Aust. J. Phys., 1984, **37**, 97–103

Cosmic Ray Anisotropy and the Knee of the Energy Spectrum

R. W. Clay

Physics Department, University of Adelaide,
G.P.O. Box 498, North Terrace, Adelaide, S.A. 5001.

Abstract

The knee of the cosmic ray energy spectrum occurs at an energy slightly below 10^{16} eV. At a similar energy significant changes are found in cosmic ray shower development and anisotropy. It is suggested that these changes can be understood if there is a general proton dominated cosmic ray flux along our spiral arm from outer galactic regions, which is exceeded by an iron dominated flux from the opposite spiral arm direction at energies between $\sim 10^{14}$ and $\sim 10^{17}$ eV.

1. Introduction

The energy spectrum of cosmic rays exhibits a feature in the vicinity of 10^{16} eV which is a steepening away from the power law generally used to describe the gross spectrum (see e.g. Hillas 1980). It would appear that a power law is only useful as a first approximation to the spectrum. There is a flatter region from about 10^{14} eV up to the knee and the effect of the steeper section at the knee is roughly to restore the flux to a continuation of the low energy spectrum.

Above 10^{14} eV, most measurements of cosmic rays are made through the cascades of secondary particles, produced by interaction with our atmosphere, known as extensive air showers. The number of secondary particles in such cascades increases with the depth of atmosphere traversed until a maximum is reached and then the number decays. The atmospheric depth at which maximum occurs reflects the way in which energy is progressively removed from the primary particle and shared between the secondaries. Above 10^{14} eV, this depth of maximum probably deviates progressively from that to be expected if protons are the initiating particles and if conventional nuclear physics is followed (Thornton and Clay 1979; Andam *et al.* 1981). The greatest discrepancy occurs near the knee and 'normal' development returns at about 10^{17} eV. I wish to show here that a third cosmic ray property, the anisotropy, changes over the same energy range in a remarkably similar way to the energy spectrum and to the shower depth of maximum. I believe that the anisotropy provides a key to our understanding of the knee and its associated properties.

2. Cosmic Ray Energy Spectrum

The energy spectrum of cosmic rays is generally quite well known but is controversial in detail. The (integral) flux falls rapidly with increasing energy and the

0004-9506/84/010097$02.00

spectrum can be roughly fitted by a falling power law with an index of $\sim 1 \cdot 75$ from $\sim 10^{12}$ eV to above 10^{19} eV. It is not surprising that a single function is not a perfect fit over such a large range. Deviations from the simple law are interesting and have been the subject of much debate. Fig. 1 illustrates one deviation from the simple power law, a 'bump' which is found between $\sim 10^{14}$ and $\sim 10^{16}$ eV. The rapid cutoff at the high-energy end of this bump is known as the knee.

The exact form of the bump is controversial; the data comprising Fig. 1 are probably conservative and we in Adelaide (Clay *et al.* 1983) have argued that it is, in reality, probably even more pronounced with the knee having a very sharp onset. The exact shape is not immediately relevant to the following argument. It is more important that the energy scale is derived similarly to those scales which specify the energies of features in the depth of maximum data and the anisotropy data. The scale used in Fig. 1 has this conventional property.

3. Shower Depth of Maximum

The shower depth of maximum is a very useful shower parameter but is difficult to measure. The shower maximum usually occurs several kilometres above the air shower array and its study demands a knowledge of a shower component which attenuates only slowly. The muon component can be useful but, in recent times, optical Cerenkov photons emitted by shower electrons have been used. A surprising result of these studies has been that, at energies below 10^{17} eV, showers develop earlier than expected. At $\sim 10^{16}$ eV, the showers have maxima which are found ~ 150 g cm^{-2} higher in the atmosphere than expected. Data significantly below 10^{16} eV are sparse but it seems likely that development is 'normal' at about 10^{14} eV (see Fig. 2 of Andam *et al.* 1981). The form of the available data is shown in Fig. 2. Whilst there are appreciable gaps, the similarity between Figs 2 and 1 is remarkable.

We do not know with certainty why 10^{16} eV showers develop early. The effect is associated with the early shower interactions and there could either be a change in the properties of proton–air nucleus interactions over a limited energy range at $\sim 10^{15}$ eV or a predominance of iron nuclei in the beam at 10^{15}–10^{16} eV. The latter is now the more conventional interpretation (see e.g. Chantler *et al.* 1983).

4. Anisotropy

The analysis of anisotropy experiments is usually accomplished by fitting sinusoids to the event rate in sidereal time (or right ascension) and the result is stated as a phase and amplitude of the fitted harmonic. It is worth noting that it is not necessary for the variation to be truly sinusoidal, nor is it necessary for the phase of the maximum to be the physically important phase (see e.g. Kiraly *et al.* 1979). For instance, a minimum at a particular R.A. would be interpreted as a phase of maximum which differs in R.A. by 180°.

