The Cosmic Ray Composition from 10^{14} to 10^{16} eV

M.A.K. Glasmacher[1], M.A. Catanese[1a], M.C. Chantell[2], C.E. Covault[2], J.W. Cronin[2], B.E. Fick[2], L.F. Fortson[2b], J.W. Fowler[2], K.D Green[2c], D.B. Kieda[3], J. Matthews[1d], B.J. Newport[2e], D.F. Nitz[1f], R.A. Ong[2], S. Oser[2], D. Sinclair[1], and J.C. van der Velde[1]

[1] *Dept. of Physics, The University of Michigan, Ann Arbor, MI 48109*
[2] *Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637*
[3] *Dept. of Physics, The University of Utah, Salt Lake City, UT 84112*
[a] *Current address: Dept. of Physics and Astronomy, Iowa State University, Ames, IA 50011*
[b] *Joint appt. with The Adler Planetarium and Astronomy Museum, Astronomy Dept., Chicago, IL 60605*
[c] *Current address: Koch Industries, Wichita, KS 67201*
[d] *Current address: Dept. of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803 and Dept. of Physics, Southern University, Baton Rouge, LA 70801*
[e] *Current address: Micro Encoder, Inc., Kirkland, WA 98034*
[f] *Current address: Dept. of Physics, Michigan Technological University, Houghton, MI 49931*

Abstract

The mass composition of cosmic rays with primary energies between 10^{14} eV and 10^{16} eV has been studied using the surface and buried scintillators of the CASA-MIA air shower array. Near 10^{14} eV the composition of cosmic rays is in agreement with direct measurements, roughly half light elements (protons and Helium) and half heavier elements. The average mass increases with energy, becoming heavier above 10^{15} eV. The mass changes coincide with the spectral steepening of the energy spectrum known as the knee. There is evidence for rigidity dependence in the spectral change. A method of calculating the primary cosmic ray energy which is insensitive to the composition is employed to achieve these results.

1 Introduction

Supernova shock wave acceleration may explain the origin of cosmic rays below about 10^{15} eV, but normal SN are expected to have neither high enough magnetic fields nor long enough shock lifetimes to accelerate particles to higher energy. Nevertheless, cosmic rays have been observed with a continuous spectrum extending to extreme energies. There is significant change in slope just beyond 10^{15} eV, perhaps indicating the SN shock acceleration limit. Another possibility is that the “knee” forms as particles attain a rigidity sufficient to escape the Galaxy. In either case it is expected that heavy particles will reach higher maximum energies than lighter ones. The observed cosmic ray composition will grow heavier in correlation with the spectral change if these models are correct.

Many experiments have attempted to determine the composition of cosmic rays with energies near the knee(Watson, 1997;Wiebel-Sooth & Biermann, 1997). Using a variety of techniques, most observe the composition becoming heavier through the knee, but some suggest otherwise. Several ground arrays (e.g., EAS-TOP, KASCADE) have suggested a trend toward heavier primaries, but the DICE experiment(Boothby et al., 1997), using air Čerenkov measurements, notes a trend toward lighter mass primaries above the knee.

The CASA-MIA detector (Borione et al., 1997) is an array of surface and underground plastic scintillators which measure the muon and electromagnetic components of air showers. The CASA-MIA data is used here to determine the probability, on an event by event basis, that a given data shower resulted from a “light” or a “heavy” primary. These distinctions are made by comparison to simulations of proton- or iron-induced air showers. A composition-independent measure of the energy is used to search for trends in the composition as a function of energy.

2 Simulations and Data

The CASA-MIA data set and the computer simulations of air showers have been described elsewhere in these Proceedings(Glasmacher et al., 1999a). As a first step toward evaluating the primary composition, the correlations between muon size N_μ and "electron" size N_{e*} are shown in Figure 1. The points represent the CASA-MIA vertical data and the heavy lines represent the averages for iron and proton simulated showers. The lighter dashed lines do the same for oxygen and helium simulations. The trend seen in Figure 1 suggests that the composition becomes heavier with increasing energy. The data appear reasonably "bounded" by the simulation predictions for iron and for protons. These simulations used the QGSJET interaction genrator; results using SIBYLL are quite similar (discussed below in Sec. 4).

