The Energy Spectrum in the Knee Region from DICE

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Abstract

Recent measurements of the change in the spectral slope of cosmic rays near 10^{15}eV have come largely from surface array detectors. Here we provide fluxes in this energy region from the air Cherenkov detections made by the DICE instrument. This new analysis of an expanded data set from this experiment provides an estimate of the energy which is less sensitive to the primary particle mass. The variation of the mean electron and muon sizes measured by CASA/MIA with this Cherenkov energy are also presented.

1 Introduction:

The Dual Imaging Cherenkov Experiment, DICE, is a ground based air shower experiment which is designed to have as little reliance as possible on the details of Monte Carlo simulations and to have the capability of comparison with direct measurements at 0.1PeV to provide an assessment of the overall systematic error. Cosmic ray events within the field of view produce a focal plane image at the DICE photomultiplier clusters which corresponds to the direction and intensity of Cherenkov light coming from the air shower. When the direction of the air shower and the distance from the telescopes are known, simple geometry can be used to reconstruct the amount of light received from each altitude of the shower. The amount of Cherenkov light produced is strongly correlated with the number of electrons in the shower and is used to estimate the electron size as a function of depth in the atmosphere from which the location of shower maximum can be determined. This procedure is essentially geometrical and is independent of simulations except for calculations which determine the angular distribution of Cherenkov light around the shower axis. The average RMS resolution of the location of shower maximum by DICE for a single event has been shown to be $\sim$30-40g/cm^2 (dependent on energy) by a comparison between fits for the same event viewed by the two telescopes and the results of simulations.

2 Experiment:

Since the method of imaging hadronic showers in Cherenkov light is a relatively recent development we provide some more detailed description of the DICE detectors and operation. The two DICE telescopes are located at the CASA-MIA site in Dugway, Utah (described in Borione et al. (1994)). They each consist of 2m diameter f/1.16 spherical mirror with a focal plane consisting of 256 close packed 40mm hexagonal photomultipliers (PMTs) which provide $\sim 1^0$ pixels with a field of view $16^0 \times 13.5^0$ centered about the vertical. The telescopes are on fixed mounts separated by 100m, (see Boothby et al. (1995, 1997a)).

The CASA/MIA installation and operation is described in detail in Borione et al. 1994. In this present work, information from CASA-MIA is used to establish the event geometry and to directly measure the electron size and muon size at ground level. Since the event acceptance is constrained by the DICE aperture, only events within $\sim 10^0$ of the zenith are analyzed, making the atmospheric depth of the size measurements to be essentially the same for all events at $\sim$860g/cm^2. For each air shower collected a simple time coincidence is used to identify the same event in both DICE clusters and CASA-MIA. Further requirements on the correlation of the DICE images with each other and with the CASA-MIA event geometry are used to reduce the overall probability of event mismatches between the detectors to $\sim 10^{-5}$.

The Cherenkov size at the two DICE detectors is obtained by summing the total amount of light detected at each photomultiplier tube (PMT) cluster. The location of shower maximum in the atmosphere (X_{max}) is determined by fitting the shape of the shower image in each of the DICE PMT clusters. A knowledge of the event geometry and the angular distribution of the Cherenkov light around the shower axis is used to find the height from which the maximum Cherenkov light emission occurs after applying a small correction for atmospheric absorption. This can be directly translated into an estimate for the height of maximum electron size development.

Previous work with DICE estimated the shower energy by a simple translation from the total amount of Cherenkov light in the image and the geometry of the shower (Boothby et al. 1997b). In this present work a more accurate estimate of energy is derived from a combination of the amount of Cherenkov light and the X_{max} determination produced by each DICE telescope. This is desirable since the lateral distribution and intensity of Cherenkov light at a given total energy depends both on the primary particle mass, hence mean X_{max}, and the distance of the measurement from the shower core. A fit for the total shower energy and primary particle mass is made to the geometry, Cherenkov size (Ch) and X_{max} location in the two DICE telescopes. The form of the Ch size function used in these fits is derived from the results of simulations using the program CORSIKA 4.50 with VENUS (Heck et al. 98).

