The Composition near the 'Knee' from Multiparameter Measurements of Air Showers

S.P. Swordy[1] **and D.B. Kieda**[2]

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

Abstract

The small change in the spectral slope of the overall intensity of cosmic rays near 1 PeV may be associated with the endpoint of supernova shock acceleration. Recent measurements at the DICE/CASA-MIA air shower installation in Dugway, Utah, USA have provided several independent air shower parameters for events in this 'knee' region. There is no evidence from these data for an increase in the mean mass of cosmic rays across region. These results show cosmic rays to be $\sim$70% protons and α particles near 10PeV.

1   Introduction:

This work is largely based on the results from the Dual Imaging Cherenkov Experiment (DICE) located at the CASA-MIA site in Dugway, Utah. An accompanying paper in this conference discusses the operation and components of DICE (Kieda and Swordy 1999), here we concentrate on the composition results of DICE in combination with the ground level muon and electron sizes available from CASA-MIA.
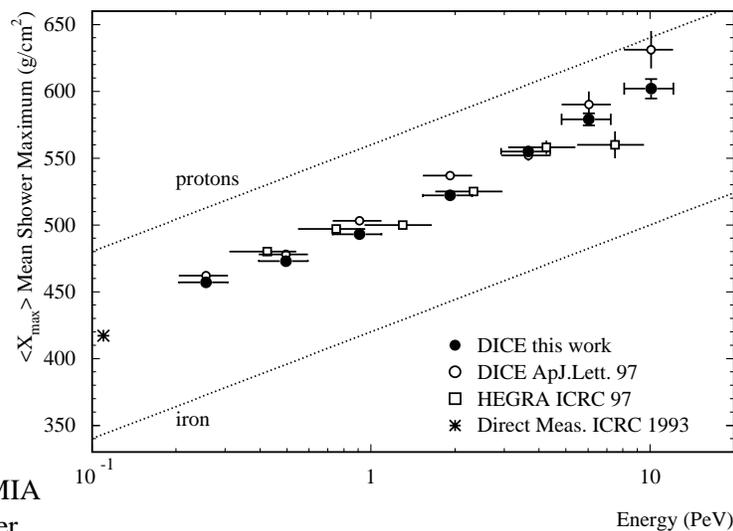
2   Experiment and Comparisons:

The mean measured values of X_{max} as a function of energy are shown in Figure 1 compared with HEGRA (Cortina et al. 1997). The star shows the expectation for the mean X_{max} based on direct composition measurements near 100TeV (Swordy 1993). The measurements show general agreement, although there is a tendency for the DICE results to show a lighter composition at high energies. The present data are in statistical agreement with the previously published results of DICE (Boothby et al. 1997), but they show somewhat less departure from constant composition at high energies. The dashed lines are for pure proton or pure iron composition.

The combination of DICE and CASA/MIA provides a unique combination of shower parameters which over-determine the characteristics of each shower. The

Figure 1: The variation of mean X_{max} measured by DICE (filled symbols) with energy compared with other data.
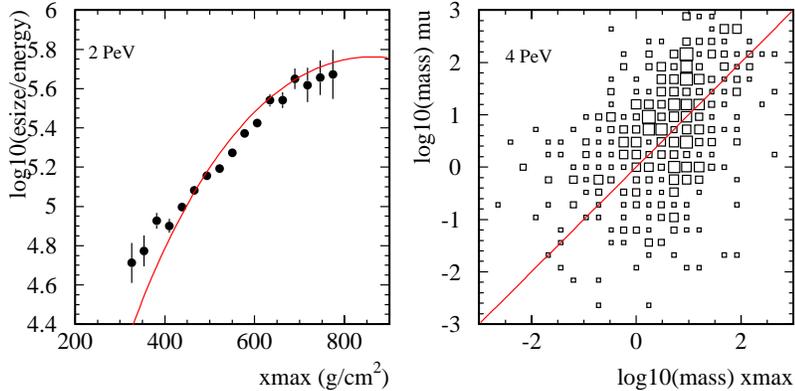
comparison of parameters from different detectors can be used to test the reliability of results. This process is already possible within DICE since the separate measurements of X_{max} and Cherenkov light made with each cluster can be compared to test consistency. A more rigorous test is a comparison of the information derived from DICE with that from CASA/MIA.

