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A Detector Simulation of the BLANCA Air Cherenkov Experiment

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Abstract

A detailed simulation of the BLANCA experiment has been developed. It allows us to determine the transfer functions relating the measured lateral distributions to the parameters of physical interest and to study the resolution with which we can make those transformations. The random energy error is 12%, with an additional 6% systematic dependence on primary species. BLANCA's composition sensitivity is close to that of an ideal detector for primary energies above 300 TeV.

1 The BLANCA Simulation

The BLANCA installation (Cassidy et al., 1997) consists of 144 angle-integrating Cherenkov detectors distributed throughout the CASA scintillator array in Dugway, Utah (Borione et al., 1994). BLANCA measures the lateral distribution of Cherenkov light around the shower core position determined by CASA. This lateral distribution indicates both the mass and the energy of the primary cosmic ray through its shape and intensity, respectively. Each BLANCA detector employs a large Winston cone optical concentrator to increase the phototube's effective area. The cones have a concentration ratio of approximately 16 and transmit light from within 11° of zenith. To interpret BLANCA measurements, we have developed a detailed simulation of the experiment's optical and other properties. This detector simulation converts CORSIKA air showers into simulated BLANCA ADC values to create "fake data."

The standard version of CORSIKA records Cherenkov light as a list of positions and directions for photons landing within a rectangular array of detectors. Instead, to save space and improve processing speed, we altered CORSIKA to store Cherenkov photons directly in a pair of two-dimensional histograms. These two histograms record arrival directions as a function of distance from the shower core, relying on the observation that the Cherenkov spatial distribution is azimuthally symmetric about the core. The BLANCA detector simulation program reads the angular distributions from these histograms, multiplies by the Winston cone transmission function, and integrates over all directions to find the total amount of light reaching each phototube. This procedure carefully combines the angular distribution of Cherenkov light with the angular response of BLANCA detectors.

Each real BLANCA detector has different gains and other properties. In the simulation, each unit is randomly assigned values for these detector "constants." Electronics pedestals and relative gains of the two-gain preamplifiers are normally distributed, while the relative gains of the phototubes are log-normal. The central values and spreads of all distributions are identical to those of the actual BLANCA detector. Imperfect detector alignment is also simulated with two perpendicular random pointing angles (each with 1° RMS). The most significant variation is in the tube gains: $\ln G$ has an RMS value of 0.4. These generated detector parameters are stored and can be compared with the values reconstructed on the basis of the artificial data itself. We find that the relative gains are estimated with a 5% error.

The detector simulation also models several fluctuations present in the real data. A constant night sky background is added to the Cherenkov signal itself, and the actual number of photoelectrons is drawn from a Poisson distribution. The simulation also models the wide range of possible charge due to each photoelectron. Besides the Cherenkov measurements, the core location and shower arrival direction are also given a random error based on the performance of the CASA surface array.

A realistic, steeply falling power-law energy spectrum is necessary in many studies, for example to test methods for extracting calibration constants from the data itself. However, the CORSIKA shower libraries