The cosmic ray beam has been found to be remarkably isotropic. Only at the very highest energies ($\gtrsim 10^{18}$ eV) is it felt with any confidence that deviations from isotropy greater than 1% have been measured. Above 10^{19} eV there is a suggestion of the anisotropy being above 10%. One consequence of anisotropies which are so low is that very long and stable experiments are required. A number of upper limits are in the available data set and many of the amplitudes (of the first harmonic) have large uncertainties (see e.g. Watson 1981).

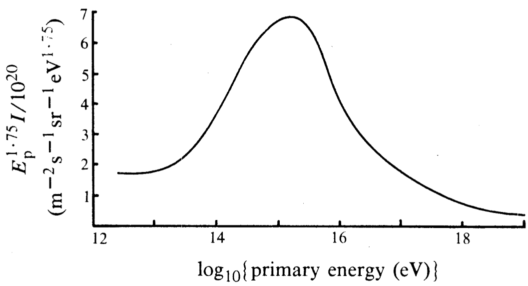

Fig. 1. Schematic diagram of the integral cosmic ray energy spectrum (redrawn from Hillas 1983). Errors in the data comprising the curve are largely systematic and are associated with the assignment of appropriate energies. The agreement in the fluxes is usually within a few per cent when realistic comparisons can be made (see e.g. Clay and Gerhardy 1982; Clay *et al.* 1983).

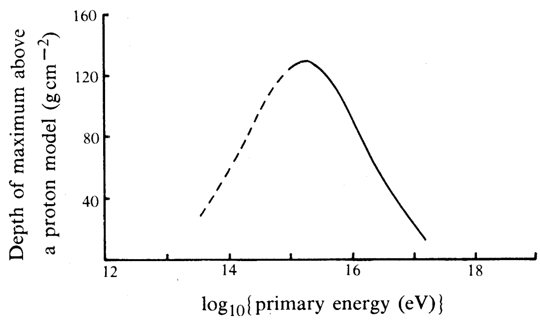

Fig. 2. Schematic diagram showing the energy dependence of the deviation of the shower depth of maximum above that expected for a proton primary particle and conventional nuclear physics (redrawn from Thornton and Clay 1979; Andam *et al.* 1981). It is assumed that there is a smooth change (dashed part of curve) in the energy range 10^{14}–10^{15} eV, which is currently devoid of data. Internal consistency in the available data suggests typical uncertainties of $\sim \pm 20\ g\,cm^{-2}$.

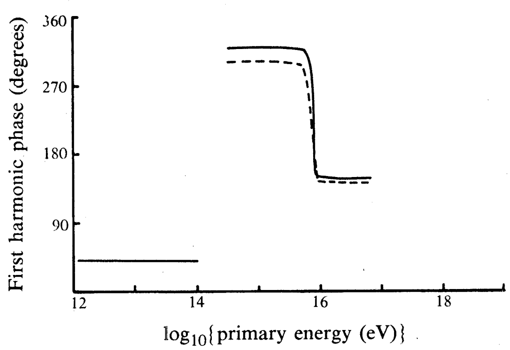

Fig. 3. Schematic diagram showing the energy dependence of the anisotropy first harmonic phase, using the data of Elliot (1979) for $E_p \leqslant 10^{14}$ eV and the data of Clay and Gerhardy (1983) and Watson (1981) for $E_p > 10^{14}$ eV. The dashed curve indicates Southern Hemisphere data and the solid curve Northern Hemisphere data. Uncertainties in these data are indicated by the hatched areas in Fig. 4.

At energies below 10^{14} eV, the first harmonic anisotropy amplitude is below $0 \cdot 1\%$ (Elliot 1979). In the next two decades of energy the amplitude probably increases to a little under 1% and this rate of increase with energy ($\sim E^{0.5}$) apparently continues up to $\sim 10^{20}$ eV. It should be noted that, with a steeply falling energy spectrum, there is a very limited number of events in each of the highest energy bins.

It is not clear that all the published positive first harmonic results are real. However, even when a first harmonic amplitude is not statistically significant, the phase of the anisotropy vector may still be defined within acceptable uncertainties. There is reason to believe then that the measured first harmonic phases may contain useful and reliable information. This belief is strengthened when independent experiments with widely differing amplitudes agree well on the phase. This is the situation in the energy region about 10^{15} eV (Linsley and Watson 1977; Pollock 1977; Clay and Gerhardy 1983). Fig. 3 shows the energy dependence of the phase of the first harmonic (measured in degrees of R.A., although many early experiments only provided a sidereal time of maximum).

