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RESULTS FROM THE CACTI EXPERIMENT: AIR-ČERENKOV AND PARTICLE MEASUREMENTS OF PEV AIR SHOWERS AT LOS ALAMOS

S. Paling[1], A. M. Hillas[1], D. Berley[2], S. Biller[1], Mei-Li Chen[2], P. Chumney[3], D. Coyne[4], D. Dorfan[4], R.A. Ellsworth[5], J. A. Goodman[2], T. J. Haines[6], C. M. Hoffman[6], L. Kelley[4], R. Schnee[4], A. Shoup[3], C. Sinnis[6], D. Williams[4], T. Yang[4], G. Yodh[3]

[1]*Physics Department, University of Leeds, Leeds LS2 9JT, UK*
[2]*University Of Maryland, College Park, MD 20742, USA*
[3]*University Of California, Irvine, CA 92717. USA*
[4]*University Of California, Santa Cruz, CA 95064. USA*
[5]*George Mason University, Fairfax, VA 22030, USA*
[6]*Los Alamos National Laboratory, Los Alamos, NM 87545. USA*

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ABSTRACT

An array of six wide angle Čerenkov detectors was constructed amongst the scintillator and muon detectors of the CYGNUS II array at Los Alamos National Laboratory to investigate cosmic ray composition in the PeV region through measurements of the shape of Čerenkov lateral distributions. Data were collected during clear, moonless nights over three observing periods in 1995. Estimates of depths of shower maxima determined from the recorded Čerenkov lateral distributions align well with existing results at higher energies and suggest a mixed to heavy composition in the PeV region with no significant variation observed around the knee. The accuracy of composition determination is limited by uncertainties in the expected levels of depth of maximum predicted using different Monte-Carlo shower simulation models.

INTRODUCTION

An improved knowledge of the composition of cosmic rays in the knee region of the spectrum may help to increase our understanding of the origins and acceleration of high energy cosmic rays and the characteristics of cosmic ray propagation and confinement within our galaxy.

Direct measurement of primary cosmic rays is confined to energies $< 10^{15}$ eV because of the rapidly diminishing flux. Various indirect methods of determining mass composition through interpretation of the measured electron, muon and photon components of air showers have been investigated, although no consistent and generally accepted results have been provided to date.

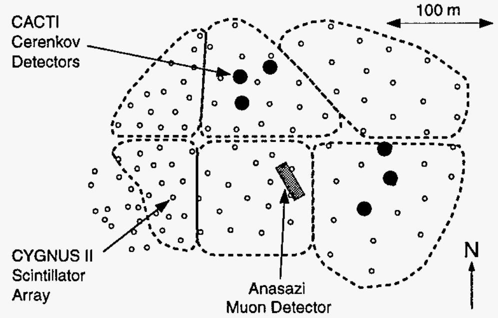

Fig. 1: A map of the CYGNUS II experiment and the CACTI Čerenkov array.

Previous investigations suggested that the shape of the Čerenkov lateral distributions (CLDs) of showers is sensitive to height of maximum (X_{max}) (Patterson and Hillas, 1983). Simulations show that showers induced by lower mass primary particles tend to reach maxima deeper in the atmosphere resulting in steeper CLDs, particularly noticeable in regions of the CLD close to shower core (eg. < 100m). In regions further from the shower core the Čerenkov light intensity is less sensitive to X_{max} and is closely related to total shower energy. Investigations of X_{max} (and hence primary mass) from Čerenkov measurements are thought to have

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the advantage over methods using electron and muon measurements of being less sensitive to core-location errors and statistical fluctuations, and less susceptible to interaction modelling uncertainties in simulation (Paling and Hillas, 1995).

The purpose of the CACTI experiment has been to investigate the mass composition in the PeV region using measurements of CLDs and the electro-magnetic and muon content of cosmic ray showers. CACTI consisted of an array of six wide-angle Čerenkov detectors built amongst the CYGNUS II array at the Los Alamos National Laboratory, USA. The experiment was operated during clear, moonless evenings in 1995. This report describes the design and operation of the experiment and summarises the results of the analysis of CLD data and the comparison of recorded data with simulations. Further results of data analysis will be presented at the conference.

EXPERIMENTAL DESIGN AND OPERATION

The CYGNUS II array, situated at an altitude of 2310m (780gcm^{-2}), consisted of 96 scintillator detectors dispersed over 6×10^4 m^2 and a 70m^2 muon detector with an energy threshold of $\sim$ 2GeV (R. Allen et al., 1992). The CACTI experiment was located towards the centre of the CYGNUS II array, and consisted of six wide-angle Čerenkov detectors positioned in two distinct groups separated by approximately 150m as shown in figure 1.

