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Cherenkov τ shower earth-skimming method for PeV–EeV ν_τ observation with Ashra

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ABSTRACT

We describe a method of observation for PeV–EeV τ neutrinos using Cherenkov light from the air showers of decayed τs produced by τ neutrino interactions in the Earth. Aiming for the realization of neutrino astronomy utilizing the Earth-skimming τ neutrino detection technique, highly precise determination of arrival direction is key due to the following issues: (1) clear identification of neutrinos by identifying those vertices originating within the Earth's surface and (2) identification of very high energy neutrino sources. The Ashra detector uses newly developed light collectors which realize both a 42°-diameter field-of-view and arcminute resolution. Therefore, it has superior angular resolution for imaging Cherenkov air showers. In this paper, we estimate the sensitivity of and cosmic-ray background resulting from application of the Ashra-1 Cherenkov τ shower observation method. Both data from a commissioning run and a long-term observation (with fully equipped trigger system and one light collector) are presented. Our estimates are based on a detailed Monte Carlo simulation which describes all relevant shower processes from neutrino interaction to Cherenkov photon detection produced by τ air showers. In addition, the potential to determine the arrival direction of Cherenkov showers is evaluated by using the maximum likelihood method. We conclude that the Ashra-1 detector is a unique probe into detection of very high energy neutrinos and their accelerators.

1. Introduction

Gamma-ray bursts (GRBs), important high energy transient phenomena, are plausible candidates for cosmic ray sources up to and including the highest energy regions [1–3]. Following the identification of GRB970228 with arcminute resolution by Beppo-Sax satellite [4], understanding of GRBs progressed dramatically, owing to the collaboration of satellite-supplied GRB triggers and follow up multi-wavelength observations. As a result, the GRB standard model based on the particle acceleration in the internal/external shocks was established [5–8]. On the other hand, observations of GRB and its afterglow made by Swift [9] and Fermi [10] satellites revealed various phenomena which are difficult to explain in the framework of the standard model. To resolve the various complicated aspects of the GRB physics mechanism, we would need "multi-particle astronomy" [11,12] which uses other particles in addition to photons. In particular, neutrinos are the most important because with them it is possible to probe the optically thick region for electromagnetic components. As we can learn from Beppo-Sax's success, identifying the source with superior angular resolution enables us to approach the physics mechanism by combining a number of observational results. To realize "multi-particle astronomy", arcminute resolution would be desirable in the field of very high energy (VHE) neutrino observation.

The All-sky Survey High Resolution Air-shower detector (Ashra) is a project which primarily aims to observe Cherenkov and fluorescence lights from the lateral and longitudinal developments of very-high-energy (VHE) cosmic-ray air showers in the atmosphere. It uses newly developed light collectors (LCs) which realize both a 42°-diameter field-of-view (FOV) and arcminute resolution. In particular, it can capture air-shower images with unprecedented precision. It is expected to determine the arrival direction of parent particle with high accuracy.

As to detection methods for VHE neutrinos, there are methods which use water and/or ice as the neutrino target [13,14], and those which utilize air showers, i.e., the deeply penetrating neutrino air-shower detection technique and recently proposed "Earth skimming tau-neutrino (ν_τ) technique" [15–19]. Some results have already been published with the Earth-skimming method (for example, see [20]). On the other hand, by combining Cherenkov emission in the optical band and "Earth skimming ν_τ technique" (Cherenkov τ shower Earth-skimming method; hereafter referred to as Cherenkov τ shower ES method), we can effectively survey an energy range which is hard to reach with the above mentioned technique. It is possible to achieve a maximum of sensitivity around 10–100 PeV in which the VHE neutrino signals from GRBs

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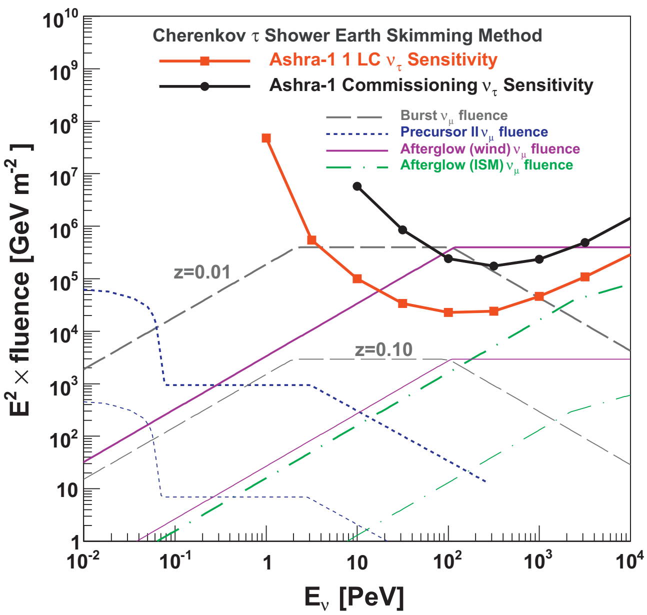