There is a close relationship between Figs 3 and 1. The change of both quantities at 10^{14} eV may be fortuitous but the exactness of the energies associated with the changes at the knee seems hardly likely to be the result of chance. Clay and Gerhardy (1983) have shown in detail the common relationship in the region of the knee. There can be little doubt that the anisotropy phase change at the spectral knee is reflected in both the energy spectrum and the shower depth of maximum. Related changes are thus probably found from 10^{14} to 10^{16} eV.

5. Phase of the Anisotropy

The phase of the anisotropy, and its changes, at energies below 10^{17} eV have generally been neglected as topics for discussion. The amplitude has been regarded as being of critical importance and has been discussed largely in terms of the approach, with increasing energy, of the radius of gyration of galactic cosmic rays to major galactic structure dimensions. For 10^{15} eV protons, one expects radii of gyration of the order of a few parsecs, a few per cent of the major galactic dimensions. This has clear implications for the type of propagation which occurs and it is surprising that the direction of propagation has not been more closely examined.

Fig. 3 shows that the anisotropy phase is probably different for northern and southern observatories below the knee (about 330° R.A. and 300° R.A. respectively) and it is statistically indistinguishable at about 150° R.A. above the knee. It is worth emphasizing that there is no particular reason why northern and southern results should be similar. Most northern observatory results were obtained at latitudes of 40°N to 60°N and most southern observations were made at between 35°S and 40°S. With limited ranges of zenith angle being accessible to most cosmic ray arrays at these energies, it is clear that limited and quite separate regions of the sky have been studied. Fig. 4 shows schematically the ranges of the sky which have been studied and also the previously noted phases of the first harmonics of the anisotropy. At energies below the knee, the Northern Hemisphere first harmonic falls close to the inward direction of our galactic spiral arm (the general flow of cosmic rays is thus probably from this direction). At energies above the knee, the Southern Hemisphere first harmonic is close to the outward spiral arm direction. The other harmonics (northern at high energies and southern at low energies) exhibit no obvious directional coincidences.

However, if one had general cosmic ray flow along our spiral arm and past us, we would find, if we could examine the whole celestial sphere, a maximum of intensity in the direction of the source arm and a minimum in the opposite direction (the other spiral arm direction). Fig. 4 shows that one arm direction is in the northern celestial

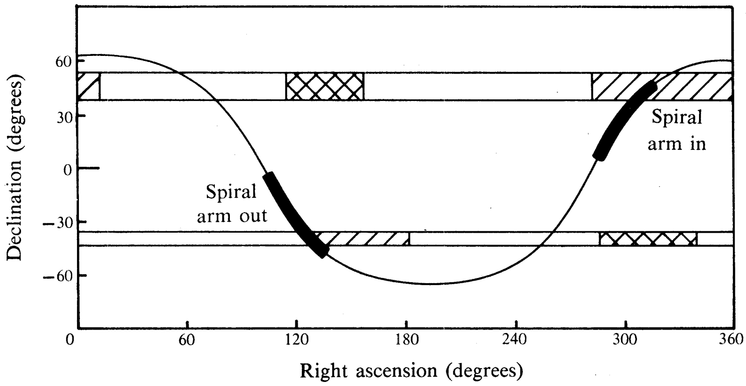

Fig. 4. Phases of the anisotropy first harmonic (for energies between $\sim 10^{14}$ and $\sim 10^{17}$ eV) on the celestial sphere. The hatched areas indicate the direction of maxima for the two energy ranges (see Section 5). The cross hatched areas correspond to the low-energy range in the Southern Hemisphere and the high-energy range for the Northern Hemisphere. The declination bands indicate the spread in latitudes of most of the available observations. Data from Mt Chacaltaya are not included as they seem to be internally inconsistent. The galactic equator and the general positions of our spiral arm are indicated.

hemisphere and the other in the southern. For such a flow, one terrestrial hemisphere would observe a first harmonic maximum in the direction of the source. An observatory located in the other hemisphere would observe a minimum along the reverse spiral arm direction and interpret the data as a first harmonic phase 180° away from the arm. One can derive the direction of the Southern Hemisphere (R.A. + 180°) for energies below the knee and the Northern Hemisphere (R.A. + 180°) for energies above the knee. The new directions again fall close to the spiral arms and are consistent with this model. The data thus indicate a cosmic ray flow past us along our spiral arm for each energy range, but the direction of flow reverses as the knee is passed.

