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Measuring the Cosmic Ray Composition at the Knee with BLANCA

L. F. Fortson[1], J. W. Fowler[1], C. H. Jui[2], D. B. Kieda[2], E. C. Loh[2], R. A. Ong[1], C. L. S. Pryke[1], P. Sommers[2]

[1]*Enrico Fermi Institute, University of Chicago, Chicago, IL 60637*
[2]*Department of Physics, University of Utah, Salt Lake City, UT 84112*

ABSTRACT

BLANCA is a new, large non-imaging Cerenkov detector located at the CASA-MIA experiment in Dugway, Utah. Using 144 individual Cerenkov detectors, BLANCA covers an area of approximately 0.2 km^2 and has an energy threshold of 300 TeV. The lateral density function (LDF) of the Cerenkov light in air showers is measured. Since the LDF depends on the primary particle species, a change in composition as a function of energy can then be determined. We report results obtained on data taken with the CASA-BLANCA detector since January, 1997.

INTRODUCTION

Composition measurements above $\sim 10^{15}$ eV are extremely difficult because direct detection via satellite experiments is not feasible due to low flux levels. In addition, this energy ($\sim 3 \times 10^{15}$ eV) is where a break in the cosmic ray energy spectrum occurs (the knee). It is commonly believed that the knee is a spectral feature which can be explained by models of cosmic ray acceleration and propagation. The favored acceleration model, involving shock waves produced by supernovae, can produce cosmic rays up to $\sim$ few $\times 10^{15}$ eV (Drury et al., 1994), but is unable to explain particles above this energy. These first order Fermi-shock acceleration models also give rise naturally to a power law $E^{-\alpha}$ with index $\alpha \sim 2$, while the measured spectral index for energies below the knee is $\alpha \sim 2.7$.

The difference in the power law predicted at the source of cosmic rays and that measured below the knee can be understood by invoking a propagation model that relies on rigidity-dependent galactic diffusion (the "leaky box" model). This model assumes that the source spectrum is modified by an energy dependent escape rate from the galaxy of $E^{-0.7}$ which, when combined with the predicted power law from the acceleration mechanism, reproduces the slope of the cosmic ray spectrum below the knee. This value of the escape rate has been indirectly determined from the abundance ratio of secondary to primary cosmic ray nuclei (Gaisser et al., 1995).

Above the knee, the slope of the all particle spectrum steepens to $\alpha \sim 3.15$ and this change is poorly understood. It is possible that the change in slope occurs because the acceleration mechanism turns off at energies near the knee or because particles are escaping from the magnetic confinement of the Galaxy. Both possibilities lead to the prediction that the composition of cosmic rays should grow heavier through the knee and above. On the other hand, it has also been speculated that cosmic rays above the knee come from a source completely external to our Galaxy, perhaps from energetic Active Galactic Nuclei (Protheroe and Szabo, 1992). In this case, the composition of cosmic rays would be expected to grow lighter through the knee. Reliable measurements of the composition are clearly needed at these energies to understand the process of acceleration and propagation of cosmic rays.

EXPERIMENTAL TECHNIQUE

To measure the cosmic ray composition with a ground array, one makes use of the properties of the produced air shower that are most closely related to the primary interaction: namely, the height in the atmosphere of shower maximum (X_{max}) and the number of muons in the shower (N_μ). The X_{max} value decreases (moves higher in the atmosphere) as the primary gets heavier, whereas the muon number increases with increasing atomic number.

The ability to measure multiple parameters for a large sample of showers over a broad range of energy is crucial to the extraction of a meaningful composition measurement. It should be emphasized that it is important for the shower energy to be measured with the same detector that determines the composition. The goal of BLANCA is to measure both the average X_{max} value and the energy of a large sample of cosmic ray air showers and combine this information with the muon number measured by CASA-MIA. In this way, we will be able to determine the *change* in the composition as a function of energy. The absolute composition determined at low energies can be compared to direct measurements.

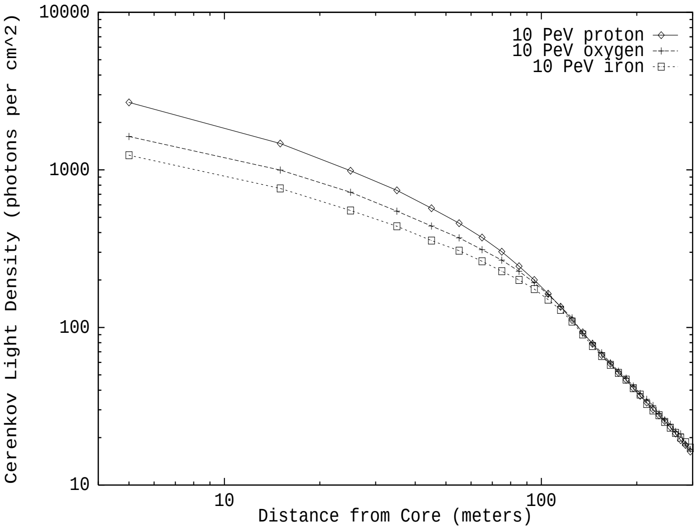

Fig. 1: The lateral density function of Čerenkov light for three species of primary cosmic rays. The slope of the light density near to the core yields information about the composition of the primary.

