation. We find that adiabatic conversion is violated for these neutrinos so we calibrate the level crossing effect. The resonance condition is reached for different energies at different radii. We note that the effective mixing angles in matter for PeV neutrinos are close to zero, so the transition probabilities from one flavor to another are almost invariant for PeV neutrinos. We plot all the transition probabilities versus the energy of TeV–PeV neutrinos from the birth place to the surface of the progenitor. With an initial flavor ratio $\phi_e^0: \phi^0_{\mu}: \phi^0_{\tau} = 1: 2: 0$, we plot how the flavor ratio evolves with energy and distance when neutrinos are still in the envelope, and we find the ratio when they reach the Earth. For PeV neutrinos, the ratio is always $\phi_e^0: \phi^0_{\mu}: \phi^0_{\tau} \approx 0.30: 0.37: 0.33$ on Earth. In addition, we discuss the dependence of the flavor ratio on energy and $\alpha$ and find a good result. This dependence may provide a promising probe of the progenitor structure.

Key words: gamma-ray burst: general – neutrinos

1. INTRODUCTION

The idea that gamma-ray bursts (GRBs) can serve as the sources of high-energy neutrinos has long been discussed (Vietri 1995; Waxman & Bahcall 1997, 2000; Mészáros & Rees 2000; Dai & Lu 2001; Mészáros & Waxman 2001; Li et al. 2002; Dermer & Atoyan 2003; Pruet 2003; Razzaque et al. 2003; Guetta et al. 2004; Ando & Beacom 2005; Rees & Mészáros 2005; Murase & Nagataki 2006; Horihchi & Ando 2008; Murase 2008; Enberg et al. 2009; Wang & Dai 2009; Gao et al. 2012; Hummer et al. 2012; Baerwald et al. 2013; Murase & Ioka 2013; Razzaque 2013; Bustamante et al. 2015).

Before breaking out, a relativistic jet punctures through the stellar envelope and transports energy to electrons and protons via shock acceleration (Woosley 1993; MacFadyen & Woosley 1999; Zhang & Mészáros 2004; Piran 2005; Mészáros 2006). Accelerated electrons dominate the radiation by synchrotron or the inverse Compton mechanism, while accelerated protons produce neutrinos by proton–proton collision and the photopion process (Waxman & Bahcall 1997, 1998; Rachen & Mészáros 1998; Alvarez-Muniz et al. 2000; Bahcall & Waxan 2001; Guetta & Granot 2003; Murase et al. 2006; Becker 2008). This neutrino signal is prior to the main burst, as a precursor. However, it has been argued that this high-energy neutrino precursor with energy ranging from TeV up to PeV scales cannot be produced for a typical GRB (Levinson & Bromberg 2008; Katz et al. 2010; Murase & Ioka 2013). The reason is that the reverse shock occurring at the interface of the jet head would be radiation mediated, resulting in inefficient shock acceleration. Nevertheless, the matter is different for low-luminosity GRBs (LL-GRBs; Murase & Ioka 2013; Xiao & Dai 2014). Due to their low power, the Thomson optical depth is low even inside a star, so efficient shock acceleration would be expected. We assume the same LL-GRB as our previous work (Xiao & Dai 2014), in which we have shown that our LL-GRB is responsible for TeV–PeV neutrinos.