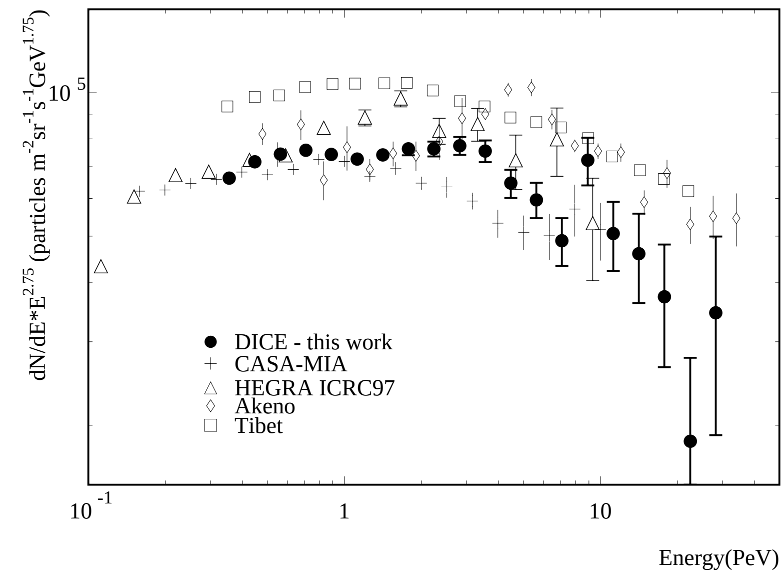

Figure 1: The differential energy spectrum of cosmic rays measured in this work (filled symbols) compared with other measurements. The vertical axis has been multiplied by $E^{2.75}$ to emphasize the comparison with other data.

Events collected by DICE in coincidence with CASA/MIA over a period from mid 1994 to early 1996 are subjected to the following selection cuts before fitting. (1) The core of the shower lies at a distance $100m < r < 225m$ from both DICE telescopes. (2) The fits of the longitudinal development in both DICE telescopes have reduced $\chi^2 < 3$. (3) The X_{max} from each telescope agree within $150g/cm^2$. (4) The arrival direction of the shower is within 6^0 of the vertical. The fits to the measured Ch and X_{max} from the two sites are made using the minimum χ^2 method. With these cuts the effective collection geometry is determined by the instrument Monte Carlo to be $\sim$3300 m^{2}sr, making the overall collecting power $\sim$125,000 m^{2}sr days. Using the detailed calculated aperture and efficiency corrections derived from an instrument Monte Carlo the cosmic ray energy spectrum can be constructed from the fit energies. This is shown as the filled circles in Figure 1 together with previous determinations of the energy spectra in this region. The fluxes have been multiplied by $E^{2.75}$ to emphasize differences between sets of data. The differences in the detailed shapes between this spectrum and the previously reported DICE energy spectrum (Boothby et al. 1997b) arise from the simplifying assumption of a composition independent relation between Cherenkov yield and energy used in the previous analysis. We believe these new measurements are a better determination of fluxes because of the primary mass dependent fitting function used for each event. These new DICE data are given in tabular form in Section 6. The 'knee' here is at an energy around 3PeV.

3 Ground Size Distributions:

With the Cherenkov energies derived from DICE the variation of the mean values of the shower muon size and electron size at ground level can be studied versus Cherenkov energy. This is valuable since the energy estimate is provided by a totally different instrument and technique from CASA/MIA. The results for muon size and electron size are shown in Figures 2 and 3 for the events which are collected by DICE and CASA/MIA and satisfy the cuts discussed above. Also shown as solid lines are the expected variation of the ground sizes from simulations using CORSIKA 4.5 with the VENUS interaction model. These simulations assume a constant composition normalized to a value derived from direct measurements at 0.1PeV (Swordy 1993). The dashed lines on these figures show a ground size proportional to energy for reference.

It is clear from these figures that in general the ground muon size rises more slowly than the shower energy, assuming a constant composition is more or less correct. The actual value of the slope of muon composition versus Cherenkov energy, E, is very close to the value $\propto E^{0.87}$ derived from simulations. These correlations imply the energy scale and muon size show some self-consistency, although this depends on the assumption of constant composition. The ground electron size rises faster than the overall shower energy, a behavior which is generally expected from simulations. A simple picture of this effect is that in addition to the overall increase in shower size the shower maximum penetrates more deeply into the atmosphere at larger energies. This produces an increase in shower size sampled at the ground which is larger than a simple proportionality to energy. In these data the rate of increase in the electron size seems smaller than $\propto E^{1.25}$ predicted by the simulation with constant composition. This could imply a steady increase in the heavy component of the cosmic rays, but this seems unlikely since the muon size shown in Figure 2 does not independently exhibit the same shift. This disagreement seems to arise from a combination of the simulation prediction being too large and a small saturation effect in the electron size measurement. This is possible since CASA was not designed to measure electron size accurately at the high densities and corrections have been made for the saturated detectors near the shower core. Importantly this saturation does

