COSMIC RAY ANISOTROPY : 10^{12} - 10^{20}eV

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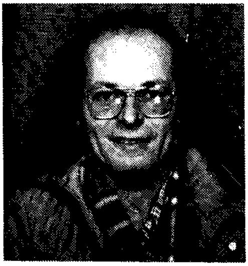


The results of experiments designed to study the arrival direction distribution of cosmic rays of energy 10^{12} - 10^{20}eV are reviewed. It is shown that at all energies there is evidence for anisotropy, the amplitude of which ranges from 0.075% at the lowest energies to 90 ± 20% above 4.10^{19}eV. The increase of anisotropy with energy is not smooth, showing features which occur at energies similar to those at which features are observed in the cosmic ray energy spectrum. At least up to 2.10^{17}eV it seems probable that the acceleration sites lie within our Galaxy, and it is hard to escape the conclusion that particles of energy $>10^{19}$eV are extragalactic. Sources of the highest energy particles ($\sim 10^{20}$eV) must lie within 200Mpc, and considerably closer if, as seems likely, the intergalactic medium is such as to prevent rectilinear propagation. Between 2.10^{17} and 10^{19}eV the location of the sources is less certain. The aim of future arrival direction experiments should be to study anisotropy as a function of primary mass composition.

1. Introduction

Seventy years after the discovery of cosmic rays, the question of their origin remains unsolved. In the early days of investigation of the properties of the radiation, experimenters hoped to find that some regions of the sky were brighter than others when viewed in cosmic ray light. It is now known that below about 10^{11}eV cosmic ray intensities are strongly influenced by the spatial and temporal changes in the magnetic fields of interplanetary space so that the Galactic anisotropy cannot be determined from the earth. At higher energies, where solar effects can be accounted for or neglected, the amplitude of anisotropy is found to be small, being less than 0.1% up to 10^{14}eV. The high degree of isotropy of low energy cosmic rays was recognized early on, and this fact, coupled with the large density of cosmic rays (0.5eVcm^{-3} at 10^9eV and 0.1eVcm^{-3} at 10^{11}eV), was a significant clue in early thinking about the possibility that our Galaxy might contain a weak but extensive magnetic field. It is of course the Galactic magnetic field, at least at the lowest energies, that thwarts attempts to locate cosmic ray sources in a manner analgous to that used to find optical or X-ray sources: the'seeing' is spoiled for cosmic ray telescopes because the Larmor radius of charged particles is very small by comparison with Galactic dimensions except at the highest energies. At 10^{14}eV a proton has a radius of gyration of only 0.04pc in a 3μG field; at 10^{18}eV the corresponding radius is 370pc, rather larger than the thickness of the Galactic disc.

In this paper I will outline the detection techniques used to measure cosmic ray anisotropies, describe the results available and discuss some tentative interpretations. I will show that features in the variation of the character of the anisotropy with energy are linked to features in the primary energy spectrum. A full understanding of the meaning of these linkages is not yet clear because information about cosmic ray mass composition, particularly above $\sim10^{14}$eV, is still rudimentary.

2. Primary Energy Spectrum and Mass Composition

As a background to our discussion of cosmic ray anisotropy it will be helpful to keep in mind our present knowledge of the cosmic ray energy spectrum and mass composition. Figure 1 shows a schematic version of the energy spectrum. The integral intensity has been multiplied by $E^{1.5}$ (E is the primary energy in eV) and is plotted on the y-axis. This procedure serves to show clearly the two prominent features in the spectrum, namely the 'knee', near 10^{15}eV, and the 'ankle' above 10^{19}eV. Both these features are well established although the flattening observed above 10^{19}eV has been observed only from the Northern Hemisphere.[1] Integral spectrum slopes are -1.65, between 10^{11} and 10^{15}eV, -2.1 between 10^{17} and 10^{19}eV and -1.4 ± 0.1 above 10^{19}eV. Between 10^{15} and 10^{17}eV there is evidence[2)] that the spectral slope is steeper than at higher energies but the experimental situation is not yet clear. It should be borne in mind that, because the observed particle densities are greater and because the shower maximum is relatively lower in the atmosphere, the properties of primaries above 10^{17}eV (and at least up to 10^{19}eV) are somewhat better established than the properties of lower energy primaries which produce smaller showers.

