Simulation of UHE Neutrino Induced Horizontal Air Showers

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Abstract: Air showers created by Ultra-High-Energy (UHE) neutrinos that penetrate horizontally the atmosphere, are modeled taking into account the Landau-Pomeranchuk-Migdal (LPM) effect and the geomagnetic field. The characteristics of electromagnetic shower profiles are studied and discussed with an assumption of the satellite-based air shower experiment.

Keywords: cosmic ray, cosmogenic neutrino, air shower, LPM effect

1 Introduction

The composition of UHE cosmic rays with energies $> 10^{19}$ eV is one of unsolved questions, and its research will provide us the fruitful information on the origin and the acceleration mechanism of UHE cosmic rays. Especially, cosmogenic neutrinos have been expected in the interactions of UHE protons with cosmic background photons \cite{1, 2}, therefore, the detection of UHE neutrinos will be a key to solve these questions. Despite their small interaction cross-section, neutrinos interact with nucleons and create Extensive Air Showers (EAS) that receive about 80 \% of neutrino energy at an average. Neutrinos create showers deep in the atmosphere, mostly largely inclined or horizontal showers, or even upward-going showers. The atmospheric depth at the EAS maximum ($X_{\text{max}}$ in g/cm\textsuperscript{2}) can be used to distinguish neutrino showers from those of primary protons or nuclei.

From the points of EAS profile generated by an electron, the geomagnetic field has a noticeable effect on the electromagnetic shower development, and the LPM effect could be also effective even in atmosphere. The electromagnetic showers, affected by the LPM effect, are quite different from the Bethe-Heitler showers. Their average behavior shows significant elongation and the individual LPM-shower profile sometimes shows multi-peak structure over wider slant depth\textsuperscript{[3]}.

From the detection capability of the LPM-showers initiated by UHE neutrinos, a huge amount of target mass is required to assured the interactions in atmosphere. The planned experiments TUS\textsuperscript{[4]} and JEM-EUSO\textsuperscript{[5]} are the suitable opportunity to observe UHE neutrino showers. They will detect the fluorescent light from the EAS by telescopes placed on satellites and have a large field of view (FOV) with a radius of 40 km and 250 km, respectively.

2 UHE Electromagnetic Showers in the Geomagnetic Field

It has become a common knowledge that at UHE the geomagnetic field becomes an effective target in which gamma rays create electromagnetic cascades. These cascades start far before entering the atmosphere. In \cite{6} it is shown that the geomagnetic field has also a noticeable effect on the shower development within the atmosphere. This effect is stronger at high altitudes and at higher energies. In Fig.1 the break-even points \textsuperscript{[7]} (altitudes where matter and magnetic field effects are the same) are shown. It can be seen from the figure that the synchrotron energy loss rate starts to compete with bremsstrahlung energy loss at energies $\gtrsim 10^{18}$ eV in the upper layers of the atmosphere.

The probability for magnetic pair production by photons decreases sharply when the photon energy decreases, so the shower development is affected mostly through synchrotron radiation.

Our one-dimensional Monte Carlo simulation code includes the LPM effect, synchrotron radiation and magnetic pair production. The longitudinal shower development was followed by direct simulation down to threshold energy, below which the LPM effect is not effective ($10^{16}$ eV). The subthreshold particles are replaced by analytical approximations. We assume that the magnetic field strength (normal component) is constant in the atmosphere.
Figure 1. The break-even points which show altitudes where matter and magnetic field effect are the same, are indicated.

The shower profiles for horizontal showers from a primary electron with energy of $10^{20}$ eV are studied for the cases with and without magnetic field ($H=0.35$ G) taken into account. In both cases the parent electron is injected in horizontal direction at 0 g/cm$^2$ slant depth. The shower traverses the atmosphere at 30 km a.s.l. and 20 km a.s.l. are studied. It can be seen that magnetic field accelerates the shower development in these cases.

Our one-dimensional simulations of UHE electromagnetic showers traversing the atmosphere horizontally show that the influence of the geomagnetic field is noticeable at higher altitudes in the atmosphere and has to be accounted for in precise calculations of shower characteristics.

It is clear, that not only horizontal showers are subject of the influence of the geomagnetic field within the atmosphere. For example, our simulations show that for a photon shower with characteristics of the record-breaking Fly’s Eye event ($3 \times 10^{20}$ eV, the same zenith and azimuth angles, Utah location) accounting for the geomagnetic field outside and within the atmosphere decreases the shower maximum by $\sim 14$ g/cm$^2$ compared to simulation results with only geomagnetic pre-shower outside the atmosphere. In lower and denser atmospheric layers the magnetic field cannot compete [8] with matter bremsstrahlung and the impact of the geomagnetic field can be neglected.

Finally, it must be noted that precision calculations of shower characteristics require accounting of all possible factors that can influence the bremsstrahlung and pair production processes at ultra-high energies. For example, in addition to the LPM suppression the external magnetic field can also suppress the bremsstrahlung and pair production cross sections [9]. This work is now in progress.

3 The Detection of UHE Neutrino Showers

The UHE neutrino simulation consists of the neutrino interaction, the EAS generation and the production of air fluorescent and Cherenkov photons in its development. The interaction cross-section with the atmospheric nucleus as a function of neutrino energy is given [10] as

$$\sigma_{\text{ex}}(\nu N) = 5.53 \times 10^{-36} \left( E_\nu / 1\text{GeV} \right)^{0.363}$$

The interaction length $L_{\text{int}}$ [g/cm$^2$] related to the cross-section in atmosphere is expressed by

$$L_{\text{int}} = 1 / (\sigma_{\text{ex}}(\nu N) \cdot N_A)$$

$N_A$ and $E_\nu$ are the Avogadro’s number and the neutrino energy. The neutrino shower is generated by the secondary electrons produced in the neutrino interaction and the ratio between the EAS energy $E_e$ and initial energy $E_\nu$ [11] is given by

$$E_e / E_\nu = (0.6724 + 0.0058 \log E_\nu)$$

Electromagnetic EASs have been generated and the individual longitudinal profiles are fitted by the Gaisser-Hillas formula [12].

