Sensitivity of JEM-EUSO to GRB neutrinos

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***Abstract*. JEM-EUSO is a mission to study ultra-high-energy cosmic rays (UHECRs) by measuring the fluorescence light from giant air showers at the altitude of the International Space Station. In the tilted mode, JEM-EUSO will become very sensitive to the Čerenkov light from the earth skimming tau neutrinos at the energy range of 10^{16-18}eV. In this paper we will discuss high-energy tau neutrinos from nearby gamma-ray bursts (GRBs). From simulations of cascade in GRB photon fields including various hadronic/leptonic processes, we estimate the neutrino flux from GRBs. Our results show that both muons and pions are dominant sources of neutrinos at the energy range of 10^{16-18} eV. We discuss the possibility of detecting the Čerenkov light of upward going showers from Earth skimming tau neutrinos coming from some closest GRBs.**

***Keywords*: Gamma-ray Bursts, Neutrinos, Air Showers**

I. INTRODUCTION

JEM-EUSO (Extreme Universe Space Observatory) [1] is an observatory that will be installed on the Japanese Experiment Module (JEM) on the International Space Station (ISS) at an altitude of approximately 400km. The launch is planned for 2013 by H2B rocket and conveyed by the HTV (H-II transfer Vehicle) to ISS. It observes extensive air showers (EAS) induced by ultra-high-energy cosmic rays (UHECRs) with the energy higher than about 10^{19} eV. The super-wide Field-of-View (FOV $\pm 30°$) yields a circle with a 250 km radius of the observational aperture of the ground area. The targets of JEM-EUSO are not only UHECRs but also upward neutrino events. The atmospheric volume in the FOV of JEM-EUSO is about 10^{12} tons. However, the effective area is increased by inclining the telescope from nadir (tilted mode), so that the target volume for upward neutrino events exceeds 10^{13} tons. On the other hand, the threshold energy to detect EAS increases too. The first half of the mission lifetime is devoted to observing the lower energy region in the nadir mode, and the second half of the mission to observing the high energy region in tilted mode.

The physical conditions of gamma-ray bursts (GRBs) inferred for internal shocks [2] indicate that protons may be Fermi-accelerated to energies of $\sim 10^{20}$ eV, making GRBs potential sources of the observed UHECRs [3]. To test this GRB UHECR scenario, it is indispensable to search for UHE proton-induced signatures of secondary neutral radiation that can be observed in coincidence with GRBs. Although the proton-induced gamma-ray emissions, such as synchrotron emission from secondary electrons/positrons injected via photomeson interactions, have been discussed frequently [4], [5], it may not be easy from photon spectra to distinguish the signature of protons from inverse Compton emissions due to primary accelerated electrons. Therefore, the detection of high-energy neutrinos from GRBs [6] is essential to verify the proton acceleration in GRBs. Many authors have estimated the cosmological neutrinos background due to GRBs [7]. The correlation between neutrino signals and GRBs may verify a GRB UHECR scenario. JEM-EUSO provides us the unique chance to detect very high-energy neutrinos above 10^{16} eV, but whose background flux is probably too low to correlate each shower event with a GRB. Alternatively, we discuss the possibility of neutrino detection from a nearby bright GRB with JEM-EUSO.