Further, in this paper we focus on the oscillation properties of these high-energy neutrinos. Neutrino oscillation in matter has been studied for a long time. The resonant conversion of neutrinos from one flavor to another with the matter effect was first discussed in the solar neutrino problem (Chen 1985). While propagating in a medium, $\nu_e$ interacts via neutral current (NC) and charged current, whereas $\nu_\mu$ and $\nu_\tau$ interact only via NC. This mechanism is called the Mikheyev–Smirnov–Wolfenstein effect (Wolfenstein 1978; Mikheyev & Smirnov 1985). As we know, solar neutrinos are relative low in energy ($\leq 100$ MeV), as are supernova neutrinos, and researching them is becoming more and more attractive (Scholberg 2012; Lund & Kneller 2013). At the same time, the oscillation of GRB neutrinos is less understood. With energy up to PeV scales, the oscillation properties of GRB neutrinos are different compared to MeV neutrinos. Kashti & Waxman (2005) discussed the electromagnetic and adiabatic energy losses of $\pi$’s and $\mu$’s, which would modify the flavor ratio produced by GRBs, and concluded that the flavor ratio on Earth $\phi_e^0: \phi^0_{\mu}: \phi^0_{\tau}$ is $1: 1: 1$ at low energy up to $1: 1$: $1$ at high energy with a transition energy around $100$ TeV. Mena et al. (2007) discussed high-energy neutrinos produced in optically thick astrophysical objects in the energy range $0.1$–$100$ TeV. They studied in detail the shower-to-muon track ratio $R$ and discussed its variation with source properties and neutrino oscillation parameters. Razzaque & Smirnov (2010) also presented a detailed and comprehensive study of flavor conversion of neutrinos from hidden sources (jets), but their results differ from the results of Mena et al. (2007). Sahu & Zhang (2010) showed that the resonant oscillation could take place within the inner high-
density region of the choked jet progenitor and the final flavor ratio detected on Earth is further modified to either 1: 1.095: 1.095 for the large mixing angle solution to the solar neutrino data, or 1: 1.3: 1.3 for maximal mixing among the muon and tau neutrinos in vacuum. Osorio Oliveros et al. (2013) studied the three-flavor neutrino oscillation of choked GRBs in the GeV–TeV energy range for three different presupernova star models. They found that for neutrino energies below $\leq 10\, \text{TeV}$ the flux ratio did not amount to 1: 1: 1, whereas it did for higher energy neutrinos. Recently, Fraija (2014) carried out an analysis of resonance conditions for GeV–PeV neutrinos created in internal shocks at different places in the star, estimating the flavor ratios on Earth.

The main difference of our paper from previous works is that at the starting point we take an LL-GRB as the source of high-energy neutrinos and hence we focus on higher energies, from TeV to PeV. We find that the mixing angles in matter for PeV neutrinos are close to zero, so the transition probabilities from one flavor to another are almost invariant, which are different with MeV–TeV neutrinos. Thus, we get a constant ratio of $\theta_1^2: \theta_2^2: \theta_3^2 \approx 0.30: 0.37: 0.33$ for PeV neutrinos on Earth. Moreover, we discuss the dependence of the flavor ratio on the index $\alpha$ and neutrino energy, providing a promising way to probe the GRB progenitor structure through a neutrino precursor signal in the future.

This paper is organized as follows. We present all the results in Section 2. NEUTRINO MIXING

2.1. Density Profile of the Envelope

In this subsection, we take $\alpha = 2$ as our premise, and discuss the dependence on $\alpha$ later in Section 2.4.

We assume a power-law envelope density profile $\rho(r)= Ar^{-\alpha}$, where $A = (3 - \alpha)M_{\text{He}}/(4\pi R^{3-\alpha})$ and $2 \leq \alpha < 3$ with $M_{\text{He}}$ and $R$ being the mass and radius of the helium envelope. For a helium core of mass $M_{\text{He}} = 2M_\odot$ and radius $R = 4 \times 10^{11}$ cm, the ambient envelope density can be expressed as $\rho(r) = 7.96 \times 10^{20} r^{-2}$ g cm$^{-3}$. The number density of electrons in the envelope is $N_e(r) = \frac{\rho(r)}{4\pi e^2} \chi_r$, where the number of electrons per nucleon $Y_e$ needs to be obtained.