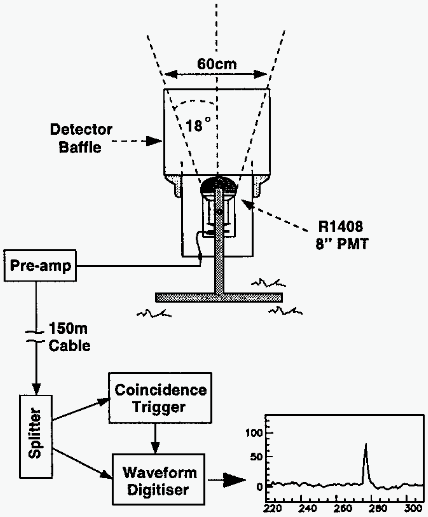

Fig. 2: Schematic of the Čerenkov detector design and data acquisition signal path

The design of the CACTI Čerenkov detectors and the data acquisition signal path is shown in figure 2. Each detector consisted of an 8" hemispherical Hamamatsu R1408 photomultiplier tube (PMT) mounted in a steel housing with a 0.31sr aperture. The PMT signals were amplified at the detector to reduce the effects of electronic pickup before traversing 150m of cable. After being further amplified and stretched to a rise time of $\sim$ 30ns, the signals were split. One copy was used for triggering (a simple multiplicity trigger) and the other was recorded by LeCroy 2262 waveform digitisers. The digitisers continuously recorded the previous 8μs of each signal waveform in 10 bit, 25ns samples, and were read out by a PC controlling the experiment whenever a multiple coincidence of Čerenkov signals had occurred.

The Čerenkov detector optics and data acquisition system were designed to reduce the level of noise due to Night Sky Background light (NSB). The PMTs used were operated with a high dynode chain current and a gain of less than $< 2 \times 10^4$ to avoid saturation effects due to operation in high background light conditions. The energy threshold of the array was $\sim$0.3 PeV, however the range of energies for which recorded events were clear of trigger biases and waveform digitiser saturation was 1 to 10 PeV.

The experiment was operated during three dark periods in 1995. Over 70,000 events were recorded in $\sim$100 hours of observation under good night sky conditions (corresponding to a duty cycle of 6%). Individual events were considered appropriate for CLD analysis only if Čerenkov samples were taken over a wide range of core distances and the incident angle was within the full viewing aperture of the detector, resulting in a selection of $\sim$15% of the total events recorded.

DATA ANALYSIS AND RESULTS

The MOCCA-92 Monte-Carlo shower simulation (Hillas, 1997) was used to investigate the performance of the experiment and develop the techniques used in data analysis. Simulations were also used for comparisons with the recorded CACTI data to investigate mass composition. Showers of varying primary energy, incident angle and mass were generated and the uncertainties due to the response of the CYGNUS, and Anasazi experiments were modelled, including the effects of core-location error, Čerenkov signal measurement and NSB noise.

For both the CACTI and simulated data, individual CLDs were determined for each event by fitting a parameterised function approximating the shape of the CLD to the six recorded Čerenkov signals. From the fitted function the expected Čerenkov signals at 40m (C40) and 140m (C140) from the shower core were determined with an accuracy of ~20% and ~10% respectively (limited principally by core-location errors and NSB noise).

The value of C140 provides an estimate of the Čerenkov intensity far from the core and is used to estimate shower energy ($E \propto C140^{0.97}$). The ratio of C40 and C140 provides a measure of the CLD steepness and is related to the average depth of shower maximum ($X_{max} \propto log\,(\frac{C40}{C140})$).

Comparison of the average CLDs for the CACTI and MOCCA data show that the recorded data compares well with simulations and most closely agrees with MOCCA simulations of iron with no significant variation observed with energy across the knee. Figure 3 shows average CLDs for recorded data and simulated data of different primary masses with energy between 1 and 3.2 PeV. The CLDs for each event have been normalised to an energy of 3.2 PeV (determined from C140) and an average incident zenith angle of 12° . The CACTI CLD is significantly flatter than CLDs of simulated primary masses lighter than iron.

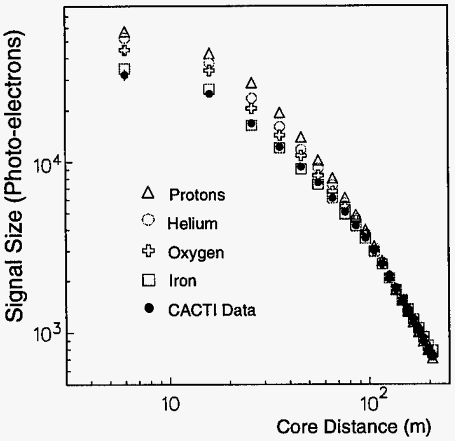

Fig. 3: Average Čerenkov lateral distributions (CLDs) for MOCCA simulations and recorded CACTI data normalised to 3.2 PeV.

