# UHECR Composition Studies with HiRes Stereo Data

G. Archbold,[1,2] and P.V. Sokolsky,[2] for the HiRes Collaboration
*(1) Lawrence Livermore National Laboratory, Livermore, California, 94551 USA*
*(2) University of Utah, Department of Physics and High Energy Astrophysics Institute, Salt Lake City, Utah, 84112 USA*

## Abstract

The composition of Ultra High Energy Cosmic Rays (UHECR) was studied with the High Resolution Fly's Eye cosmic ray observatory (HiRes). The QGSJet01 and SIBYLL 2.1 hadronic interaction models were used in the CORSIKA event generator to study predicted elongation rates and $X_{max}$ distribution widths in the UHECR regime. The CORSIKA-generated EAS were incorporated directly into a detailed atmospheric and detector Monte Carlo. Elongation rate and $X_{max}$ distribution results will be shown for our stereo data.

## 1. Introduction

The distribution of positions of shower maxima ($X_{max}$) in the atmosphere has been shown to be sensitive to the composition of cosmic rays. The rate of change of $X_{max}$ with the log of the energy of the primary, $dX_{max}/d\log(E_\circ)$, is known as the elongation rate and is denoted by $\alpha$ in Linsley's expression [7]

$$\alpha = (1 - B)K\lambda \left[1 - \frac{dlog(\langle A \rangle)}{dlog(E_\circ)}\right]. \tag{1}$$

B contains the dependence of $\alpha$ on the hadron-air nucleus interactions. How the energy dependencies of the cross-sections, multiplicities, and inelasticities are handled by and evidenced in the different hadronic interaction models is discussed in [5].

Previous experiments [1, 2] (stereo Fly's Eye, HiRes prototype-MIA) have shown evidence for an elongation rate of 80-90 gm/cm$^2$ in the energy rage from $10^{17}$ to $10^{18.5}$ eV. No information has been hitherto available on the behavior of the elongation rate near $10^{19}$ eV and above.

## 2. Methods

Individual EAS with full fluctuations were generated using CORSIKA 6.005 and 6.010 [4], using both QGSJet01 [6] and SIBYLL 2.1 [3] hadronic models

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for both protons and iron nuclei. Thinning was set at $10^{-5}$. Electrons, positrons, and photons were tracked down to energies of 100 keV. Hadrons and muons were tracked to 300 MeV. At least 400 iron showers and 500 proton showers were generated using each hadronic interaction model in each 0.1 step of log(E/eV) from $E = 10^{17.5}$ to $10^{20}$ eV.

Nearly equal numbers of proton- and iron-initiated showers were thrown in a detailed detector and atmospheric Monte Carlo, with an equal number of SIBYLL and QGSJet showers for each species. The thrown energy distribution followed the Fly's Eye Stereo Spectrum.

Data were collected in stereo from November 1999 to September 2001. For most events hourly atmospheric parameters are available and were used during reconstruction. If no measurement existed in the database, the events were reconstructed with the average atmospheric description [8]. Periods during which the optical depth measurement was larger than 0.12, the operators' comments suggested bad weather, or the steerable lasers indicated that the aperture was cloudy were discarded.

The final data set was comprised of 553 events. When the same cuts used on the data were applied to the Monte Carlo, the resolution was 30 $\mathrm{gm/cm^2}$ in $X_{max}$ and 13% in energy.

## 3. Results

Figure 1 shows the elongation rate result. The QGSJet and SIBYLL model predictions and the HiRes Prototype result are also indicated. The measured elon-

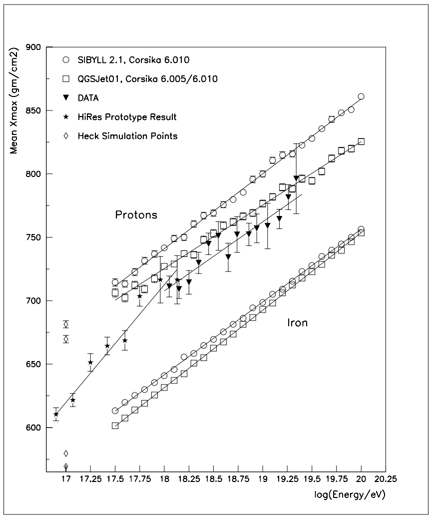

**Fig. 1.** Elongation rate result. The predictions for QGSJet and SIBYLL protons and iron are shown for comparison. The stars show the HiRes Prototype result.

