FLY'S EYE MEASUREMENT OF THE COSMIC RAY COMPOSITION ABOVE 10^{17} EV

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Abstract

We present measurements of the depth of maximum for extensive air showers (EAS) produced by cosmic ray nuclei with energies above 10^{17}eV. The air showers were observed using the University of Utah's Fly's Eye detectors operating in stereo mode. The data show an elongation rate of 69 ± 5 g/cm^2 per decade above 10^{17}eV before correction for triggering and resolution effects. These effects contribute approximately +5 g/cm^2 per decade to the apparent elongation rate. The depth of maximum distribution is not consistent with the expectation of a composition dominated by protons.

Introduction The Fly's Eye detectors observe the nitrogen fluorescence light produced by large air showers in the atmosphere and are located at an atmospheric depth of 860 g/cm^2 in the western desert of Utah. Details of the experiment are given elsewhere (Baltrusaitis et al 1985). The two Fly's Eye detectors, FE1 and FE2 are separated by a distance of 3.4 km. The data discussed in this report represent events detected simultaneously by both instruments. This 'stereoscopic' view of air showers significantly improves the geometrical reconstruction of the data, important in studies sensitive to position dependencies such as composition.

Depth of Maximum Measurements The Fly's Eye detectors directly measure the longitudinal development profiles of large EAS and allow a straightforward extraction of the depth of shower maximum (X_{max}), an indicator of primary composition. We have made a thorough investigation of possible systematics involved with this measurement (Cassiday et al 1989), including those associated with geometric reconstruction, atmospheric scattering of light, assumptions about the atmospheric density profile, Cerenkov light contamination, and the form of the assumed development profile. We find that these sources of systematic error amount to shifts of less than ± 20 g/cm^2 in the average value of the depth of maximum, and of less than ± 5 g/cm^2 in the value of the width (ó) of the depth of maximum distribution.

Interpretation of the depth of maximum data involves the use of a detector Monte Carlo program which takes into account the triggering efficiencies and reconstruction resolution of the detectors. One input for the detector simulation are files of one dimensional shower development profiles which have been generated using a variety of interaction models and primary masses. Each of these profiles, along with random assignments of geometrical parameters, is passed through the detector simulation program which uses the known efficiencies for nitrogen fluorescence and Cerenkov light production to calculate the light produced by each shower.

Solid angle effects and Rayleigh and aerosol scattering processes are taken into account in order to calculate the amount of light arriving at the detectors. The optical and electronic characteristics of the detectors are modelled to produce an output consisting of a list of firing photomultipliers with the associated pulse amplitude and timing information. These results are then analyzed using the standard analysis procedure, giving a simulated data sample that reflects the triggering acceptance and reconstruction resolution of the experiment (Cassiday et al 1989).

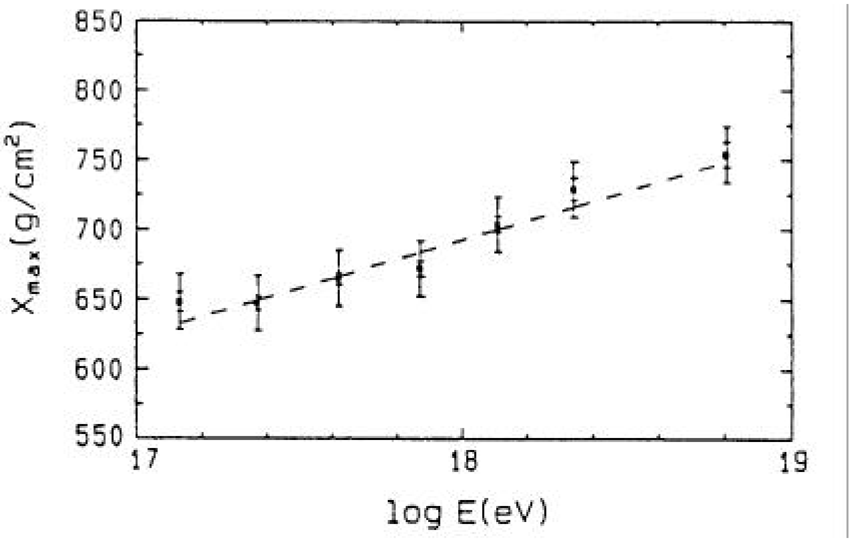

FIGURE 1: Depth of maximum versus energy. The error bars represent both the statistical and systematic (± 20 g/cm^2) uncertainties. The least-squares fit to the data (weighted by statistical errors) is shown.