The interaction probability of UHE neutrinos in an atmospheric volume defined by a FOV of the fluorescent telescope at the satellite, is shown in Fig.2, as a function of the energy. The target atmospheric mass is assumed as the acceptance of TUS experiment with a FOV of $\pm 4.5$ degrees from a height of 550 km in this calculation. $10^7$ neutrinos for each energy between $10^{19.2}$ and $10^{21}$ eV are injected to the FOV with zenith angles between 0 and 95 degrees. The interaction probability which indicates the ratio between the number of interacted neutrinos and all incident ones, is nearly 0.003% at the energy of $10^{20}$ eV and it increases with energy. In the figure, the probability in a case that both interaction and $X_{\text{max}}$ is fully contained in a FOV, is indicated by closed circle, and it gives 0.0012 % at the energy of $10^{20}$ eV.
The neutrino EAS is generated at the first interaction point where is determined by the assumed interaction mean free path. To examine the detection capability of UHE neutrino EAS by the satellite-based telescope, therefore, the emission of air fluorescent and Cherenkov photons from EAS particles are also calculated in our code. The Rayleigh scattering of photons in atmosphere is also taken into account in their propagations. The number of arrival photons at the TUS telescope is estimated with its known features. The EAS developed in a lower air density at a higher atmosphere, produces a larger number of photons than that in the lower atmosphere, because the fluorescent photon yield in a unit of photons/(m²•sr•ns) does not depend so much on the height between 0 and 20 km. In addition to the fluorescent photons, longer tails can be found in the profiles as a contribution of the scattered Cherenkov photon component.

Figure 3. The time profiles of arrival photons of neutrino EASs with the energy of $10^{20}$ eV and the zenith angle of 90 degree. EASs passing through at the different altitudes of 0, 10, and 20 km.

The number of arrival photons at the TUS telescope is estimated with the known features, (i) the optical mirror size of 1.8 m in a diameter, (ii) the observation from the height of 550 km with a FOV of ±4.5 degree, (iii) the Time-Resolution-Unit (TRU) of 0.8 µs and the size of ground segment of 5.5 km. The time profiles of arrival photons at the telescope are shown for horizontal EASs binned in every 0.8 µs. Arrival photons from EAS particles are also calculated in our code. The Rayleigh scattering of photons in atmosphere is also taken into account in their propagations.

In order to estimate the detection capability of neutrino EASs by the TUS, following assumptions and procedures have been taking into account, (i) the 3 different neutrino energy spectra (a) $I=(1.7\times10^{11})\times E^{-2.2}$, (b) $I=(5.4\times10^{9})\times E^{-2.5}$ and (c) $I=(5.4\times10^{20})\times E^{-3}$ are assumed in this calculation, (ii) $5\times10^6$ neutrinos are injected with energies sampled from each energy spectrum, (iii) After confirming the interaction in a FOV, EAS initiated by neutrino is generated in atmosphere and the characteristics of arrival photons at the telescope; the arrival time, the wave length and the emission point (x, y, z), are recorded as the output data, (iv) The judgement on event trigger is done by satisfying the condition of 5 successive TRUs with >35 photons in each TRU. This required photon number in a TRU corresponds to a level of 3σ higher than the average background photons of 500 photons/(m²•sr•ns) assumed in this calculation. The expected numbers of neutrino EASs with $>10^{19.9}$ eV are $5.6\times10^3$, $1.8\times10^3$ and $1.4\times10^3$ events/year for the energy spectra of (a), (b) and (c), respectively.

4 Conclusion

The LPM-shower profiles are expected to be produced by UHE neutrinos, and their average and individual profile have been studied to estimate for the detection capability by the satellite-based experiment. Actually, the LPM effect becomes stronger in the denser atmosphere and typically in an energy region $>10^{20}$ eV. The LPM-shower initiated by UHE neutrinos with largely inclined angles and energies $>10^{20}$ eV undergo large fluctuations, which show sometime multi-peak structures as a variety of LPM-shower profile shapes. This is an advantageous characteristics when the candidate of neutrino EAS is identified from a large amount of hadronic EASs. In addition, the $X_{max}$ distribution of neutrino EASs is almost uniform over the cumulative atmospheric depth of 72000 g/cm² while one for the hadronic EASs is not exceeding 1400 g/cm² with a probability of $3\times10^{-6}$. The detection of UHE neutrinos is much expected through the observation of EAS profiles by the satellite-based air fluorescent telescope with a large acceptance and target material mass.

The expected numbers of neutrino EASs with $>10^{19.5}$ eV could be $7.0\times10^3 - 2.8\times10^3$ events for 5 years TUS observation with assumptions of neutrino energy spectra. This is not enough detection capability with a present spec of the TUS experiment, however the TUS telescope has a cumulative exposure of $3\times10^4$ km²•sr year in 5 years observation which is equivalent to the one by a 5 years AUGER experiment. The detection capability of UHE neutrinos is strongly dependent on the neutrino flux and few statistics will be expected even in an optimistic case. The TUS experiment has still potential to detect UHE neutrinos with the best reliability as the first EAS observation from the satellite.

References