OBSERVATIONAL SEARCH FOR PeV–EeV TAU NEUTRINO FROM GRB081203A

Y. Aita1, T. Aoki1, Y. Asaoka1, T. Chonan4, T. Jobashi1, M. Masuda1, Y. Morimoto1, K. Noda1, M. Sasaki1, J. Asoh1, N. Ishikawa1, S. Ogawa2, J. G. Learned3, S. Matsuno3, S. Olsen3, P.-M. Binder4, J. Hamilton4, N. Sugiyama5, and Y. Watanabe6

(ASHRA-1 COLLABORATION)

1 Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan; asaoka@icrr.u-tokyo.ac.jp, sasakim@icrr.u-tokyo.ac.jp
2 Department of Physics, Toho University, Funabashi, Chiba 274-8510, Japan
3 Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA
4 Department of Physics and Astronomy, University of Hawaii at Hilo, Hilo, HI 96720-4091, USA
5 Department of Physics and Astrophysics, Nagoya University, Nagoya, Aichi 464-8601, Japan
6 Department of Engineering, Kanagawa University, Yokohama, Kanagawa 221-8686, Japan

Received 2011 April 29; accepted 2011 June 10; published 2011 June 28

ABSTRACT

We report the first observational search for tau neutrinos ($\nu_\tau$) from gamma-ray bursts (GRBs) using one of the Ashra light collectors. The Earth-skimming $\nu_\tau$ technique of imaging Cherenkov $\tau$ showers was applied as a detection method. We set stringent upper limits on the $\nu_\tau$ fluence in PeV–EeV region for 3780 s (between 2.83 and 1.78 hr before) and another 3780 s (between 21.2 and 22.2 hr after) surrounding GRB081203A triggered by the Swift satellite. This first search for PeV–EeV $\nu_\tau$ complements other experiments in energy range and methodology, and suggests the prolonge of “multi-particle astronomy" with a precise determination of time and location.

Key words: gamma-ray burst: individual (GRB 081203A) – methods: observational – neutrinos

Online-only material: color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs) eject the most energetic outflows in the observed universe, with jets of material expanding relativistically into the surrounding interstellar matter with a Lorentz factor $\Gamma$ of 100 or more. Energy dissipation processes involving nonthermal interactions between particles are thought to play an important role in GRBs, but remain observationally unresolved. The detection of PeV–EeV neutrinos ($\nu_\tau$'s) from a GRB provides direct evidence for the acceleration of hadrons into the EeV range, and of photo-pion interactions in the GRB. The GRB standard model (Mészáros 2006, and references therein), which is based on internal/external shock acceleration, has been used to describe the general features of a GRB and the observed multi-wavelength afterglow. However, the standard model cannot well reproduce recent observational results. The early X-ray afterglows detected by Swift exhibited a canonical behavior of steep-flat-steep in their light curve (Nousek et al. 2006). In 10%–15% of GRBs, precursor activities were observed (Burton et al. 2008). In some cases, the precursor preceded the main burst by several hundred seconds with significant energy emission. In the Fermi observations of GRB090510 and GRB090902B, spectral fits revealed a hard power-law component (Abdo et al. 2009). The Swift and Fermi observations of GRB090510 detected gamma rays (\gamma's) in the GeV range up to 200 s after the lower energy trigger (De Pasquale et al. 2010). Although many authors have proposed theoretical models to reproduce the complicated time evolution of GRBs and the high energy components in the prompt emission, none of these models are conclusive (Ackermann et al. 2010). To better understand the ambiguous mechanisms of GRBs, observational probes of the optically thick region of the electromagnetic components, as well as hadron acceleration processes throughout the precursor, prompt, and afterglow phases are required. Very high energy (VHE) $\nu_\tau$'s can be used as direct observational probes, which are effective even in optically thick regions. A monitor search with sufficient time and spatial resolution and survey capability for VHE\gamma's associated with GRBs is plausible.