Experimental Results The stereo data discussed here were collected during the period between November 1986 (the beginning of operation of the completed Fly's Eye II) and August 1988 (1400 hours running time). There have been two selection cuts applied to the data: a) the estimated relative error in the depth of maximum is less than 12% (the mean value of the error distribution), and b) the angle between all viewing tubes and the shower track must be larger than 20° (ensuring no contamination from Cerenkov light).

The elongation rate is a parameter measured in many studies of air shower development. It can be defined as the change in the average depth of maximum per decade of shower energy, and is useful in detecting rapid changes in shower behavior over a particular energy range (e.g. Linsley and Watson 1981). The present data set has been broken up into seven bins ranging in energy from 10^{17}eV to above $5x10^{18}$eV (Figure 1). A least squares fit to these data points (weighted by statistical errors) gives an elongation rate of 69.4 ± 5.0 g/cm^2 per decade (chi-squared per d.f. 2.72). We note that a simulated data sample with an input elongation rate of 65 g/cm^2 (model HN, below) gives an elongation rate of 69.9±5.3 g/cm^2 after being passed through the detector Monte Carlo and reconstruction programs. Thus over the energy range of our measurement, the combination of triggering efficiency and resolution effects contribute to a systematic increase of the apparent elongation rate of only 5 g/cm^2.

The depth of maximum distribution for the 926 events with energies above $3X10^{17}$eV is shown in Figure 2. The mean value of the depth of maximum is

690 ± 3 g/cm^2 and the width (standard deviation) of the distribution is 85 ± 2 g/cm^2.

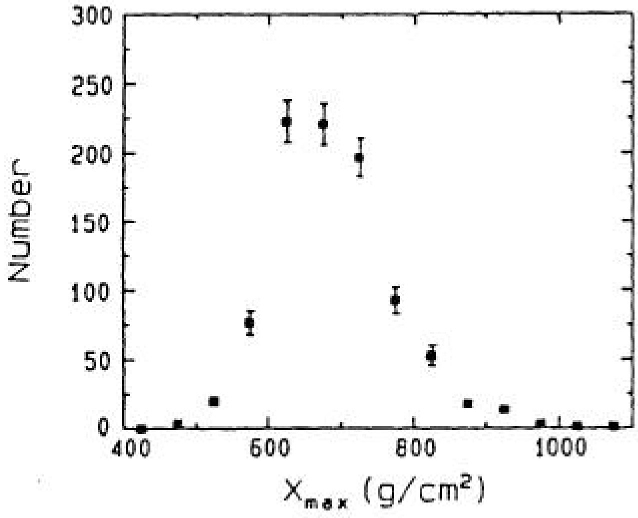

FIGURE 2: Depth of maximum distribution for E > 3X10^{17}eV.

Discussion The combination of the EAS simulation and the detector Monte Carlo describes reasonably well the properties of the detected showers. It does however have one major shortcoming we cannot at present understand the rising edge of the experimental X_{max} distribution which is 25-30 g/cm^2 shallower than the rising edge of the pure Fe simulation. The following discussion concentrates on broad conclusions that are not affected by this remaining uncertainty.

It is always very difficult to use experimental information on the width (ó) of the X_{max} distribution. Our Monte Carlo shows that for the wide energy interval shown in Fig. 2 the width of the X_{max} distribution is determined mainly by the detector resolution. However, this width information can immediately rule out pure compositions of either iron or CNO, given the small statistical and systematic (± 5 g/cm^2) errors in o (see Table I).

The average value of the experimental X_{max} distribution, however, is too low to be consistent with any composition model which does not contain a significant fraction of heavy nuclei. Table I shows the average X_{max} and the standard deviation of the X_{max} distributions before and after accounting for the detector properties for three major types of primary nuclei.