BLANCA detects the Čerenkov light emitted by the charged particles and reconstructs the lateral density function (LDF) of the Čerenkov light. Figure 1 shows a simulation of the average LDF obtained for twenty showers of three species (H, O, Fe) at a single energy (10 PeV). The top curve is for protons, the middle curve for oxygen and the bottom curve for iron. The light density within ~ 100 meters of the shower core depends on the position of shower maximum and hence on the species of the primary particle. The light density far from the core (≥ 120 meters) is insensitive to the depth of maximum but proportional to the energy of the primary and can therefore be used for measuring the energy of the event (Patterson and Hillas, 1983).

BLANCA DESIGN

The Broad LAteral Non-imaging Čerenkov Array (BLANCA) was recently built at the CASA-MIA installation in Dugway, Utah. To measure the Čerenkov LDF it is necessary to sample the light pool at a number of places on the ground. From simulations, we determined that an array of 144 Čerenkov detectors would measure the LDF with sufficient accuracy to obtain useful values of X_{max} and energy. The individual detectors consist of PVC enclosures containing Winston cones and photomultiplier tubes (PMTs) pointed in the vertical direction. The half-angle of the optics is 12.5 degrees. A shutter protects the PMT during the daytime, while the enclosure is sealed with a UV transmitting glass cover that is heated and angled to remove frost and snow. The detectors are distributed over an area of $\sim 0.2\ \mathrm{km}^2$ that corresponds identically with the area covered by the CASA-MIA experiment. CASA provides BLANCA with the cosmic ray trigger and data acquisition system where a separation of the data streams is done offline. BLANCA also makes use of the core location and electron size distribution information from the CASA data. In addition, BLANCA will use the muon information provided by MIA, buried three meters below CASA-BLANCA. A more detailed description of the detector is given in an accompanying paper in these proceedings (Cassidy et al., 1997).

RESULTS

Data-taking with the full BLANCA array commenced on January 16, 1997. Although we have over 200 hours of data recorded since then, the preliminary results presented here are taken from one 6-hour run containing 30800 BLANCA events. Figure 2 shows a one-event display with both CASA and BLANCA data plotted. The outline of the display is the fully enclosed area of CASA-BLANCA.

The overlap of the shower core in the two arrays is clearly indicated by the intensity scale where black is highest intensity. The numbers on the intensity scale show that BLANCA has a much larger dynamic range than CASA. BLANCA is fully efficient for showers produced by primary particles with energies above 300 TeV. Considering the planned completion of the experiment in April, 1998, this threshold will permit BLANCA to collect data spanning two orders of magnitude in energy, which will bracket the knee region in the cosmic ray spectrum. The expected total number of events registered by BLANCA above the knee energy of 3 PeV is $\sim$ 8000.

The lateral density distribution of the Čerenkov light for the event in Figure 2 is shown in Figure 3. Individual BLANCA stations that were known to be bad for the entire run were removed. The relative gains of the stations were calculated from the lateral density distributions plotted for the individual station over the entire run. Each of the 144 LDF's were then fit with a power law. The normalization of the fit to each station's LDF was then taken as the gain of the station. A correction factor weighted by the average gain over all stations was then applied to each station. The resulting gain-corrected LDF is then separated into the set of tubes registering positions within 120 meters ("inner") of the CASA core and the set with positions greater than or equal to 120 meters. The inner set is fit with the function $C(r) = C(120) * (r/120)^{\eta - r/100}$ where η is the slope of the light density near to the core and therefore is predicted to be sensitive to primary species. This is an arbitrary, empirical function which we believe describes the data well while using only one free parameter. The light density at 120 meters from the core, C(120), is considered to be proportional to energy.