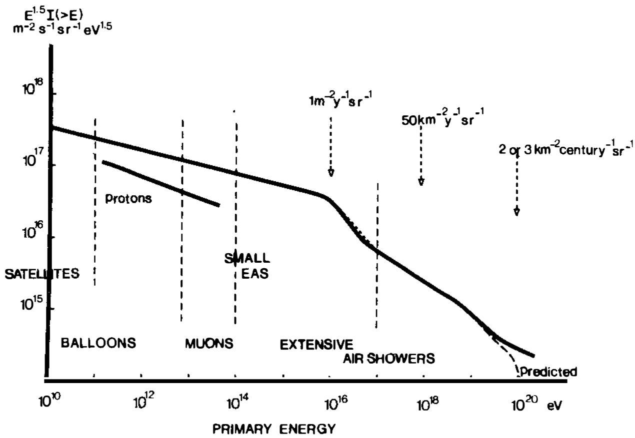


Figure 1 The cosmic ray energy spectrum above 10^{10}eV. The detection techniques used in various energy regions are indicated. The dashed curve near 10^{16}eV marks an energy range in which the spectral shape is uncertain. The curve above 10^{19}eV marked 'predicted' is the calculation[6)] of the Greisen-Zatsepin effect[4,5)].

Explanations for the two major features are not yet agreed. About 20 years ago Peters proposed that the 'knee' at 10^{15}eV might reflect the inability of our Galaxy to retain cosmic rays protons of this energy (Larmor radius $\sim$0.4pc). A prediction of this hypothesis was that heavy nuclei would begin to dominate the primary beam above 10^{15}eV. No convincing evidence has been obtained to support this prediction and counter evidence has been offered that Fe-nuclei are becoming dominant at energies less than 10^{15}eV.[3)] Hillas [2)] has reviewed the situation and concluded that composition and spectrum data cannot be reconciled with the Galactic leakage model. He proposes that the change is induced in the spectrum by photonuclear or pair production reactions occuring near to the source. The spectral feature at 10^{15}eV would thus reflect the radiation field in the acceleration region.

The 'ankle' feature above 10^{19}eV is even more puzzling. Following the discovery of the 2.7K black body radiation in 1965 it was predicted by Greisen[4] and by Zatsepin and Kuzmin[5] that if ultra high energy cosmic rays were produced only in sources which were at cosmological distances (e.g. quasars) then the intensity of cosmic rays above $\sim 5 \times 10^{19}$eV would fall so dramatically that no events of 10^{20}eV would be observed with the giant air shower arrays then being brought into operation. Reality is different. The three Northern Hemisphere installations (Volcano Ranch (U.S.A.), Haverah Park (U.K.) and Yakutsk (U.S.S.R.)) all find that the spectrum is flatter above 10^{19}eV than at lower energies. The total exposure achieved at the highest energies in these experiments is $\sim 300\,\mathrm{km}^2\,\mathrm{yr\,sr}$ and at least 7 events with energies above 10^{20}eV have been observed. Using the theoretical predictions of Strong et al[6] about 0.2 events would have been expected. There is a consensus that this result implies that the age of the cosmic rays above about 3×10^{19}eV is less than 10^8 yr (e.g. Puget et al[7]). The arrival direction distribution of these particles, which will be discussed in detail below, is not that expected if the most energetic particles were produced within our Galaxy.

