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Study of Air Shower Front Structure using the Telescope Array Surface Detector Data

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Abstract: The Telescope Array is the largest cosmic ray detector in the northern hemisphere. It is a hybrid detector consisting of an array of scintillator detectors and three fluorescence telescope stations which observe the atmosphere above the ground based array. It is located in the western desert of central Utah. It observes the air showers induced by ultra high energy cosmic rays. The lateral distribution and time profiles of particles in the extensive air shower evolve along the cascade propagation in the atmosphere. We report on the data measured with the surface array of the Telescope Array experiment and compare these to the results of Monte Carlo simulations.

Keywords: Ultra High Energy Cosmic Ray, Telescope Array, Air shower development

1 Introduction

The study of the lateral distribution of shower particles is important as a fundamental ground parameter of an extensive air shower (EAS) from the following points of view. For the primary energy estimation, the total number of particles in EAS have to be determined accurately. For the primary component measurement, it is expected to find the good parameters which depend sensitively on the longitudinal development of EAS. Though many measurements of the lateral distribution of secondary particles have been reported, it is difficult to compare these results directory. One reason of this difficulty is that the NKG function does not give a good fit to the lateral distribution of shower particles for a single value of the age parameters over a large range of distances from the shower axis. Therefore, the size and age of the same shower are differently estimated according to radial distance. In this report, we present a study of the lateral distribution observed by Telescope Array (TA) using the local age parameter which is explained later, and its dependence on energy, Xmax and zenith angle.

We also studied the arrival time delay from the plane shower front. The shower particle swarm is actually not a plane, but is approximately a cone. The slope of the cone measured from the shower core is known as the curvature of the shower front. The circular symmetry of the shower curvature for vertical showers is broken when considering inclined showers. There is an asymmetry arising from the evolution of the shower and the attenuation of the particles traveling longer paths in the atmosphere in the upper than the lower side of the plane perpendicular to the shower axis. Furthermore, most particles are not propagating strictly in the shower direction but are on average going away from the axis. This also cause this azimuthal asymmetry.

2 Telescope Array

The West Desert in Utah, USA is the experimental site. The TA consists of 507 plastic scintillation counters (SD) which cover the ground area of 700 km^2 in 1.2 km grid and 3 fluoerscence telescope stations (FD stations) which surround the array and look inward. [1] [2]

The Field of view (FOV) of each FD station is $3^\circ \sim 34^\circ$ in elevation angle and 120° in azimuthal angle. There are 12 telescopes in each FD station. The FOV of each telescope is 15.5° in elevation and 18° in azimuthal. Each telescope has spherical mirror of 3.3 m in diameter. The shower image is recorded by a camera composed of 2-inch hexagonal PMTs placed on image plane.

Each partcile detector of the SD has 2 layers of plastic scintillator. **??** The area is 3 m^2 and the thickness is 1.2cm. The scintillation photons are fed into PMT via wave length shifter fibers installed in grooves cut on the surface of the scintillator. The output signal from PMT is digitized by 12bit 50Hz Flash ADC (FADC). When the PMT signals of both layer exceeds the threshold level ($\sim$ 0.3 MIP), data is stored in the memory. The trigger timing information of local SD which has the signal above 3MIP is sent to the central DAQ system via 2.5GHz wireless LAN. If the central DAQ find triggers from 3 or more adjacent SDs, the waveform information of triggered SD ($>$0.3MIP) collected and stored in the central DAQ system. All SD clocks are synchronized by 1pps signal received from a GPS unit (Motorola M12+ on-core module) and run at 50 MHz for 20 nsec time resolution.

For present analysis, we use SD data from May 2008 to May 2012. Data is reconstructed by TA standard analysis programs. **??**

To make SD Monte Calro simulation data library, CORSIKA 6.960 simulation package is used. It is configured to use the QGSJET-II-03 and FLUKA2008.3c hadronic models at high and low energies, respectively, and the EGS4 electromagnetic model. Using GEANT4, the energy deposited in each SD is calculated.

