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Simulation and analysis of wide angle Cherenkov Telescope data

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Abstract. WACT is an array of wide angle Cherenkov telescopes built around the Milagro Gamma Ray Observatory. WACT will record information about the Cherenkov light distribution of cosmic ray showers that trigger Milagro, providing a more complete picture of these showers including the nature of the primary particle. This experiment has been simulated in detail, the results of which will be presented. Methods to analyze data taken from the telescopes and Milagro will also be presented.

1 Introduction

The Wide-angle Air Cherenkov Telescope (WACT) array is located at the Fenton Hill Observatory, near Los Alamos, New Mexico at an altitude of 2650 meters (750g/cm^2). WACT consists of six telescopes surrounding the Milagro Gamma Ray Observatory. Three of the telescopes are located approximately 60m from the center of the Milagro detector and the other three are located about 120m from Milagro as shown in Figure 1.

Each telescope consists of a 3.8m^2 spherical mirror with a focal length of 2.35m. The telescope cameras will consist of an array of 20-25 photomultiplier tubes (PMTs) fitted with hexagonal faced light cones to give each PMT a 3.4 square degree field of view for a total field of view of $\sim$78 square degrees or 0.024sr. The telescopes are housed in a steel framed, cloth building which can be rolled off the telescope pad during operation.

The WACT array will be sensitive to cosmic ray induced air showers from 10 TeV to beyond the knee in the cosmic ray spectrum. This will allow this instrument to provide data overlap between existing direct measurements at the lower energies and existing ground based measurements in the region of the knee.

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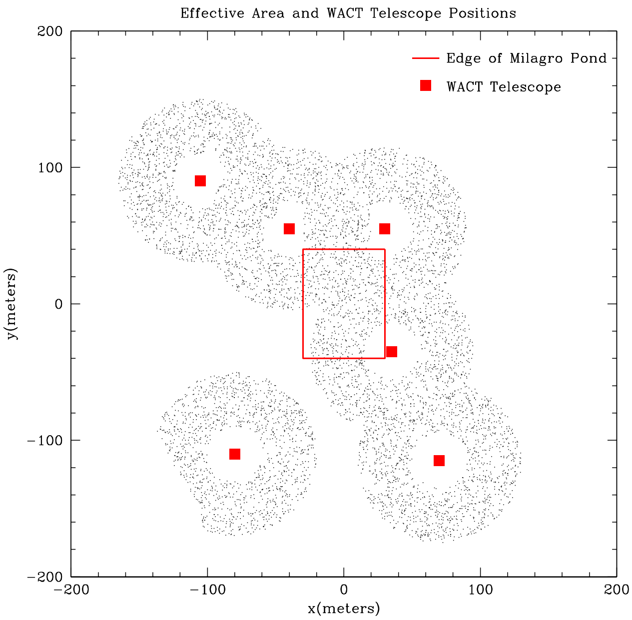

Fig. 1. This figure shows both the effective area of the WACT array and the position of the air Cherenkov telescopes relative to the Milagro detector. The large rectangle in the middle is the Milagro Pond, the small squares represent the positions of the air Cherenkov telescopes and the shaded region represents the effective area of the array. The shaded area covers $\sim$50000m^2 as given in the text.

2 Simulation Description and Data Analysis

Modeling of the WACT array is accomplished in three parts. First, air showers of various species and energies are simulated using a modified version of CORSIKA v5.63 (Heck *et al.* 1998). The standard CORSIKA code was modified to allow the exact placement of our telescopes instead of using a regularly spaced Cherenkov detector array as required by the unmodified code. The Cherenkov photon bunches and particles generated by CORSIKA for the air showers are written to separate files.

