The Cosmic Ray Composition Above 0.1 EeV

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ABSTRACT

We discuss the cosmic ray composition above 0.1 EeV by comparing recently reanalized stereo Fly's Eye data with expectations for a number of pure compositions. Evidence for a change from a predominantly heavy to a predominantly light composition above 0.3 EeV is presented.

1. INTRODUCTION

In two recent papers, we have discussed Fly's Eye data on shower maximum distribution (X_{max}) as a function of energy (Cassiday et al 1990), and interpreted the implications of this data by comparing it to expectations based on proton, Carbon, and Fe Monte Carlo data using three different hadronic models (Gaisser et al 1993). The conclusions of these papers were: a. The overall data from 0.3 to 10. EeV is not consistent with a pure composition of either protons, C or Fe, but rather requires a mixture of components. b. The three hadronic models which we have tried predict an elongation rate which is much smaller than the observed rate. This lead us to the conclusion that Fly's Eye data are consistent with a mixed composition which is growing lighter with energy.

In the present paper, we present further evidence to substantiate these claims. The results presented here come from the total stereo Fly's Eye data, from Nov 1986 to July 1992. This data set represents a substantial increase in statistics relative to the previous papers, both due to additional running time and to the use of a more efficient matching and reconstruction algorithm for stereo data. This increase in statistics allows us, for the first time, to examine the composition of cosmic rays near 10 EeV.

2. THE TECHNIQUE

The Fly's Eye detector uses scintillation light produced by extensive air showers as a means of establishing the event geometry (zenith and azimuth angles and impact parameter to the detector) and the longitudinal shower development curve. The shower development curve can be integrated to yield the event energy in a largely model independent way. The position of the shower maximum in the atmosphere (X_{max}) in gm/cm^2 is also sensitive to the composition of the parent particle. Protons, for instance will interact more deeply in the atmosphere than heavy nuclei. Air showers produced by protons are also expected to have larger fluctuations than those produced by heavy nuclei. As a result, measuring the distribution of shower X_{max}'s can be used to infer the primary cosmic ray composition.

3. THE DATA AND MONTE CARLO SIMULATION

The present data set uses events seen simultaneously by Fly's Eye I and II in

stereo. We use the identical selection cuts used in our previous papers - requiring $\delta X_{max}/Xmax \leq 0.12$ and the minimum viewing angle to the track to be ≥ 20 degrees. The first cut removes poorly reconstructed events while the second removes events with strong Cherenkov light contamination from the data set. The effects of atmospheric variation, residual Cherenkov light subtraction and trigger aperture on this data are discussed in detail in the papers refered to above. Since this data is to be compared to Monte Carlo data, it is important that we be well above the detector threshold so that the detector response is well understood and well modelled. This implies an energy cut of ≥ 0.1 EeV. With these cuts, the present data includes 8790 events for the energy range from 0.1 to 30 EeV, and 5129 events from 0.3 to 30 EeV. This is to be compared to 2529 events above 0.3 EeV in Gaisser et al 1993. This is due partly to on-time (3065 hours) and partly to improvements in event matching and reconstruction algorithms for running periods that had been already analyzed.

Monte Carlo data is generated by using two different kinds of simulations. The first simulates the extensive air shower development. It utilizes three different hadronic models. The first two are high inelasticity models (QCD Pomeron and QCD minijet) while the third is a low inelasticity statistical model. The parameters of the models are described in (Gaisser et al 1993) in more detail. All three models are good fits to accelerator data for p-p interactions, but represent different extrapolations of the behaviour of the fragmentation region to the energy range of interest. Nucleus - air interactions are modelled by following the reinteractions of the beam in the nucleus in a way that is appropriate for each hadronic model. In a previous paper, we have shown that the statistical model as implemented by us is a very poor fit to the data and is ruled out. The QCD Pomeron and minijet model both are adequate fits and differ little in their predictions. The QCD Pomeron model results in somewhat better fits however, and in the interest of brevity, we will use this model alone in this paper.

The second simulation takes the generated extensive air shower profile and generates the appropriate scintillation and cherenkov light, propagates the light thru the atmosphere and determines which tubes in F.E. I and II would trigger. For triggered tubes, the program determines the resulting pulse integrals and relative firing times. The program then generates a fake event, whose format is identical to the real data. This fake data set is then reconstructed using the same programs that we use for real data.

