A Comparison of Cosmic Ray Composition Measurements at the Highest Energies

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Abstract

In recent years the Fly's Eye and Akeno groups have presented analyses of the cosmic ray mass composition at energies above 10^{17}eV. While the analysis of the Fly's Eye group points to a likely change in mass composition from heavy to light at energies above 10^{18}eV, the Akeno analysis favours an unchanging composition. However, the two groups base their conclusions on simulations using quite different hadronic models. Here we present a comparison of the experiments using the same hadronic model and find that the agreement between the experiments is much improved. Under this model, both experiments measure a composition rich in iron around 10^{17}eV which becomes lighter at higher energies. However, the agreement is not complete, which indicates scope for improvement of the interaction model, or perhaps the need for a re-examination of the experimental results.

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1 Introduction

Measurement of the mass composition of cosmic rays at the highest energies is a challenging and vital task. A known mass (and therefore charge) spectrum can provide strong constraints on the acceleration and propagation of the highest energy particles known in the Universe. Such a measurement is as important as measurements of the energy spectrum or anisotropy.

Mass composition measurements are difficult to interpret because of quite understandable deficiencies in our knowledge of hadronic interactions at the highest energies. This is particularly true at energies discussed here, with primary cosmic ray energies above 10^{17}eV. However, progress is being made in these models, with some constraints being imposed by cosmic ray data. Our intention here is to show that two sets of mass composition data, previously thought to be inconsistent, are in fact somewhat reconcilable. The degree to which the experimental results agree could be a test of the validity of a given interaction model.

Two very different experiments have reported mass composition interpretations in the recent past. The University of Utah Fly's Eye detector [1] observed the longitudinal development of energetic air showers via the emission of fluorescence light in the atmosphere. This technique effectively uses the atmosphere as a calorimeter and extracts both energy and mass composition information from the longitudinal profile. Heavy nuclei produce showers which develop, on average, more rapidly than proton showers of the same energy, and the depth at which a shower reaches its maximum size, $X_{\rm max}$ is used as the mass composition indicator.

A complementary technique is employed by the Akeno group in Japan. Their giant array AGASA [2] covers $100\,{\rm km}^2$ and contains shielded and unshielded detectors to measure, respectively, the muon and charged particle densities at the detector depth of 920 $\rm g\,cm^{-2}$. Here the energy is estimated by $S_0(600)$, the unshielded scintillator density 600 m from the shower core corrected for zenith angle. The mass composition is characterised by the muon measurements, with an expectation that showers initiated by heavy nuclei will, on average, have a higher muon content at a particular energy.

As already mentioned, the interpretation of the results from these experiments requires assumptions about hadronic interactions at energies well beyond the reach of accelerators. In [3] the Fly's Eye group investigates 3 different interaction models, one of which is ruled out by the $X_{\max}$ data. The two remaining models, known as KNP and minijet, are both characterised by increases in inelasticity with energy (inelasticity being the fraction of energy used in an interaction in the production of secondary particles), with the KNP model said to provide close to an upper bound on the rate of increase in inelasticity [4]. These models predict rather low values of the elongation rate ($d\log(X_{\max})/d\log E$) which are quite inconsistent with the data. The conclusion from both models is that the data indicate a decrease in the mean cosmic ray mass with energy, with an iron dominated flux around 10^{17} eV and a significantly lighter one at around 10^{19} eV.

The Akeno group base their composition conclusions [5] on the hadronic model contained in the 1992 version of MOCCA, an air shower simulation written by A.M. Hillas. This hadronic model is based on results from fixed target accelerator experiments. The model makes a prediction for the way the muon content (as expressed by the density of muons 600 m from the shower core) increases with energy. Based on this expectation, the Akeno group see no evidence for a change in composition in the same energy range explored by the Fly's Eye experiment.

In recent years a new hadronic interaction generator named SIBYLL has been used within the MOCCA shower simulation code. We have used this generator to investigate the longitudinal development and muon content of large air showers for comparison with the experimental data.

2 The SIBYLL Hadronic Generator

The SIBYLL interaction generator [6] is built around the "minijet" model used in the Fly's Eye analysis, and was designed to reproduce features observed in collider experiments. As we have said, the original MOCCA hadronic driver (as used by the Akeno group [5]) was written to reproduce interactions at more modest fixed target accelerator energies. The differences in physics are described in [6], but briefly the original MOCCA featured a flat Feynman-x distribution of the leading nucleon, Feynman scaling of resulting momentum distributions, and charged particle multiplicity distributions with mean values increasing as $\ln(s)$ (s being the square of the centre of mass energy). In contrast, SIBYLL uses a model which has multiplicities increasing more rapidly with energy (as $\ln^2 s$), and the minijet character of the model allows a more sophisticated treatment of correlations between transverse momentum and multiplicity.

Scaling is violated, but not in an extreme way. The authors regard SIBYLL as a lower-bound on scaling violations. Compared with the model within the original MOCCA, SIBYLL predicts air showers with a more rapid development, with expected differences in measurable quantities like the elongation rate and muon content.

We have generated vertical and inclined proton and iron showers at several energies using MOCCA+SIBYLL at a thinning level of 10^{-6} (see [7] for a description of thinning). We record the longitudinal development profiles, and ground particle information appropriate for the AGASA atmospheric depth.