In order to study composition more thoroughly, a more detailed fit of all events is performed after the standard fitting. These fits are also based on the NKG and Greisen functions. Three parameters sensitive to composition are extracted: the density of surface particles ρ_e and the slope α of the lateral distribution near the core, and the density of muons ρ_μ at large core distance.

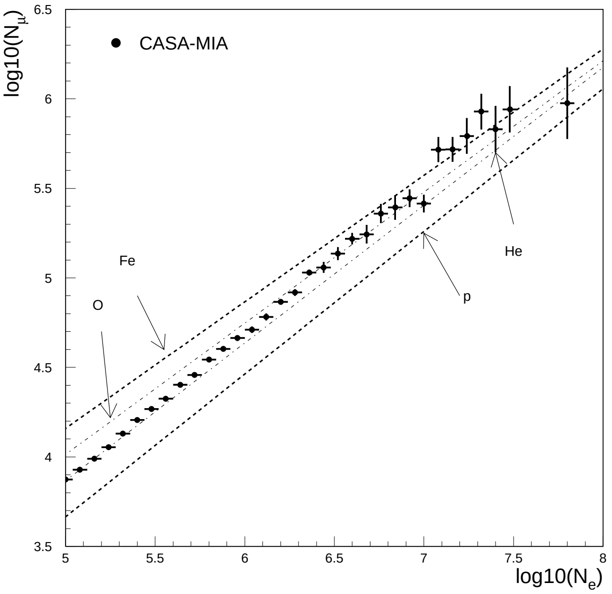

Figure 1: *Fitted muon and electron sizes.*

3 The KNN Test

The parameters ρ_e, ρ_μ, and α are tabulated for data and for simulation events. Data events are classified as "iron-like" or "proton-like" depending on whether these parameters most resemble iron or proton simulation events. The "K" Nearest Neighbor (KNN) test is employed to quantify this decision (Glasmacher,1998; Glasmacher et al., 1999c). Each data event is placed in the three-parameter space defined by ρ_e, ρ_μ, and α. A large set of simulated iron and proton events also populate the space. Suitably normalized "distances" (computed in units of the variance of each parameter, with correlations included) between the datum and individual simulation events is calculated. The nuclear types of the five nearest simulation events are then tallied. The use of $K = 5$ is optimal for this analysis (Glasmacher, 1998). Using too few simulation points is subject to fluctuations, using too many would sample simulation points with very different primary energies.

Each CASA-MIA event takes one of six possible values, corresponding to whether it has $0 - 5$ proton neighbors out of the five nearest neighbors examined. Using separate simulated calibration sets in place of data, it is found that more than 90% of events will have a majority of neighbors of their own species;

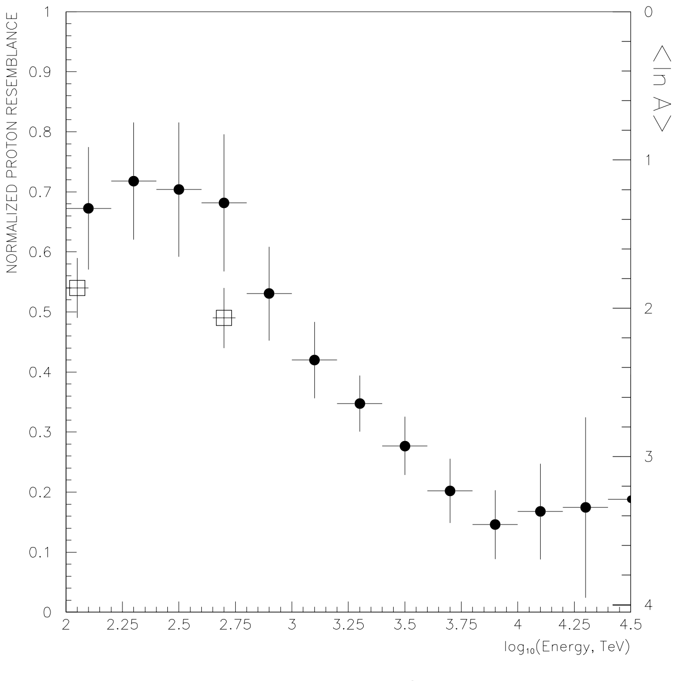

Figure 2: *Composition trend of CASA-MIA data.*

about 50% have all nearest neighbors of their own kind.