4. ENERGY AND X_{max} RESOLUTION

The energy and X_{max} position resolution of the stereo F.E. detector have been studied using the fake data. This estimated resolution has been confirmed by comparing the two independent measurements of X_{max} from F.E. I and F.E. II. Briefly, the stereo X_{max} resolution on an event by event basis is 45 gm/cm^2 and the energy resolution is 24%. Uncertainties in the makeup of the atmosphere and residual Cherenkov light produce a systematic error in X_{max} of not more than 20 gm/cm^2. There is also an estimated systematic error in the Monte Carlo predictions of 10 gm/cm^2, due to the effect of approximations in the shower development calculations. As in our previous papers, the Monte Carlo predictions are shifted by -25 gm/cm^2, since otherwise even iron nuclei could not account for the early rise of the experimental X_{max} distribution. This shift is consistent with the systematic uncertainty in data and Monte Carlo. The systematic error in energy is 20%, mainly due to uncertainties in N_2 fluorescence efficiency.

5. ELONGATION RATE

The elongation rate is the rate of change of the average depth of shower maximum per log_{10} of shower energy. Fig 1 shows this dependence for data, pure Fe and pure proton showers using the QCD Pomeron hadronic model. Note that all detector aperture and resolution effects have been included for the Monte Carlo data, as described above. The elongation rate for any pure elemental composition is 50 gm/cm^2

per decade of energy. It follows that a mixed but unchanging composition is also expected to have the same elongation rate. The elongation rate for the data, from 0.1 to 10 EeV is 69+/-1.8 gm/cm^2. However, examination of the data shows that a single straight line is not a good fit. Indeed, there is evidence for a change in the elongation rate near 0.3 EeV. The elongation rate from .3 to 10 EeV is 78.9 +/- 3 gm/cm^2 while the elongation rate below .3 EeV is consistent with the expected 50 gm/cm^2. The elongation rate of the data is inconsistent with a pure or mixed but unchanging composition above .3 EeV. It also implies a composition that is growing lighter with energy, going from a heavy composition near .1 EeV to a proton dominated composition near 10 EeV.

The break in the elongation rate at 0.3 EeV is a direct indication that either the hadronic physics or the composition undergoes a change near this energy. All three hadronic models investigated, although they differ somewhat in their prediction of the absolute position of the mean X_{max} for various pure compositions, all have essentially the same elongation rate. Hence, at least in this context, the measured elongation rate as well as the apparent change in elongation at 0.3 EeV argues for a significant change in the cosmic ray composition from 0.1 to 10 EeV.
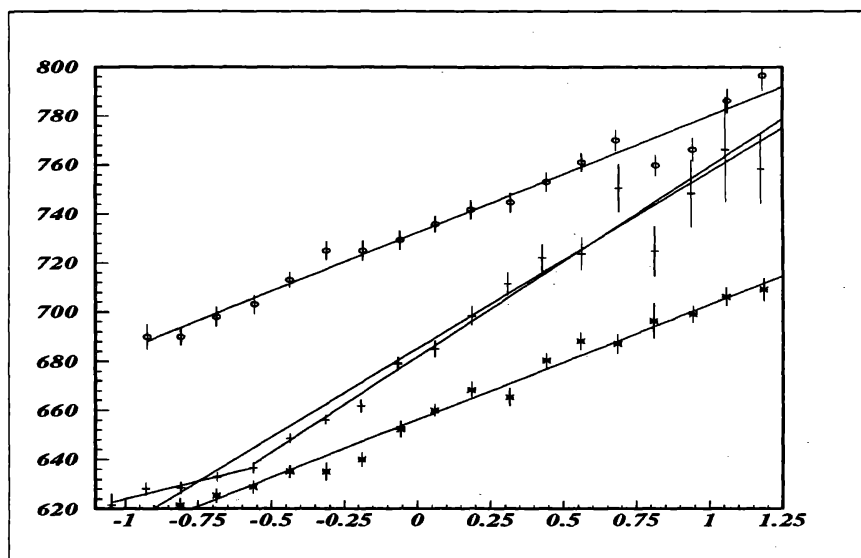

Figure 1: Elongation rate, data (crosses), Fe (stars) and protons(cirlces). X axis is $log_{10}(E)$. Y axis is X_{max} in gm/cm^2. The error bars indicate the statistical error on the mean.