3 Data Sets

We compare simulation results with data from the Fly's Eye and Akeno experiments. The Fly's Eye data set is that published in [3]. In the case of Akeno, we have used different sources for the data collected by the A1 and A100 arrays. The full A1 array [8] began operation in October 1981, covers an area of approximately $1\,\text{km}^2$, and is populated with surface scintillator detectors and shielded muon detectors. The latter have a muon energy threshold for vertical particles of 1 GeV. Our analysis of this array is based on data from [5].

The A100, or AGASA, array covers an area of $100\,\text{km}^2$ and has operated since 1992. Roughly half of this area is also serviced by muon detectors, in this case with a vertical muon energy threshold of 0.5 GeV. We have used a recent set of data from this array [9]. This represents more than a seven-fold increase in the size of the data set presented for A100 in the original analysis [5].

In both papers, the practice of the authors has been to reduce the A100 muon densities $\rho_\mu(600)$ by a factor of 1.4, to allow comparison with A1 data (A1 having a higher muon energy threshold) and their simulations, which were calculated for a threshold of 1 GeV. We prefer to separately compare A1 data with 1 GeV simulations and A100 data with 0.5 GeV simulations, since we have seen in the simulations that the 1.4 factor, though experimentally measured at one energy (10^{17}eV [10]), appears not to be valid for all energies and mass compositions. For example, our MOCCA+SIBYLL simulations show a ratio of 1.41 ± 0.01 for iron at 10^{17}eV, but a value of 1.19 ± 0.01 for protons at the same energy.

In [9] the A100 muon densities are given as a function of primary energy. In [5] A1 muon densities are given as a function of the scintillator density 600 m from the shower core, $S(600)$. In each case the sample of showers has a $< \sec\theta >= 1.09$ (θ being the zenith angle). Later we will plot these A1 data as a function of primary energy. The primary energy has been calculated from $S(600)$ in two steps. First $S_0(600)$, the expected scintillator density for vertical showers is calculated, assuming a shower attenuation length of 500 g cm^{-2} [11]. The primary energy is then assumed to be $E = 2 \times 10^{17} S_0(600)$ [12, 13].

4 Treatment of Detector Effects

It is important to understand experimental biases in the analysis of composition data. These biases can occur in the triggering of the experiment or in the analysis of the data. The triggering and reconstruction biases of the Fly's Eye have previously been studied in great detail by ourselves and others. We have used one such study [14] to apply corrections to the MOCCA+SIBYLL-simulated elongation rate for proton and iron showers. That study generated proton and iron showers with energies sampled from a E^{-3} differential spectrum. The showers were passed through a detailed detector simulation and reconstructed using the same analysis routines used for the real data. Such a process takes account of effects like triggering bias (there is a small bias in the Fly's Eye against detecting iron showers around the threshold energy of 10^{17}eV), and small shifts in reconstructed values of $X_{\rm max}$, this partly due to the assumption of a gaussian form for the longitudinal profile.

The $X_{\rm max}$ behaviour of our MOCCA+SIBYLL generated showers is similar to that used in [14]. At a given energy, proton $X_{\rm max}$ values differ by around 20 g cm^{-2} and iron values differ by around 30 g cm^{-2}. From [14] we parametrize triggering and reconstruction shifts in terms of energy and $X_{\rm max}$. Because of the two-dimensional parametrization we feel confident applying these shifts to our data, despite slight differences in $X_{\rm max}$. In addition to these shifts we have reduced all simulated $X_{\rm max}$ values by 20 g cm^{-2}. This was done in the original study [3], and is also needed here to ensure that the real data at 10^{17}eV do not imply a composition *heavier* than iron. Such a shift is entirely consistent with possible systematic effects in the Fly's Eye experiment [3].

To investigate any trigger bias in the Akeno experiments, we take showers from MOCCA+SIBYLL and simulate their interaction with the A1 and A100 arrays. For each simulated shower we obtain the muon lateral distribution and the lateral distribution expected for 5 cm thick plastic scintillator detectors. The muon energy threshold is assumed to be 1.0 GeV for the A1 array and 0.5 GeV for the A100 array. The showers are thrown at random core locations within the arrays, the densities are statistically fluctuated, and the trigger conditions are applied for both the scintillator detectors and the muon detectors.

We find that at energies of interest above 10^{17}eV the densely instrumented A1 array is free of triggering bias, with equal triggering efficiencies for both proton and iron-induced EAS in both the scintillator and muon detector parts of the array. We assume that this array will, on average, correctly measure the two shower parameters of interest - the scintillator density $S(600)$ and the muon density $\rho_\mu(600)$ at a core distance of 600 m.

In contrast we find that the larger and sparser A100 array has some composition-dependent triggering efficiency. To investigate this, we generated simulated showers at a zenith angle of 23 degrees, to match the mean $\sec\theta$=1.09 of the data set. (The A1 simulations were performed with vertical showers. We determined that an extra 9% of atmospheric depth would not affect our conclusion regarding any possible triggering bias).

The Akeno group has opted for an A100 triggering scheme which minimizes trigger bias. We have applied this scheme in our simulations. The first requirement for a shower is that it triggers the surface array, with a minimum of 5 nearest-neighbour stations registering particles. A muon station will self-trigger if two (non-neighbouring) proportional counters fire within that station. A muon station may also be triggered (and data read out) if it fails to meet the 2 proportional counter requirement, but only if the scintillator detector at the same location records a signal above threshold. This is known as an assisted muon trigger. A shower is accepted for the analysis if it satisfies the electron array trigger and if there is at least one self-triggered or assisted-triggered muon station. Obviously, some of the assisted muon triggers record a zero particle count.