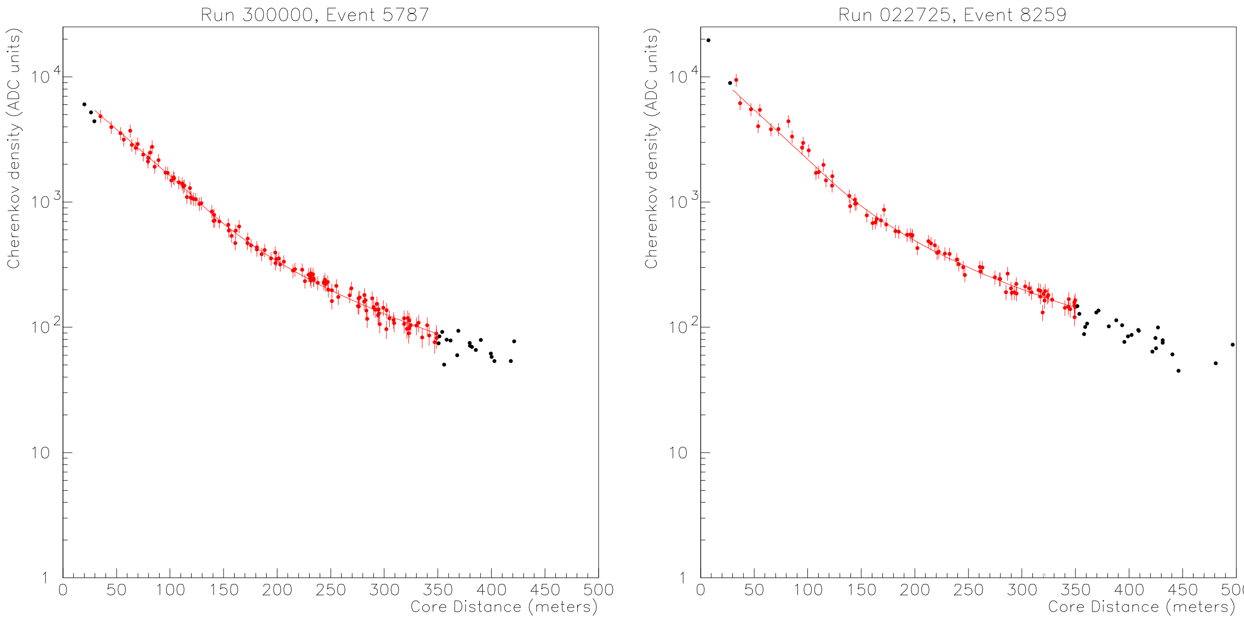

Figure 1: Sample Cherenkov lateral distributions. *Left:* 1 PeV proton simulation. *Right:* An actual shower.

contain a uniform distribution in $\log E$. We simulate a falling spectrum by sampling from this distribution according to the desired power-law. Therefore, lower energy events are sampled many times while only a fraction of the most energetic events are used even once.

2 Cherenkov Lateral Distribution Fits

The BLANCA analysis uses a three-parameter function for fitting the Cherenkov lateral distribution. This function falls with radius as $f(r) \propto e^{-sr}$ out to 120 m and as a power law beyond that. The function's three parameters are the value at 120 m (called C_{120}), the exponential inner slope (s), and the power law index of the outer fall-off. This function is motivated by the Cherenkov distributions of CORSIKA showers over a wide range of energies and from all three primary species (p, N, Fe). The best fit to this chosen function describes simulated distributions very well; fitting in the range 30–350 m, the RMS deviation is only 5%.

A simple but surprisingly accurate interpretation of the fit parameters is that C_{120} is proportional to the primary energy, while the inner slope s is proportional to the atmospheric depth of shower maximum, X_{max}. Deeper X_{max}, in turn, correlates with smaller primary mass. Figure 1 shows a simulated and a real lateral distribution with similar fits. The inner slope of the real event is steeper than those of most nitrogen or iron showers, suggesting that a light nucleus initiated the real event.

3 Primary Energy Reconstruction

We use the complete air shower and detector simulations to determine the best way to estimate primary energy from the Cherenkov lateral distribution fits. The Cherenkov intensity at core distances less than 120 meters is an increasingly biased energy estimate, because this inner region of the lateral distribution depends on X_{max} and thus on primary mass. At more than 200 meters from the core, the Cherenkov intensity correlates well with energy and depends only weakly on primary mass. However, the BLANCA detector simulation also shows that measurement error degrades the C_{200} resolution for low energy showers. Therefore, we use C_{120} itself as the BLANCA energy parameter, correcting it slightly to reduce composition effects.

