

STUDY OF THE COMPOSITION OF COSMIC RAYS WITH ENERGIES NEAR 10^{18} eV

R.M. Baltrusaitis, G.L. Cassiday, R. Cooper, B.R. Dawson, J.W. Elbert,
 B.E. Fick, K.D. Green, S. Ko, D.F. Liebing, C.P. Lingle, E.C. Loh,
 J.D. Smith, P. Sokolaky, and D. Steck.

Physics Department, University of Utah, Salt Lake City, UT 84112 USA

T.K. Gaisser and T. Stanev
 Bartol Research Institute, University of Delaware,
 Newark, Delaware, USA

Abstract

The longitudinal shower development of EAS with energies between 3×10^{17} and 3×10^{19} eV observed by the Fly's Eye is used to determine the distribution of X_{\max} , the depth in the atmosphere of the EAS maximum. Work in progress to compare data, and Monte Carlo simulations of proton and iron primaries is described. Evidence is in favor of a mixed composition with 45% of protons.

1. Introduction. The overall longitudinal development of the EAS detected by the Fly's Eye (1) can be used to determine the depth in the atmosphere of the EAS maximum X_{\max} . The distribution of X_{\max} which is a convolution of the distribution of first interaction point with shower development fluctuations, is in principle sensitive to the composition of the primary particles. Iron nuclei (protons) will give rise to X distributions -that peak at shallower (deeper) depths and have narrower (broader) widths, respectively. It also follows that a mixed composition will have a broader X_{\max} distribution than any single source.

2. Shower Size Measurement. A fit to the relative time of arrival of light at successive phototubes in the event-detector plane yields R_p , the impact parameter of the shower to the detector, and the zenith and azimuthal angles of the EAS. Measured values of optical gathering power, efficiencies and electronic gains and pedestals are used to convert photo-electron yields into apparent brightness, i.e., numbers of photons arriving at the detector from the source. This can be converted into intrinsic source fluorescent brightness after correcting for: (a) directly produced Cherenkov light beamed in the direction of the detector; (b) Cherenkov light scattered in the direction of the detector due to Rayleigh and Mie scattering; and (c) atmospheric

attenuation of light. The details of these corrections are described in reference 1. The intrinsic fluorescence brightness can be translated directly into a shower size using the known nitrogen fluorescence efficiency.

The size versus depth distributions are fitted with a Gaussian form and the X_{\max} and energy of the event determined. The Gaussian form fits most showers well. Figure 1 shows a typical shower profile.

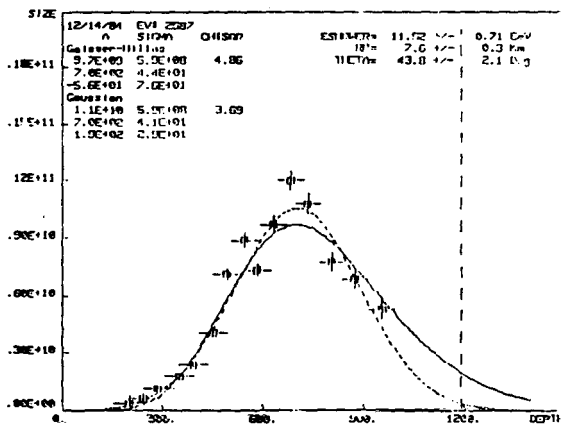


Figure 1. Typical Longitudinal Shower Profile

3. Data Analysis. The Fly's Eye sensitivity has been increased in the past two years by the addition of optical filters with a band width of 3200 to 3800Å. These filters increase the signal to noise ratio and allow detection of a given energy shower over larger distances (see paper OG-9 in these proceedings).

We have analyzed data from ~ five years of running. There is no systematic difference in X_{\max} distributions between runs with filters and without. Since geometrical reconstruction errors in the zenith (θ_z) and impact parameter (R_p) of the track results in errors in the position of X_{\max} , we impose constrains on those parameters of the data. These are: $R_p > 2.0$ km, projected track length $> 50^\circ$, $\Delta R_p / R_p < .3$, $\Delta \theta_z < 10^\circ$ and relative uncertainties in Gaussian width, X_{\max} , and energy of $< .5$. These cuts also make the resultant X_{\max} distribution insensitive to the details of Cherenkov light model parameters.

The resultant X_{\max} distribution for 2106 well reconstructed events has $\langle X_{\max} \rangle = 761 \pm 3.3$ g/cm² and $\sigma(X_{\max}) = 151.2 \pm 2.3$ g/cm². This X_{\max} distribution spans an energy range from 3×10^{17} eV to 3×10^{19} eV with an average energy of 8.5×10^{17} eV.

We have examined the data for evidence of the expected increase of X_{\max} with energy. Table 1 gives $\langle X_{\max} \rangle$ for different energy bins and the average energy for each bin. There is clear evidence for elongation of $\langle X_{\max} \rangle$ as a function of energy. Since detector acceptance in X_{\max} varies as a function of E, this data must be compared to Monte Carlo data with proper accounting of detector acceptance. Preliminary evidence suggest that the observed elongation rate is consistent with expectation for the composition described below.

