Studies of Air Showers above 10^{18} eV with the CHICOS Array

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CHICOS (California HIgh school Cosmic ray ObServatory) is presently an array of more than 140 detectors distributed over a large area ($\sim$400 km^2) of southern California, and will consist of 180 detectors at 90 locations in the near future. These sites, located at area schools, are equipped with computerized data acquisition and automatic nightly data transfer (via internet) to our Caltech lab. The installed sites make up the largest currently operating ground array for ultra-high energy cosmic ray research in the northern hemisphere. The goal of CHICOS is to provide data related to the flux and distribution of arrival directions for ultra-high energy cosmic rays. We have performed detailed Monte-Carlo calculations to determine the density and arrival-time distribution of charged particles in extensive air showers for the CHICOS array. Calculations were performed for proton primaries with energies 10^{18} to 10^{21} eV and zenith angles out to $\simeq 50°$. We have developed novel parameterizations for both distributions as functions of distance from the shower axis, primary energy, and incident zenith angle. These parameterizations are used in aperture calculations and reconstruction of shower data, enabling preliminary analysis of ultra-high energy shower data from CHICOS.

1. Introduction

CHICOS, the California HIgh school Cosmic ray ObServatory, is a large ground array of plastic scintillator detectors located at schools and universities in the Los Angeles, California area. Siting the array in a large urban area takes advantage of existing infrastructure to power the array as well as school internet connections for data transfer. The array has been observing extensive air showers since early 2003, with the goal of measuring the flux and arrival direction distribution for ultra-high energy cosmic rays (above 10^{18}eV in primary energy). The CHICOS array covers an area of $\sim$400 km^2 with an average site-to-site spacing of approximately 2 km (see Figure 1). CHICOS uses thin ($\lesssim$ 10 cm) plastic scintillators of area $\approx 1m^2$ to measure the energy deposited in the detectors by charged particles. When a series of individual detector hits passes cuts and is considered a candidate shower event, the measured densities are used to determine the location and energy of the primary cosmic ray. The time of hits in each detector is used to determine the primary direction. To properly reconstruct the arrival direction, it is necessary to know the shape of the shower front. Furthermore, the direction and energy are correlated since a more inclined shower must traverse a greater atmospheric slant depth resulting in an "older" shower. Since CHICOS is sited at an atmospheric depth of $\sim$975g/cm^2, well beyond shower maximum, inclined showers are attenuated relative to vertical showers. In the analyses presented here, "ground" refers to an elevation of 250m MSL (see Figure 1a).

In order to reconstruct ultra-high energy showers from CHICOS data, we have performed extensive simulations of proton-initiated showers in the energy range 10^{18} to 10^{21} eV, using the AIRES simulation package for extensive air showers[1]. We present CHICOS-appropriate parameterizations for both the charge density, or
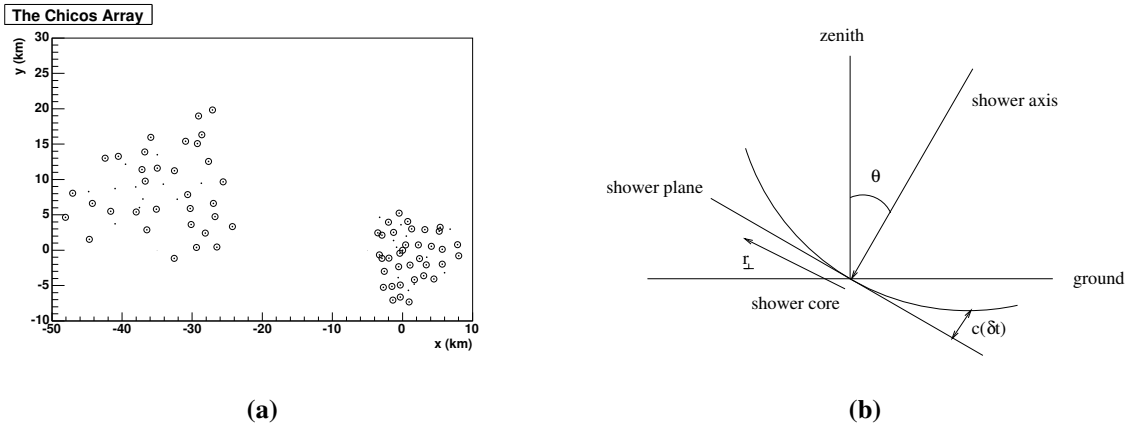
Figure 1. (a)The CHICOS array in the San Gabriel and San Fernando Valleys of Los Angeles County, California. Each site contains two scintillator detectors separated by ∼5m. Circled dots and bare dots are sites installed and in progress, respectively. The array averages approximately 250m above sea level, with individual detector sites ranging from ∼100m to ∼400m in altitude. (b)The geometry of an extended air shower showing the definition of $r_\perp$ and the time delay δt.