The Earth-skimming tau neutrino ($\nu_\tau$) technique, which detects extensive air showers (Fargion 2002), has the advantage of a large target mass, since it uses air showers produced by decay particles of tau leptons ($\tau$'s) in the atmosphere as the observed signals. $\tau$'s emerge out of the side of the mountain or the ground facing the detector; they are the product of interactions between VHE $\nu_\tau$ and the Earth matter they traverse. Above 1 EeV, air fluorescence observations based on the Earth-skimming $\nu_\tau$ technique have been reported (Abraham et al. 2008). No air Cherenkov observation has been made to date based on the Earth-skimming $\nu_\tau$ technique with air showers induced by $\tau$ decays (hereafter referred to as the Cherenkov $\tau$ shower method). But it can achieve sufficient detection sensitivity in the PeV–EeV region to be useful in the search for $\nu_\tau$'s originating from hadrons accelerated to EeV at astronomical objects. Additional advantages of the Cherenkov $\tau$ shower method are its perfect shielding of cosmic-ray secondary particles, highly precise arrival direction determination for primary $\nu_\tau$ and negligible background contamination by atmospheric $\nu_\tau$'s in the PeV–EeV energy range.

2. ASHRA EXPERIMENT AND OBSERVATION

The all-sky survey high-resolution air-shower detector (Ashra) is a complex of unconventional optical collectors that image VHE air showers in a 42° diameter field of view (FOV) covering 77% of the entire night sky with a resolution of a few arcminutes (Sasaki 2008; Aita et al. 2008a; Sasaki et al. 2008). The first phase of the Ashra experiment (Ashra-I) was constructed on Mauna Loa at 3300 m above sea level on Hawaii Island, and includes an observatory. Ashra-I uses electrostatic lenses (Asaoka & Sasaki 2011) in addition to an optical system to generate convergent beams, enabling a very low cost and high...
performance image sensor, providing a high resolution over a wide FOV. The electron optics use an image pipeline to transport the image from the focal sphere of the reflective mirror optical system. After the light from the image is split, it is transported to both a trigger device and high-gain, high-resolution complementary metal-oxide semiconductor image sensor.

One of the Ashra light collectors built on Mauna Loa has the geometrical advantages of not only facing Mauna Kea, allowing it to encompass the large target mass of Mauna Kea in the observational FOV, but has also an appropriate distance of $\sim$30 km from Mauna Kea, yielding good observational efficiency when imaging air-shower Cherenkov lights which are directional with respect to the air-shower axis. Using the advanced features, we performed commissioning search for Cherenkov $\tau$ showers for 197.1 hr between October and December of 2008. We served limited 62 channels of photomultiplier tubes (PMTs) as trigger sensors prepared for the commissioning runs to cover the view of the surface area of Mauna Kea, maximizing the trigger efficiency for Cherenkov $\tau$ showers from Monte Carlo (MC) study, as shown in Figure 1. Adjacent-two logic was adopted to trigger the fine imaging, by judging discriminated waveform signals from each pixel of the multi-PMT trigger sensor. During the search period, $\sim$2 hr before the trigger of GRB081203A (Parsons et al. 2008), GRB counterpart (R.A. 15:32:07.58, decl. +63:31:14.9) passed behind Mauna Kea, as viewed from the Ashra-1 observatory. Using the same light collector but continuously taking fine images of split lights just before the trigger and readout sensors in the image pipeline, we set a limit on the light curve as a function of time in the region of 300 s bracketing the $\textit{Swift}$ trigger time for GRB081203A, including the precursor and prompt afterglow optical counterpart (Aita et al. 2008b).