At atmospheric depths deeper than X_{max}, the shower size declines in a manner which is dominated by

the atmospheric hadronic interaction length. If the size is measured at a depth relative to the location of X_{max} the fluctuations produced by variations in the initial interaction point are removed. We can perform a simple test on the data discussed here: Does the electron size at ground level measured by CASA fit with the shower energy and location of X_{max} determined by DICE? By using the shower development function quoted by Gaisser (1990) we can compare the expected ground electron size with the CASA measurement. Since showers at a given energy have values of X_{max} which fluctuate, we can sample a range of potential electron sizes versus X_{max} for a specific primary energy range. The left hand panel of Figure 2 shows how this test works for X_{max} and energy determined from DICE and electron size from CASA for an energy bin centered on 2PeV. The panel shows the average log10(electron size/energy) plotted versus shower X_{max}. The line is the expected function for average air shower development. The good agreement between the function and the data provide confidence that the location of X_{max} determined by DICE and the electron size at ground level are measured correctly at energies near 2PeV. It is important to realize that not just the shower shape but the absolute normalization of the shower size versus X_{max} is determined by the Gaisser expression, there is no arbitrary vertical normalization of the curve shown in Figure 2.

Figure 2: (Left hand panel) The correlation between normalized electron size and X_{max} at 2PeV. (Right hand panel) Correlation between mass estimates from X_{max} and muon/electron sizes at 4PeV, the box size is proportional to the particle count in the bin.

A study of these correlations over a range of energies has shown that the CASA electron size saturates slightly at large values. This is a possibility since CASA, primarily built for observations near 100TeV, was not designed to accurately determine air shower core densities at 10PeV. A small correction is made to the electron sizes above 5PeV; this is of the order $\sim 7\%$ near energies of 10PeV and $\sim 4\%$ near 5PeV. Importantly this change is not large, but illustrates the power of correlating apparently redundant measurements. These can be used to explore systematic problems with various measured quantities.

3   Mass Estimates:

In this analysis we adopt a slightly different philosophy from previous work by using combinations of measured parameters to derive an incident particle mass, A, on a shower by shower basis. With the information presented above we form two estimates for the mass, one from the location of X_{max} and the fitted shower energy and another from the muon and electron sizes in combination with the fitted energy. The X_{max} mass estimate is based on a simple superposition model with an elongation rate of $80g/cm^2$ per decade, the muon/electron mass is also based on superposition with a muon size scaling $\propto E^{0.87}$.

Shown in the right hand panel of Figure 2 is the correlation between the mass estimates from X_{max} and muon/electron size. The correlation is clearly present and has an RMS width of ~ 1 in log10(A).

Using these methods a mass for each event can be derived from (i) X_{max}, (ii) muon and electron size, and (iii) a combination of the two. This last method has the advantage of somewhat increased resolution because these are independent methods. The accuracy in these estimates is dominated by the inherent fluctuations in the shower process. For example the 1σ resolution in log10(A) derived from X_{max} for a proton event at 3PeV is ~ 0.8, the 1σ resolution for an iron nucleus at the same energy is ~ 0.5. These values are close to

the values which could be achieved if X_{max} is determined with arbitrary precision. It is sobering to realize iron is separated by only $\sim 2.5\sigma$ from protons for single events. The results of these mass determinations are shown in Figure 4. Here both the mean mass and the apparent fraction of p+α for the X_{max} mass is shown. This latter technique involves introducing a cut on mass distributions to isolate a sample of events which are predominantly light nuclei, in this work events with log10(A)<0 are selected. After corrections for efficiency and heavy nuclei 'spill over' an estimate of the fraction of light nuclei can be made.