lateral distribution function (LDF), and the time distribution function (TDF) of ground particles in an ultra-high energy shower. These parameterizations are employed in the analysis of CHICOS shower data using a chi-squared minimization algorithm, giving preliminary reconstructions of energy and arrival direction for observed events above 10^{18} eV.

2. Shower Characteristics and Monte-Carlo Simulation

Showers in the CHICOS energy range typically contain 10^9 to 10^{10} particles, and may have an density of $\geq 1/m^2$ out to 1km or more from the shower core. The time distribution of a typical shower, at km-scale distance from the core, is characterized by both shower curvature delay and shower time spread in the range of several microseconds. See Figure 1b for a schematic shower front and the definition of terms used to describe the shower's geometry.

The CHICOS data acquisition system samples the amplitudes and times of scintillator signals at 12.5ns intervals. Multiple hits within a shower are individually resolved. Reconstructing primary energy and direction from this data requires mathematical models for both the LDF, $\rho(r_\perp; E, \theta)$, and the arrival time distribution, $T_d(\delta t; r_\perp, E, \theta)$.

We used version 2.6.0 of the AIRES extensive air-shower simulation program[1] to simulate proton-initiated UHECR showers. Hadronic interactions were modeled with QGSJET[2]. We performed simulations at zenith angles $\cos\theta = (0.95, 0.85, 0.75, 0.65)$ and primary energies $log_{10}(E[eV]) = (18, 18.5, 19, 19.5, 20, 20.5)$. Simulations at these energies almost always employ *thinning* or statistical sampling of particles. We set thinning to begin at $E_{th} = 10^{-7} \times E_{primary}$, with the AIRES statistical weight factor set to $W_f^{(EM)} = 1$. Shower particles were tracked down to $E_{e\pm,\gamma} = 1MeV$ and $E_{\mu\pm} = 20MeV$. Finally, all ground particles were required to have energy $\geq 5MeV$ to correspond to CHICOS detector thresholds. We performed 10 simulation runs at each set of shower parameters. In the analysis four categories of histograms were considered:

1. The number of electrons and positrons as a function of $r_\perp$ in 50-m bins from 100m to 10000m.
2. The number of electrons and positrons as a function of $r_\perp$ and δt in 50m and 50ns bins respectively.
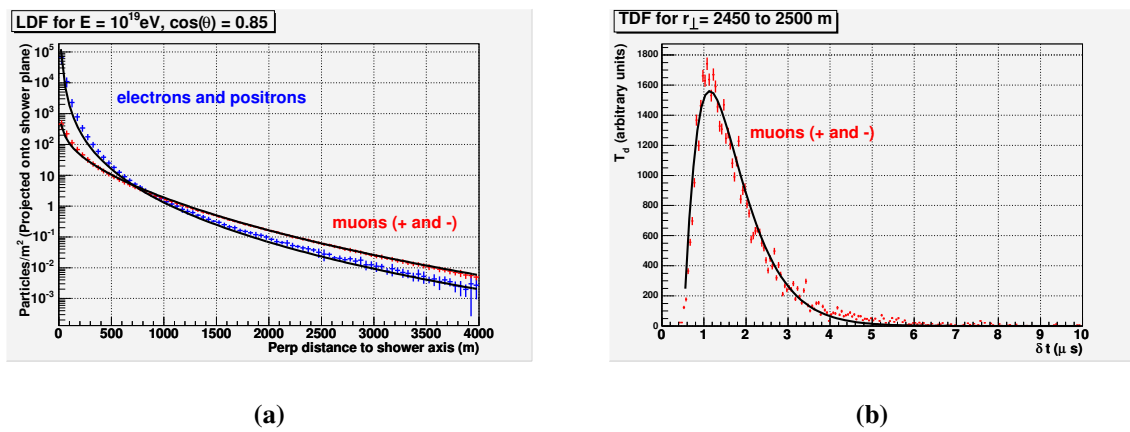
(a) **(b)**

Figure 2. (a) The behavior of particle densities as a function of $r_\perp$ for proton primary of energy 10^{19} eV and zenith angle of $\cos\theta = 0.85$. Points with error bars are AIRES output (mean and standard deviation of 10 runs). The solid curve overlay shows the final muon and electron LDF parameterizations. (b)Arrival time distribution for muons at radius $2450m < r_\perp < 2500m$, shower parameters of (a).

