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Mass discrimination of cosmic rays by topological multi-parametric patterns

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HIGHLIGHTS

- In this paper, the new observables are utilized.
- The measurements are also done in a different way.
- The dependence of sampling area to primary cosmic ray mass discrimination is investigated.

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ABSTRACT

This paper discusses an effective classification method for primary mass of cosmic rays (CRs) to give a comprehensive view about different properties of near vertical Extensive Air Showers (EASs) at Alborz-1 array ($35°43'N51°20'E$, 1200 m a.s.l corresponding to an average atmospheric depth of 890 gcm^{-2}) observation level. The method is based on the analysis of topological multi-parametric patterns which have been produced by simulated EASs. Iron, Oxygen, and proton were selected as primary CRs. Muon and electron multiplicities in specified distances of shower core as well as muon and electron sizes, as mass-sensitive observables of a common EAS, were selected to make the patterns. Primary energies are 100 TeV, 500 TeV, 1 PeV, 5 PeV, 10 PeV and a continuous energy spectrum from 200 TeV to 1 PeV with a spectral index of $\gamma = 2.7$. Three sets of EASs were simulated and applied to the patterns to examine the method. This investigation have been carried out for showers simulated by QGSjet II-04 + GHEISHA and also SIBYLL + GHEISHA interaction models. The obtained results show that the primary mass discrimination determined by this method, strongly depends on the distance from sampling area to the showers core and also we observed that the results obtained by QGSjet II-04 and SIBYLL are almost identical. Moreover, the results demonstrate the effectiveness of the method.

1. Introduction

Since the discovery of cosmic rays, great efforts has been devoted to the study of mass discrimination of primary CRs. Mass discrimination plays an important role in CRs studies, because it helps to investigate the acceleration mechanism of primary CRs (Fraschetti, 2008) and the mass composition of cosmos (Simpson, 1983). Since, it is believed that the mass composition of the cosmic rays is a function of primary energy, it is important to investigate primary composition of cosmic rays in different region of energy spectrum, at the ultra-high energy regions of all particles spectrum, due to their drastically rare flux and also unknown properties of hadronic interaction in these regions, mass composition of CRs remains partly undetermined (Glushkov and Sabourov, 2015). On the other hand, around the so called knee energy where the power law spectral index of cosmic ray energy spectrum steepens from ~ -2.7 to about -3.1, experimental results, show that proton component exhibits cut-off which implies that beyond the knee energy, the cosmic ray composition would be heavier, dominated by Fe nuclei (Banik et al., 2017). Behavior of primary cosmic ray nuclei spectra in the vicinity of the 'knee' is, undoubtedly, one of the key elements for solution of problem of high energy cosmic rays sources and for establishment of acceleration mechanisms. It is generally accepted that each composition has its own knee and the superposition of all compositions gives the observed break of the all-particle spectra at $\sim$4 PeV. Previous studies indicate that CRs mass composition could be obtained by studying of different EASs observables. Based on Merit Factor values, the best mass-sensitive observable is the maximum depth (X_{max}) which is obtained by measurement of lateral distribution function of Cherenkov photons collected by Cherenkov telescope (Berezhnev et al., 2015). In the same primary energies, the showers initiated

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by lighter CRs reach to their X_{max} in the deeper regions of the atmosphere than heavy ones. The observatories which use hybrid detection technique data, including particle and Cherenkov detectors, can reach high resolutions of mass discriminations. Another mass-sensitive observable is muon pseudorapidity which is obtained by muon tracking detectors (MTD). Previous studies showed that this observable operates appropriately, especially for near vertical Showers and on the base of this parameter, it found that the mass composition changes in knee region (Rastegarzadeh and Nemati, 2015a; Zabierowski et al., 2006).

The distribution of secondary muons and electrons as well as the observables noted above, can be used to estimate the primary mass composition (Zha, 2011). A modified NKG function (Kamata and Nishimura, 1958) with a variable age parameter can describe well the lateral distributions of these two particles. Muons lateral scattering along the EAS propagation is less than electrons and its distribution is flatter than electron distribution. Muon to electron ratio in EASs can be used to determine the border of light and heavy primaries. The results offered by Weber et al. (Weber et al., 1999) suggest that the border is 0.85 for KASCADE array and the showers with ratios higher than 0.85 are considered as heavy primaries. The muon to electron ratio in showers, as they grow, reach their maximum and decline. It is due the fact that the muon multiplicity may not change dramatically in a shower beyond the shower maximum. All parameters and observables which together are used to determine the mass composition, must be correlated with each other.

There are various approaches to interpret the measurements of ground based arrays such as multivariate fitting, KNN-method (Altman, 1992), Bayesian approach (Rossi et al., 2006) and neural networks (Wasserman, 1993). In recent years, significant improvements have been occurred in the equipment of arrays and this has been lead to accurate measurements with high resolutions.