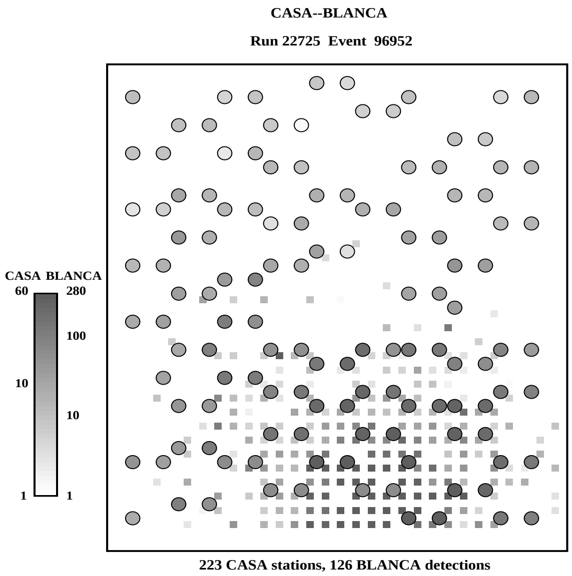

Fig. 2: One-event display for a shower taken on February 11, 1997. The CASA data are shown by the rectangles. The BLANCA data are shown by the circles. The broad nature of the Čerenkov lateral distribution can clearly be seen.

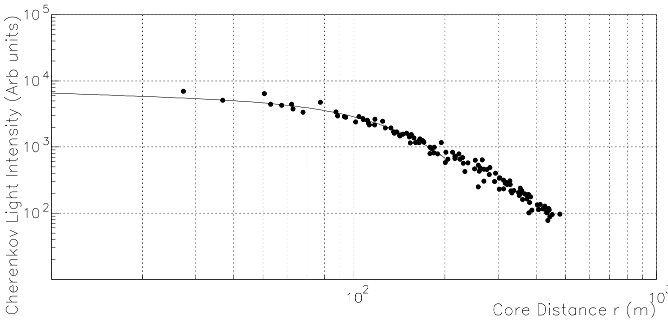

Fig. 3: The lateral density distribution of Čerenkov light for a single event. The horizontal axis is the distance in meters from the core of the shower determined by CASA. The vertical axis is the gain-corrected pulse height (in arbitrary units) for participating BLANCA stations. The number of BLANCA stations used in the inner fit is 23. The event direction is $5.3°$ *and estimated energy based on CASA hits is 3000 TeV.*

Each event in the data run passing preliminary selection cuts is processed in this way. The entrance angle of the shower is reconstructed by CASA and is required to be less than 9 degrees. The number of BLANCA stations participating in the event is required to be greater than 5 stations. There is no restriction on the number of CASA stations in an event. A total of 5021 events has been analyzed with this very preliminary method. The normalization values, C(120), are plotted in Figure 4 with the fit yielding the power law that would be expected from the cosmic-ray spectrum if the C(120) values were proportional to energy. Because we do not have as yet an absolute energy calibration, we are not able to set a scale on this plot. However, the fact that we obtain a power law (index of $\alpha = -2.75$) shows that we are indeed measuring something which is indicative of the cosmic ray spectrum.

CONCLUSIONS

Measurements in the early 1980's of the Čerenkov LDF were limited by the technology and by the cost required to instrument enough detectors to make accurate measurements. These early experiments typically only used eight to ten detectors. With 144 elements, BLANCA is the largest Čerenkov array built to date. The combination of BLANCA and CASA-MIA represents a unique and powerful multi-parameter cosmic ray airshower detector. Although this paper presents only the most preliminary indications of the results from CASA-BLANCA, we believe that in the future we will be able to make a significant measurement of the cosmic ray composition at ultra-high energies.

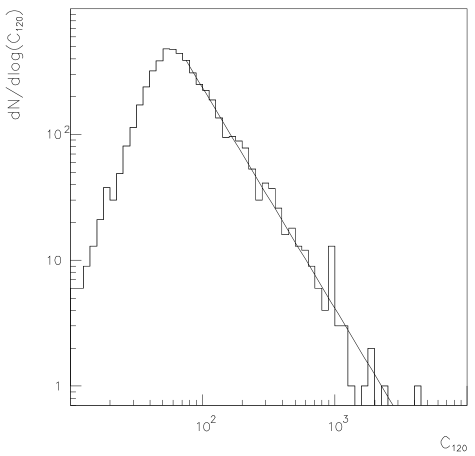

Fig. 4: The distribution of the C120 values, where C120 is the Čerenkov light density measured at 120 meters from the core of each event.

ACKNOWLEDGEMENTS

We acknowledge the extensive assistance of the CASA-MIA collaboration. We also acknowledge the help of the University of Utah High-Resolution Fly's Eye (HiRes) group and the staff of the U.S. Army Dugway Proving Ground. We thank D. Bird, M. Pritchard, K. Riley, J. Smith, S. Thomas, W. Wingert for their assistance in constructing BLANCA. Special thanks go to M. Cassidy for his essential contributions as our technician. This work is supported by the U.S. National Science Foundation and the U.S. Department of Energy. RAO acknowledges the support of the Grainger Foundation and the Alfred P. Sloan Foundation.

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