If the self- or assisted-triggered muon station is at a core distance between 500 and 800 m it is used in the calculation of an average $\rho_\mu(600)$ for the appropriate $S(600)$ bin. Every such muon density is scaled to the expected density at 600 m using the published AGASA muon lateral distribution function [5]. The resulting scaled densities are averaged to find the mean $\rho_\mu(600)$. Note that some showers might contribute 5 or more numbers to the average. Some other showers contribute a single zero to the average. The latter case occurs when the only triggered muon station in that event is an assisted trigger with a measured density of zero. (This seems a good strategy. A measured muon count of zero is a perfectly valid fluctuation from a mean expectation that might be as low as 0.2 muon m^{-2} at the lowest energies).

Given the A100 triggering scheme, we simulated the response of the array to our MOCCA-generated showers, and calculated the mean $\rho_\mu(600)$ for those showers triggering at each energy. We also took note of the triggering efficiency as a function of energy for proton and iron initiated showers. We find that at 3×10^{17}eV the triggering efficiency (electron+muon) for proton showers is 80% of the iron shower efficiency. The efficiencies equalize above 3×10^{18}eV. These figures are used later in our estimate of the fraction of iron present in the primary cosmic ray beam.

In graphs that follow we will plot the energies of MOCCA simulations. We do this in the following way. In the case of the vertical showers from the A1 simulation, we take from the simulations the mean value of the scintillator density at 600 m, S(600). (Of course, this is actually $S_0(600)$ because the showers are vertical). We convert this to primary energy assuming the Akeno conversion factor $E = 2 \times 10^{17} S_0(600)$ [12, 13]. In the case of the A100 simulation with inclined showers, we follow the same procedure, except that we convert the measured mean S(600) into $S_0(600)$ by assuming a shower attenuation length of $500\,\mathrm{g\,cm^{-2}}$. While the resulting energies in both the A1 and A100 simulations appear somewhat inconsistent with the primary energies injected into the original MOCCA+SIBYLL simulation, we do this to follow the procedure used with the real data.

5 Results and Discussion

Our comparison of Fly's Eye $X_{\max}$ data with MOCCA+SIBYLL (Figure 1) is similar to the result obtained by previous authors using the minijet model [3]. The simulated elongation rates for proton and iron showers are significantly smaller than the elongation rate observed by the Fly's Eye, and so we conclude that the model requires a change from an iron-dominated composition to a lighter one above 10^{18}eV. The change in composition is not as striking as that required by the more extreme KNP model [3], but a change is nonetheless required.

We present results from our Akeno analysis in Figures 2 & 3. Here we show data from A1 and A100 compared with simulations appropriate to the muon energy threshold for the particular array.

A note on the energy scales in these two figures: as described above, the simulation points (see figures) are assigned energies on the basis of the mean value of $S_0(600)$ and the Akeno energy conversion factor. This results in the assigned energies being low compared to the primary energies injected into the simulation. That is, according to the SIBYLL model, the Akeno procedure *underestimates* primary energy by around 30%. (Actually, the apparent underestimation is around 30% for the vertical showers used in the A1 simulation and 20% for inclined showers used in the A100 simulation. There is no obvious energy dependence to these figures). Such an inconsistency was noted in the original Akeno paper on the $S(600)$ to energy conversion [13] in which the conversion factor was compared with other experiments and models. Not surprisingly, there is model dependence in the conversion factor.

In Figure 4 we show the implied fraction of iron nuclei in the primary beam at the top of the atmosphere, from A1 and A100 data assuming a simple mixture of protons and iron nuclei. For A100 data we have included the effect of the small trigger bias in favour of iron showers at the lowest energies. The line on the figure represents a fit to the A1 data. We note that there is good agreement between the A1 and A100 results, encouraging since they are separate experiments with different muon energy thresholds and analysis methods.

In Figure 5 we show the corresponding plot for the Fly's Eye analysis. We include in this figure the A1 array best-fit line from Figure 4. Comparing the results, we observe the following

- Both AGASA and Fly's Eye support a heavy composition (100% iron in the two component model) near 10^{17}eV.

- Both experiments require that the composition becomes significantly lighter in the energy range up to 3×10^{18}eV. At that energy, both experiments require a fraction of iron of around 55-70% in this two component fit under the SIBYLL model. Above this energy, statistical uncertainties preclude a definitive statement.

- The way in which the fraction of iron changes from 100% to around 60% is different in the two experiments. The change in the Akeno data occurs at lower energy. One possible explanation for this concerns the energy calibration. For illustration purposes, we will assume that AGASA underestimates primary energy by 30%. This happens to be the disagreement with the energy scale of SIBYLL, but we might have chosen to suppose that the Fly's Eye overestimates energy by the same amount. This allows us to shift the A1 array line in Figure 5 giving slightly better agreement between the experiments.

- In the spirit of investigating possible experimental systematics, we have assumed that the systematic error in $X_{\rm max}$ assignment might be as large as $30\,{\rm g\,cm^{-2}}$ rather than the $20\,{\rm g\,cm^{-2}}$ assumed by us above, and as assumed by Gaisser et al.[3]. Figure 6 shows the fraction of iron plot for Fly's Eye under this assumption. This, together with 30% shift in the A1 energy scale, brings the results into better agreement.

- Of course, it is just as likely that there are no experimental systematic problems with energy or $X_{\rm max}$. The difference between the experimental results may result from physics assumptions within the SIBYLL model. There may be scope for learning something about the model (or its implementation within the MOCCA shower code) from differences uncovered in this study.