Figure 2 shows the results of the KNN test applied to CASA-MIA data. Shown is the normalized average fraction of simulation event neighbors of data which were protons, binned according to the data's reconstructed energy. This "proton resemblance" was normalized to the results of analyzing separate simulation calibration sets of pure iron and of pure protons. For example, near 100 TeV, the average fraction of proton nearest neighbors for a pure proton calibration sample is 68%; at the same energy a pure iron sample has only 16%. The average for CASA-MIA data is 51%. In Figure 2, this point is plotted at $(.51 - .16)/(.68 - .16) = 0.67$ of the distance between the extremes of pure protons or pure iron. Thus, if the data were in fact purely composed of protons, the point in that bin would acquire a value of 1.0, while pure iron data would have a value 0.0.

The computed proton resemblance is approximately proportional to $\langle \ln A \rangle$, the mean value of the natural logarithm of atomic number of the sample (Glasmacher,1998; Glasmacher et al., 1999b). The points in Figure 2 therefore reflect the average composition, as indicated by the right-hand axis. The open squares in the figure indicate the mean mass of the direct measurements of JACEE (Cherry, 1997). The CASA-MIA data is consistent with these direct measurements at the lower end of its energy range. The trend toward heavier masses is apparent, occuring at energies (calculated with a composition-independent algorithm) which correspond to the knee of the all-particle energy spectrum (Glasmacher, 1998; Glasmacher et al., 1999a).

4 Energy Spectra of Mass Groups

As a consistency check, the energy spectra of events are obtained after dividing them according to their KNN-identified mass. Precise mass divisions cannot be performed here, but the spectra can be examined after being divided into coarse mass categories. If the knee of the spectrum is a result of cosmic rays escaping the galaxy or the upper limit of supernova acceleration, then we would expect that the energy spectra of heavy and of light elements will differ, with lighter nuclei exhibiting the knee at a lower energy than heavy ones.

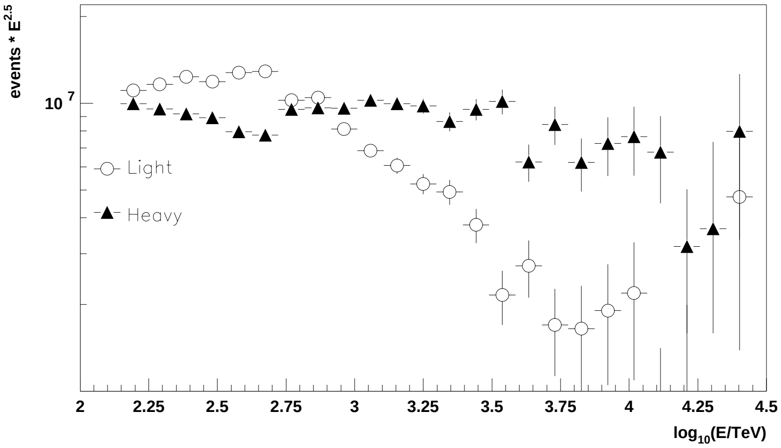

Figure 3: *Energy spectra of data grouped by composition.*

Figure 3 gives the energy spectra of CASA-MIA data, having been divided into two large groups of composition. The data labeled "light" are defined to have more than half proton nearest neighbors, and those labeled "heavy" have fewer than half. In a uniform distribution of primary types, or one similar to the measured JACEE mixture, the light sample would be dominated by protons and Helium nuclei. The error bars are statistical, and do not include energy uncertainty.

The spectra of the heavy and light components appear similar (within uncertainties magnified by the $E^{2.5}$ flux multiplier) below 500 TeV, at which point the lighter component's spectral index steepens. The heavier component shows no such "knee" at that energy, but may steepen at higher energy. Given CASA-MIA's mass resolution and the mass groupings above, we estimate that the heavy component would exhibit a spectral change at about 10 times the energy of the corresponding knee of the lighter component if the composition is distributed as in the JACEE results, and if it is experiencing cutoffs of each component at fixed rigidity.

