Identifiability of UHE Gamma-ray Air Showers by Neural-Network-Analysis

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Abstract: The chemical composition of Ultra-High-Energy (UHE) comic rays is one of unsolved questions, and its study will provide us for the information on the origin and the acceleration mechanism of UHE cosmic rays. Especially, a detection of UHE gamma-rays by hybrid experiments will be a key to solve these questions. The characteristics of UHE gamma-ray showers have been studied on lateral and longitudinal structure by AIRES and our own simulation code, so far. There are apparent differences in a slope of lateral distribution (η) and a depth of shower maximum (Xmax) between gamma-ray and proton induced showers because UHE gamma-ray showers are affected by the LPM effect and the geomagnetic cascading process in an energy region of $> 10^{19.5}$eV. Different features between gamma-ray and proton showers are pointed out from the simulation study and an identifiability of gamma-ray showers from proton ones is also discussed by the method of Neural-Network-Analysis.

Introduction

In an energy spectrum of $>10^{19}$eV, the GZK cutoff [1] [8] has been predicted to be few cosmic ray flux above 10^{20}eV. However, AGASA had observed 11 events with energies well beyond 10^{20}eV [6]. There are several acceleration models to produce UHE gamma-rays and neutrinos with such a huge energy. Z-burst model predicts that UHE gamma-rays are produced as secondary particles through an interaction between UHE neutrino and cosmic neutrino background. GZK gamma-rays are also expected as a secondary component in GZK process. As the top-down scenario, a decay process of Super Heavy Relic, topological defects, i.e. cosmic string, monopole, etc., are candidates of the top-down sources.

Air showers initiated by UHE gamma-rays have characteristic profiles in comparison with hadronic showers. An influence of the LPM effect [2] [4] on shower structures leads to a significant elongation of electromagnetic cascading and a large fluctuation of shower developments at an energy region above $10^{19.5}$eV. On the other hand, once electron-positron pair is produced in UHE gamma-ray interaction with the geomagnetic field away from the Earth's surface, it initiates an electromagnetic cascading before entering the atmosphere [3]. As a result, an energy of "primary gamma-ray" is shared by a bunch of lower energy "secondary gamma-rays". Therefore, an influence of the LPM effect on subsequent showers is significantly weakened. An effect of the geomagnetic cascading on shower structures strongly depends on arrival direction and gamma-ray energy above $10^{19.5}$eV [7]. In the present work, both a slope of lateral distribution(η) and a depth of shower maximum(Xmax) are used as observables to estimate for an identifiability of UHE gamma-ray showers from proton ones.

Simulations

The atmospheric air shower simulation has been carried out by AIRES code (Ver.2.6.0) [5] for primary proton and gamma-ray showers. Individual longitudinal and lateral structure were fitted by the Gaisser-Hillas formula with 3 parameters[1], and by the modified NKG function with 2 parameters[2], respectively. Here, a_2 was defined as a slope of

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1. $N(x) = a_1 \left(\frac{x}{a_2}\right)^{a_2 \times a_3} \times \exp\left[(a_2 - x)a_3\right]$
2. $N(R) = a_1 \left(\frac{R}{R_m}\right)^{-1.2} \left(1 + \frac{R}{R_m}\right)^{-(a_2-1.2)} \left(1 + \left(\frac{R}{1\text{km}}\right)^2\right)^{-0.6}$

lateral distribution (η). Atmospheric showers of proton and gamma-ray primaries have been generated in an energy region of 10^{17}eV-10^{21}eV with ΔLog(energy)=0.1 step and zenith angles of 0, 20, 30, 45, 60, 75°. 100 events for each combination of an energy and a zenith angle were simulated, and fitted parameters of lateral and longitudinal structure were accumulated in a library. To simulate showers initiated by UHE gamma-rays, we calculated the geomagnetic cascading starting with a single UHE gamma-ray far away from the Earth's surface down to the top of the atmosphere by own simulation code (the location in Utah TA site was assumed in this calculation). Secondary particles that reached the top of the atmosphere were set as an inputs component for the calculation of atmospheric shower. Atmospheric gamma-ray shower was constructed as a superposition of lower energy gamma-ray sub-showers which were recorded in a library mentioned above.