Other choices of hadronic model might result in different conclusions about mass composition. In particular, the KNP model used in the original Fly's Eye study required a more rapid change in composition, from near pure iron to a protonic composition at the highest energies. Unfortunately, we did not have access to this model for 3D calculations of muon density, so it could not be applied to the AGASA analysis. It would be interesting to do such a study to see if less conservative hadronic models give better agreement between AGASA and Fly's Eye results.

We are aware of a new analysis (in preparation) of EAS seen in coincidence with the HiRes prototype detector and the MIA muon array. While the energy range covered is only from 10^{17}eV to 10^{18}eV, we expect that these results will greatly help our understanding of correlations between longitudinal shower development, muon content and mass composition.

6 Conclusion

We have used recent data from two experiments that measure the mass composition of the highest energy cosmic rays in very different ways. Under the assumption of a single hadronic model, we find that the data-sets provide quite similar conclusions. We trust this will correct a widely held view that the results are totally inconsistent.

7 Acknowledgements

We greatly appreciate the discussions we have had with members of the Fly's Eye and Akeno groups, including M. Nagano and Y. Matsubara. We are especially indebted to N. Inoue who provided us with a great deal of insight into the operation of AGASA, and suffered our many naive questions.

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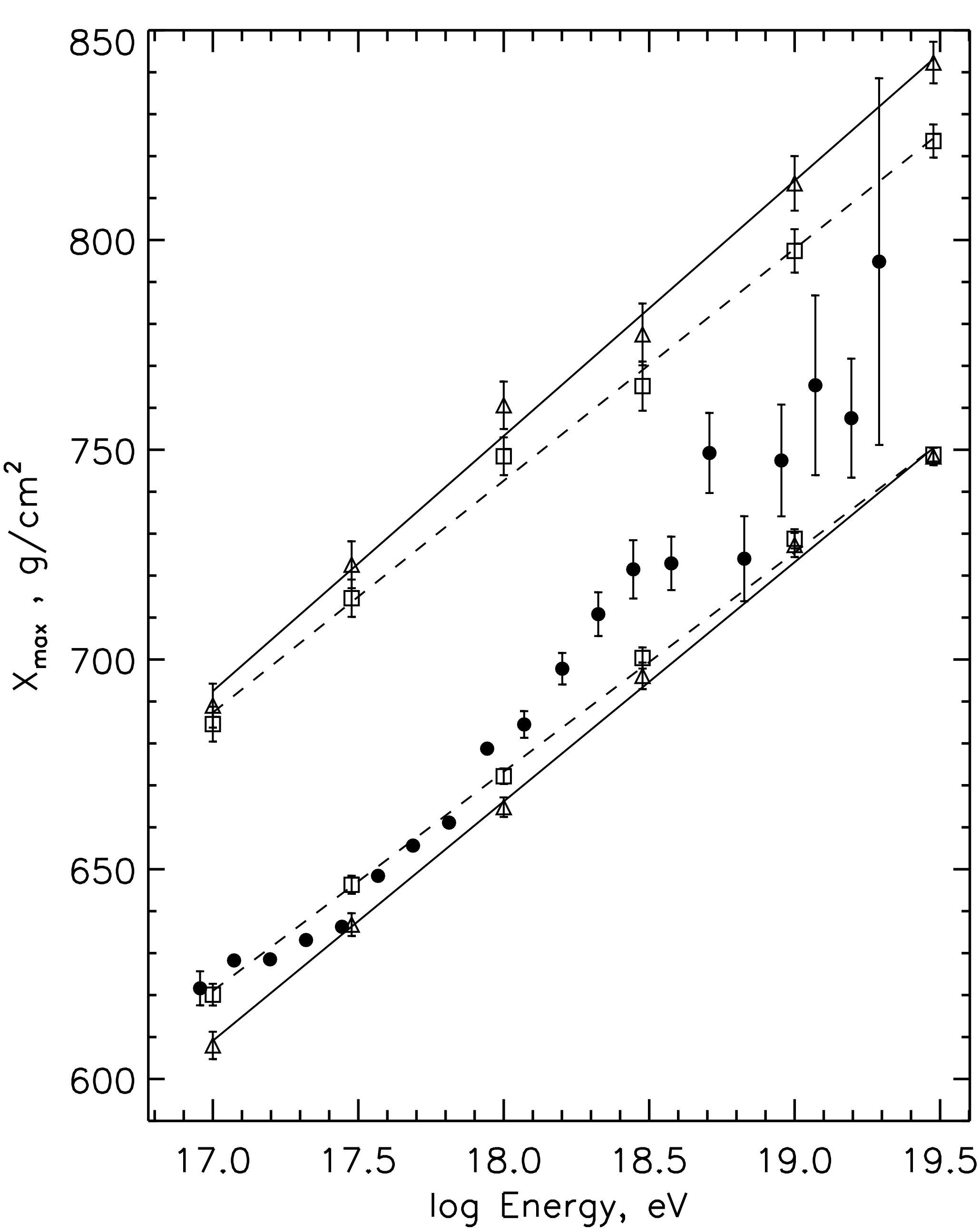

Figure 1: Plot of the Fly's Eye X_{max} vs Energy. The solid lines (triangles) are the unreconstructed MOCCA+SIBYLL simulation data. The dashed lines (squares) are the reconstructed simulated data, which also include a coherent 20 $g\,cm^{-2}$ shift (see text). Top lines represent pure protons, bottom lines represent pure iron. The uncertainties on the proton points are larger because of larger intrinsic fluctuations in shower development.

