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Cosmic Ray Showers at 10^{16} eV

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Abstract

A summary is made of some cosmic ray shower results obtained at the University of Adelaide Buckland Park air shower array. It is demonstrated that a number of air shower parameters undergo appreciable changes at common shower sizes.

1. Introduction

In recent years, significant new data have become available on the properties of cosmic ray showers in the medium energy range (from 10^{15} to 10^{17} eV, with sea level sizes from 10^5 to 10^7 particles). These have included the results of measurements, as functions of shower size, of shower parameters such as shower age, depth of maximum, intensity and, most recently, anisotropy. These parameters give valuable clues concerning the nature and origin of the primary cosmic rays. All four parameters have now been studied at the University of Adelaide Buckland Park air shower array (Clay *et al.* 1981; Thornton and Clay 1979, 1981; Clay and Gerhardy 1982; Gerhardy and Clay 1982) and, whilst some have now been better measured elsewhere (see e.g. the Akeno work of Hara *et al.* 1981, and references therein), they provide us with a unique opportunity to make comparisons at common shower sizes since no array intercalibrations are now necessary for defining a common shower size parameter.

In the present paper we draw together Buckland Park data from a number of experiments in order to clarify, on a common size scale, the changes occurring in the Southern Hemisphere cosmic ray beam as shower sizes change through 10^6 particles (an energy of about 10^{16} eV).

2. Buckland Park Results

A summary of measurements made in recent years at Buckland Park is shown in Fig. 1. In each case (intensity, shower age, depth of shower maximum, and anisotropy), no major changes would be expected *a priori* in this range, i.e. the dependences of these parameters on shower size should be rather weak. This is clearly not so.

The age and depth of maximum functions (Figs 1*b* and 1*c*) indicate that the character of the showers changes between $\lesssim 5\times 10^5$ and 10^7 particles. This may be interpreted as either a change in the composition of the primary particle or a change in its interaction characteristics.

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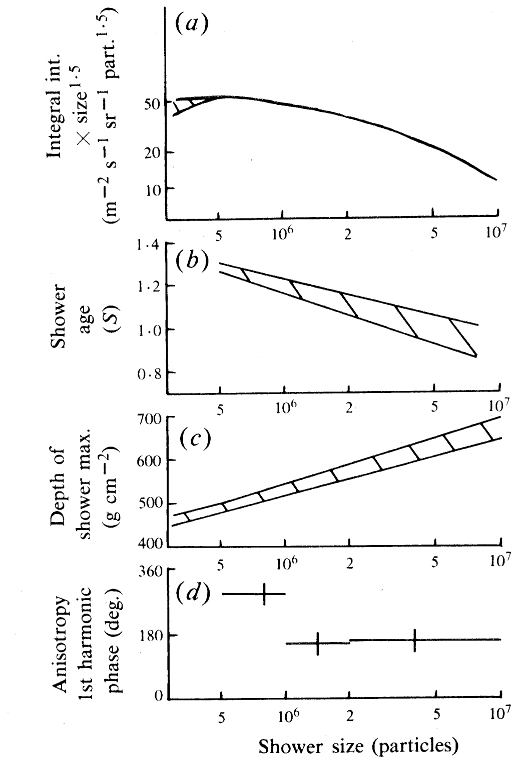

Fig. 1. Variation of shower parameters with shower size as measured at Buckland Park. Hatched areas indicate experimental uncertainty. Data are redrawn from (*a*) Clay and Gerhardy (1982); (*b*) Clay *et al.* (1981); (*c*) Thornton and Clay (1981); (*d*) Gerhardy and Clay (1982).