The KNN analysis was also performed using the SIBYLL hadron interaction generator. None of the results

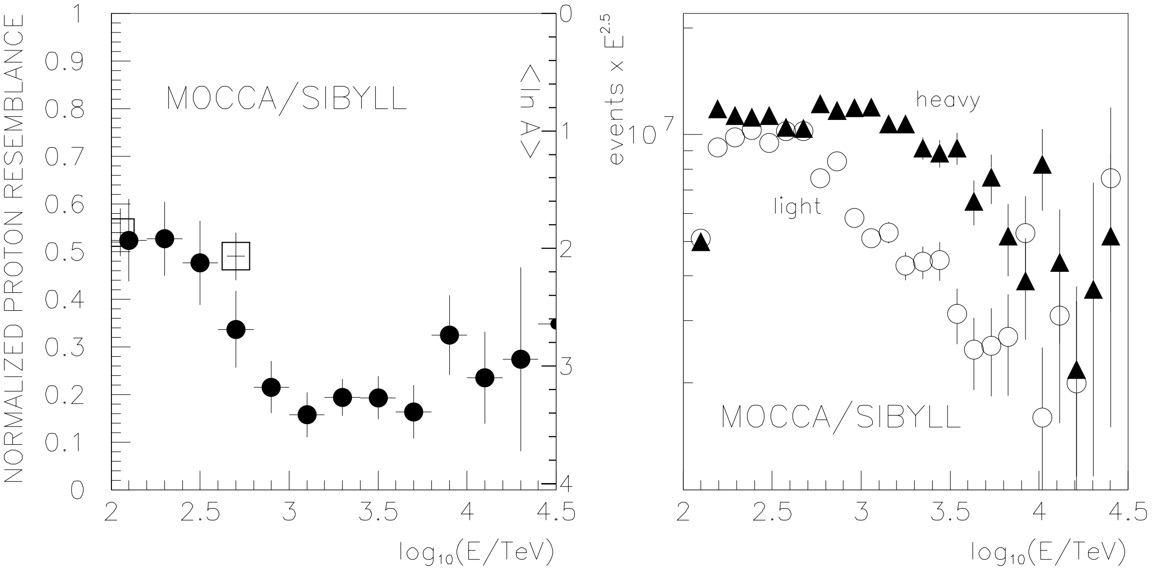

Figure 4: *Results using MOCCA/SIBYLL. Notation as in Fig. 2 and Fig. 3.*

are significantly altered when this is done. Figure 4 shows the analysis using SIBYLL, with the notation of the plots the same as was shown in Figures 2 and 3. The trend toward a heavier average composition through the knee region remains apparent, as is the consistency with previous direct measurements at lower energy. A rigidity-dependent spectral knee is also strongly suggested.

5 Summary

The composition measured near 10^{14} eV is consistent with other direct measurements and becomes heavier through the knee region of the spectrum. Spectra constructed separately for broad mass groups are consistent with cutoffs proportional to the particles' rigidity. These results qualitatively do not depend on whether the hadronic interaction simulations are based on the QGSJET model or on the SIBYLL code.

References

Boothby, K. et al., 1997, ApJ 491, L35
Borione, A. et al., 1994, Nucl.Instr.Meth. A346, 329
Cherry,M.L., 1997, Proc. Conf. Intersec. Part. Nucl. Phys. (Big Sky, 1997), p. 1022 (New York: A.I.P.)
Glasmacher, M.A.K., 1998, Ph.D. Dissertation (U. Michigan, unpublished)
Glasmacher, M.A.K. et al., 1999a, these Proceedings, paper OG 1.2.26
Glasmacher, M.A.K. et al., 1999b, Astrop. Phys. 10, 291
Glasmacher, M.A.K. et al., 1999c, to appear in Astrop. Phys.
Knapp, J., 1997, Proc. 25th ICRC (Durban, 1997), v.6, p.121; see also J.Knapp et al., Forsch. Karlsruhe Rep. FZKA 5828 (unpublished, 1996).
Watson, A.A., 1997, Proc. 25th ICRC (Durban, 1997), Rapporteur, v.8, p.257
Wiebel-Sooth, B. & Biermann, P.L., 1999, "Cosmic Rays", in Landolt-Börnstein, Group VI, v.3C, p.37 (Berlin/Heidelberg: Springer Verlag)