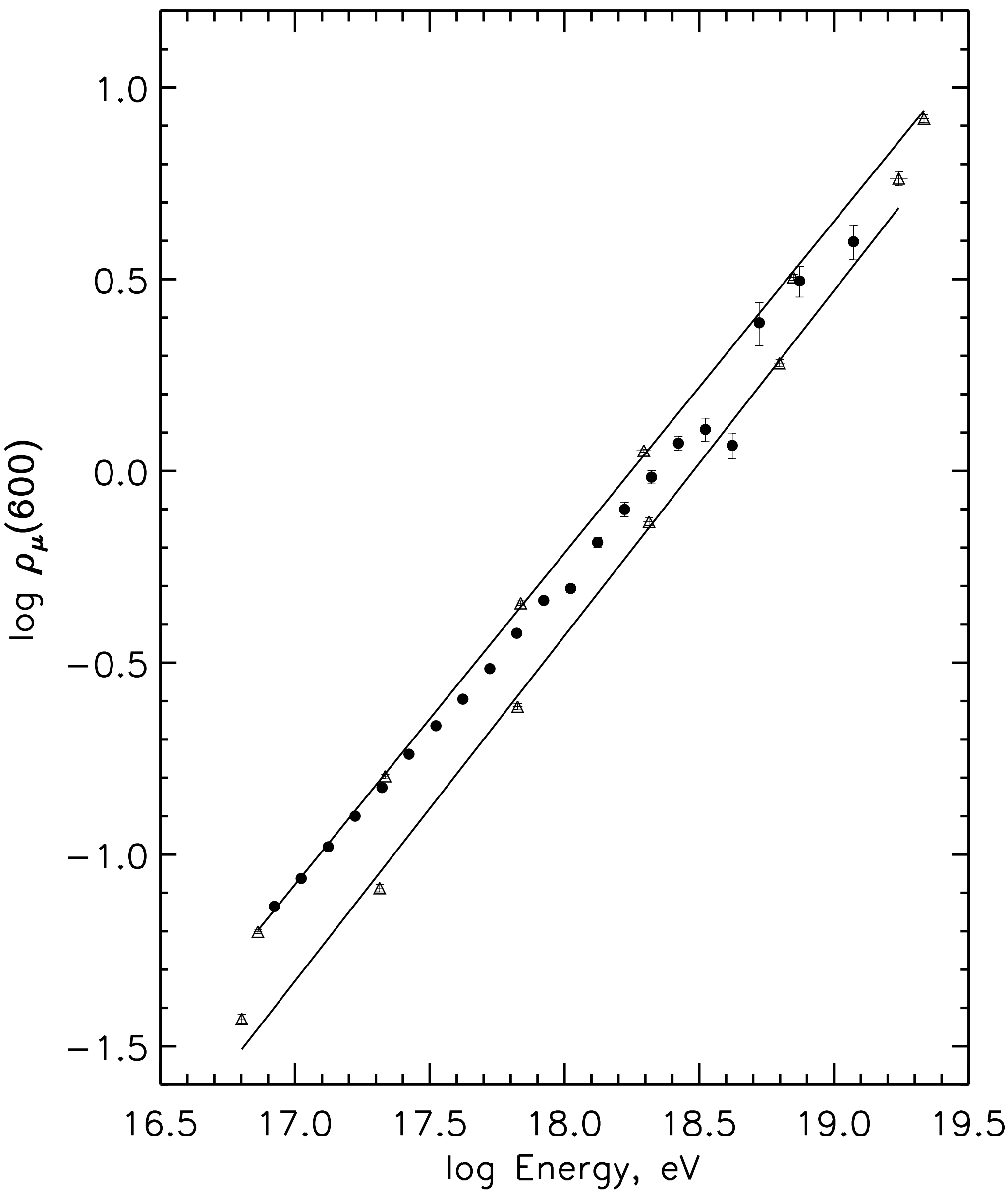

Figure 2: Data from the Akeno A1 array up to April 1993 (solid points, [5]) compared with MOCCA+SIBYLL simulations (triangles and solid lines). The top line represents iron primary particles, the lower line protons. Calculations were done for a muon energy threshold of 1 GeV. Array response simulations show no triggering bias towards either proton or iron-induced showers. The energy scale is defined using the Akeno method described in the text. The scale is somewhat inconsistent with the MOCCA+SIBYLL calculations - triangles show simulations at 10^{17}eV, 3×10^{17}eV, 10^{18}eV, 3×10^{18}eV, 10^{19}eV and 3×10^{19}eV.