The average value of the ratio of C40 and C140 for CACTI data also agrees with MOCCA simulations of iron (as expected from the previous result). However the observed spread in the ratio of C40 and C140 is significantly larger than would be expected for a pure iron composition, and is consistent with a lighter or mixed composition. Figure 4 shows the distributions of the C40/C140 ratios for CACTI and simulated data for events between 1 and 3.2 PeV again normalised to 3.2 PeV and an average incident angle of 12° . It is unlikely that there is a significant component of cosmic rays of mass > 56, consequently these results indicate a systematic uncertainty in the steepness of the CLDs predicted by the MOCCA simulation. This would agree with previous investigations of the MOCCA 92 program (Hillas 1997) suggesting an over-estimation of X_{max} due to inaccuracies in the modelling of hadronic interactions.

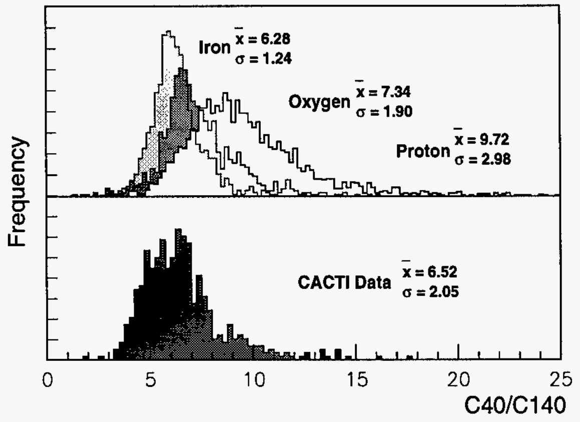

Fig. 4: Distributions of the ratio of the Čerenkov signals at 40m (C40) and 140m (C140) from the core for MOCCA simulations and CACTI data normalised to 3.2 PeV.

Figure 5 shows the variation in estimated X_{max} for the CACTI data with increasing shower energy in comparison to a variety of simulation models: MOCCA 92, SIBYLL (Fletcher et al.,1994) and QGSJET (Ostapchenko et al.,1997). Also shown are the results of previous measurements of X_{max} at higher energies by Fly's Eye (Bird et al.,1993) and Yakutsk (Dyakonov et al.,1993).

The X_{max} measurements for the CACTI data appear to agree well with a continuation of the Fly's Eye and Yakutsk data to lower energies.

A significant disagreement in the prediction of X_{max} by each of the simulation models used is clearly seen. Estimations of primary mass from the measurements of X_{max} are hence strongly dependant on the simulation model used. Comparison with MOCCA suggests an average mass composition of iron for all of the X_{max} measurements between 10^{15} and $> 10^{19}$ eV, once again indicating a systematic uncertainty in the MOCCA simulation. The SIBYLL and QGSJET simulations appear to agree more closely. Comparison with data suggests a mixed to heavy composition for the CACTI data with no significant variation observed around the knee and a mixed composition for the Fly's eye and Yakutsk data becoming lighter at higher energies.

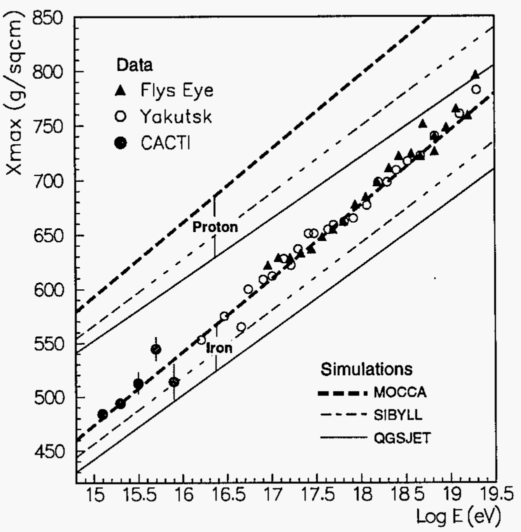

Fig. 5: Depth of shower maximum (X_{max}) verses primary energy for recorded data and various shower simulation models.

CONCLUSIONS

A relatively simple array of Čerenkov detectors in conjunction with data from a scintillator array has been used to record event by event Čerenkov lateral distributions and investigate the depth of maxima and primary mass of cosmic ray showers in the PeV region.

The depths of shower maxima verses energy determined for recorded data between 1 and 10 PeV appear consistent with a continuation of existing results at higher energies from the Fly's Eye and Yakutsk experiments. Comparison with simulations suggest a mixed and heavy average mass composition in the PeV region with no significant variation observed around the knee. Absolute composition determination from depth of maxima measurements is limited by uncertainties in the predictions of Monte-Carlo air shower simulations used.

Comparisons of recorded data with MOCCA-92 simulations add to existing evidence for a systematic uncertainty in the prediction of depth of maxima by the current version of the program.

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