For the purposes of interpreting arrival direction information details about the mass composition of the primary cosmic rays are crucial. At energies less than 10^{13}eV the arrival direction distributions observed refer mainly to protons as the experiments which have been possible are selective in their triggering and respond dominantly to muons produced by proton primaries. At higher energies the only method of getting information about primary cosmic rays is by studying features of the extensive air showers which they produce (electrons, muons, air-Čerenkov light, air-scintillation light etc). The problem of extracting the mass composition is particularly difficult because the particles cannot be observed directly and because the necessary nuclear physics must be extrapolated from lower energies. Recently progress has been made by studying the change of the depth in the atmosphere at which the number of electrons in the shower reaches its maximum. The variation of this depth with energy (the elongation rate) for a fixed primary composition depends principally upon the multiplicity of the pions produced in hadronic interactions.[8] If it is assumed that p-p cross-sections continue to rise at the rate observed at accelerator energies then it appears that the primary particles are very light ($\overline{\ln A} = 0^{+0.6}_{-0}$) above 3×10^{16}eV and rather heavy ($\overline{\ln A} = 4 \pm 2$) near 10^{15}eV.[9] The rapid change of the depth of maximum with energy between 10^{15}eV and 3.10^{16}eV expected on such a picture is indeed observed.[10] A detailed summary of mass composition determinations is given elsewhere in these Proceedings by Yodh. A review of properties of the highest energy cosmic rays has been given by Linsley.[11]

3. Arrival Direction Data

Kiralty et al [12] have reviewed arrival direction data at all energies while more recently Elliot [13] has discussed the measurements available at energies below 10^{14}eV. The present experimental situation is summarized in figure 2. What is plotted (figure 2(a)) is the amplitude of the 1^{st} harmonic of the cosmic ray anisotropy as a function of energy. At energies less than 6.10^{16}eV the first harmonic is computed in sidereal time and is an average over the range of declinations (typically $\pm 30^0$) which lie within the reception cone of the detector system. At the higher energies, where information on the energy and direction of individual events is available, the first harmonic is measured in right ascension. The data shown refer to all declinations above -6^0; analyses in declination are discussed briefly below. The directions of maximum amplitude (the phase) are shown in figure 2(b).

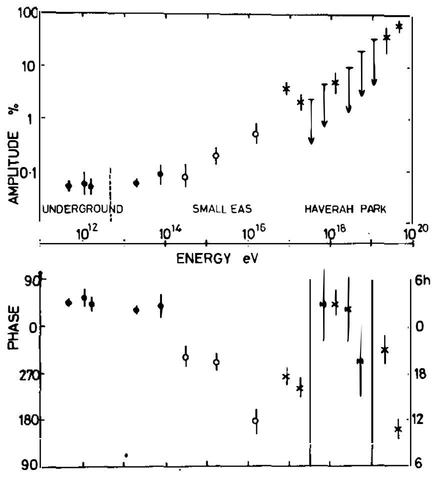


Figure 2 Summary of cosmic ray anisotropy data, after (11). The top half of the diagram (figure 2a) shows the amplitudes measured in various experiments. The filled circles are from references (14-18) as reviewed in (13). The open circles are from the compilation of Linsley and Watson[19] while the crosses are from the Haverah Park experiment[20,21]. The lower half of the diagram (figure 2b) shows the time of maximum amplitude (the phase). The error bars correspond to ± 1 standard deviations; the upper limits are shown at the 95% confidence level.

The three points below 10^{13}eV are from measurements made in underground laboratories[14,15,16] at depths between 40 and 507 m.w.e. where muons from the decay of pions produced high in the atmosphere by the incoming primaries are detected. The energy refers to the energy/nucleon of the primaries which are dominantly protons. The next two points (between 10^{13} and 10^{14}eV) are from the work of the Japanese[17] and Hungarian[18] groups who have measured the time variation of the rates of small air showers produced at mountain altitudes. Above 5.10^{11}eV the trajectories of the primaries are relatively little influenced by the interplanetary magnetic field (or the effect has been accurately allowed for). The constancy of the amplitudes and directions between 5.10^{11} and 10^{14}eV is striking, and must be considered as well established.

Kirally et al[12] in a clear discussion of these data, have linked the invariance of phase and amplitude to the persistence of the direction of the local interstellar magnetic field out to distances of a few parsecs, the field direction being inferred from the steady flow of interstellar gas in the region just outside the solar cavity. Kirally et al also deduce that under these circumstances features of cosmic ray propagation do not change very much between 10^{11} and 10^{14}eV.