Saha’s Equation reads

$$\log \frac{N_{e+1}}{N_e} = \log \frac{2u_{e+1}(T)}{u_e(T)} + \frac{5}{2} \log T - \frac{5040}{T} \chi_r - \log P_e - 0.48,$$

where $N_r$, $u_r$, and $\chi_r$ stand for the number density, partition function, and ionization energy of the $r$th ionization ions, respectively. $T$ is the temperature and $P_e \equiv N_e kT$ is the electron pressure. For our pure helium envelope, we can get

$$\frac{N(\text{He}^+)}{N(\text{He})} = 1.65 \times 10^{-11}, \quad \frac{N(\text{He}^2+)}{N(\text{He})} = 0.69,$$

if we adopt typical values of $T = 15, 000\, \text{K}$, $\chi_0 = 24.58\, \text{eV}$, and $Y_e = 1.3$. We can see that the second ionization of helium is negligible, so $Y_e \approx \frac{N(\text{He}^+)}{N(\text{He})+N(\text{He}^+)} \approx 0.408$.

The effective potential of neutrinos can be expressed as

$$V_{\text{eff}} = \sqrt{2} G_F N_e,$$

where $G_F$ is the Fermi coupling constant.

2.2. Adiabatic Conversion Violation

Before we start to consider the neutrino oscillation, we need to check whether the adiabatic approximation is valid. The adiabatic parameter $\gamma$ is defined as

$$\gamma \equiv \frac{\delta m^2}{2E} \sin 2\theta \tan 2\theta \frac{1}{\frac{2 \ln N}{dr}|_{\text{res}}},$$

where $\delta m^2$ is the mass square difference between the neutrino mass eigenstates, $E$ is the neutrino energy, and $\theta$ is the mixing angle. The subscript “res” represents the place at which resonance happens. We can easily see that $\gamma$ is in proportion to $1/E$ and the adiabatic approximation requirement $\gamma \gg 1$ is usually fulfilled for neutrinos with relative low energy of $\leq 100\, \text{MeV}$, such as solar neutrinos and supernovae neutrinos. However, in this paper we focus on high energy from TeV to PeV scales, and we find that adiabatic conversion is not applicable now. We plot the adiabatic parameter versus neutrino energy in Figure 1 and it is obvious that $\gamma \gg 1$ is violated for high-energy neutrinos. Only $\gamma_1$ and $\gamma_3$ are needed because there are at most two level crossings for neutrinos in the three-flavor case (Dighe & Smirnov 2000; Yasuda 2014). The vacuum oscillation parameters we adopt are $\delta m^2_{12} = 7.54 \times 10^{-5}\, \text{eV}^2, \delta m^2_{23} = 2.43 \times 10^{-3}\, \text{eV}^2, \sin^2 \theta_{12} = 0.307, \sin^2 \theta_{13} = 0.241 \times 10^{-2}, \sin^2 \theta_{23} = 3.86 \times 10^{-1},$
CP violation phase $\delta = 1.08\pi$, and a normal mass hierarchy is assumed (Fogli et al. 2012).

For the reason above, we are obliged to calibrate the level crossing effect. The jumping probability is approximately computed using the WKB method (Kuo 1989; Yasuda 2014):

$$ P = \frac{\exp\left[-\frac{\pi}{2} F\right] - \exp\left[-\frac{\pi}{2} F \sin^2 \theta\right]}{1 - \exp\left[-\frac{\pi}{2} F \sin^2 \theta\right]}, \quad (5) $$

where $F$ is a factor depending on the density profile. Then in Figure 2 we plot $P_{H}$ and $P_{L}$ versus neutrino energy, representing the jumping probability from energy eigenstate $\nu_{1m}$ to $\nu_{3m}$ and from $\nu_{1m}$ to $\nu_{2m}$, respectively.