We first extract a simple fit of primary energy to C_{120} alone. This fit uses an equal mix of proton, nitrogen, and iron primaries with energies from 0.1 to 31.6 PeV. In all four hadronic models, energy grows approxi-

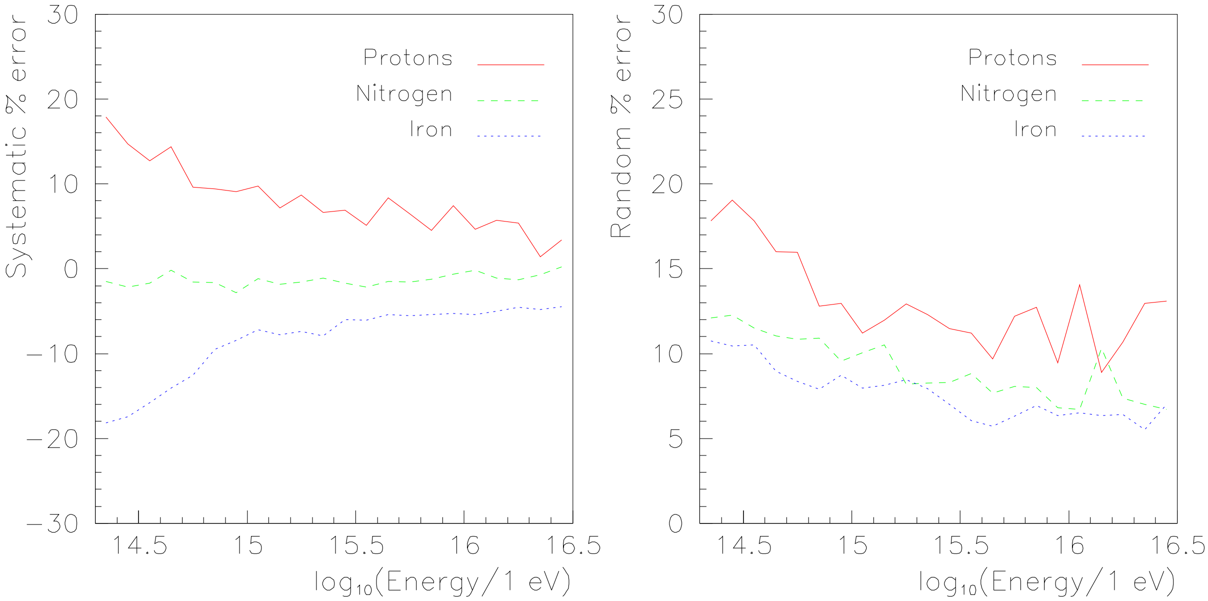

Figure 2: Energy resolution from QGSJET folded with detector simulation: systematic and random errors.

mately as $(C_{120})^{0.91}$. The Cherenkov intensity rises faster than primary energy, along with the energy fraction in the electromagnetic cascade. A slight curvature reduces this tendency at higher energies, so the basic energy fit uses a quadratic function of C_{120}. The hadronic models disagree about the Cherenkov intensity C_{120} at 10^{15} PeV. HDPM and VENUS predict about 12% less light than SIBYLL, with QGSJET between the extremes.

The simple energy function of C_{120} suffers from an inherent composition bias. Since BLANCA can measure the inner slope — a parameter sensitive to composition — we apply an energy correction based on the slope. A steeper inner slope indicates a deeper shower, suggesting a lighter primary. Since proton primaries produce more electromagnetic shower particles and thus more Cherenkov light, the simple method overestimates proton energies. However, a very few protons can develop so late in the atmosphere that the shower reaches the ground without producing its usual share of Cherenkov light. In such cases, C_{120} will actually underestimate the primary energy. These events can be recognized by their especially steep inner slopes. To account for both effects, we modify the initial energy estimate with a cubic function of inner Cherenkov slope.

Figure 2 shows the energy resolution for fake data generated from the QGSJET shower library. The energy transfer function is determined from an equal mix of the three primary types, and then applied to each in turn. The left frame shows the systematic energy error of each different species; the slope correction reduces, but does not eliminate, the composition bias in energy estimation. The right panel shows the corresponding random errors. As in any air shower observable, the reconstructed energy fluctuates more for proton showers than for heavier primaries. Although both systematic and random errors contribute to the total energy error, their relative importance depends on the unknown cosmic ray composition.