We can also compare the shape of the mass estimates with the predictions from the simulation. This provides a test of the overall consistency of the method used and can exclude certain extreme composition possibilities. The left hand panel of Figure 3 shows the RMS value of log10(A) compared with expectations from simulations for mixed composition (Swordy 1993), light (p+α), and heavy (A>4) composition. The comparison of the complete distribution for the X_{max} mass at 4PeV is shown in the right panel of Figure 3 as data points with errors. This also shows the expected distributions for a mixed composition (line), light (dashes), and heavy (dots). Although
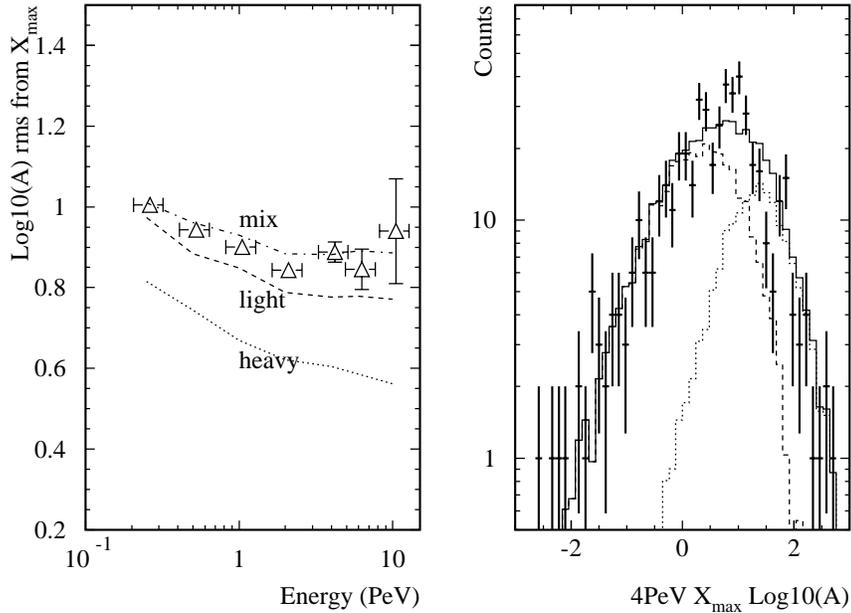
Figure 3: (Left hand panel) X_{max} mass distribution widths compared with simulations. (Right hand panel) Detailed X_{max} mass distribution at 4PeV compared with simulations.

this is not the method of choice for the most accurate composition determination, these data alone seem to exclude a pure Fe composition near 10PeV.
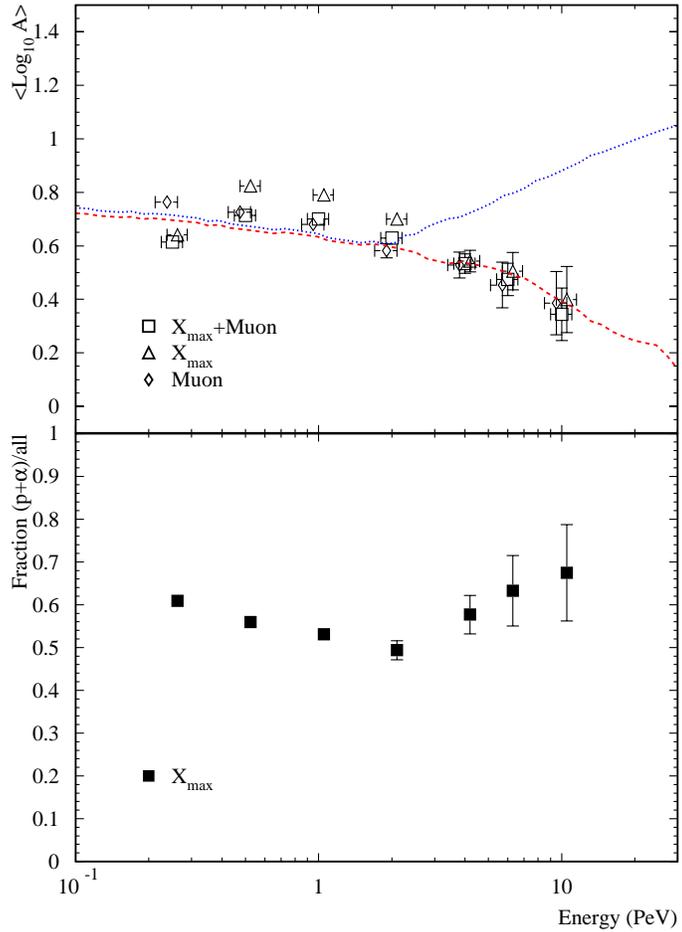
4   Discussion:

An analysis of multiple parameters measured from invidual air showers can be used to estimate the energy and assign an incident particle mass on an individual shower basis. The correlations between these parameters can be used to provide confidence there are no large systematic errors present.

A composite mean log(A) using both estimates shows a decreasing mass across the energy range of the knee region. For comparison two models of possible cosmic ray mass variation near the knee are plotted in Figure 4. The dotted curve is the model given by Swordy 1995, where a new source spectrum $\propto E^{-3}$ is introduced above the knee region. This model provides an increase in mass across the knee of a size which is larger than for models based on particle rigidity alone. The lower dashed line, with which the data seem more consistent, is a model which has similar low energy behavior as the rigidity model but which introduces a proton source which compensates for the lost flux above the cutoff rigidity, assumed here to be 10^{15} V. This is similar to the suggestion of Protheroe and Szabo 1992. These data seem more consistent with this latter model, where cosmic rays become progressively lighter across the knee region. However, they do not exclude the possibility that the composition is more or less constant across this energy range. A sudden change in composition to becoming predominantly iron nuclei (log10(A)=1.75) seems strongly excluded.

Contrary to conventional wisdom these results do not support a simple 'rigidity steepening' which would lead to a steady increase in mass across the knee region. If the cosmic ray abundances below the knee are provided with a simple steepening from a spectrum of $E^{-2.75}$ to $E^{-3.0}$ the size of the effect should be an increase of $\sim$0.2 in the mean value of log10(A) across the knee. The combination of experimental measurements discussed here have the sensitivity to detect an increase of this order if it were present.

To explore the sensitivity of the results to the parameters used in the mass functions some simple numerical examples can be used: If the elongation rate used to derive a mass from X_{max} had been set at $75 g/cm^2$ per decade instead of the $80 g/cm^2$ used, the apparent mean log10(A) would have decreased by an additional amount $\sim$0.07 over the energy range given here. If the muon scaling had been assumed to be $\propto E^{0.82}$ rather than the value $E^{0.87}$ used, the apparent mean log10(A) would have *increased* by $\sim$0.2 over the energy range of these measurements. With these reasonable ranges of parameters it is clear the mass estimates from ground particle densities are far more sensitive to the precise values used in the analysis. The most significant challenge in these type of measurements

Figure 4: (Top) Various mass function means, (Bot.) Fraction of (p+α) for the X_{max} mass.

is the identification and quantification of systematic errors in either the measurements or the simulations used for analysis. By making use of multiparameter measurements of the same showers we can directly explore our level of understanding of these issues.

Thanks are due to our colleagues who collected much of these data, these include Kevin Boothby, Curtis Larsen, Kevin Green, and the entire CASA-MIA group.

References

Boothby, K., et al. Ap. J. Lett., 1997, 491, L35-L38.
Cortina, J et al. 1997, Proceedings of the 25th Int. Cosmic-Ray Conf. (Durban), vol 4, p69.
Kieda, D.B. and Swordy, S.P. 1999 Proceedings of this Conference.
Gaisser, T. 1990, Cosmic Rays and Particle Physics, Cambridge U. Press, pg 239.
Protheroe, R.J. and Szabo, A.P. 1992 Phys. Rev. Lett., 69, 2885.
Swordy, S.P., 1993, Proceedings of the 23rd Int. Cosmic-Ray Conf. (Calgary), Invited and Rapporteur, p243.
Swordy, S.P., 1995, Proceedings of the 24th Int. Cosmic-Ray Conf. (Rome), vol 2, p697.