2.3. Three-neutrino Mixing

2.3.1. Neutrino Oscillation in the Envelope

The evolution equation for neutrinos in matter is given by

$$ i\frac{d\Psi}{dt} = \left[H_0 + U V_{\text{eff}}\right]\Psi, \quad (6) $$

where $H_0 = \frac{1}{2\epsilon}\text{diag}(\delta m_{12}^2, 0, \delta m_{23}^2)$ and $\Psi^T \equiv (\nu_e, \nu_\mu, \nu_\tau)$ is the flavor eigenstate (Fraija 2014). $U$ is the three-neutrino mixing matrix,

$$ U = \begin{pmatrix}
    c_{12} c_{13} & s_{12} c_{13} \\
    -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} \\
    s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} \\
    s_{13} e^{-i\delta} & s_{23} c_{13} \\
    s_{23} c_{13} & c_{23} c_{13}
\end{pmatrix}, \quad (7) $$

where $s_{ij} \equiv \sin \theta_{ij}, c_{ij} \equiv \cos \theta_{ij}$.

Neutrino mixing angles in matter can be expressed as (Fraija 2014; Yasuda 2014)

$$ \sin 2\theta_{13,m} = \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} - 2E_{\text{eff}}/\delta m_{13}^2)^2 + (\sin 2\theta_{13})^2}}, $$

$$ \sin 2\theta_{12,m} = \frac{\sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} - 2E_{\text{eff}}/\delta m_{12}^2)^2 + (\sin 2\theta_{12})^2}}. \quad (8) $$

The effective mixing angles $\theta_{13,m}, \theta_{12,m}$ become maximum, $\pi/4$, as resonance conditions $\cos 2\theta_{13} = 2E_{\text{eff}}/\delta m_{13}^2$ and $\cos 2\theta_{12} = 2E_{\text{eff}}/\delta m_{12}^2$ are fulfilled, respectively. We can see that $\theta_{13,m}, \theta_{12,m}$ are functions of neutrino energy and radius since $V_{\text{eff}} = V_{\text{eff}}(r)$. We plot $\theta_{13,m}, \theta_{12,m}$ versus energy at radius $r_0 = 1.0 \times 10^{11}$ cm in Figure 3(a) and find that $\theta_{13,m}$ reaches maximum for $\sim 2$ TeV neutrinos. Here the radius $r_0$ is treated as the birth site of high-energy neutrinos. The reason for this is that the Thomson optical depth is $\tau_T = n\sigma_T m_e / (\rho c^2)$ and at $r = r_0$ we have $\tau_T \approx 1$, thus ensuring efficient shock acceleration (Xiao & Dai 2014). We also plot the effective mixing angles versus energy at the progenitor surface $R = 4 \times 10^{11}$ cm in Figure 3(b) and how they evolve with propagation distance for 1 TeV neutrinos in Figure 3(c). In addition, we find that the effective mixing angles tend to be constantly zero for PeV neutrinos, which is the main reason for the constant flavor ratio and will be shown later.

The transition probability from one flavor to another after level crossing calibration can be expressed as (Yasuda 2014)

$$ P(\nu_\alpha \rightarrow \nu_\beta) = \left|U_{\alpha 1,m} P_{1, \beta 2} U_{\beta 2, 3, m} \right|^2 \chi \left( \begin{array}{ccc}
    1 - P_{H} & P_{H} & 0 \\
    P_{H} & 1 - P_{H} & 0 \\
    0 & 0 & 1
\end{array} \right) \chi \left( \begin{array}{ccc}
    1 - P_{H} & 0 & P_{H} \\
    0 & 1 & 0 \\
    P_{H} & 0 & 1 - P_{H}
\end{array} \right) \chi \left( \begin{array}{cc}
    |U_{\alpha 1,m}|^2 & |U_{\alpha 2,m}|^2 \\
    |U_{\alpha 3,m}|^2
\end{array} \right), \quad (9) $$

where $\alpha, \beta = e, \mu, \tau$ and $U_{\alpha i,m}, U_{\beta j,m}$ are the mixing matrix elements in matter.