Above 10^{14}eV all measurements are derived from studies of air showers. Between 10^{14} - 10^{17}eV (open circles) the data have been taken from a compilation[19] of all available evidence recorded between 1951 and 1965. The results are based on 23 experiments in which the counting rate of small air showers was recorded as a function of time. The directional accuracy possible in these early experiments was rather poor as it relied upon atmospheric collimation. Likewise the energy resolution was limited as analysis of individual events was not possible. Nonetheless there is evidence for an anisotropy which changes both in amplitude and phase as the energy increases The validity of this claim is strengthened by the fact that the amplitude of the first of the older air shower points, at 3.10^{14}eV, is $0.075 \pm 0.020\%$, in excellent agreement with the mean amplitude of the 5 independent measurements made with EAS and muon techniques in more recent experiments at lower energies. The difference between the phase of the first of the older points and that of the lower energy data is not particularly disturbing as the Larmor radius of a proton of this energy is $\sim$0.1pc in the canonical field, and variations in magnetic field and/or cosmic ray gradient on this scale may well occur in directions away from the Galactic plane. As the energy increases the amplitude of anisotropy starts to rise and there is a steady change in the phase of maximum.

Above about 6.10^{16}eV the data shown in figure 2 derive from the Haverah Park experiment[20,21]. At the present time these data are the most numerous available; between 10^{17} and 10^{18}eV the number of showers recorded exceeds those from other experiments by roughly an order of magnitude; between 10^{18} and 10^{19}eV the Haverah Park data set exceeds that of Volcano Ranch[22)] by more than a factor of 5 while above 10^{19}eV the events available from Northern Hemisphere experiments are Yakutsk[23)] (34), Volcano Ranch[24)] (44), Haverah Park[24)] (144). The discussion of data above 6×10^{16}eV which follows concentrates mainly on the Haverah Park results but where comparison has been possible the agreement of these results with the broad features of other experiments is found to be good (see reference (20) for more details). In the Haverah Park experiment the direction of each event is known to within 10^{-2} sr and the energy resolution is better than 40%. Partition of the events into energy bins a factor of 2 wide has been adopted.

The data from the Yakutsk, Volcano Ranch and Haverah Park cover mainly the sky region above $\delta = 0^0$. There are limited statistics from Haverah Park down $\delta = -6^0$ and from Volcano Ranch down to $\delta = -30^0$. A major experiment has been operated in the Southern Hemisphere by the University of Sydney[25)]. Analysis is still in progress and the final results are keenly awaited as the exposure achieved in this single experiment was comparable to that from the three Northern Hemisphere arrays combined. Particularly at the highest energies the absence of data from the Southern Hemisphere severely hampers interpretation of the measurements which are available.

The variation of anisotropy with energy above 10^{16}eV which is summarised in figure 2 is extremely complex. Near 10^{17}eV there appear to be two significant amplitudes, in adjacent energy bins separated by a mean energy of a factor 2. The direction of maximum is similar in both bins when the data are examined over all declinations, but differences in detail are revealed when individual declination strips are examined. In the lower energy bin (E1, 6×10^{16} - 1.25×10^{17}eV) there is a slight excess near 240^0RA in each bin, whereas bin E2 (1.25 - 2.5×10^{17}eV) shows an excess dominantly in the strip with $20^0 < \delta < 30^0$ (figure 3). In the search for anisotropy[20)] 100 such declination strips were examined; the chance of finding one such remarkably anisotropic strip is computed, taking into account the number of strips, as 8×10^{-3}. No data from other experiments are available to check the reality of this result but figure 4 shows the phases and amplitudes from all other experiments in which measurements were made near 10^{17}eV. The agreement with the Haverah Park results, averaged over all declinations, is impressive.

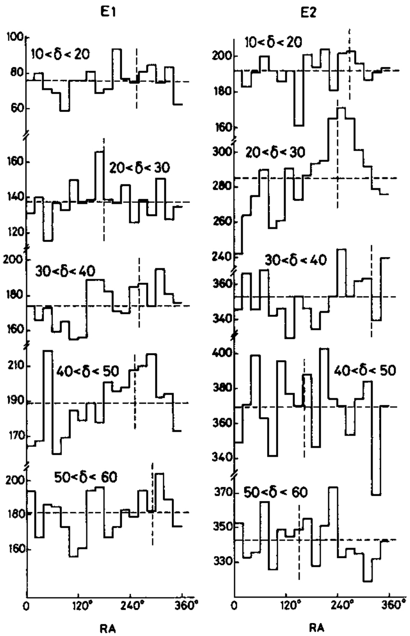


Figure 3 Right ascension distributions in 5 declination strips for energy bins E1 (6×10^{16} - 1.25×10^{17} eV) and E2 (1.25 - 2.5×10^{17}eV) of Haverah Park data[21]. The dashed horizontal line in each histogram is the mean number for that interval; the vertical dashed line shows the phase of the first harmonic in right ascension.