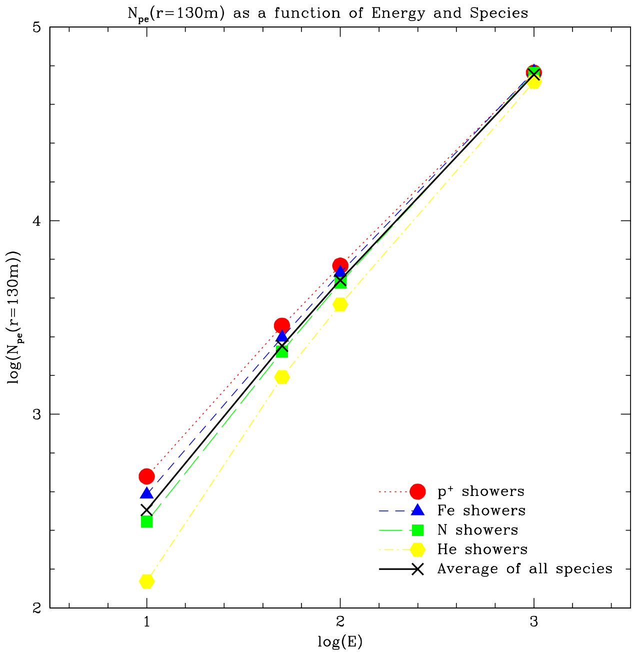

Fig. 2. This figure shows the correlation between N_{pe}(r=130m) and shower energy. As can be seen, the correlation is nearly linear from 10 TeV to 1000 TeV. The dotted and dashed lines represent individual primary species while the solid line represents the average over all species.

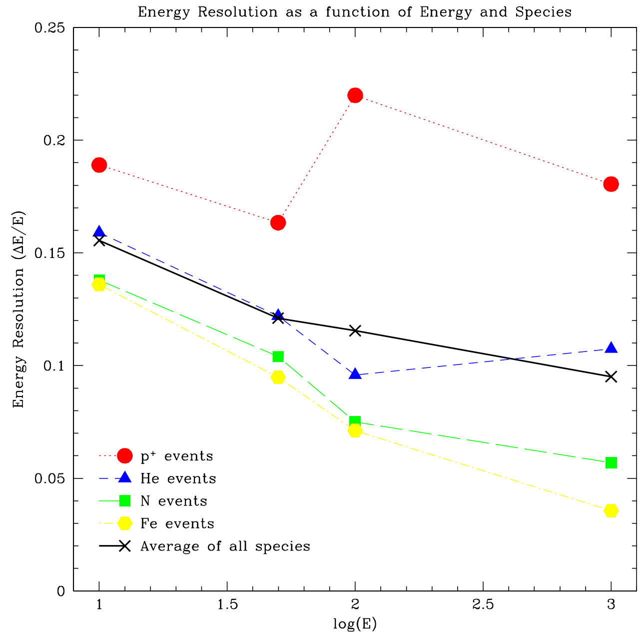

Fig. 3. This figure shows the energy resolution of the WACT array as a function of energy and species. The dashed and dotted lines represent the individual species, while the solid line is the average over all species. As expected the energy resolution improves with increasing energy and with increasing atomic weight. The large variations in the energy resolution for protons is due to the large fluctuations of proton induced air showers.

The particle file is processed through a GEANT simulation of the Milagro detector which gives as output the number of photoelectrons in each of Milagro's ~750 PMTs and the timing of these signals. The Cherenkov bunches are analyzed by a simulation of the WACT array telescopes. This simulation first corrects for atmospheric extinction, night sky background, mirror reflectivity and PMT quantum efficiency. It then ray traces the photons from the mirror up to the focal plane and generates an image of the shower on the PMT camera. This simulation gives as output the number of photoelectrons on each PMT for each telescope and the relative timing across the whole array.

The events simulated are analyzed to determine energy and composition. The energy is determined by fitting the lateral distribution of Cherenkov light measured by the six WACT telescopes. Using this fit the number of photoelectrons that would have been observed at a distance of 130m from the shower core, N_{pe}(r=130m), is calculated. This is a good indicator of the particle energy, independent of particle species (Patterson and Hillas 1983) as the relation between log(N_{pe}(r=130)) and log(E) is nearly linear as seen in Figure 2.

Once an initial energy is determined the slope of the fit as well as data from Milagro are used to make an inital estimate of the cosmic ray species. With this species estimate the energy of the particle can be more accurately defined. This process is then iterated until it converges at a solution for the event.

3 Simulation Results

3.1 Energy Resolution

Figure 3 shows the energy resolution as a function of energy for the WACT telescopes. Each point on the figure represents 500 simulated events of that particlular species and energy. As one would expect the resolution generally improves with increasing energy and increasing atomic weight.

Figure 4 shows a comparison between the actual and reconstructed energies for a number of events. Events were thrown between 10 and 1000 TeV and reconstructed using the process described in section 2. From Figures 3 and 4 we see that $\Delta E/E$=15.6% at 10 TeV, improving to $\Delta E/E$=11.5% at 100 TeV and $\Delta E/E$=9.5% at 1000 TeV.

