Study on Mass Composition of Ultra-High Energy Cosmic Rays by Telescope Array

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Abstract: Results from the TA mass composition studies are reviewed. From the analysis of longitudinal development of air showers using the fluorescence detector data we obtained $\langle X_{\text{max}} \rangle$, the average depth of shower maxima, as a function of energy. This is the best estimator for cosmic ray composition because of its strong dependence on primary mass. The data provided by the surface detectors for the ground-level information of showers are also used to improve the FD shower reconstruction accuracy. The obtained $X_{\text{max}}$ data are compared with expectations from particular composition models, pure proton and iron. The TA data prefers a proton-dominant composition in the energy range $\log_{10}(E/eV) = 18.3 \sim 19.5$.

Keywords: mass composition, ultra-high energy cosmic rays, Telescope Array

1 Introduction

Observations in the last decade revealed that there is a steepening in the highest energy end of cosmic ray spectrum. This was first claimed by HiRes [1], and confirmed by Auger [2] and the Telescope Array [3,4]. This may be a consequence of cosmic ray energy losses in inter-galactic space due to interaction with cosmic microwave background photons, as predicted by Greisen, Kuzmin and Zatsepin [5]. The expected position of the steepening depends on the mass of cosmic rays, therefore experimental determination of cosmic ray composition is of crucial importance in interpreting the structures in the energy spectrum. Mass composition is also important to understand anisotropies in the arrival directions of cosmic rays to clarify their origins.

Cosmic ray mass composition is studied from longitudinal profiles of extensive air showers using the data of fluorescence detectors. The depth at the shower maximum $X_{\text{max}}$ is most sensitive to nuclear type of primary cosmic rays. It is easily shown that the $X_{\text{max}}$ of a shower is proportional to the logarithm of primary energy $E$, $X_{\text{max}} \propto \log E$ [6]. The shower generated by a nucleus of mass $A$ can be described by a superposition of $A$ showers initiated by individual nucleons with primary energies $E/A$, therefore its $X_{\text{max}}$ is proportional to $\log(E/A)$. The "elongation rate" plot, $(X_{\text{max}})$ vs $\log E$, is conventionally used to discuss the mass composition of cosmic rays and its energy dependence, as shown in Fig.1. In this paper Telescope Array $X_{\text{max}}$ analyses are reviewed.

2 Telescope Array

The Telescope Array (TA) is a hybrid detector for cosmic ray observation located in the desert of Utah, USA. TA utilizes fluorescence detectors (FDs), installed in three stations named Black Rock (BR), Long Ridge (LR) and Middle Drum (MD). In the BR and LR stations 12 newly developed FDs are installed [7]. In the MD station 14 refurbished HiRes-I mirrors are used, which enables us to make direct comparison of the TA and HiRes data [8]. An array of surface detectors (SDs) spread over $\sim 700 \text{km}^2$ allows detection of shower particles at the ground [9].

Fig. 1: Energy dependence of $X_{\text{max}}$ calculated with CORSIKA simulation package. Predictions for proton and iron showers are shown with three hadronic interaction models, QGSJET-I, QGEJET-II and SIBYLL.

2.1 Shower reconstruction

The FD data are mainly used for $X_{\text{max}}$ analysis: once the shower geometry of an air shower (the arrival direction and the position at which the shower axis hit the ground) is given, the longitudinal development of the shower can directly be determined with good accuracy from the amount of fluorescence light emitted at different points in the sky. The first step of geometrical reconstruction is to determine the shower-detector plane (SDP), which contains the shower track and the detector site. This can be obtained from a bundle of pointing vectors of phototubes that detected fluorescence light. In monocular mode observation in FD, the inclination angle of the shower track in the SDP is determined from arrival timing of the fluorescence light at a single site [10]. In this method, however, the resolution in shower geometry determination is rather poor, being typically $\sim 7^\circ$ error in zenith angle, which results in poor
The situation can be significantly improved in two ways: the first is by stereo reconstruction using data of two or more sites seeing air showers from distances ~20 km apart each other [11], the second is by hybrid reconstruction using the SD data [12, 13, 14]. In stereo reconstruction the shower track is determined as the line of intersection of two SDPs that are individually defined by the two stations. In hybrid reconstruction with the SD data, the time at which the air shower plane crosses the ground is known and this gives an anchor in the time fitting. In both cases the angular resolutions are improved at the level of ~1° and 10~20 g/cm^2 in \(X_{\text{max}}\). Note that the difference in \(X_{\text{max}}\) of proton and iron showers is \(\sim 70 \text{ g/cm}^2\) at primary energies around \(10^{19}\) eV.

3 Results

The latest \(X_{\text{max}}\) analysis result from the MD-hybrid reconstruction is shown in Fig. 2. All the events are denoted by dots, and the average \(\langle X_{\text{max}} \rangle\) in energy bins are shown by filled squares. The dashed line is the expectation of \(\langle X_{\text{max}} \rangle\) from a Monte-Carlo (MC) with a pure-proton composition, and the solid line is for the iron expectation.

Resolution of \(X_{\text{max}}\):

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4 Conclusions

The TA \(X_{\text{max}}\) analysis shows that the data is consistent with a light composition in the energy range \(\log_{10} E (\text{eV}) = 18.3 \sim 19.5\). This result may support the scenario of forming a "dip" around \(\log_{10} E (\text{eV}) = 18.7\) due to e^+ pair creation by interaction of cosmic rays and the CMB photons [16], and a steepening at \(\log_{10} E (\text{eV}) = 19.7\) due to cosmic ray energy losses through pion-pion production [5, 17]. This also supports the relevance of our searches for cosmic ray anisotropies above \(\log_{10} E (\text{eV}) = 19.0\) [18], where magnetic deflections of protons are not as significant as in the case of heavier nuclei. We will also present updated BR/LR stereo and hybrid analyses at the conference.

References