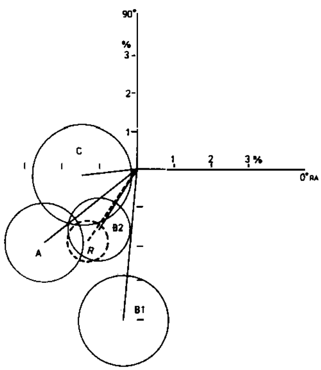


Figure 4 Comparison of data from a number of experiments near 10^{17}eV. The circles indicate rms amplitudes. A (Cornell[26], 19000 events, 7.5×10^{16}eV); B (Haverah Park[20] (1, 13825 events 6×10^{16} - 1.25×10^{17}eV; 2, 31266 events, 1.25 - 2.5×10^{17}eV)); C (other experiments, 11059 events, see[20] for details, 6×10^{16}- 5×10^{17}eV). R is the resultant vector.

In the two energy bins immediately above those just discussed only upper limits can be set to an anisotropy. The limits shown (figure 2) are 95% confidence limits and it therefore appears that the amplitude of anisotropy may not increase as rapidly with energy beyond 2.10^{17}eV as it appears to do between 10^{15} and 10^{17}eV. Note that the phase of bin E3 ($2.5 - 5 \times 10^{17}$eV) is unknown. By contrast bin E4, again showing only an upper limit, has a phase which can be estimated and is similar to that in the 2×10^{18}eV region (bins E5 and E6) where there is limited evidence for an anisotropy in right ascension. This result is supported (see figure 5) by experimental evidence which is available from other work[22,26-29] carried out near 10^{18}eV.

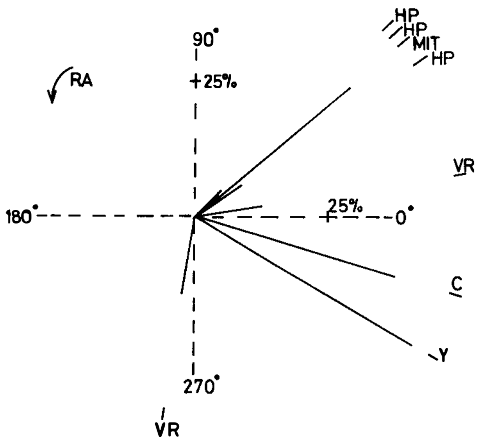


Figure 5 Comparison of data from a number of experiments near 10^{18}eV. C (Cornell[33]), MIT (MIT group[27]), HP (Haverah Park[28]), VR (Volcano Ranch[22]), Y (Yakutsk[29]). The variation in amplitude between experiments is large but the agreement in phase is striking.

At the very highest energies ($>4.10^{19}$eV) there is accumulating evidence for an excess of events from high Galactic latitudes. Such a possibility was first noted in 1973[30] and as further events have been recorded the tendency for energetic events to arrive preferentially at large angles to the Galactic plane has persisted. The current situation (for $\delta>0^0$ and $E>4.10^{19}$eV) is summarised in figure 6; the Volcano Ranch and Haverah Park events are those listed in the World Data Centre Catalogue[24] while the Yakutsk points were reported by Krasilnikov[23]. The cut in energy has been taken at 4.10^{19}eV so as to correspond with the highest energy band discussed by Krasilnikov.