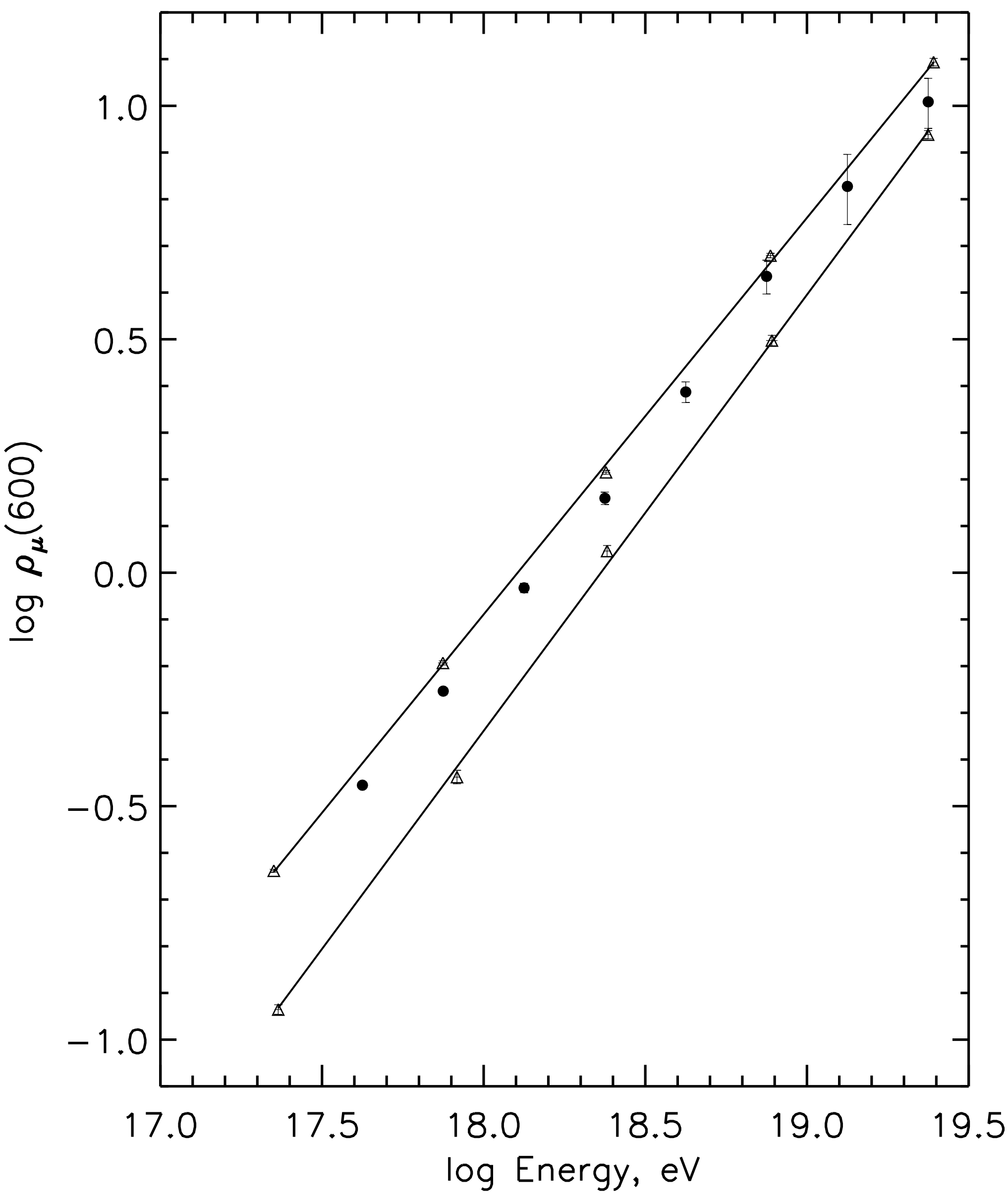

Figure 3: Data from the AGASA A100 array (muon threshold of 0.5 GeV) from [9], with the 1.4 multiplicative factor removed (see text). Sold lines and triangles show simulations from MOCCA+SIBYLL for iron (top) and proton (bottom) primary particles. A small triggering bias is present in A100 at lower energies which cannot be indicated here. The simulations were performed at energies of 3×10^{17}eV, 10^{18}eV, 3×10^{18}eV,10^{19}eV and 3×10^{19}eV