3. ANALYSIS

To investigate the features, selection criteria, detection efficiency, and background rate for the observation of Cherenkov $\tau$ shower images, we generated $\nu_{\tau}$ MC events with primary energies of 1 PeV to 100 EeV by 0.5 decade steps, which entered into the rock of Mauna Kea uniformly and isotropically from a sufficiently large aperture. We used a geodetic database around Hawaii island (Mooney et al. 1998), and surveyed for ourselves the position of the observatory and the terrain of the mountain and its surroundings. To study the generation and propagation of $\tau$’s in the Earth and in the mountain, we used PYTHIA (Sjöstrand et al. 2001) to simulate the charged current interaction of $\nu_{\tau}$’s with nucleons and GEANT4 (Agostinelli et al. 2003) for the energy loss due to pair production and bremsstrahlung in $\tau$ propagation. Photonuclear interaction was estimated using the differential cross section given in Iyer Dutta et al. (2001) and Abramowicz & Levy (1997). TAUOLA (Jadach et al. 1993) was used for $\tau$ decays, and CORSIKA (thinning $= 10^{-7}$; Heck et al. 1998) for air showers induced by $\tau$ decays. To simulate the Ashra detector, we took into account the geometry, light collection area, mirror reflection, corrector lens transmittance, and the quantum efficiency of the photoelectric tubes, so that the fine images corresponding to the trigger judgement were simulated in an event-by-event manner. $\Delta \theta_{\nu}$, the deflection angle of $\tau$ with respect to the primary $\nu_{\tau}$, was estimated to be significantly less than 1 arcmin at energies above 1 PeV due to the physical processes occurring in the rock of the Earth and of the mountain (Y. Asaoka & M. Sasaki 2011, in preparation).

In addition, the reconstructed $\tau$ shower axis can point toward the $\nu_{\tau}$ object within an accuracy of 0.1 if the resolution of the image is sufficiently high. Therefore, the Cherenkov $\tau$ shower induced by PeV–EeV $\nu_{\tau}$ is a fine probe into VHE hadron accelerators once an image is obtained with sufficient resolution. Such images can be obtained with the Ashra detector.

The photometric and trigger sensitivity calibration of the Ashra light collector was based on a very stable YAP (YAlO$_3$:Ce)-light pulser (Kachanov et al. 1992) which was placed at the center of the input window of the photoelectric lens image tube mounted on the focal sphere of the optical system and illuminated it. Non-uniformity in the detector gain due to the input light position was relatively corrected by mounting a spherical plate uniformly covered with luminous paint on the input window. To correct for the time variation of the photometric and trigger sensitivity because of variations in atmospheric optical thickness, which were mainly due to clouds and hazes during the observation period, we performed careful cross-calibration to compare the instrumental photoelectric response with the photometry of standard stars such as BD+75D325 of B-magnitude 9.2, for which the detected images passed through the same optical and photoelectric instruments except for the final trigger-controlled readout device. We estimated the systematic uncertainty on the basis of our understanding of the detector sensitivity to be 30% after applying a combination of the above three complementary calibration procedures.

To validate the detection sensitivity and gain calibration for the Cherenkov $\tau$ shower, we detected and analyzed 140 events of ordinary cosmic-ray air-shower Cherenkov images for a total of 44.4 hr in 2008 December using the same instruments used in the Ashra light collector, but after rearranging the trigger pixel layout to view the sky field above Mauna Kea (Figure 1). In
the cosmic-ray observation, the trigger pixel layout is centered at zenith angle of \( \sim 65^\circ \). Due to the directionality of the air-shower Cherenkov lights, the photometric detection of the lights \( \mathcal{N}_\mathcal{Y} \) was strongly dependent upon the impact parameter \( R_p \) in addition to the primary energy \( E \). From a detailed study of MC-simulated proton shower events generated with CORSIKA, we obtained a correction function to estimate the observed primary energy \( \hat{E} \) as a function of \( \mathcal{N}_\mathcal{Y} \) and the long axis length \( \hat{L} \) calculated using Hillas analysis (Hillas 1985), where \( \hat{L} \) was used as an estimator of \( R_p \). As a result, the total MC reconstructed energy resolution was estimated to be 62% by evaluating the rms of the \( \Delta E/E = (\hat{E} - E)/E \) distribution, for which the error was dominated by the ambiguity in \( R_p \). The same reconstruction procedure was applied both to the observed data and the MC data. The observed and MC cosmic-ray flux spectra are shown in Figure 2, in which the MC prediction used data and the MC data. The observed cosmic-ray flux spectrum with bars indicating statistical and systematic errors and the MC predictions for proton primary (hatched band) and iron primary (shaded band) assumptions. The width of the bands shows the evaluated systematic error of 30% of the MC prediction (see the test).