4 Determining Primary Composition

An angle-integrating Cherenkov array distinguishes air showers of different primary mass and energy by measuring the shape and intensity of the Cherenkov lateral distribution. Probably the *air shower* parameter most fundamentally related to primary mass is X_{max}. However, even perfect knowledge of X_{max} and energy

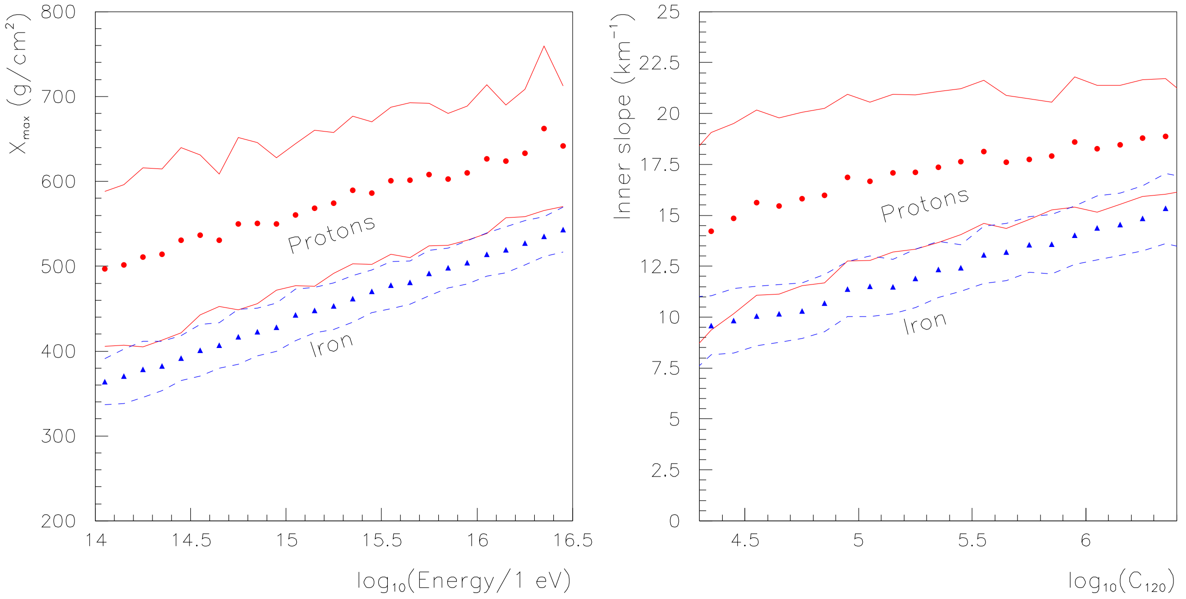

Figure 3: *Left:* The 1-σ range of X_{max} as a function of energy for the extreme species. *Right:* An equivalent plot showing raw measured quantities, and including detector resolution.

would allow only partial separation of proton and iron cosmic ray showers. Figure 3 shows the 1-σ range of X_{max} plotted against energy for the two species. It also shows an equivalent range of inner slope values in bins of $\log(C_{120})$, including detector effects. The similarity of these two plots demonstrates that sampling effects and measurement errors are relatively small for BLANCA. Except at the bottom end of the energy range, the measured parameters separate primary mass nearly as well as an ideal measurement of X_{max} and energy. We use this plot simply as an example of what a "zero-order" analysis could achieve — as discussed we actually make a much more sophisticated attempt to extract primary energy and mass from the data.

We use the CORSIKA libraries and detector simulation to find the relationship between composition and measured quantities by a method similar to, but simpler than, the energy procedure. Although BLANCA cannot directly measure the depth of maximum, simulations show it to be strongly correlated with the measured inner Cherenkov slope. We convert slope to X_{max} using a polynomial fit. For QGSJET we find that a slope increase of 1 km^{-1} corresponds to X_{max} being approximately 20 g/cm^2 deeper. We find $\ln A$ (primary mass) is also linear with slope, but that the dependence changes with energy. To account for this we make separate fits in bands of C_{120} and interpolate. In paper OG 1.2.02, both relations are used to infer average X_{max} and $\ln A$ as functions of energy from BLANCA observations. A more sophisticated analysis is underway which uses the *shape* of the inner slope distributions to fit a multi-component model to the data.

References

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Cassidy, M. et al., Proc. 25th ICRC (Durban, 1997) OG 10.3.32