Fig. 1. The sensitivity of Cherenkov τ shower ES method with Ashra-1 where occurrence of GRB behind the mountain is assumed (see the text). Solid square shows the differential sensitivity of the Ashra-1 observation using one light collector and solid circle shows that of the commissioning observation. Note that differential sensitivity represents the fluence where 2.3 events are expected at the corresponding energy range of $\Delta \ln (E_\nu)$ [50]. Also shown are the scaled neutrino fluence expected from GRB030329 occurred at $z = 0.01$ and $z = 0.1$ in each phase of GRB [21]. The nearest and second nearest GRBs to date were occurred at $z = 0.0085$ (GRB980415 [22]) and $z = 0.0331$ (GRB060218 [23]), respectively. The dashed, dotted, solid and dash-dotted lines show the components of burst, precursor, afterglow in wind environment, and afterglow in ISM environment, respectively.

are expected. Fig. 1 shows the expected neutrino fluence from nearby GRB, in which the calculated fluence from GRB030329 shown in Ref. [21] is scaled to different redshifts (z). The expected sensitivities of the Ashra-1 detector by using Cherenkov τ shower ES method are also plotted in the figure, where occurrence of GRB behind the mountain is assumed. The sensitivity calculation is performed by using the Monte Carlo simulation described in detail in this paper.

This paper is organized as follows: Section 2 introduces the Ashra-1 detector, Section 3 describes the detailed method to simulate Earth-skimming ν_τ events, including the discussion about the deflection during their propagation. Section 4 shows the result of a sensitivity estimation. Section 5 discusses the systematic errors due to the incorporated Monte Carlo simulation, background estimation and angular reconstruction accuracy of τ shower events. We conclude in Section 6.

2. Ashra-1 detector

The All-sky Survey High Resolution Air-shower detector Phase I (Ashra-1) is an optical-telescope based detector system [24] optimized to detect VHE particles. Ashra-1 is distinguished by two features: (1) an ultra wide optical system in which 42° FOV is demagnified to 1 in. by using photon and electron optics [25]; (2) the high resolution imaging system with trigger. Ashra-1 combines these unique features, resulting in very cost-effective pixels compared to conventional photomultiplier arrays at the focal surface of an optical telescope. Ashra-1 can observe the whole sky with arcminute resolution with 12 detector units pointing at different directions, where a detector unit consists of a few LCs pointing at the same direction.

The Ashra-1 detector system is designed so that the focal image is split into trigger/image capture devices after amplification. This feature enables us to simultaneously obtain three kind of phenomena which have different time scales, i.e., Cherenkov emission (ns), fluorescence (μs), and starlight (s) without sacrificing the signal to noise ratio. By fully utilizing these distinct features, Ashra is aiming to undertake the full-fledged astronomical observation using VHE particles and trying to achieve the detection of VHE neutrinos for the first time using the Earth and the nearby mountain as the target [26], an arrangement provided by the Ashra-1 observatory being located on the Mauna Loa (3300 m) on Hawaii Island, opposite to the Mauna Kea. It can also be used to optically observe transient objects like GRBs as it monitors the whole sky simultaneously [27,28].

3. Earth skimming τ neutrino

3.1. Neutrino detection method

To detect VHE neutrinos, a large target volume is required in order to compensate for the very small neutrino-nucleon cross section. On that basis, the secondary particles produced by the first neutrino interaction are required to be detected through some method. The detection method using water and ice as a target detects Cherenkov light from secondary muons taking advantage of the fact that ice and water are to some extent optically transparent. This method can be categorized by identical target and detection volume. On the other hand, the detection method using deeply penetrating air showers from higher-energy neutrinos uses atmosphere as a target and detection volume. This method enables achieving a huge detection volume as the atmosphere has very high transmittance. However, it is difficult to obtain a larger target mass due to low atmospheric density. The detection method called Earth-skimming ν_τ technique [15–19] can realize a huge target mass and detection volume at the same time by separating the target and detection volume utilizing the interaction process of ν_τ. The detection method is described as follows (see Fig. 2): a VHE ν_τ interacts in the Earth or mountain and produces a τ lepton (τ). τ penetrates the Earth and/or mountain and enters in the atmosphere. Subsequently, it decays and produces an air shower. Cherenkov photons from the air shower are detected. Owing to the separation of the first interaction where ν_τ produces τ and τ decay generating air shower, air shower observation becomes possible while preserving the huge target mass required to compensate for the low cross section of the first interaction. For this detection method, it is crucial for the τ to go through the Earth and/or mountain before its decay, and to develop the air-showers in the atmosphere in front of the detector after its decay. Note that the decay length of 100 PeV τ is 4.9 km. Here, "Cherenkov τ shower ES

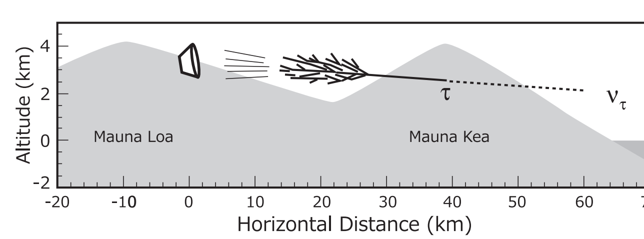

Fig. 2. Schematic view of Cherenkov τ shower ES method. Mauna Kea is used as the target mass for neutrino charged current interaction. The produced air shower is observed from Mauna Loa. In addition to the fact that the mountain can be viewed with large solid angle from the observatory, the distance of about 30 km from the observatory to the Mauna Kea surface is appropriate for the air shower development in 10–100 PeV energy range, resulting in the huge advantage of the Ashra-1 observatory.