II. MODEL

We employ the numerical code in Asano et al. (2009) [8] (see also [5]) to simulate hadronic cascade processes in GRBs with Monte Carlo techniques. While Asano et al. (2009) focused on the photon emissions due to accelerated protons, the numerical code automatically outputs resultant neutrino spectra. The physical processes taken into account are 1) photon emission processes of synchrotron and Klein-Nishina regime Compton scattering for electrons/positrons, protons, pions, muons, and kaons, 2) synchrotron self-absorption for electrons/positrons, 3) $\gamma\gamma$ pair production, 4) photomeson production from protons, 5) photopair production ($p\gamma \rightarrow pe^+e^-$) from protons, 6) decays of pions, muons, and kaons. For photomeson productions, the method is the same as Asano & Nagataki (2006) [9]; we adopt experimental results for the cross sections of $p(n)\gamma \rightarrow n\pi^+(\pi^0)$, $p\pi^0(\pi^-)$, $n\pi^+\pi^0(\pi^-)$, and $p(n)\pi^+\pi^-$, while theoretically obtained values [10], [11] are adopted for kaon productions via $p\gamma \rightarrow \Lambda K^+$, $\Sigma^0 K^+$, and $\Sigma^+ K^0$, or $n\gamma \rightarrow \Lambda K^0$, $\Sigma^- K^+$, and $\Sigma^0 K^0$. More details on the treatment of meson production and their decay products can be found in Asano (2005) [12] and Asano & Nagataki (2006) [9].

Both electrons and protons are assumed to be injected with power-law energy distributions as $\propto E^{-p}\exp(-E/E_{\rm max})$. In order to make a GRB UHECR scenario viable, the proton spectrum index is required to be $p_{\rm p}=2$, which is harder than the typical index of electrons $p_{\rm e}$ obtained from GRB photon spectra. Although the injection spectra for the two species are expected to be the same at low energies where their gyroradii overlap, $p_{\rm e}>p_{\rm p}$ may be effectively realized if the proton spectrum covering 7-8 decades in energy deviates from a pure power-law and becomes concave. Such possibilities are shortly mentioned in Asano et al. (2009) [8]. Hence, we adopt $p_{\rm p}=2$ and $p_{\rm e}=2.5$ in our simulations as optimistic cases. The maximum proton energy is determined by equating the acceleration timescale and cooling/dynamical timescale, taking into account synchrotron, IC, and photomeson cooling.

We consider relativistically expanding shells, where all photons and particles are distributed isotropically in the shell frame and treated in the one-zone approximation. We use conventional notation $\epsilon_{\rm e}$, $\epsilon_{\rm p}$ and $\epsilon_{\rm B}$, for the energy fractions of accelerated electrons, protons and magnetic fields to the shock-dissipated internal energy. The minimum Lorentz factor of electrons is chosen so that the corresponding synchrotron photon energy is always 300 keV. Thus, the full set of our model parameters consists of the bulk Lorentz factor Γ, variability timescale $\Delta t=R/c\Gamma^2$ (or emission radius R), energy of accelerated electrons in the shell $E_{\rm sh}$, the energy fractions $\epsilon_B/\epsilon_{\rm e}$ and $\epsilon_{\rm p}/\epsilon_{\rm e}$. In the plasma rest frame, we follow all physical processes mentioned above in a volume $4\pi R^3/\Gamma$ during a timescale $R/c\Gamma$ with sufficiently short time steps.

Fig. 1 shows the photon spectrum obtained by our simulation assuming the equipartition between protons and electrons, $\epsilon_{\rm p}/\epsilon_{\rm e}=1.0$. The other parameters are denoted in the figure caption. The proton cascade processes enhance the photon energy by $\sim 7\%$. We can clearly see the effects of $\gamma\gamma$ absorption and synchrotron self-absorption around GeV and 100 eV energies, respectively. The deviation from a simple power-law spectrum near the synchrotron self-absorption energy is due to the heating via self-absorption, which modifies the effective electron distribution (the synchrotron boiler effect [13]). The contribution of inverse Compton emission is suppressed because of the Klein-Nishina effect in spite of the lower value of $\epsilon_B/\epsilon_{\rm e}=0.1$.

As shown in Fig. 1, a significant amount of muons is produced via photomeson production. Since our code outputs escaped photons and neutrinos simultaneously, the resultant neutrino spectra are consistent with obtained photon spectra, taking into account cooling of pions, muons and kaons.