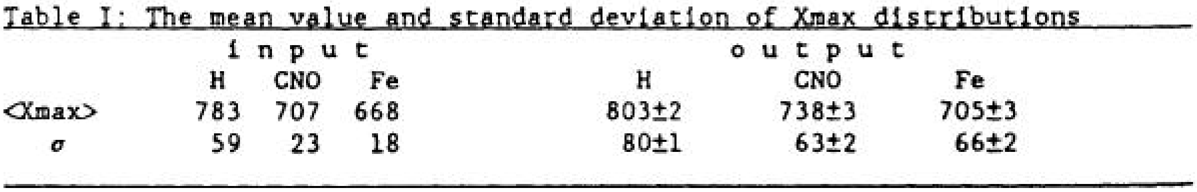

Table I: The mean value and standard deviation of Xmax distributions

	input			output		
	H	CNO	Fe	H	CNO	Fe
<Xmax>	783	707	668	803±2	738±3	705±3
σ	59	23	18	80±1	63±2	66±2

A proton dominated composition with about 20% heavier nuclei would fit the experimental data if the simulated showers were shifted to shallower X_{max} by about 110 g/cm^2. Having in mind the uncertainty in extrapolating the models of inelastic interactions to lab energy three orders of magnitude higher than the Tevatron, the crucial question now is if we could in fact shift X_{max} of proton showers by more than 100 g/cm^2.

To understand the relation between X_{max} and the properties of the A inelastic hadronic interactions we simulated proton showers with three quite different interaction models. The average X_{max} values from these runs are shown in Table II for two cross-section energy dependences. These values do not include the effect of detector resolution and therefore are comparable with those in the first three columns of Table I. The energy dependence of the detector acceptance and the cosmic ray spectrum are, however, folded into the calculation.

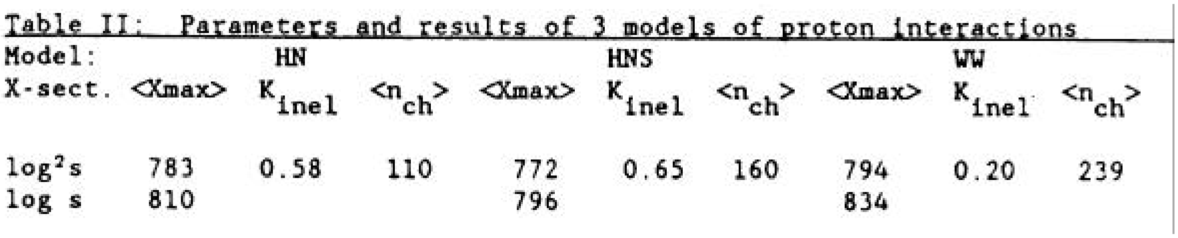

Table II: Parameters and results of 3 models of proton interactions

Model:	HN			HNS			WW		
X-sect.	<Xmax>	K_{inel}	$<n_{ch}>$	<Xmax>	K_{inel}	$<n_{ch}>$	<Xmax>	K_{inel}	$<n_{ch}>$
$\log^2 s$	783	0.58	110	772	0.65	160	794	0.20	239
log s	810			796			834		

The proton inelasticity coefficient K(inel) and the average charged multiplicity generated by the models at 10^{18} eV are also shown in Table II. The model indicated with HN is tuned to reproduce the mild scaling violation in the fragmentation region of the interaction that comes from the rising 'minijet' cross-section (Gaisser and Stanev 1989). The HNS model has a higher K(inel) and a softer secondary spectrum. WW stands for the model of Wdowczyk and Wolfendale (1983). The physics behind the energy behavior of K(inel) is discussed in Gaisser et al (1990).

Table II illustrates how difficult it is to move X_{max} for proton showers. The result is extremely stable and varies only by 22 g/cm^2 ($\log^2 s$) and 38 g/cm^2 between different interaction models. Even if we take into account the shift of about 20 g/cm^2 introduced by the detector (Table I) and our uncertainty related to the rise of the X_{max} distribution, all models are far from describing the experimental data with a light composition.

The experimental data do not indicate rapidly changing interaction features in the range > 3x10^{17} eV. The elongation rate of Fig. 1 is fully consistent with the one produced by the HN interaction model.

Further work to understand possible systematic effects in the relationship between Monte Carlo results and measurements is needed before a definite conclusion can be stated. However the discrepancy between the measured X_{max} distribution and that calculated for pure protons for a range of interaction models is so great that we believe the composition above 3x10^{17} eV must contain a large fraction of heavy nuclei. At the same time, the width of the distribution precludes a pure heavy composition.

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