(A color version of this figure is available in the online journal.)

The Astrophysical Journal Letters, 736:L12 (5pp), 2011 July 20

Figure 2. Observed cosmic-ray flux spectrum (filled box) with bars indicating statistical and systematic errors and the MC predictions for proton primary (hatched band) and iron primary (shaded band) assumptions. The width of the bands shows the evaluated systematic error of 30% of the MC prediction (see the text).

4. RESULTS

Figure 3 shows the effective areas for Cherenkov \( \tau \) showers induced by \( \nu_\tau \)'s from the GRB081203A counterpart as a function of \( \nu_\tau \) energy \( E_{\nu_\tau} \) assuming seven original positions on the counterpart trajectory (at elevation angles of \( -3^\circ 62 \sim 0^\circ 51 \)) with the Ashra light collector.

(A color version of this figure is available in the online journal.)

Figure 3. Effective area for Cherenkov \( \tau \) showers induced by \( \nu_\tau \)'s from the GRB081203A counterpart as a function of \( \nu_\tau \) energy \( E_{\nu_\tau} \) assuming seven original positions on the counterpart trajectory (at elevation angles of \( -3^\circ 62 \sim 0^\circ 51 \)) with the Ashra light collector.

candidate for the event. To ensure that \( C \) was within the effective fiducial FOV, the coordinates of the center of gravity (the center of the FOV was (0,0)) \((X_C, Y_C)\) of \( C \) were required to satisfy \(|X_C| < 13^\circ 8\), and \((X_C, Y_C)\) could not overlap any obstacles such as rocks or the Mauna Loa surface within the FOV. Sometimes, “car light events” were triggered when the light beams of a car on the Mauna Kea access road entered the FOV. We determined the coordinates of the original position \((X_{\text{car}}, Y_{\text{car}})\) by averaging \((X_C, Y_C)\) for events that were apparently identified as car light events in the FOV. The geometric distance \( D_{\text{car}} \) in the FOV between \((X_C, Y_C)\) and \((X_{\text{car}}, Y_{\text{car}})\) had to satisfy \( D_{\text{car}} > 0^\circ 2\). Remaining night sky backgrounds (NSBs) were rejected by requiring that \( \Sigma_C > 10 \Sigma_C \), where \( C \) was defined as the second largest cluster. The NSB rejection was also fairly effective at removing contamination from cosmic-ray \( \mu \) events, in which Cherenkov lights from cosmic-ray \( \mu \)'s passing through the input window glass (8 mm thick) of the photovoltaic lens image tube tended to separate into two or more clusters in the same image frame. In the MC study, the total selection efficiency for Cherenkov \( \tau \) showers after satisfying all requirements was estimated to be 99.9%, and the expected number of events of cosmic-ray \( \mu \) contamination was \( 5.8 \times 10^{-3} \) events. We evaluated a small residual contamination of the final candidate samples from secondary particles in large angle cosmic-ray air showers of \( 1.3 \times 10^{-4} \) events using CORSIKA with the curved Earth option. From the 197.1 hr of observation, five clusters were pre-selected as shower candidates after the fiducial FOV cut. Out of these five clusters, three were removed by the car light cut and two were removed by the NSB cut, yielding a null result.