Figure 5 shows some actual and reconstructed spectra from this process. For each species 1000 events were thrown on a $E^{-2.7}$ spectrum from 10-1000 TeV. The individual events were then processed as described in Section 2 to determine energy and species. Overall, the energy fit is independent of particle species and thus independent of composition model. There is some slight flattening or steepening of the spectrum for the individual particle spectra. This is do to the misclassification of the particle species which results in an overestimation of the energy for protons and Helium nuclei and an underestimation of the energy for iron and nitrogen nuclei. As our composition resolution improves so will the spectrum reconstruction.

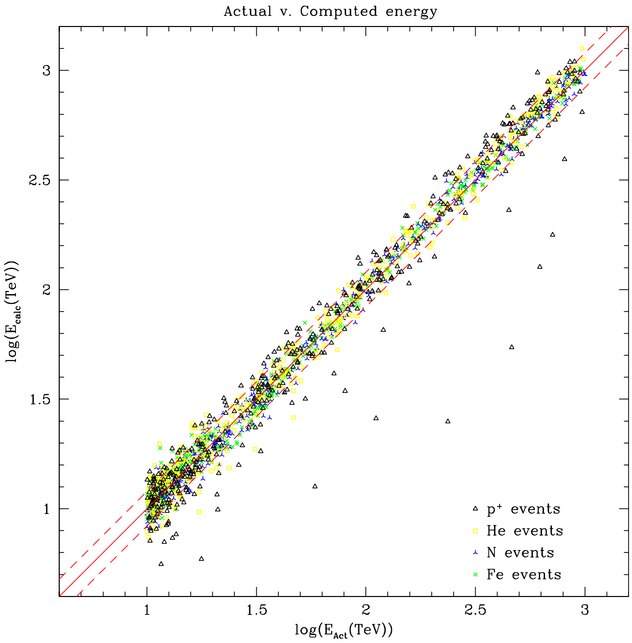

Fig. 4. This figure shows the correlation between the actual energy and the energy calculated by the data analyis. The dashed lines represent a $\Delta E/E$ of 20%.

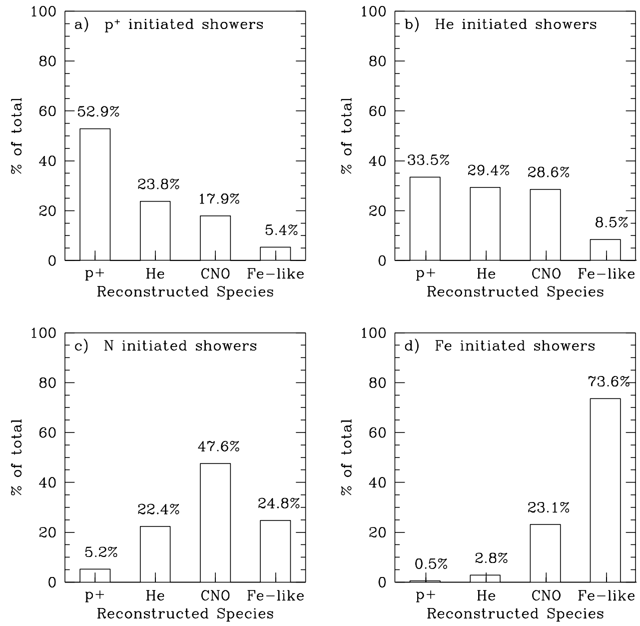

Fig. 6. This figure shows the WACT array's sensitivity to composition. Each panel show the reconstructed composition for various primary species: a) protons, b) α-particles, c) Nitrogen nuclei and d) Iron nuclei. For each primary species the fraction of events reconstructed into each composition bin is shown.

3.2 Composition

Figure 6 shows the results of a composition fit using only the air Cherenkov data. Composition is determined by trying to fit each event as either a proton, an α-particle, CNO nucleus or heavy, iron like nucleus. Each panel in Figure 6 shows the results of analyzing events of a particular species. For example, panel a shows the composition results for a purely proton sample: 52.9% protons, 23.8% alphas, 17.9% CNO and 5.4% iron like. Our composition resolution will improve as more information from the Milagro detector, such as muon content, is incorporated.