We plot the nine mutual transition probabilities between three neutrino flavors as functions of neutrino energy at different radii in Figures 4(a) and (b) and the evolution with propagation distance for given energies in Figures 4(c) and (d). Given an initial flavor ratio $\phi^0_\alpha; \phi^0_\beta; \phi^0_\tau = 2: 0: 0$, we can plot how the flavor ratio changes with energy and distance when neutrinos are still in the envelope in Figures 5(a)–(d). The deviation from 1: 2: 0 at the birth site $r_0$ is due to the level crossing effect for different energies. We can see the trend that the flavor ratio changes more gently for neutrinos with higher
energies. For PeV neutrinos, the flavor ratio is almost a constant value \( \phi_{\text{Earth}} \approx \nu_\tau : \nu_\mu : 0.21 : 0.77 : 0.02 \) in the envelope.

### 2.3.2. Neutrino Oscillation from the Progenitor to Earth

Neutrinos go through vacuum oscillation after leaving the progenitor surface, which is widely understood. We can express the transition probability \( P^0_{\alpha \beta} \) as the first-order expansion of the small parameter \( \sin \theta_{13} \) (Xing & Zhou 2006):

\[
\begin{align*}
P^0_{ee} & = 1 - \frac{1}{2} \sin^2 2\theta_{12}, \\
P^0_{\mu \mu} & = \frac{1}{2} \sin^2 2\theta_{12} \cos^2 \theta_{23} \\
& \quad + \frac{1}{4} \sin 4\theta_{12} \sin 2\theta_{23} \sin \theta_{13} \cos \delta, \\
P^0_{e\tau} & = \frac{1}{2} \sin^2 2\theta_{12} \sin^2 \theta_{23} \\
& \quad - \frac{1}{4} \sin 4\theta_{12} \sin 2\theta_{23} \sin \theta_{13} \cos \delta, \\
P^0_{\mu \tau} & = \frac{1}{2} \sin^2 2\theta_{23} - \frac{1}{2} \sin^2 2\theta_{12} \cos^2 \theta_{23} \\
& \quad - \frac{1}{2} \sin 4\theta_{12} \sin 2\theta_{23} \cos \theta_{23} \sin \theta_{13} \cos \delta, \\
P^0_{\tau \tau} & = 1 - \frac{1}{2} \sin^2 2\theta_{23} - \frac{1}{2} \sin^2 2\theta_{12} \sin^2 \theta_{23} \\
& \quad + \frac{1}{8} \sin 4\theta_{12} \sin 4\theta_{23} \sin \theta_{13} \cos \delta,
\end{align*}
\]

The flavor ratio on Earth is

\[
\begin{pmatrix}
\phi_{\nu_e} \\
\phi_{\nu_{\mu}} \\
\phi_{\nu_\tau} \\
\phi_{\nu_{\text{Earth}}}
\end{pmatrix} =
\begin{pmatrix}
P^0_{ee} & P^0_{\mu e} & P^0_{\tau e} \\
P^0_{\mu e} & P^0_{\mu \mu} & P^0_{\mu \tau} \\
P^0_{\tau e} & P^0_{\mu \tau} & P^0_{\tau \tau}
\end{pmatrix}
\]

**Figure 3.** Effective mixing angles in matter for neutrinos with different energies at different radii: (a) born site \( r_0 = 1 \times 10^{11} \) cm, (b) progenitor surface \( R = 4 \times 10^{11} \) cm, and (c) 1 TeV neutrinos. In all three panels, the red line represents \( \theta_{13,m} \) and the blue line is \( \theta_{12,m} \). All angles are measured in radians.
We plot the flavor ratio versus neutrino energy just as it leaves the progenitor and on Earth in Figures 6 (a) and (b). We can clearly see that the flavor ratio varies with energy in a range of less than 100 TeV, while the flavor ratio stays invariant: \( \phi_\nu \approx 0.30: 0.37: 0.33 \) for PeV neutrinos.