Results and Discussion

Characteristics of UHE gamma-ray shower structure

Figure 1 (top) shows Xmax distribution for proton showers , gamma-ray showers with geomagnetic cascading process "ON" and ones with "OFF". Primary energies above $10^{19.6}$eV are sampled from an power law energy spectrum with an index of -2.7. A zenith angle of 45° is assumed and an azimuthal angle is assigned randomly. When the geomagnetic cascading process is taken into account as a reasonable assumption, atmospheric gamma-ray showers tend to have smaller Xmax with a smaller fluctuation. Therefore Xmax distribution of gamma-ray showers approaches near to a region of proton showers and partly overlapped to each other. Figure 1 (bottom) shows η distribution for proton and gamma-ray showers. The effects of LPM and geomagnetic cascading process also contribute to gamma-ray showers, just as the case of Xmax distribution.

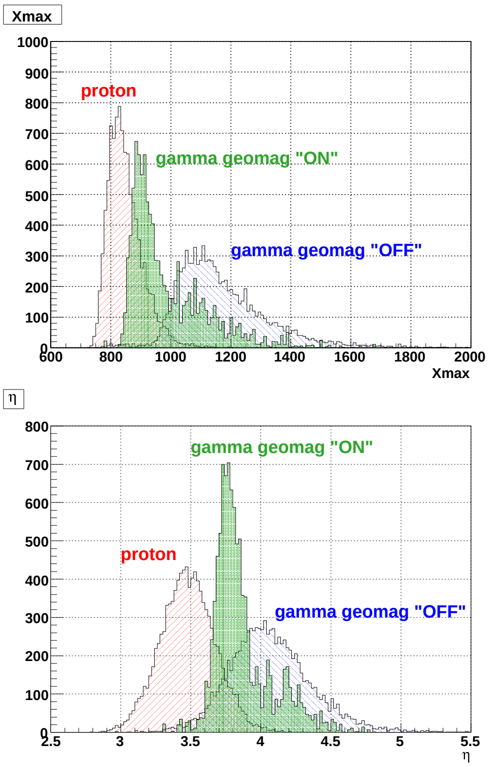

Figure 1: Distributions of Xmax (top) and η (bottom) for proton and gamma-ray showers above $10^{19.6}$eV. Gamma-ray showers with the geomagnetic cascading process "ON" and "OFF" are also shown.

Neural-Network-Analysis

An identifiability of gamma-ray/proton showers has been studied with the method of Neural-Network-Analysis(NNA). The used network consists of input, middle and output layer. Three parameters of longitudinal structure, two parameters of lateral structure, a primary energy and an azimuthal angle ϕ are given into the first layer. Firstly, the network studies on longitudinal and lateral features of simulated proton and gamma-ray showers(10000 events each) with energies sampled as shown in 3.1 and a zenith angle of 45°, in order to quantify the combination weights among layers, by the back propagation method. A set of convergent weights is applied for event identification test. Other datasets of proton and gamma-ray showers (10000 events each) have been tested by NN algorithm and resulting output values from last layer are evaluated to estimate for a degree of reality of identification. Output values are in a range of 0.0-1.0. Events with 0.0 and 1.0 show the most likely