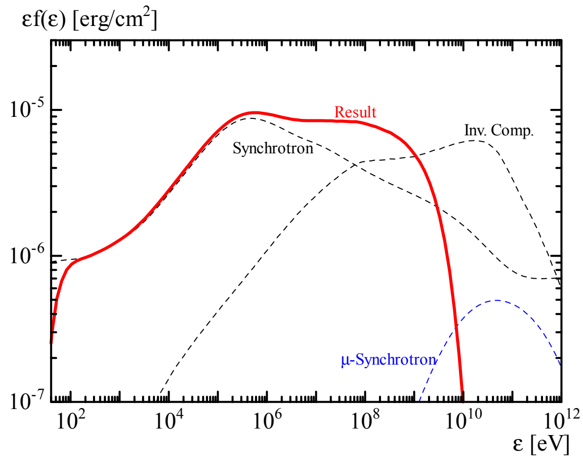

Fig. 1: Photon spectrum (bold solid curve) of a GRB pulse at 1 Gpc of the luminosity distance ($z=0.2$) with $\Gamma=500$, $\Delta t=50$ ms, $E_{\rm sh}=10^{52}$ erg, $\epsilon_B/\epsilon_{\rm e}=0.1$, and $\epsilon_{\rm p}/\epsilon_{\rm e}=1.0$. Fine dashed curves denote separately electron/positron synchrotron, inverse Compton, and muon synchrotron components without the absorption effects.

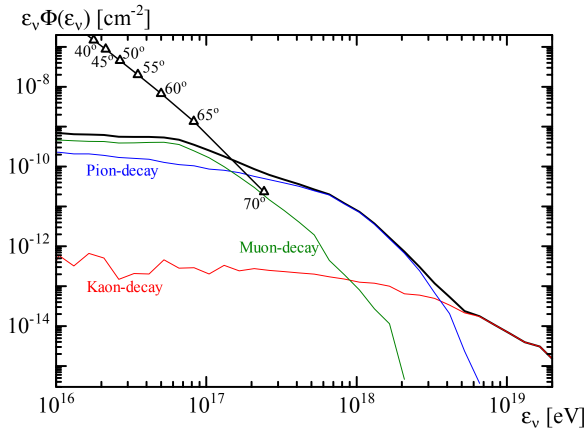

Fig. 2: τ-neutrino spectra (bold solid curve) for the same parameter set as Fig. 1. 100 identical pulses are assumed to be emitted from a GRB at 1 Gpc (the total energy of gamma-rays $\sim 10^{54}$ erg). Fine solid curves denote neutrinos from decay of muons, pions, and kaons as labeled. The triangles show the threshold energy and the 99% C.L. flux sensitivity with JEM-EUSO as a function of the nadir angle as labeled.

III. Neutrino Detection Sensitivity

Assuming the neutrino cross section $\sigma_{\nu{\rm N}}=2.0\times10^{-33}(\varepsilon_\nu/10^{16}{\rm eV})^{0.363}{\rm cm}^2$, τ-deacy length $500(E_\tau/10^{16}{\rm eV})$ m, reflective index of air $n=1.0003$ (the Čerenkov light cone of 1.4°), and density of the mantle $4.5{\rm g/cm}^3$, we estimate the sensitivity and threshold energy of τ-neutrinos as a function of the nadir angle for JEM-EUSO at an altitude of 400km (see Fig. 2).

Since almost all neutrinos in the nadir direction are absorbed within the earth, it may be very difficult to detect EAS due to τ-decay in the nadir mode (the nadir angle of neutrinos $< 30°$). As the nadir angle of neutrinos in the FOV increases, the threshold energy of neutrinos gets higher, since the mean distance to EAS and atmospheric absorption both increase. However, the larger nadir angle and resultant higher energy threshold lead to a larger target volume due to the longer lifetime of τ in the Earth crust, which give us a effectively thicker target volume. The larger nadir angle also lead to a longer distance between tau showers and the detector which produces a larger light pool of Cerenkov and effectively gives a wider target area on the Earth. These two effects give us a huge effective target volume for the detection of showers induced by tau neutrinos. As a result, the sensitivity increases with the nadir angle of neutrinos. In this estimate we have not performed detailed Monte Carlo simulations of development of EAS etc., which is in preparation now, so that the sensitivity curve in the figure is preliminary.