2.4. Dependence on \( \alpha \)

It is reasonable to argue that the final neutrino flavor ratio depends on the density profile of the progenitor envelope. Apparently, with the same assumed envelope mass and radius, different values of the power-law index lead to different ambient envelope densities, thus the effective potentials are different. This will have an impact on the resonance conditions, effective mixing angles in matter, and transition probabilities.

In this subsection, we investigate how large this impact could be. Here, we adopt the same helium progenitor but with different a power-law index \( \alpha = 2.5, 2.7 \). Respectively, we can write them as \( \rho(r) = 2.52 \times 10^{26} r^{-2.5} \) g cm\(^{-3} \) and \( \rho(r) = 3.16 \times 10^{28} r^{-2.7} \) g cm\(^{-3} \) and all calculations have been repeated for these two cases.

We present our results in Figure 7. For simplicity, we only show the flavor ratio at the surface of the progenitor (Figure 7(a)) and on Earth (Figure 7(b)). It is clear that \( \alpha \) has an impact on the flavor ratio. At a given radius, the resonance conditions are shifted to higher energies for larger \( \alpha \). The lower limit of the neutrino energy for a constant flavor ratio is highest for \( \alpha = 2.7 \), which is several PeV, compared with sub PeV for \( \alpha = 2.5 \) and \( \sim 100 \) TeV for \( \alpha = 2 \). The reason is that the effective potential of neutrinos is lower for a steeper envelope density profile at the same radius, so higher neutrino energies are required to reach resonance conditions. Furthermore, the flavor ratio is evidently different before it reaches a constant for the three cases, so we can use the observed ratio of neutrino energy from TeV to several hundred TeV scales to probe the stellar structure, provided that we can observe...
precursor neutrinos of a GRB with km² scale detectors like IceCube in the future.

3. DISCUSSIONS AND CONCLUSIONS

High-energy neutrinos can be produced while the jet is still propagating in the envelope, and LL-GRBs with typical parameters are responsible for TeV–PeV neutrinos. These neutrinos will oscillate with the matter effect in the envelope and go through vacuum oscillation after leaving the progenitor until they arrive at Earth. We investigate the three-neutrino mixing properties with the matter effect and then get the expected flavor ratio on Earth, given an initial ratio $\phi_0 = \nu_\tau : 1 : 2 : 0$.

We note that adiabatic conversion is violated because the level crossing effect is non-negligible for such high-energy neutrinos. After calibrating this effect, we get the neutrino mixing angles in matter and nine transition probabilities. We find that the effective mixing angles tend to be zero for neutrinos on the high-energy end ($\sim$PeV), resulting in a constant transition probability and constant flavor ratio. For PeV neutrinos, we always get $\delta_\nu : \delta_\mu : \delta_\tau \approx 0.30 : 0.37 : 0.33$ on Earth.

From our expectations, the final neutrino ratio will depend on the density profile parameter $\alpha$. We take $\alpha = 2, 2.5, 2.7$ to verify the dependence, and the result is clear in Figure 7. While the flavor ratio on the high-energy end stays constant, it is evidently different for neutrinos with energies from TeV to several hundred TeV scales, thus providing a promising way to probe the stellar structure in the future.

In this paper, we only investigate the high-energy neutrino oscillation of one typical LL-GRB for the given parameters. Changing these parameters may have an impact on the flavor ratio–neutrino energy dependence in the TeV range: at a given radius, the resonance energy may differ and the lower limit of the neutrino energy for a constant flavor ratio is also different, similar to the features shown in Figure 7. However, it does not influence the final flavor ratio of PeV neutrinos because the envelope is always too “dense” for PeV neutrinos, the effective mixing angles of which always tend to be constantly zero. The case is the same when changing the envelope temperature $T$. Although the number density of the electrons varies for different $T$, the effective mixing angles for PeV neutrinos are always zero and the constant flavor ratio $\delta_\nu : \delta_\mu : \delta_\tau \approx 0.30 : 0.37 : 0.33$ on Earth is still expected. However, this constant value may differ from 0.30 : 0.37 : 0.33 due to the uncertainties.