3 Air shower structure

3.1 Lateral distribution

Nishimura and Kamata solved the 3-Dimensional shower equations in Approximation B numerically to obtain the lateral distribution of electrons propagating in a medium of

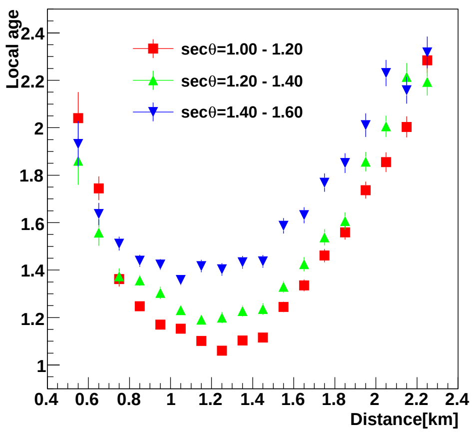

Fig. 1: Distribution of events above $10^{19.1}$ eV : The radial variation of LAP for different zenith angles.

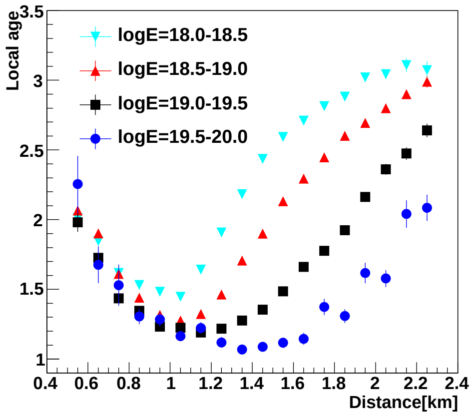

Fig. 2: Distribution of events with zenith angle $\theta < 45°$: The radial variation of LAP for different primary energies.

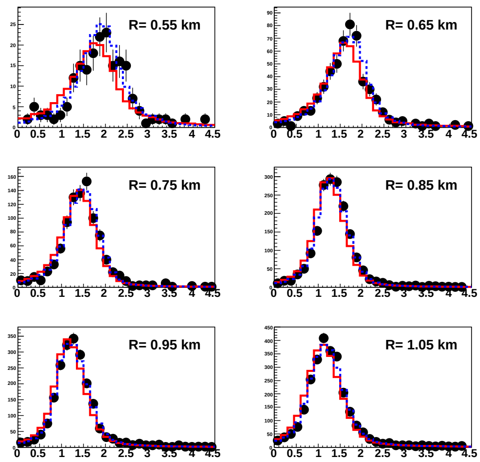

Fig. 3: LAP distribution of events with $\theta < 55°$ and $E < 10^{19.1}$ eV: Comparison betweeen data and MCs.Solid circle is data. Red histogram and blue histogram are proton MC and iron MC respectively.

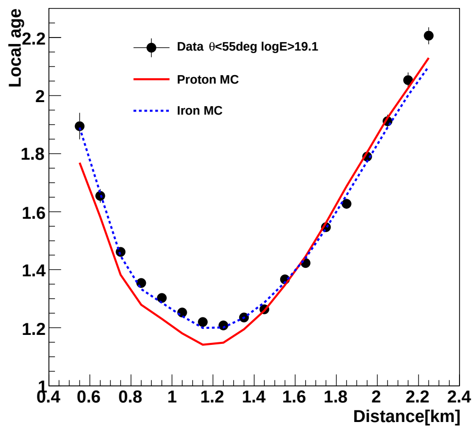

Fig. 4: The radial variation of LAP of events with $\theta < 55°$ and $E < 10^{19.1}$ eV: Comparison betweeen data and MCs.

constant density. [4] The results obtained on lateral density distribution of cascade particles by Nishimura and Kamata can be approximated by the well known NishimuraKamataGreisen (NKG) structure function proposed by Greisen. It is given by

$$f(r) = C(s)(r/r_m)^{s-2}(1+r/r_m)^{s-4.5} \quad (1)$$

,where

$$C(s) = \frac{\Gamma(4.5-s)}{2\pi\Gamma(s)\Gamma(4.5-s)}. \quad (2)$$

The lateral shower age varies with radial distance in real. In order to examine the dependence of age on core distance, the local age parameter(LAP) S_{ij} between core distance r_i and r_j was defined by Capdevielle and Gawin. [5] From two neighboring pointsi and j, we can give a LAP for any distribution $f(x)$(where $x = \frac{r}{r_m}$) which characterizes the best fit by a NKG-type function in $[x_i; x_j]$:

$$S_{local}(i,j) = \frac{ln(F_{ij}X_{ij}{}^2Y_{ij}{}^{4.5})}{ln(X_{ij}Y_{ij})} \quad (3)$$

where, $F_{ij} = \rho_i/\rho_j$, $X_{ij} = r_i/r_j$, and $Y_{ij} = (x_i+1)/(x_j+1)$.