6. COMPARISION OF DATA X_{max} DISTRIBUTION WITH MONTE CARLO

We can test this conclusion further by comparing the measured X_{max} distributions to expectations for pure Fe and pure proton monte carlo data in four energy bins. Fig 2 shows data and Fe and proton monte carlo simulated data normalized to equal area. As expected, the pure Fe and pure proton X_{max} distributions differ by having the peaks of their distributions approximately 70 gm/cm^2 appart, and by having significantly different widths. The falling part of the X_{max} distribution depends on the inelastic cross section with air nuclei, hence the proton distribution in this region falls more slowly than the iron distribution. The falling slope of the data is consistent with the proton slope in this region, but the rise and the peak of the data distribution is the same as predicted for iron, at least in the lower energy bins. This is the basis for our longstanding claim that a mixed composition is required at these energies, with a significant admixture of iron or similar heavy nuclei. Data in the higher energy bins clearly require a larger admixture of protons while the 3 to 10 EeV bin data can be largely accounted for by protons alone.

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7. CONCLUSIONS

We have confirmed that the elongation rate for cosmic rays in the energy interval from 0.1 to 10 EeV is inconsistent with predictions based on a range of hadronic models and a pure or mixed and constant composition. The composition changes from a heavy to a predominantly light one in the range from .3 to 10 EeV. The elongation rate from 0.1 to .3 EeV is consistent with a constant but heavy composition.

It is interesting to note that our measurement of the cosmic ray spectrum using the same stereo data set (see OG 6) shows clear evidence for a change in slope above 3 EeV, the region where the composition becomes significantly lighter. This can be interpreted as additional evidence for the emergence of a new cosmic ray componet, mostly light and having a much flatter energy spectrum than the lower energy component - perhaps the long awaited extragalactic cosmic ray flux.
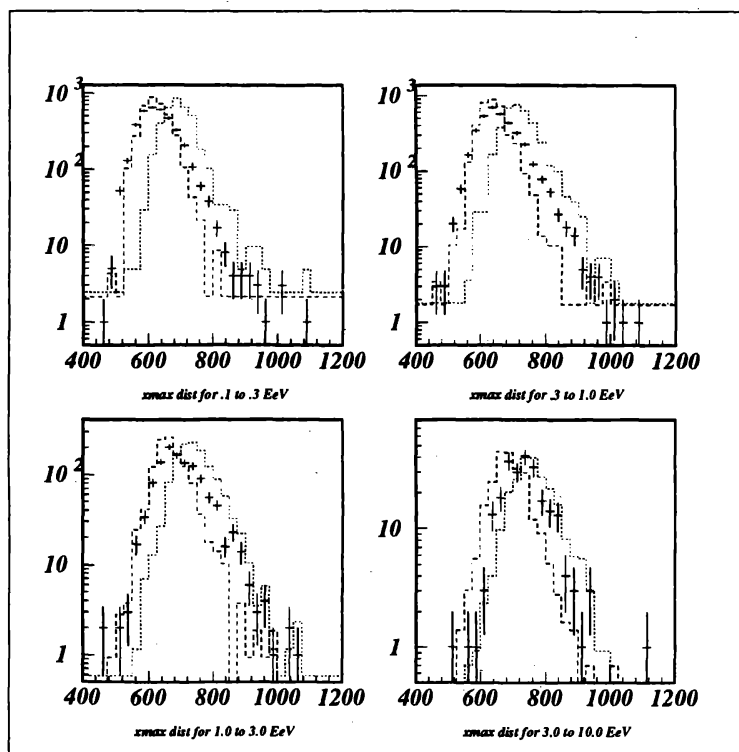
9. ACKNOWLEDGMENTS

Figure 2: X_{max} distribution for data (crosses), Fe (short dashes) and protons (long dashes) for four energy bins: 0.1 to 0.3 EeV .3 to 1.0 EeV; 1.0 to 3.0 EeV; and 3.0 to 10.0 EeV.

REFERENCES

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