33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

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 $\langle X_{\max} \rangle$, 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 $X_{\max}$ 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 $\log_{10}(E/\mathrm{eV}) = 18.3 \sim 19.5$.

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 $X_{\max}$ is most sensitive to nuclear type of primary cosmic rays. It is easily shown that the $X_{\max}$ of a shower is proportional to the logarithm of primary energy E, $X_{\max} \propto \log E$ [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 $X_{\max}$ is proportional to $\log(E/A)$. The "elongation rate" plot, $\langle X_{\max} \rangle$ 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 $X_{\max}$ 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 a re 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 $\sim 700\,\mathrm{km}^2$ allows detection of shower particles at the ground [9].

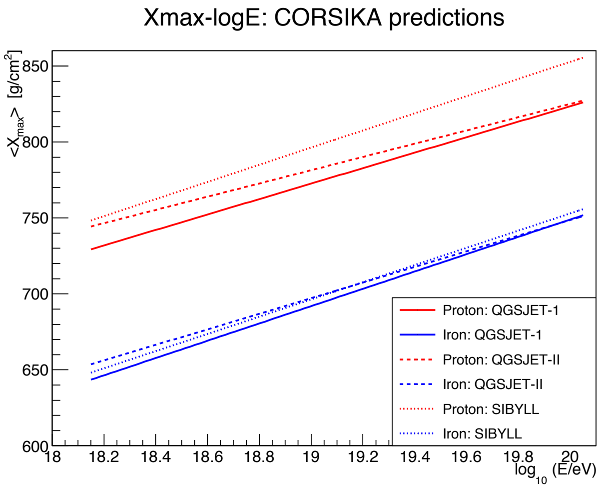
Xmax-logE: CORSIKA predictions

Fig. 1: Energy dependence of $X_{\max}$ 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 $X_{\max}$ 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

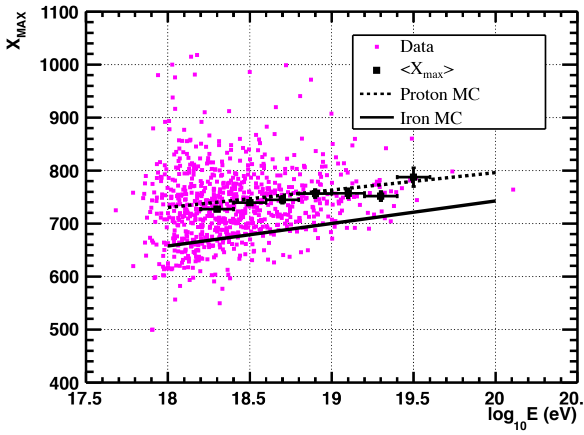

Fig. 2: The $X_{\max} - \log_{10} E$ plot from the MD hybrid data. The dots denote the events, and squares show the average of $X_{\max}$ in the energy bins. The dashed line is the expectation of $\langle X_{\max} \rangle$ from a Monte-Carlo (MC) with a pure-proton composition, and the solid line is of the iron expectation.

resolution of $X_{\max}$.

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 $\sim$ 20km 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 $\sim 1^\circ$ and $10 \sim 20 \mathrm{g/cm}^2$ in $X_{\max}$. Note that the difference in $X_{\max}$ of proton and iron showers is $\sim 70 \mathrm{g/cm}^2$ at primary energies around 10^{19}eV.

3 Results

The latest $X_{\max}$ analysis result from the MD-hybrid reconstruction is shown in Fig. 2. All the events are denoted by dots, and the average $\langle X_{\max} \rangle$ in energy bins are shown by filled squares. The dashed line is the expectation of $\langle X_{\max} \rangle$ from a Monte-Carlo (MC) with a pure-proton composition, and the solid line is for the iron expectation. The QGSJET-II hadronic interaction model is used. Note that the lines of expectation are not the same as in Fig. 1. This is because of the bias in data selection due to the limited field of view of the detectors. In this plot the data and MC passed exactly the same procedures in reconstruction and event selections, therefore these can be compared directly. One can see that the TA data is consistent with the proton expectation up to $\log_{10}(E/\mathrm{eV}) = 19.5$. The $X_{\max}$ distribution in the energy bins also prefer the protonic composition in all the range above $\log_{10}(E/\mathrm{eV}) = 18.3$.

4 Conclusions

The TA $X_{\max}$ analysis shows that the data is consistent with a light composition in the energy range $\log_{10}(E/\mathrm{eV}) = 18.3 \sim 19.5$. This result may support the scenario of forming a "dip" around $\log_{10}(E/\mathrm{eV}) = 18.7$ due to $e^{\pm}$ pair creation by interaction of cosmic rays and the CMB photons [16], and a steepening at $\log_{10}(E/\mathrm{eV}) = 19.7$ due to cosmic ray energy losses through photo-pion production [5, 17]. This also supports the relevance of our searches for cosmic ray anisotropies above $\log_{10}(E/\mathrm{eV}) = 19.0$ [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.

Acknowledgment: The Telescope Array experiment is supported by the Japan Society for the Promotion of Science through Grants-in-Aid for Scientific Research on Specially Pro- moted Research (21000002) Extreme Phenomena in the Universe Explored by Highest Energy Cosmic Rays and for Scientific Research (S) (19104006), and the Inter-University Research Program of the Institute for Cosmic Ray Research; by the U.S. National Science Foundation awards PHY-0307098, PHY-0601915, PHY-0703893, PHY-0758342, PHY-0848320, PHY-1069280, and PHY-1069286 (Utah) and PHY-0649681 (Rutgers); by the National Research Foundation of Korea (2006- 0050031, 2007-0056005, 2007-0093860, 2010-0011378, 2010-0028071, 2011-0002617, R32-10130); by the Rus- sian Academy of Sciences, RFBR grants 10-02-01406a and 11-02-01528a (INR), IISN project No. 4.4509.10 and Belgian Science Policy under IUAP VI/11 (ULB); by the Grant-in-Aid for the Scientific Research (S) No. 19104006 by the Japan Society for the Promotion of Sci- ence. The foundations of Dr. Ezekiel R. and EdnaWattis Dumke, Willard L. Eccles and the George S. and Dolores Dore Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the co- operation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management and the U.S. Air Force. We also wish to thank the people and the officials of Millard County, Utah, for their steadfast and warm support. We grate- fully acknowledge the contributions from the technical staffs of our home institutions and the University of Utah Center for High Performance Computing (CHPC).

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