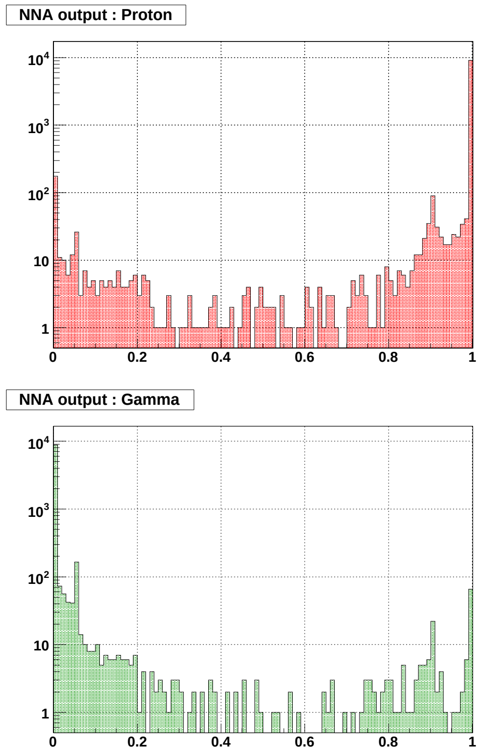

Figure 2: Distributions of NNA output values for proton showers(top) and gamma-ray showers(bottom). Test has been done for 10000 samples of each composition above $10^{19.6}$eV and with a zenith angle of 45°.

gamma-ray and proton shower candidate, respectively, and an intermediate value shows a degree of uncertainty of particle identification.

Figure 2 shows distributions of NNA output values for proton showers(top) and gamma-ray showers(bottom) with the geomagnetic cascading process "ON". When 0.5 is assumed as a judging standard value for an identification between proton and gamma-ray primary, a few proton events with <0.5 and gamma-ray events with >0.5 could be found in both figures as misidentified fake events. A correct answer ratio of tested proton and gamma-ray showers is 97.21%.

To examine an UHE gamma-ray flux or an assessed reliability of a flux limit, a study of misidentified ratio of proton showers is essentially important. Figure 3 shows misidentified ratios of proton showers for zenith angles of 30°, 45°, 60°. Misidentified ratio of proton showers with a zenith angle of 30° does not depend on energy so much. However, ones with zenith angles of 45° and 60° increase quickly upto $10^{19.8}$eV, and then they become smaller above $10^{19.8}$eV because gamma-ray shower profiles become to be similar to ones of proton showers due to the effect of geomagnetic cascading process. In figure 4 misidentified ratios of proton showers with azimuthal direction of 0-180° (from southern half) and 180-360° (from northern half) are shown in addition to ones over all direction.

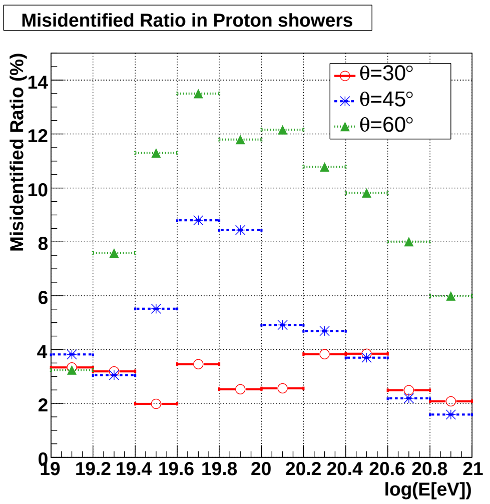

Figure 3: Misidentified ratios of proton showers as a function of primary energy for zenith angles of 30°, 45°, 60°.

The NNA is one of the powerful methods to estimate for an UHE gamma-ray flux getting behind proton primary pool. A study is in progress to increase a reliability of identification with an additional observable of the time structure of shower particles and with experimental uncertainties of Xmax and η.

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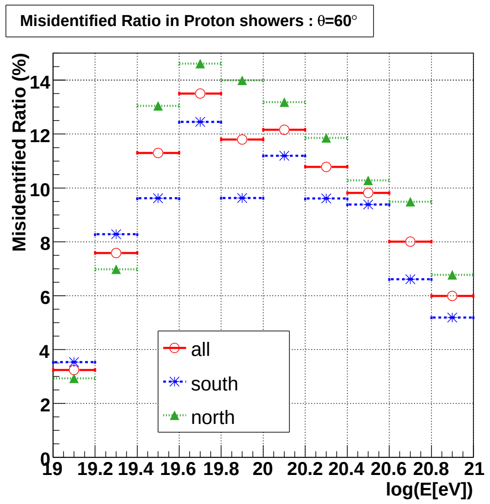

Figure 4: Misidentified ratios of proton showers for zenith angles of 45°. Ratios of showers from north and south direction are plotted distinctively.

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