In Fig. 2, we plot τ-neutrino spectra, assuming that neutrino oscillation makes the fraction of tau-neutrinos 1/3. As Asano & Nagataki (2006) [9] pointed out, neutrinos from kaons dominate in the highest energy range above 10^{19} eV, because kaons, heavier than pions, do not lose so much energy before they decay into neutrinos. In the energy range of 10^{17}-$10^{18.5}$ eV, the dominant component is neutrinos from $\pi^{\pm}$-decay, while neutrinos from μ-decay is the primary component below 10^{17} eV. The maximum energies of neutrinos are determined by the balance between the cooling time and the decay time of seed particles. The obtained spectrum shows a complex shape reflecting the difference in the cooling of seed particles.

The feasible tilt angle of JEM-EUSO may be below $35°$, so that a nadir angle should be $< 65°$. Even for this nearby (1 Gpc) and bright (total gamma-ray energy $\sim 10^{54}$ erg) GRB, we need $> 65°$ for the nadir angle of neutrinos, though more sophisticated estimates via EAS simulations may significantly improve the sensitivity.

IV. Proton-Dominated GRBs

While the equipartition between protons and electrons is assumed in the former section, we should consider the possibility that GRBs contain a significantly larger amount of energy in protons compared to that radiated by the accelerated electrons. From the local UHECR emissivity at proton energy $\sim 10^{19}$ eV, the necessary isotropic-equivalent energy per burst in accelerated protons integrated over $\sim 10^9 - 10^{20}$ eV is $\sim 2 \times 10^{54} - 3 \times 10^{55}$ erg [14]. On the other hand, isotropic-equivalent gamma-ray energy is typically $\sim 10^{53}$ erg and up to $\sim 10^{54}$ erg. Thus, in order for GRBs to be viable sources of UHECRs, the latest observations point to a highly proton-dominated energy budget, $\epsilon_{\rm p}/\epsilon_{\rm e} \sim$ 10-100, which is approximately independent of the actual beaming factor. In the internal shock model, shocks convert a fraction of the bulk kinetic energy of outflows into

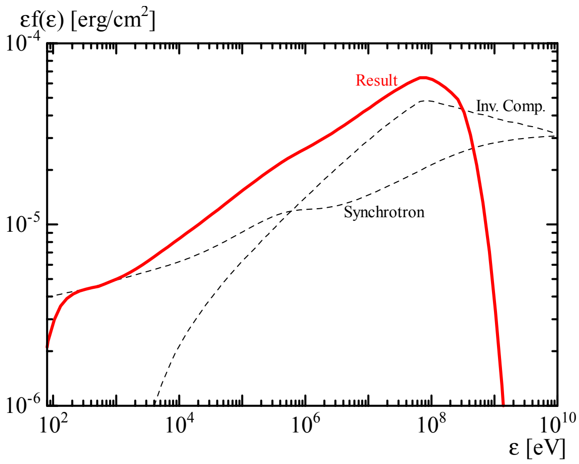

Fig. 3: Same as Fig. 1 but for $\epsilon_{\rm p}/\epsilon_{\rm e} = 30$.

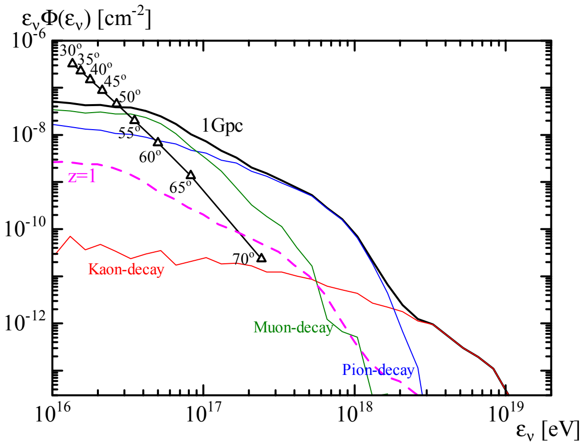

Fig. 4: Same as Fig. 2 but for $\epsilon_{\rm p}/\epsilon_{\rm e} = 30$. The bold solid line is for a GRB at 1 Gpc, while the dashed line is for $z = 1$.