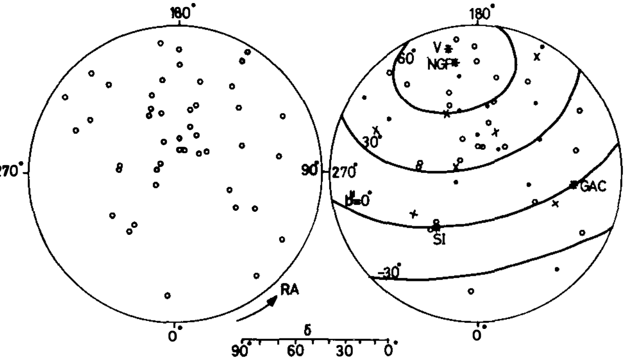


Figure 6   The arrival directions of the 45 most energetic events ($>4\times10^{19}$eV) observed at $\delta>0^0$. The projection used is an equal area projection; $\delta=90^0$ lies at the centre of the circle which has circumference, $\delta=0^0$. The open circles in the left hand diagram are identifiable in the right hand diagram (13 filled circles, Yakutsk[23]; 7 crosses, Volcano Ranch[24] and 25 open circles, Haverah Park[24]). In the right hand diagram lines of Galactic latitude, b''=60^0, 30^0, 0^0, -30^0, are marked as are the directions of spiral-in, the Galactic anti-centre, the north Galactic pole and the centre of the Virgo cluster.

Individual energies have yet to be published for the Russian data. The first harmonic in right ascension of these 45 events has an amplitude of $90\pm20\%$ (probability of arising by chance from an isotropic distribution = 1.4×10^{-4}) and a phase of 180 ± 14^0RA. It is also clear that there is no enhancement towards the Galactic plane as predicted by Syrovatsky[31]. The probability of a 2:1 enhancement in the region of the plane with respect to the Pole ($|b''|<30^0$ compare with $|b''|>30^0$) can be strongly rejected, ($p<<10^{-3}$).

An alternative way of presenting this result is to determine the deviation from expectation of the mean Galactic latitude of these data. It has been pointed out before[1] that the Haverah Park data set reveal an increase of $<\sin b''>$, over the value expected for isotropy, above the energy at which the energy spectrum flattens. A similar analysis has been made with the available showers from Volcano Ranch and Yakutsk and is shown alongside the Haverah Park result in figure 7. There is some support from these experiments for a change in the Galactic latitude distribution at the energy in question. Above 4.10^{19}eV, $<\sin b''>$ for 48 events is 0.50 ± 0.07 compared with the isotropic expectation of 0.30. For $1\text{-}2\times10^{19}$eV (the other energy band for which Yakutsk directions are available) $<\sin b''>=0.210\pm0.045$ (isotropic expectation = 0.22) for the showers recorded in the three experiments.

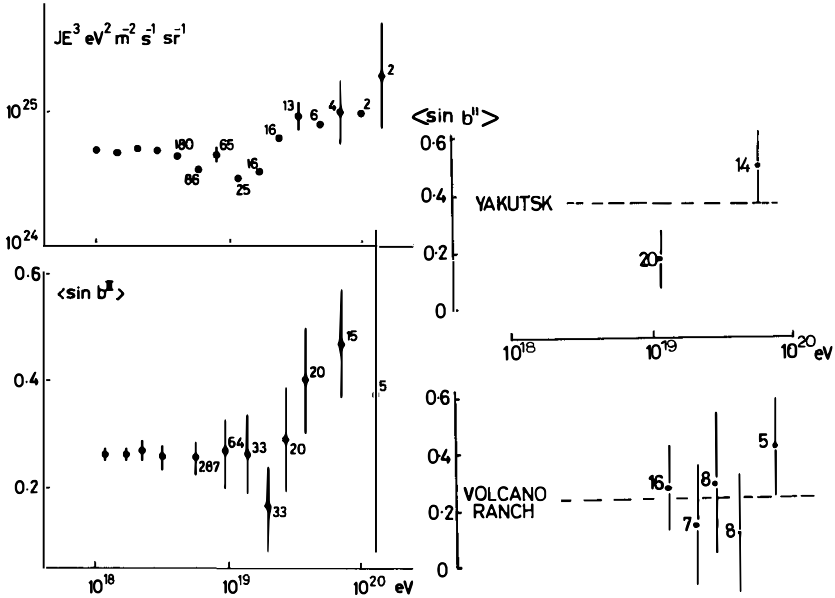
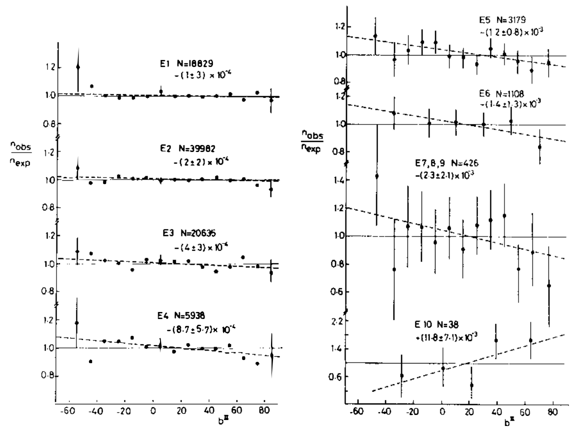