For the \( \nu_\tau \) search, we used image data acquired using the trigger for 197.1 hr in only case of the data status defined as good out of the total observation time of 215.8 hr. Using a Source Extractor (Bertin & Arnouts 1996), we extracted “clusters” by requiring that of fired pixels \((N_{px})\) assigned to the cluster satisfied \( N_{px} > 4 \), where accumulated charge \((Q_{px})\) in the fired pixel \((px)\) was required to be \( Q_{px} > 6 \) ADC units. The primary cluster \( C \), defined as the cluster with the largest accumulated charge of fired pixels in the cluster \((\Sigma_C)\), was chosen as a pre-selected shower
Magnitude corrected the effect of
after 1.5 hr from each GRB between GRB081203A (Volkov et al. 2002), the VHE supernova before a GRB (Razzaque et al. 2004; Vietri & Stella 2001) during our observation periods. A precursor model based on existing models of external forward shock in a GRB (Vietri 1998a, 1998b; Dar & De Rujula 2001). Afterglow models based on mass accretion choked jet generated by a GRB (Razzaque et al. 2004) calculated the VHE flux in reverse shock. It was applied to forward-shock afterglow by taking into account the optical-afterglow correction. As a result, our limit between 21.2 and 22.2 hr after GRB081203A rejects a flux of $2 \times 10^5$ times larger than the model assuming neutrino oscillation. If wind environment is assumed and the reverse shock model is applied with the correction due to $d_L$ (Wright 2006) and $r^{-1}$ dependence of the expected neutrino luminosity (Vietri 1998b), the same limit rejects a flux of $3 \times 10^5$ times larger than the model. Although our result is in agreement with the model, it might constrain extreme cases such as very effective proton acceleration and/or pion production in forward shock. Due to the lack of detailed knowledge of the evolution of the accelerated proton spectrum in the forward shocks, there is huge ambiguity in calculation of neutrino fluxes (Li et al. 2002). It is important to set observational limit especially on each burst which would have a much different environment burst by burst.

For comparison, Figure 4 shows other observational limits on the $\nu$ flux from point sources (Abbasi et al. 2010; Besson et al. 2007). Our results are the most stringent in the PeV–EeV region and complementary to the IceCube results for the sub-PeV energy region, and indicate the advanced instantaneous sensitivity of the system even during this commissioning phase. Full-scale Ashra observations are expected to have 100 times better sensitivity, since the trigger pixel size is halved (1/4 the pixel area) and the trigger sensor will cover the entire FOV of the light collector. With this higher sensitivity, contamination of 0.55 clusters of air-shower secondary particles is expected in one year of observation data. The advanced angular determination of Ashra for Cherenkov $\tau$ showers to within 0.1 will allow perfect rejection against contamination from air-shower secondary particles, and will provide a viable search method for Earth-skimming $\nu_e$ events, fully utilizing the zero background conditions. Our first search for PeV–EeV $\nu$ reported in this Letter complements other experiments in energy range and methodology, and suggests the probe of “multi-particle astronomy” (Sasaki 2000) with a precise determination of time and location.

We thank R. Yamazaki for his comments. The Ashra Experiment is supported by the Coordination Fund for Promoting Science and Technology and by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology in Japan.

REFERENCES

Abbasi, R., et al. 2010, ApJ, 710, 346
Abdo, A. A., et al. 2009, ApJ, 706, L138
Abraham, J., et al. 2008, Phys. Rev. Lett., 100, 211101
Abramowicz, H., & Levy, A. 1997, arXiv:hep-ph/9712415v2
Ackermann, M., et al. 2010, ApJ, 716, 1178
Agostinelli, S., et al. 2003, Nucl. Instrum. Methods Phys. Res. A, 506, 250
Aita, Y., et al. 2008a, Proc. 30th ICRC, 3, 1405
Aita, Y., et al. 2008b, GCA Circ., 8632
Amonomori, M., et al. 2008, ApJ, 678, 1165
Andrev, M., Sergeev, A., Babina, J., & Pozanenko, A. 2008, GCA Circ., 8615
Antoni, T., et al. 2005, Astropart. Phys., 24, 1
Asaoka, Y., & Sasaki, M. 2011, Nucl. Instrum. Methods A, 647, 34
Berini, E., & Arnouts, S. 1996, A&A, 117, 393