We have studied the muon and electron multiplicities, as two mass sensitive observables, in certain distances of showers core at the Alborz-1 array. It is a small array located in physics department of Sharif University of technology in Tehran (1200 m a.s.l. $\equiv$ 890 gcm^{-2}). It used to investigate anisotropy of cosmic rays, finding gamma ray sources, atmosphere thickness effect on EASs and atmospheric muons (Abdollahi et al., 2013). It will be equipped with further detectors and able to measure secondary particles density. This study and other related studies (Rastegarzadeh and Nemati, 2015b) are performed beside the development of the array to give an overview to its capability.

In this work, topological multi-parametric patterns have been used to classify the EASs which are initiated by different primaries. This method is based on the correlation of several EASs observables which are sensitive to special features of primary CRs. This method was proposed by Ambrosio et al. (Ambrosio et al., 2004) for determining of the mass composition of the primary CRs at the PeV energy region for the total numbers of muons and electrons which are measured by KASCADE array. This analysis shows that the method works well for determining of mass composition.

This paper is organized as follows: in the Section 2 we describe the details of simulations and in Section 3 we explain the way that the patterns are built and Section 4 is dedicated to analyze the results of the method and Section 5 discuss about the differences between the results obtained by QGSjet II-04 and SIBYLL and finally in last section we discuss about our conclusions.

2. Simulations

CORSIKA 7.4 simulation code, which is based on Monte Carlo method, have been used to simulate EASs. The simulations has been performed for Alborz-1 array altitude. QGSJET II-04 (Ostapchenko, 2012), SIBYLL 2.1 and GHEISHA (Fesefeldt, 1985) models have been used to generate simulation samples with primary energy range which once have been selected as discrete energies include 100 TeV, 500 TeV, 1 PeV, 5 PeV, and 10 PeV and once again as energy spectrum from 200 TeV to 1 PeV with a spectral index of $\gamma = 2.7$. Proton, Oxygen, and Iron have been selected as primary cosmic rays. . The zenith and azimuth angles of cosmic rays arrival has been selected randomly by simulation program between 0 – 20° and 0 – 360° respectively. Energy threshold for muons and electrons detecting were selected 0.3 and 0.003 GeV respectively.

At first, for discrete primary energies, five sets of EASs each one containing 100 showers for primary CRs were simulated by QGSjet II-04 + GHEISHA models in order to make the topological patterns. The patterns for primary energies spectrum 200 TeV–1 PeV was made by 300 showers for each primaries. Then pure samples containing 50 showers were simulated to test these patterns. In the same way the simulations and analysis were repeated for showers which simulated by SIBYLL 2.1 + GHEISHA models that the analysis results will be expressed in the following.

3. Topological multi-parametric patterns

As said in the previous section, in order to make topological patterns, the samples of showers were simulated for primary energies and masses, and then the shower muon and electron sizes as well as the multiplicities of muons and electrons in three distance intervals from showers core including 0–20 m, 90–110 m and 180–200 m were obtained. Because the secondary particles distribution differs for different primary mass and energy, in order to improve mass discrimination accuracy and avoid the difficulties of estimating the size of muons and electrons, we have proposed that the sampling is carried out in certain distances from shower core instead of accounting the total number of electrons and muons.

Table 1 shows the Spearman correlations between muon and electron multiplicities measured in the three intervals noted above. If this parameter is closer to 1, the correlations between observable are stronger and therefore the shower to shower fluctuations are lower and vice versa.

After determining showers muon and electron sizes and also their multiplicities in the specified intervals, the simulated showers were demonstrated as two-dimensional scatter plots which y and x axis are representative of the muons and electrons logarithmic multiplicities, respectively. Then *xy*-plane had been divided to cells which the dimensions of each cell are determined according to the measurement accuracy of muons and electrons multiplicities.

In this paper, because the accuracies of measurements are undetermined for Alborz-1 array (especially in certain distances which the errors are obviously less than total multiplicity measurement errors), the dimensions of cells were considered as 0.1 × 0.1, until the measurement capabilities of the new array are determined. Because the geometric spaces can only be defined in three dimensions, therefore, only 3 correlated parameters of the EASs can be included in this method. Fig. 1 shows the patterns for discrete and continuous primary energies and three core distances. As it can be seen, in low energies the shower to shower fluctuations is strongly high and as primary energies increased, the fluctuations decreased. Whenever the pattern cells contain a lot of EASs, mass discrimination carried out with high resolution. Also with increasing primary energies, the fluctuations become less and less for heavier primaries but the fluctuations of proton showers continuously remain even for high primary energies. Regarding Fig. 1, it can be concluded that the distribution of showers follow linear functions especially for high energies and heavier primaries and also this functions can be another mass discrimination parameter for muons and electron multiplicities.