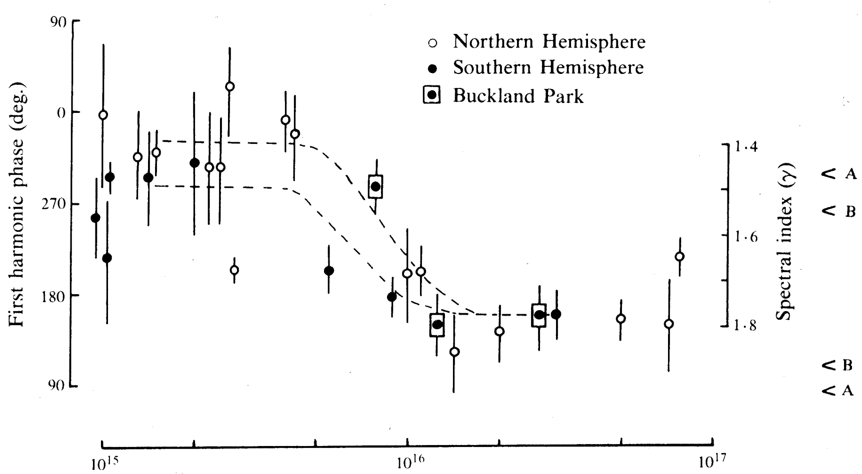

Fig. 2. Relationship between the phase of the first harmonic of the cosmic ray anisotropy and primary energy. Northern and Southern Hemisphere results are from the compilation of Linsley and Watson (1977) plus data from Haverah Park redrawn from Lloyd-Evans and Watson (1982). Buckland Park results are from Gerhardy and Clay (1982). Low latitude ($\leqslant 30°$) data and data from experiments with less than 5000 events were excluded. The general directions of the galactic plane observed at northern and southern mid-latitudes are indicated by A and B respectively. Dashed curves indicate the integral spectral index found at Adelaide for the shower array density spectrum (Clay *et al.* 1983).

The cosmic ray intensity spectrum (Fig. 1*a*) shows a steepening above about 5×10^5 particles. Clay *et al.* (1983) have shown that the steepening occurs over a rather limited range of shower size, through a study of the shower array density spectrum. We have shown (Gerhardy and Clay 1982) that the phase of the cosmic ray anisotropy (Fig. 1*d*) changes rapidly also. [Even when an anisotropy amplitude is poorly defined, the phase may be quite well defined (see e.g. Pollock 1978). The phase is therefore a particularly useful parameter for many anisotropy studies.] The phase dependences are displayed in Fig. 2 which also includes data from an anisotropy phase compilation by Linsley and Watson (1977). The agreement in the form of the dependences of spectral index (dashed curves) and anisotropy on shower size is striking. Both the absolute shower size [converted by a simple multiplicative factor to energy (see Protheroe 1977)] and range of sizes of the change are in good agreement.

The picture which emerges at about 10^{16} eV is that, at a sea-level shower size between $\sim5\times10^5$ and 10^6 particles, the cosmic ray anisotropy changes phase by almost 180° and, at *exactly* the same size, there is a change in the index of the shower size spectrum. As shown by Thornton and Clay (1979, 1981), this size also corresponds to a rapid change in the shower elongation rate. It is remarkable, and almost certainly significant, that these changes coincide and occur over a range of shower sizes which, with limited instrumental size resolution, may not even be resolved.

3. Observations at 10^{17} eV

There are difficulties in examining the literature on 10^{17} eV showers. These are associated with the historical fact that medium size detectors are close to their upper limits here and the large arrays are close to their thresholds. It does appear though that, at about 10^{17} eV ($\sim10^7$ particles), the effects at 10^{16} eV are reversed, but possibly rather less rapidly. Size spectra tend to show some flattening (see e.g. Khristiansen *et al.* 1974), the elongation rate reduces (Thornton and Clay 1979, 1981; Linsley and Watson 1981) and the anisotropy reverts to its original low energy direction (see e.g. Lloyd-Evans 1982). There is evidence that at least the anisotropy and energy spectrum change again at $\sim3\times10^{18}$ eV as they did at 10^{16} eV (see e.g. Lloyd-Evans 1982).

4. Discussion

We draw attention here to the remarkable agreement between the cosmic ray showers associated with changes in the cosmic ray beam. The *same* showers are associated with changes in anisotropy, size spectrum, and interaction characteristics at about 10^6 particles (10^{16} eV).

Indicated in Fig. 2 are the general directions of the galactic plane observed from Northern (A) and Southern (B) Hemisphere mid-latitudes. There is some evidence that the anisotropy change corresponds to a shift from one galactic region (centre?) to another (anticentre?). It should be emphasized that the anisotropy is only at the 1% level whereas the other changes discussed refer to the cosmic ray beam as a whole.

The information drawn together here is clearly pertinent to a discussion of the cosmic ray origin problem but, whilst the relationship between energy spectrum and anisotropy may be natural from an astrophysical point of view, it is less obvious how to understand the depth of maximum data. The shower size of 10^6 particles corresponds to only a start in the period of high elongation rate (Fig. 1*c*), not, as one might have expected *a priori*, somewhere in the middle of the range. This would seem to argue somewhat against the natural assumption of the beginning of a composition change at 10^{16} eV, since rigidity dependent changes would occur progressively as the nuclear charge changed. A second component hypothesis is attractive from the point of view of the anisotropy change (perhaps dominating between 10^{16} and 10^{17} eV), but it is not at all clear how the reduced elongation rate above 10^{17} eV would fit into any such scenario. One may have to also postulate some change in the cosmic ray interaction properties which causes both the depth of maximum change and also astrophysical changes. In this case there would be cosmic ray absorption in the source–interstellar region causing both the local dominant cosmic ray source and the intensity spectra to change, whilst the corresponding changing properties of interactions in the atmosphere would cause shower development to change.

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