Figure 5. Evolution of the flavor ratio in matter vs. radius for neutrinos with four different energies: (a) 1 TeV neutrinos, (b) 10 TeV neutrinos, (c) 100 TeV neutrinos, and (d) 1 PeV neutrinos. In all four panels, the red line represents the fraction of $\nu_e$, the green line is $\nu_\mu$, and the blue line is $\nu_\tau$. 

(a) Flavor ratio evolves versus radius for 1TeV neutrinos

(b) Flavor ratio evolves versus radius for 10TeV neutrinos

(c) Flavor ratio evolves versus radius for 100TeV neutrinos

(d) Flavor ratio evolves versus radius for 1PeV neutrinos
of the vacuum oscillation parameters and neutrino mass hierarchy.

The IceCube experiment has recently reported the observation of 37 high-energy ($\geq 30$ TeV) neutrino events, separated into 28 showers and 9 muon tracks, and being consistent with an extraterrestrial origin (IceCube Collaboration 2014). To correlate with the observations, we use the hypothesis that all the IceCube neutrinos are produced by LL-GRBs before the jet breakout. Mena et al. (2014) claimed that $\phi_{\nu} = \phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1: 1: 1$ at Earth is disfavored at 92% C.L. with the recently released three-year data, while the newest analysis showed a best fit of $0.02: 0.8$ (IceCube Collaboration 2015). On one hand, the neutrino flavor ratio in the detector may be changed by the Earth matter effect (Varela et al. 2014). On the other hand, this does not conflict with our conclusion. We recommend an analysis of the observed shower-to-track ratio in different energy bins when performing the data reduction since we know that the flavor ratio depends strongly on the neutrino energy and an overall 1:1:1 ratio does not make any sense. Nevertheless, we expect a constant flavor ratio for PeV neutrinos but we have observed only three PeV events now. So our result is to be verified with a larger data set of TeV–PeV neutrinos from IceCube in the future. If this constant value appears in the next few decades, when we will have observed tens of PeV neutrino events, we can constrain the structure of LL-GRB progenitors and the vacuum oscillation parameters by exactly measuring this value. If there is no sign of such a constant ratio, the most probable reason is that there exist other dominant PeV neutrino sources. The hypothesis that all observed neutrinos are produced in the jet propagation process of LL-GRBs may not be complete because they may also originate from other cosmic-ray sources like active galactic

(a) Flavor ratio versus energy when neutrinos are just leaving the progenitor

Figure 6. Neutrino flavor ratio vs. energy before and after long-distance vacuum oscillation: (a) when neutrinos are leaving the progenitor and (b) on Earth. As in Figure 5, the red line represents the fraction of $\nu_e$, the green line is $\nu_\mu$, and the blue line is $\nu_\tau$.

(b) Flavor ratio versus energy on Earth

(a) Comparison of flavor ratios versus energy when neutrinos are just leaving the progenitors for three different envelope power law indexes

(b) Comparison of flavor ratios versus energy on Earth for three different progenitor envelope power law indexes

Figure 7. Dependence of flavor ratios vs. energy before and after long-distance vacuum oscillation on the progenitor envelope power-law index: (a) when neutrinos are leaving the progenitor and (b) on Earth. The red lines represent the fractions of $\nu_e$, the green lines are $\nu_\mu$, and the blue lines are $\nu_\tau$. Additionally, solid lines show $\alpha = 2$, dotted lines $\alpha = 2.5$, and dashed lines $\alpha = 2.7$. 

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nuclei or they can be produced in other stages of a GRB event such as by internal and external shocks. We hope that one day we can observe the neutrino precursor of a GRB event; this neutrino–GRB correlation is crucial for our understanding of the structure of the progenitor envelope and the jet propagation dynamics. For a complete comparison with the observation, the flavor ratio in the TeV range of the diffuse neutrino background produced by GRBs needs to be done and is beyond the scope of this paper.

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