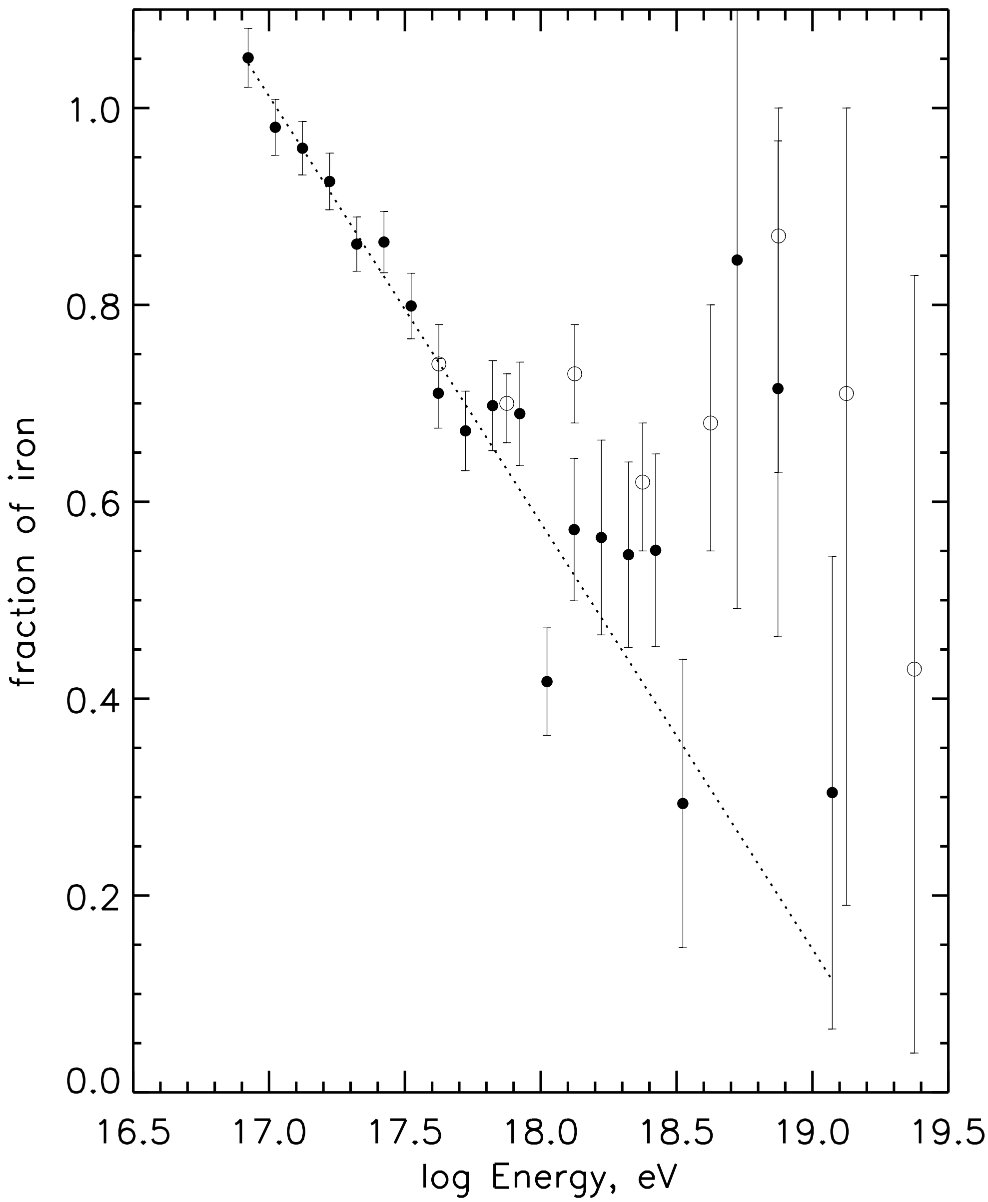

Figure 4: Predicted fraction of iron nuclei in the cosmic ray beam at the top of the atmosphere, from the AGASA A1 (filled circles) and A100 (open circles) experiments. We assume a simple proton/iron mixture, and the hadronic physics contained in SIBYLL. Error bars are calculated using the uncertainties in the experimental muon densities and uncertainties in the logarithmic fits to the Monte Carlo predictions in Figures 2 & 3. The dotted line represents a fit to the A1 points, a fit mainly influenced by the lower energy data. The results from the two arrays (with different muon energy thresholds) appear consistent in the region where they overlap.