Figure 7 Variation of <sin b''> with energy. The left hand diagram shows the Haverah Park results[1] for <sin b''> and the energy spectrum. The right hand diagram shows the results derived for <sin b''> for the Volcano Ranch[24] and the Yakutsk[23] data sets.

The reason, 'a priori', for investigating the anisotropy above and below 4×10^{19}eV is that above this energy the spectrum is flatter than at lower energies whereas if the sources of these multi-Joule particles are at cosmological distances (quasars for example), the spectrum is predicted to steepen rapidly. I have been unable to think of any systematic error which, if it were present, would simultaneously flatten the spectrum and cause the showers to arrive with an anomalous intensity at high Galactic latitudes. The two effects combine to provide an important clue as to the origin of the most energetic particles.



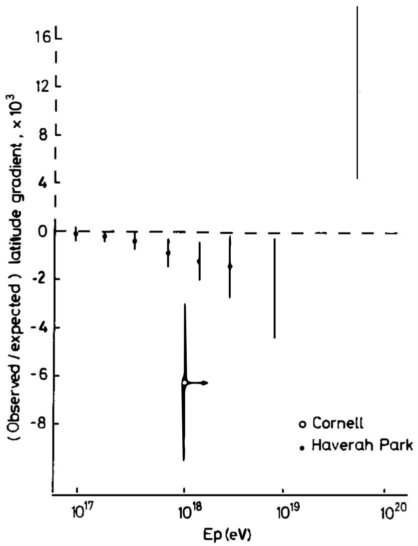


Figure 8 Distribution of high energy cosmic rays in Galactic latitude[32]. The upper diagram shows the ratio of the observed to expected number of showers as a function of Galactic latitude and energy. Showers are grouped in energy bins which, apart from E10, are a factor 2 in width. E5 encompasses $1-2 \times 10^{18}$eV and E10 contains all showers with energy $>3.2 \times 10^{19}$eV. Note that E7, E8 and E9 are treated as a single group and that there is a change in the vertical scale for E10. In the lower diagram the gradient of each of the upper graphs is plotted as a function of primary energy. There is a change of scale above the dotted line which shows the gradient expected for an isotropic distribution in Galactic latitude. The Cornell data are from reference (33).

A more detailed analysis in Galactic latitude has recently been made by the Haverah Park group[32] for showers with energies below 4.10^{19}eV. The 9×10^4 events with energies above 6×10^{16}eV have been grouped into factor of 2 bins in energy. For each energy bin the ratios of the observed to the expected number of events have been calculated as a function of Galactic latitude and are shown in figure 8. The statistics allow only a description of the systematic deviations from uniformity in Galactic latitude. The gradient of a linear least squares fit to the data of each energy bin is shown in the figure. The result for bin E10 is a restatement of the result just discussed, that showers above 4×10^{19}eV arrive preferentially from high Galactic latitudes. The remaining energy bins show a systematic enhancement at low Galactic latitudes. Although no energy bin shows a very significant enhancement on its own, a trend of steeper gradients at higher energies is apparent when the fitted gradients are plotted as a function of energy. Direct comparison is possible only with data from the Cornell group[33] who have reported the co-ordinates of 166 events having E>10^{18}eV. The gradient is comparable in magnitude and of the same sign as those obtained with Haverah Park data. For the Haverah Park events alone the mean gradient at energies less than 3.2×10^{19}eV is $(-3.1 \pm 1.4) \times 10^{-3}$, significantly different from zero.