Fig. 1 shows the dependence on zenith angle of primary particle. LAP initially decreases with radial distance and reaches at 1.0 $\sim$ 1.4 km, then starts increasing with radial distance. At same distance, LAP increases as incident zenith angle increases.

In Fig. 2, the primary energy dependences of LAP is shown. Value of LAP increases as the primary energy increases. Radial distance where LAP is minimum increases as primary energy become large.

Comparison of LAP of real data, proton MC and iron MC is shown in Fig. 4 and Fig. 3 It is seen that the LAP decreases as radial distance increases and reaches minimum at around 1.0 km beyond which it increases again. This radial distance dependence is not changed much by primary particle. Data is consisten with both of proton MC and iron MC. Around 1.0 km away, the measured LAP is larger than LAPs expected by MCs.

3.2 Shower curvature

AGASA group developed functions for shower curvature.[6] Here, T_d [nsec] and T_σ [nsec] are the delay time of the first

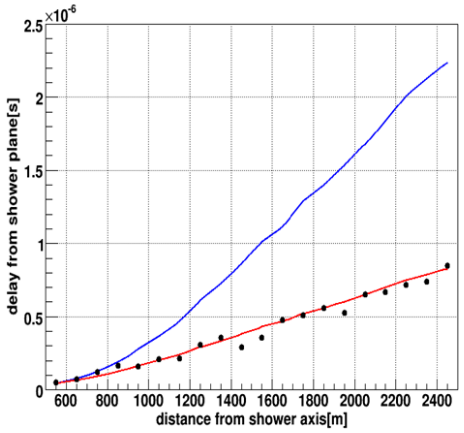

Fig. 5: Shower curvature (T_d) of the inclined shower ($\sec\theta = 1.6 \sim 1.8$, $\zeta = 90° \sim 120°$). Balck dots: MC, Blue line: AGASA function, Red line: this work

particle obesrved by each detector from the plane shower front ant its fluctuation of shower particles aroud the average.

$$T_d = 2.6(1.0 + \frac{R}{30})^a \rho^b \quad (4)$$

$$T_\sigma = 2.6(1.0 + \frac{R}{30})^c \rho^d \quad (5)$$

where R [m] is distance from the shower axis and ρ [$/m^2$] is the number density of particles observed by each detector. a, b, c and d are 1.5, -0.5, 1.5 and -0.3 respectively.

From the comparison with our MC data, we found that these functions are not good for the inclined showers. When the zenith angle is more than 45°, the azimuthal asymmetry of T_d and T_σ become large. In this paper, we assume that a, b, c and d have dependences on zenith angle θ and azimuth angle in shower plane ζ. The incoming direction of the shower is defined as $\zeta = 0°$ ($0° \leq \zeta \leq 180°$). Using MC data set, we obtained the following functions.

$$a = 1.78 - 0.25\sec\theta - 0.00065\zeta \quad (6)$$

$$b = -1.1 - 0.50\sec\theta - 0.00050\zeta. \quad (7)$$

Practically, the arrival time distribution is not symmetric around the average T_d. Therefore we estimate T_σ in two cases.

$$c_{t<T_d} = 1.49 - 0.19\sec\theta - 0.00080\zeta \quad (8)$$

$$c_{t>T_d} = 1.38 + (0.00079 - 0.0011\sec\theta)\zeta \quad (9)$$

$$d_{t<T_d} = -0.45 + 0.002(-1.0 + \sec\theta)\zeta \quad (10)$$

$$d_{t>T_d} = -0.3 - 0.2\sec\theta + 0.003(-1.0 + \sec\theta)\zeta \quad (11)$$

Fig. 5 shows the shower curvature (T_d) of the inclined shower ($\sec\theta = 1.6 \sim 1.8$).

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