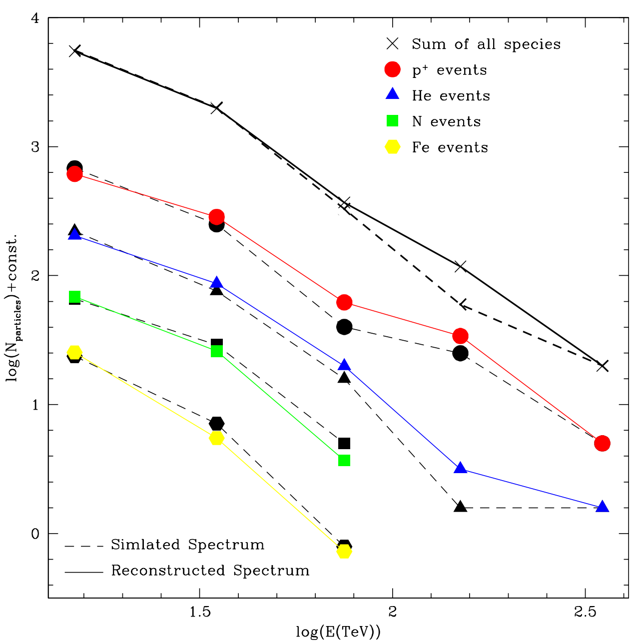

Fig. 5. This figure shows an actual and reconstructed energy spectrum from the data analysis process. The dashed lines are the actual spectrum from the CORSIKA simulations. The solid lines are the spectrum reconstructed from the WACT array data analysis algorithm. For each species, the spectrum consists of 1000 events thrown on a $E^{-2.7}$ spectrum.

3.3 Effective Area

In order to have a good fit to the lateral distribution we have the following requirements on the data. We require at least one telescope to have a core distance of 20-60m, one telescope to have a core distance of 100-180m and at least 4 telescopes with core distances of 20-250m. This requirement gives us an effective area of $\sim$50000m^2 for the whole array as shown in Figure 1.

This effective area, combined with the large field of view the the array telescopes gives the WACT array an effective collection area of $\sim$1200m^2-sr. Using the spectra published by JACEE (Asakimori *et al.* 1998), and assuming an 8% duty cycle for the array, this corresponds to $\sim$52000 events per year from 100-1000 TeV and $\sim$3.18x10^6 events per year from 10-100 TeV. At this rate we should be able to easily reproduce the JACEE number statistics in one month of operation.

4 Construction Status

The WACT array is nearing completion and should begin data collection by September 2001. As of this writing all six telescopes have been constructed and the mirrors aligned. Final construction of the PMT cameras is underway and should be completed by July 2001.

5 Conclusions

The WACT array will provide a powerful tool for understanding cosmic ray composition up to and beyond the knee in the cosmic ray spectrum. With its low energy threshold and large collection area, WACT will be able to compare with and calibrate against existing direct measurements of the cosmic ray energy sepectrum and composition and extend those measurements to higher energies at and beyond the knee.

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References

K. Asakimori et al., 1998 *ApJ*, **502**, 278-83.

H. Fesefeldt, Report **PITHA-85/02** (1985), RWTH Aachen

D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz, and T. Thouw, Report **FZKA 6019** (1998), Forschungszentrum Karlsruhe

N.N. Kalmykov and S.S. Ostapchenko, *Yad. Fiz.* **56** (1993) 105; *Phys. At. Nucl.* **56** N3 (1993) 346; N.N. Kalmykov, S.S. Ostapchenko, and A.I. Pavlov, *Izv. RAN Ser. Fiz.* **58** (1994) N12 p.21; N.N. Kalmykov, S.S. Ostapchenko, and A.I. Pavlov, *Bull. Russ. Acad. Science (Physics)* **58** (1994) 1966; N.N. Kalmykov, S.S. Ostapchenko, and A.I. Pavlov, *Nucl. Phys. B (Proc. Suppl.)* **52B** (1997) 17

A.A. Lagutin, A.V. Plyasheshnikov, and V.V. Uchaikin, *Proc.* 16^{th} *Int. Cosmic Ray Conf.*, Kyoto (Japan), **7** (1979) 18; J.N. Capdevielle for KASCADE Collaboration, *Proc.* 22^{nd} *Int. Cosmic Ray Conf.*, Dublin (Ireland), **4** (1991) 405

W.R. Nelson, H. Hirayama, and D.W.O. Rogers, Report **SLAC 265** (1985), Stanford Linear Accelerator Center

J.R. Patterson and A.M. Hillas, 1983, *J Phys G: nucl Phys*, **9**, 1433-1452.