gation rate is 54.5 ± 6.5 (statistical uncertainty only; see Section 4.), compared to the model predictions of 50 and 61 for QGSJet protons and iron nuclei, respectively, and 57 and 59 for SIBYLL protons and iron nuclei, as well as to the HiRes Prototype result of 93.0 ± 8.5 (stat) ± 10.5 (sys).

Figure 2 shows the $X_{max}$ distribution width result. The histograms representing the hadronic interaction models in Figure 2 include nearly 2500 events of each type which survived the same cuts as the data. The areas of the Monte Carlo histograms are normalized to the area of the data histogram. The width of the data distribution in Figure 2 indicates that the composition is predominantly light.

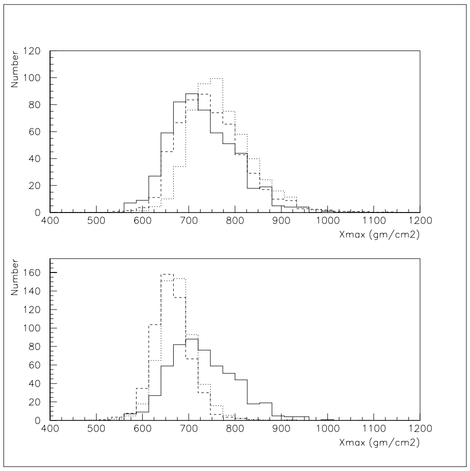

**Fig. 2.** $X_{max}$ distribution width result. In both plots, the solid line is the data, the dashed line is the QGSJet model, and the dotted line is the SIBYLL model. The top plot shows model predictions for a purely protonic composition, and the bottom for purely ferric.

The data are consistent with a nearly purely protonic composition, especially when compared to the QGSJet model. Assuming a simple two-component toy model where the primary flux is some mix of only protons and iron nuclei, the best fits are at 80% protons for QGSJet and 60% for SIBYLL.

## 4. Systematic Uncertainty in $X_{max}$

Systematic errors in the absolute value of $X_{max}$ could artificially move the measured $X_{max}$ values too deep in the atmosphere. Table 1 summarizes our conservative estimates of potential systematic uncertainties in $X_{max}$ for energies above $10^{19}$ eV. Adding the individual uncertainties in quadrature gives an overall worst case systematic uncertainty of less than 20 gm/cm$^2$.

**Table 1.** Potential systematic uncertainties in $X_{max}$

| Uncertainty | gm/cm$^2$ |
|---|---|
| Pointing Direction | 15 |
| Atmospheric Variations | 10 |
| Reconstruction Bias | 5 |
| Sum in Quadrature | 18.7 |

## 5. Conclusions

The measured elongation rate result is consistent with a constant or slowly changing composition between $10^{18.0}$ eV and $10^{19.4}$ eV. The data are also in very good agreement with the HiRes Prototype data in the region where they overlap. The HiRes Prototype result showed a composition change from heavy to light in the $10^{17}$ to $10^{18}$ eV range, but the HiRes data do not show a continuation of this elongation rate, exhibiting instead strong evidence for a transition to a predominantly light and slowly changing composition above $10^{18}$ eV. The widths of the $X_{max}$ distributions in the UHECR regime strengthen this conclusion.

## 6. Acknowledgements

This work is supported by US NSF grants PHY-9322298, PHY-9974537, PHY-0098826, by the DOE grant DE-FG03-92ER40732, and by the Australian Research Council. We gratefully acknowledge the contributions from the technical staffs of our home institutions. The cooperation of Colonels Fisher and Harter, the US Army, and Dugway Proving Ground staff is appreciated.

## 7. References

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