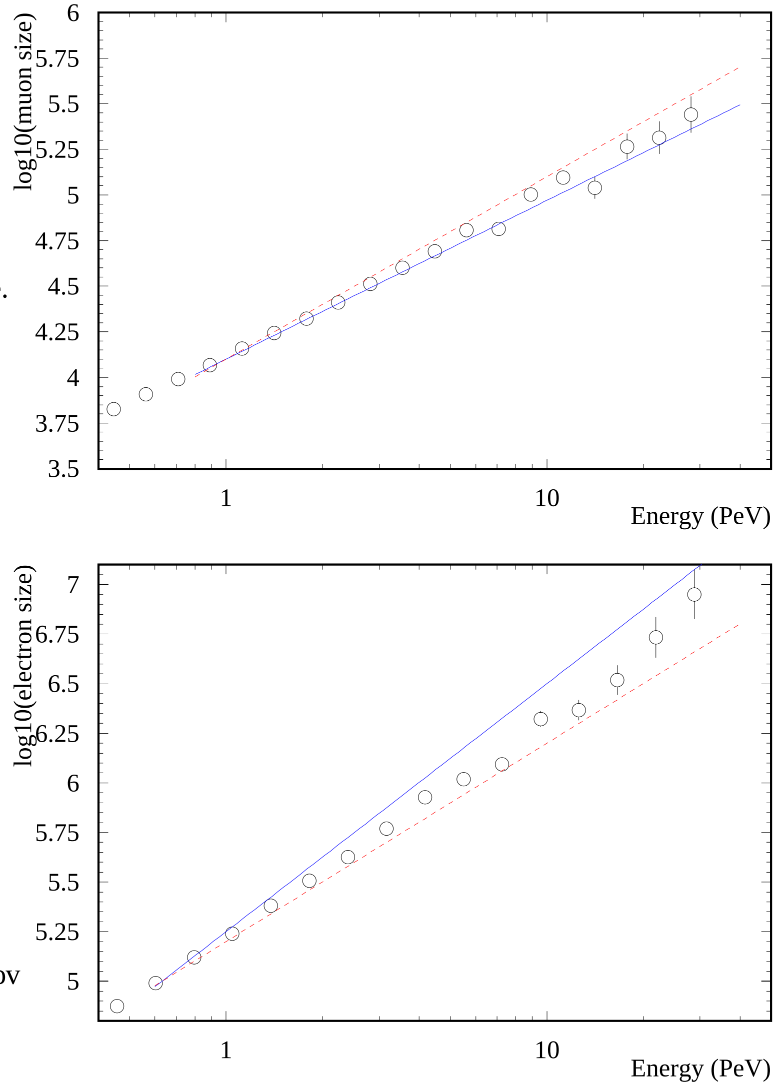

Figure 2: The variation of muon and electron size measured by CASA/MIA with DICE Cherenkov energy. The solid lines correspond to a constant composition simulation, the dashed lines are simple proportionality to energy.

not have to be large, and is discussed further in an accompanying paper (Swordy and Kieda 1999)

4 Conclusions and Results:

These measurements of cosmic ray fluxes in the region of the knee show a break in the spectrum consistent with other detectors in this energy range. The method used provides a simultaneous fit to the mass and energy of each event providing a more unbiased estimate of shower energy than a simple fit based on Cherenkov size alone. This is possible with the DICE images since the shape of the light distribution in the focal plane provides a measurement of the location of shower maximum and the total amount of light is related to the energy. The spectral break is located near ∼3 PeV and the data are consistent with a smooth transition from a spectral slope of $\sim E^{-2.7}$ below the knee to $\sim E^{-3.0}$ above this region, however the data are sparse at high energies. The absolute fluxes of these data are consistent with previous measurements in this energy region. The systematic uncertainty of the absolute flux is ∼30% because of the intrinsic uncertainty in the energy scale derived from the Cherenkov luminosity of 15%.

Total Particle Energy (GeV)	Flux $(m^2\ sr\ s\ GeV)^{-1}$	Flux Error $(\pm(m^2\ sr\ s\ GeV)^{-1})$
0.355E+06	0.361E-10	0.50E-12
0.447E+06	0.208E-10	0.30E-12
0.562E+06	0.115E-10	0.18E-12
0.708E+06	0.619E-11	0.11E-12
0.891E+06	0.322E-11	0.65E-13
0.112E+07	0.167E-11	0.39E-13
0.141E+07	0.906E-12	0.24E-13
0.178E+07	0.496E-12	0.15E-13
0.224E+07	0.263E-12	0.96E-14
0.282E+07	0.142E-12	0.61E-14
0.355E+07	0.734E-13	0.38E-14
0.447E+07	0.333E-13	0.23E-14
0.562E+07	0.163E-13	0.14E-14
0.708E+07	0.711E-14	0.82E-15
0.891E+07	0.557E-14	0.64E-15
0.112E+08	0.207E-14	0.35E-15
0.141E+08	0.999E-15	0.21E-15
0.178E+08	0.430E-15	0.12E-15
0.224E+08	0.113E-15	0.57E-16
0.282E+08	0.112E-15	0.50E-16

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