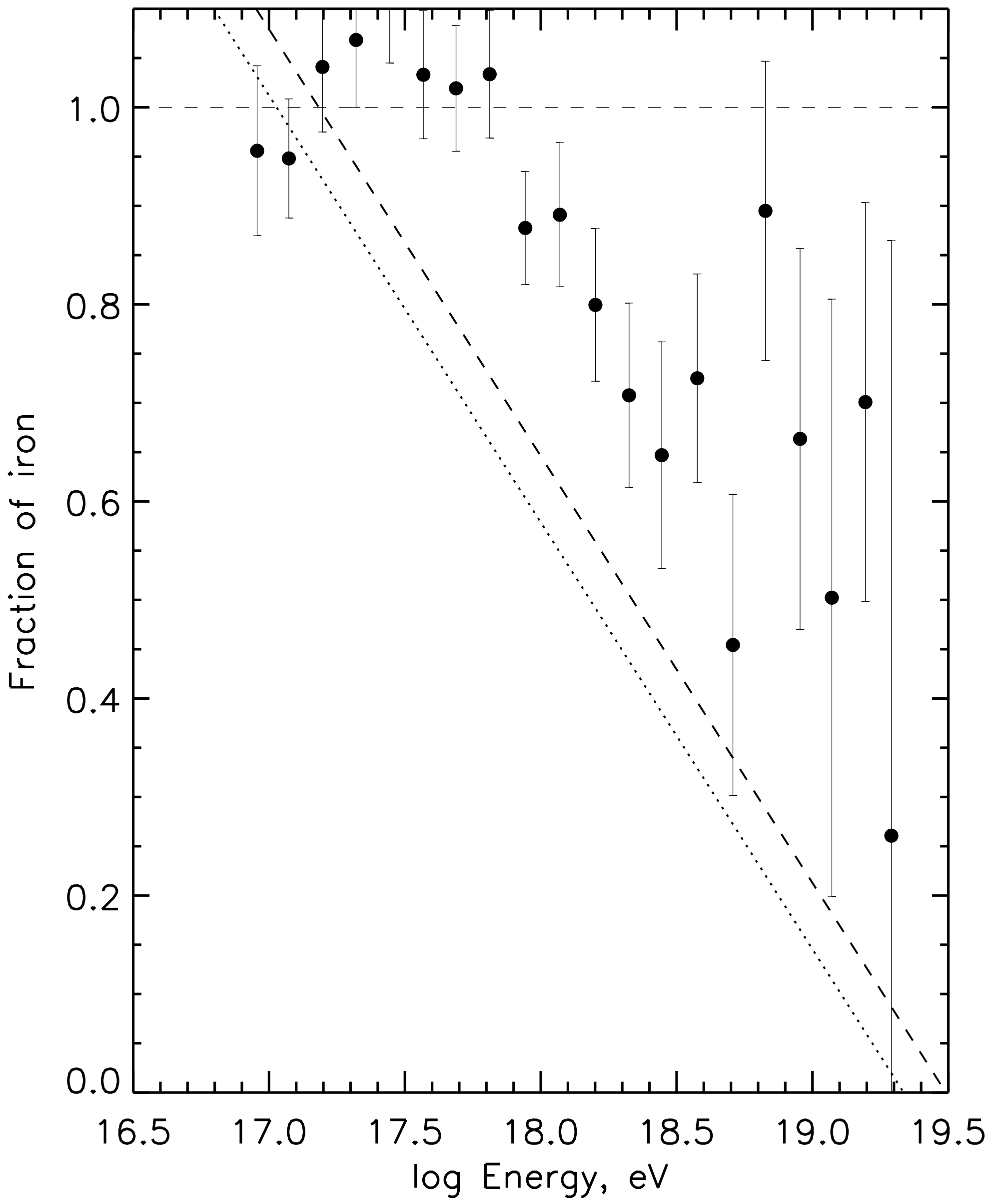

Figure 5: Predicted fraction of iron nuclei in the cosmic ray beam at the top of the atmosphere, from the Fly's Eye data under the assumption of the SIBYLL hadronic model. A simple two-component composition model is assumed. Errors are calculated using the data-point error estimates, and errors from the logarithmic fits to the Monte Carlo proton and iron expectations. The dotted line shows a fit to the A1 data from Figure 4. The dashed line is that same fit shifted under the assumption that the A1 analysis underestimates primary energy by 30%.

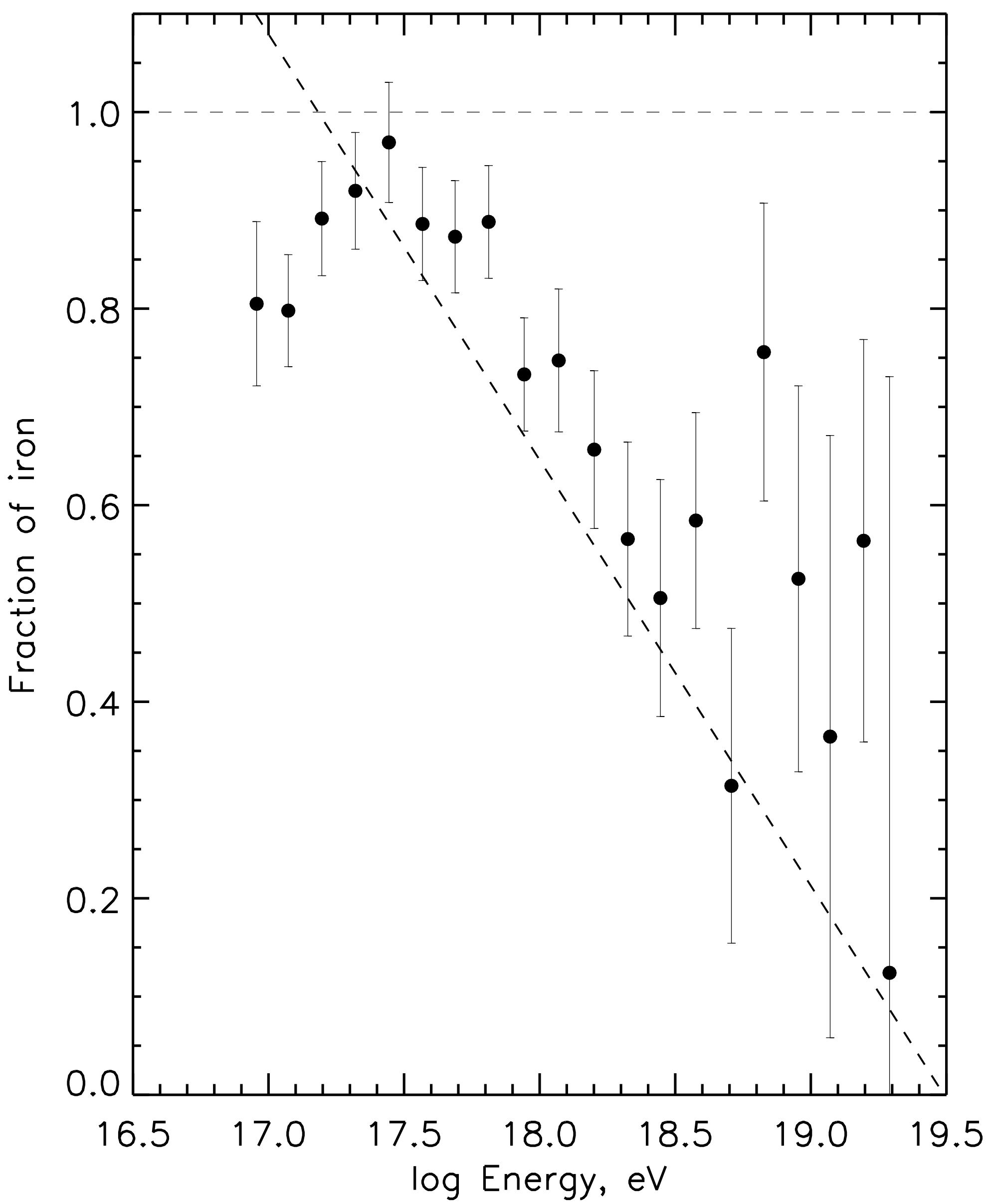

Figure 6: Like Figure 5, but here we attempt to show the effect of possible systematic errors in the data or hadronic model. We assume that the A1 analysis underestimates energy by 30%. We also assume that there is a further $10\,\mathrm{g\,cm^{-2}}$ systematic shift required in either the Fly's Eye data or in the $X_{\max}$ simulation results.