Table 1

X_{\max} vs. Energy		
E(EeV)	$\langle X_{\max} \rangle$ g/cm ²	$\langle E \rangle$ (EeV)
.3-1.0	742.3 ± 3.9	.60
1.0-3.0	768.1 ± 5.9	1.62
3.0-10.0	784.3 ± 10.9	4.9
10.0-30.0	810.0 ± 28.3	15.2

4. Monte Carlo Generation. Proton, CNO, and iron induced showers are generated in a Monte Carlo program with the following input. The interaction model has an increasing rapidity density in the central region at low (100 GeV) energies. At higher densities scaling is violated in the central region, but not in the fragmentation region. A constant hadronic elasticity of 0.37 is used for all energies. Correlations such as production of leading lambdas with kaons and productions of K pairs is incorporated. The implementation is to sample particles from the corresponding particle spectra until the interaction energy is used up. A \log^2 's energy dependence of the inelastic hadronic cross-section is used, transformed for hadron-air interactions as in ref. 2. We use these showers to predict the number of photo-electrons and relative time delays observed in the detector and generate Monte Carlo events which are then passed through the same reconstruction and analysis programs as the real data.

5. Comparison with data. We have tried both two-component (Fe and p) and three component (p,CNO,Fe) fits of acceptance corrected Monte Carlo X_{\max} distributions to the data. (See Fig. 2 and Fig. 3) To decrease fluctuations due to the large energy spread of the detected showers we have divided all data in two bins of energy 0.4-1 EeV and 1-6.3 EeV. The X_{\max} distributions of both samples can be fitted reasonably well with Monte Carlo data, except for the experimentally observed tail of deeply developing showers. To fit the tail we need to use an inelastic cross-section rising with energy slower than \log^2 's, in agreement with the published Fly's Eye results/3/. We find strong evidence for a mixed composition, based on the following observations:

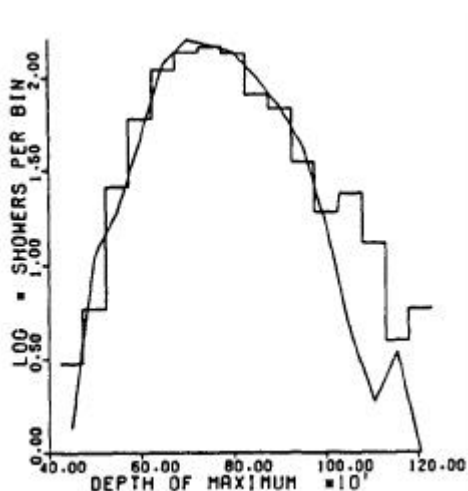


Fig. 2. Event distribution and fit to 3 component M.C. with $E < 1.0$ EeV

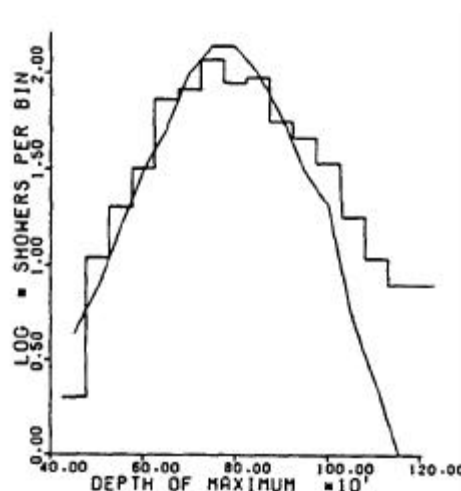


Fig. 3. Events distribution and fit to 3 component M.C. with $E > 1.0$ EeV

1. The X_{\max} distribution requires $45 \pm 12\%$ protons, the rest being consistent with Fe and CNO.
2. The rapid rise of the distribution, around 600 gm/cm^2 can only be accounted for by the presence of Fe at least at the $30\% \pm 10\%$ level.
3. The overall width of the distribution is inconsistent with any single component (see Table 2).

The details of the interaction model used do not strongly affect these conclusions. Increased scaling violation would decrease the width of the proton X_{\max} distribution. An extreme two component model (scaling with constant cross-section and extreme scaling violation) increases the proton X_{\max} distribution by less than 20 gm/cm^2 .

	$E < 1 \text{ EeV}$	$E > 1 \text{ EeV}$
protons	84 ± 4	92 ± 6
CNO	67 ± 3	80 ± 4
Fe	61 ± 3	76 ± 4
Data	140 ± 3.4	165 ± 4.3

6. Conclusions. Both protons and heavy nuclei are required to fit the rising and falling edges of the X_{\max} distribution. The required proton contribution is $\sim 50\%$. The width of the X_{\max} distribution is inconsistent with a single component and this conclusion appears to be independent of a range of interaction models. We observe the expected elongation rate but this information is not yet precise enough to be useful in the composition study.

More precise data based on stereo detection and reconstruction will be available in the near future and will allow a determination of the relative contributions of a three component flux as well as the use of the elongation rate information.

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