6. Discussion

A lack of detailed information on the structure of the galactic magnetic field and the spiral arms themselves makes the interpretation of a spiral arm flux difficult. Bell *et al.* (1974) have considered cosmic ray propagation models in the presence of a large scale ordered galactic field together with magnetized clouds of dimensions in the range 10–100 pc. Their major interest was to describe the knee in terms of a propagation model and they did not emphasize the possibility of a second spiral arm component (which in the model presented above, might be dominated by iron nuclei). Some of their results are of considerable relevance however if one assumes that the 'iron' primaries propagate like protons at the same rigidity. Bell *et al.* considered amongst others, a model of spiral arm propagation. For 'iron' primaries, their predicted anisotropies were below the experimental upper limits and thus were not contradicted by experiment. There is no suggestion of a knee at 10^{16} eV for iron primaries, although protons would exhibit a reduced spiral arm lifetime above this energy as containment becomes inefficient. A mean iron containment lifetime of near 10^6 yr seems possible at 10^{16} eV. It would seem that the source of the second component need not be particularly local on a galactic scale and also that the origin of the cutoff of this component at the knee is not associated with its galactic propagation. This must be a source effect.

The cutoff in the second component can be illustrated by subtracting off a power law energy spectrum from the observed spectrum to leave the second component. Fig. 5 shows the resulting spectrum after allowance has been made for the effect of a changing depth of maximum on the energy assignment (as in Clay *et al.* 1983). The cutoff occurs quite sharply at a little over 10^{15} eV. Below this energy, the spectrum is rather flat with a form which can be approximated by a power law with an index of about 1 (integral spectrum).

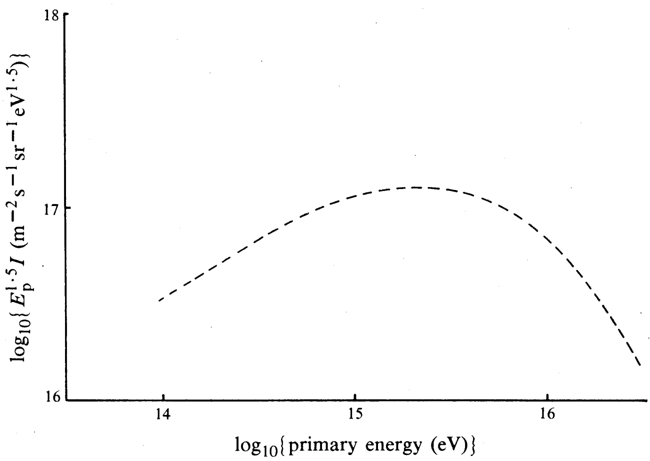

Fig. 5. Energy spectrum of a second component which dominates the observed cosmic ray beam between $\sim 10^{14}$ and $\sim 10^{17}$ eV. Uncertainty in the subtracted spectrum would cause a systematic uncertainty of $\sim \log_{10}(3\times10^{16})$ in the ordinate for these data points. Random errors probably contribute less than 10% (see Clay and Gerhardy 1982).

7. Anisotropy above 10^{17} eV

There is evidence that the flow from outer galactic regions follows the spiral arm only over a limited energy range. This is probably not surprising. At 10^{17} eV, protons will have a radius of gyration approaching 100 pc in the intercloud magnetic field and even iron primaries will be at energies where propagation characteristics must change. Haverah Park data for energies above 10^{17} eV (Lloyd-Evans 1982) showed remarkable changes up to the highest energies. These data have not been confirmed yet by other experiments but, as they stand, they indicate a complete, progressive phase change through 360° between 10^{17} and 10^{18} eV. The phase then appears to begin to reverse at energies up to 10^{19} eV. It is possible that such changes might result from a relatively local ($\lesssim 1$ kpc) source and a uniform local galactic magnetic field as suggested by Hillas (1983). Unless data at these energies are obtained from arrays at different latitudes it would seem unlikely that a unique solution to the arrival direction problem above 10^{17} eV can be found. In particular, there is an urgent need for Southern Hemisphere data to provide some balance in our view of the celestial sphere.

8. Conclusions

Several parameters of the cosmic ray beam show changes between 10^{14} and 10^{17} eV which are remarkably similar and are apparently consistent with an underlying cosmic ray propagation inwards along our galactic spiral arm; this propagation is dominated by a second component, possibly of iron nuclei, between 10^{14} and 10^{16} eV from the opposite, outward flowing, direction. This second component has probably retained a spectrum similar to that which it had at its source. The energy spectrum of the second component is rather flat up to a sharp cutoff which forms the knee of the total cosmic ray energy spectrum.

Acknowledgment

This work was supported by the Australian Research Grants Committee.

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Manuscript received 18 July, accepted 19 September 1983