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Study of UHECR Composition Using Telescope Array's Middle Drum Detector and Surface Array in Hybrid Mode

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The seven year Telescope Array (TA) Middle Drum hybrid composition measurement shows agreement between Ultra-High Energy Cosmic Ray (UHECR) data and a light composition obtained with QGSJetII-03 or QGSJet-01c models. The data are incompatible with a pure iron composition, for all models examined, for energies $\log_{10}$(E/eV)>18.4. This is consistent with previous TA results. This analysis is presented using an updated version of the pattern recognition analysis (PRA) technique developed by TA.

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1. Introduction

The composition of Ultra-High Energy Cosmic Rays (UHECR's) is important for the unsolved question of their origin. The GZK cutoff [1], [2] has been seen by a number of experiments including the Telescope Array (TA) [3] and Pierre Auger Observatory (PAO) [4]. These results suggest sources of UHECR's are nearby $\lesssim$ 100 Mpc. If galactic and extragalactic field models are correct a light cosmic ray composition should become anisotropic at the highest energies. Recently, TA has published evidence of anisotropy in arrival directions of UHECR [5] and does not rule out sources within this radius.

Results from Fly's Eye, HiRes and Telescope array indicated a predominantly light composition of cosmic rays ([6], [7], [8]). The PAO's hybrid publication in 2012 also states that for UHECR of energy "10^{18} to $10^{18.5}$ eV... the shape of the X_{max} distribution is compatible with there being a substantial fraction of protons..." [9].

Extensive air showers (EAS) created by incident UHECR in the atmosphere reach a maximum in particle density called X_{max}. Heavy primaries have a narrower distribution with an average X_{max} higher in the atmosphere, protons will interact more deeply with a wider distribution. The two distributions have significant overlap. Indirect detection techniques are unable to determine an individual UHECR's mass due to these large statistical fluctuations inherent to EAS. Hence, the distribution of a large number of measurements must be used to make inferences about composition. Since the flux of UHECR is on the order of an event per square kilometer per year, indirect detection utilizing the Earth's atmosphere is necessary.

This is done using the air-fluorescence method pioneered by the Fly's Eye experiment [10] which accurately measures the air-shower longitudinal shape. Charged particles in the developing EAS excite molecules in the atmosphere which then emit fluorescence light that fluorescence detectors (FDs) can measure. The composition analysis in this paper uses seven years of observation from the Middle Drum (MD) FDs and Surface Scintillation Detector (SD) array for a set of hybrid measurements . This site consists of telescopes repurposed from the HiRes-1 experiment [11].

These observations are compared to a set of distributions created by Monte Carlo (MC) simulations that use a detailed model of the detector. We introduce a 'shift Plot' which compares the full shape of the data and MC distributions, and their evolution with energy, using the two sample Cramér-Von Mises (CVM) test [12].

2. Hybrid Event Reconstruction

Particle density and timing from SDs are combined with FD tube timing and geometry to generate a longitudinal profile, from which X_{max} is calculated. Initial geometry and core location calculation of the shower is performed using the trigger times of the SDs. Then a lateral distribution function is used to fit the particle densities perpendicular to the shower core location, generating a more accurate geometrical reconstruction of the shower. This geometry is used for the hybrid analysis.

Shower profile creation is the final step of the hybrid reconstruction and is used to find the X_{max} of the shower. Each PMTs view of the shower is converted into slant depth, in g/cm^2, and compared to a library of Monte Carlo (MC) simulated showers generated by CORSIKA [13]. This gives the value of X_{max} and energy for the event. This hybrid reconstruction method has been used and explained in further detail in [8], [14], and [15].

3. Cuts Optimized for Minimized X_{max} Resolution Energy Dependence

Since UHECR particle composition could be energy dependent (PAO results indicate an energy dependent narrowing of the X_{max} distribution [16]) a set of cuts is needed to minimize the energy dependence of the X_{max} resolution. Resolution energy dependence comes from events that do not show a pronounced shower maximum in the detector field of view. Typically these are lower energy events. Chi-square cuts on the G-H fits are not sufficient to reject most events that have poorly defined X_{max}.

In this paper an updated version of the pattern recognition analysis (PRA) method, (as described in [8] and [17]) which selects events that have a clear rise and fall in shower profile signal, is used. This updated version is called the Quality Factor Analysis (QFA) and applies logistic regression to the output of the PRA to set a scale of 'quality' for each event on the data set. This is described in some detail in [17].

Events with X_{max} in the field of view (FOV) of the detector could still be incorrectly reconstructed, therefore, cuts which take into account the geometry of the events need to be applied in addition to the QFA cut. The geometry cuts were optimized for further minimizing the energy dependence of the X_{max} resolution while also taking into account overall resolution and bias for both X_{max} and energy and maximizing the total number of events accepted. The set of optimized geometry cuts, applied to the events that passed the QFA, are listed below. Events which satisfy the inequalities are removed from the data set.

1. Weather cut: Clouds not limiting the FD FOV; nights with no visible clouds are in the sample.
2. Failmode: Events that failed the profile reconstruction are removed from the set.
3. Energy $< 10^{18.4}$ eV
4. Zenith angle $> 58^\circ$
5. Boundary Distance < -500 m (negative values are outside the array)
6. Hybrid/Surface Core Difference > 1600 m
7. Geometry Fit χ^2/DOF > 5
8. Start X_{max} Bracket: (X_{max} - X_{start}) < 0 g/cm^2
9. End X_{max} Bracket: (X_{end} - X_{max}) < 0 g/cm^2

The result of this composition analysis will be presented at the 34th International Cosmic Ray Conference.

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