   3. The same (items 1 and 2) for muons (μ^+ and μ^-).

These histograms were averaged over the ten runs and the standard deviation of the runs was used as the uncertainty in the histogram.

3.   Charge Density and Time Distributions

To model the LDF, we began with the approach of the AGASA experiment, which was similar to CHICOS in many ways but with important differences in location and hardware. AGASA used a parameterization of a modified NKG formula[3]. Thus we also began with the functional form:

$$\rho(r_\perp) = \mathcal{C} \left(\frac{r_\perp}{R_M} \right)^{-\alpha} \left(1 + \frac{r_\perp}{R_M} \right)^{-\eta+\alpha} \left\{ 1 + \left(\frac{r_\perp}{1000} \right)^2 \right\}^{\delta} \tag{1}$$

where $r_\perp$ is in meters and ρ is in particles/m^2. All parameters are potentially functions of the zenith angle θ, energy E (in eV), and species of the primary cosmic ray. Note that R_M is an *effective* Molière radius allowed to vary in order to fit the shower shape subject to the energy threshold.

Figure 2 shows the simulation with $E_{\text{primary}} = 10^{19}$eV and $\cos\theta = 0.85$. This example shows the typical contrast between muon and electron distributions, motivating us to parameterize the distributions independently of one another. For each species, we employed an iterative process of fitting all individual histograms, fixing or partially fixing parameter values, and refitting for the remaining parameters. Our final LDF parameterizations are given by Equation 1 with the parameters listed in Table 1. Examples of these formulae are drawn as solid curves over the AIRES output histograms in Figure 2a.

Turning to the shower front curvature delay and the spread of arrival times, we note that there is no well-motivated and accepted model similar to the modified NKG formula. Therefore a purely phenomenological model was developed. As with the lateral distribution function, muons and electrons are treated separately in our parameterizations. Rather than fitting an average arrival time and spread, we model the shape of the shower

Table 1. LDF Parameters

Particle Type	R_M	α	δ	η	$log_{10}(C)$
Electron	2477	2.513	0.03107	$8.391 - 5.315(sec(\theta) - 1)$	$0.1 - 1.45(sec(\theta) - 1)$ $+0.96(log_{10}(E) - 19)$
Muon	2560	0.7701	0.01939	$9.020 - 2.552(sec(\theta) - 1)$	$1.2 - 0.72(sec(\theta) - 1)$ $+0.97(log_{10}(E) - 19)$

with a full time distribution function for curvature time delay:

$$T_d(\delta t; r_\perp, E, \theta) = \begin{cases} N(\delta t - a)^b \exp[-c(\delta t - a)] & \text{if } \delta t \geq a; \\ 0 & \text{if } \delta t < a. \end{cases} \quad (2)$$

where N is an overall normalization constant. We find that in fact, over the CHICOS energy range, a, b, and c may be considered functions of $r_\perp$ and θ without introducing a dependence on E. An example of the muon TDF model is shown in Figure 2b. We are presently working to integrate the final TDF parameterization in our shower reconstruction algorithm; it will replace a modified AGASA time delay formula currently in use.

4.   Conclusions

The AIRES simulations and resulting shower parameterizations presented here are appropriate for the CHICOS location and instrumentation. As such, these results allow preliminary shower reconstruction; final reconstructed energies and directions await further refinements in our treatment of individual detector response. A smaller-scale "Chiquita" array has been deployed within CHICOS to build a data set for showers at energies $\sim 10^{16}$ to 10^{18}eV; analysis of the Chiquita data is presented elsewhere in these proceedings and provides us with a test bed for the reconstruction technique and detector modeling[4]. In analyses of Chiquita showers we have also performed limited comparisons of AIRES outputs with the results of the CORSIKA simulation package[5], finding good agreement between the two.

5.   Acknowledgements

References

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