Fermi-accelerated relativistic electrons. Initially, however, most of the kinetic energy as well as the internal energy generated via shock dissipation are likely carried by protons, The simple 1$^{\rm st}$ order Fermi acceleration theory may predict higher acceleration efficiency of protons compared to electron acceleration, because the Larmor radius of shock-dissipated electrons is smaller than that of protons.

As Asano et al. (2009) [8] supposed, we calculate photon and neutrino spectra for proton-dominated GRBs as shown in Figs. 3 and 4. In our parameter choice $\epsilon_{\rm p}/\epsilon_{\rm e} = 30$, the proton-induced secondary emission totally overwhelms any primary electron component, resulting in a hard spectrum peaking at 100 MeV, which is determined by $\gamma\gamma$ optical depth. The dominant components are inverse Compton and synchrotron emission from secondary electrons/positrons. The proton contribution enhances resultant gamma-ray energy by a factor of 5. Although the obtained photon spectrum differs from the typical GRB spectra, Kaneko et al. (2008) [15] reported a similar GRB spectrum with a high peak energy > 170 MeV, as well as a few other

GRBs with significant high-energy excess. Some studies have also indicated potential observational biases against detections of high peak energies [16]. If we adopt a larger Γ, the proton cascade efficiency is diminished, which can lead to a typical shape of GRB spectra. However, lower efficiency of the proton cascade weakens neutrino emission, too.

The τ-neutrino spectrum for such an optimistic case is plotted in Fig. 4. The larger amount of protons and higher efficiency of pion production amplify the neutrino flux. As shown in Fig. 4, if such a nearby and bright GRB with the nadir angle $> 50^\circ$ occurs inside the FOV of JEM-EUSO, EAS due to τ-neutrinos will be detected. For the nadir angle of $\sim 70^\circ$, more distant GRBs at $z \sim 1$ can be detected.

V. Discussion

If a nearby (< 1 Gpc) GRB fortunately occurs, a considerable neutrino flux has been predicted by our model for the nadir angle $\sim 65^\circ$. Post-*SWIFT* estimates of the local rate of long GRBs range from $0.2-1\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ [14], if the GRB rate is proportional to the star formation rate. Therefore, we may expect a few GRBs within 1 Gpc per year. For a tilt angle of 35°, neutrinos from the nadir angle 65° yield a very tiny solid angle in the FOV. If we can take a larger tilt angle, though it may be not realistic, the solid angle for the nadir angle 65°-70° can be ~ 0.1 rad. So the detection possibility of nearby GRBs may be a few percent per year in this case, though we should take into account the dead time of observation. If proton-dominated GRBs at 1 Gpc, which is compatible with the GRB-UHECR scenario, are actual cases, neutrinos with the nadir angle $> 50^\circ$ can be detected. The solid angle of such neutrinos is ~ 0.1 rad in the FOV for the tilted mode of 35°, which implies a few percent of the GRB detection possibility per year. Although the above estimate of the GRB rate in the FOV may sound pessimistic, those finite possibilities are not negligible. The luminous neutrino flux in the proton-dominated model encourages us to detect neutrinos from GRBs even at $z \sim 1$, which is the typical redshift of GRBs (~ 100 events per year). In this optimistic scenario, the larger volume within $z \sim 1$ enhances the detection possibility, while we need a larger tilt angle.

A more realistic sensitivity curve for upward neutrino events is now in preparation by the JEM-EUSO collaboration. The unique capability of JEM-EUSO provides us with an exclusive chance to detect very high-energy neutrinos from GRBs.

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