4. Discussion and Interpretation

I have attempted to summarise the present state of knowledge about cosmic rays in figure 9 where the energy dependence of the mean mass, the integral slope of the energy spectrum and parameters associated with the anisotropy, are displayed. The breaks in the various parameters are not, of course, as sharp as indicated but are shown as discontinuities to highlight the possibility that changes in spectral features appear to coincide with changes in features of the

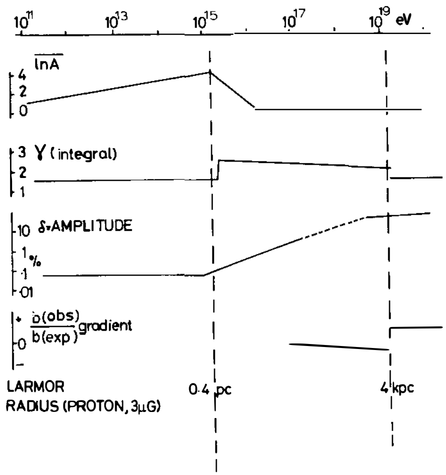


Figure 9 Summary of experimental data on cosmic rays. $\overline{\ln A}$ is the mean of the logarithm of the primary mass, A; γ is the slope of the integral energy spectrum; δ is the amplitude of the 1st harmonic in sidereal time or right ascension and the b'' gradient ratio is a summary of the data of figure 8. The Larmor radius of a proton in a 3μG magnetic field is shown at two energies.

anisotropy. The two most clearly established changes in the slope of the energy spectrum occur near 10^{15}eV and 3×10^{19}eV. Near the lower energy the amplitude of the first harmonic in right ascension is observed to start to increase with energy; at the higher energy a tendency for particles to arrive preferentially from high Galactic latitudes is observed. There may be a less pronounced spectral feature near 10^{17}eV where the anisotropy amplitude changes and where the phase and declination distribution behaves in a complicated manner; more measurements of the spectrum are required in this region.

It is evident from figure 9 (and figures 2 and 8) that cosmic rays are anisotropic at all energies between 5.10^{11} and 10^{20}eV. There is suggestive evidence, derived from analysis of the distribution of 100MeV γ-rays, that cosmic rays of 10^{9} - 10^{10}eV have their origin in our Galaxy[34]. It is conservative and unexceptionable to suppose that cosmic rays up to at least 2.10^{17}eV are also of Galactic origin. The relatively large amplitudes, several percent, observed near 10^{17}eV and the complex distribution in declination (see figure 3) could hardly arise as a result of some anisotropic, extragalactic, distribution of sources because diffusion of the particles in intergalactic space is expected to render their distribution highly isotropic. Rather one might seek to interpret the observed patterns as arising from the convolution of the magnetic field structure within a few Larmor radii of the earth with an anisotropic distribution of Galactic objects which would accelerate such particles. In this context it is noted that the currently attractive shock acceleration model might operate up to energies of 10^{18}eV[35]. Suitable shocks might be, or might have been, associated with features such as the Heiles supershells[36]. Theoretical studies of methods of acceleration of light nuclei in such systems would be of enormous help in interpreting the data.

Extensive efforts have been made in the last 10 years to understand the fact that cosmic rays of 10^{20}eV are observed at a rate $(5(^{+2.4}_{-4.2})\times10^{-16}m^{-2}s^{-1}sr^{-1})$ significantly greater than expected if the sources of such particles lie only at cosmological distance. The point is that protons of this energy interact very strongly with the 3K radiation (producing pions) and have an attenuation length of about 200Mpc at 10^{20}eV. Thus 10^{20}eV protons from the Coma cluster would be reduced in intensity by $\sim$2.7 even if diffusion in intergalactic space was negligible. If all of the primaries were iron nuclei (in contradiction to the limited experimental evidence) photodisintegration by the 3K photons would be effective in depleting the intensity by a similar amount[7]. The sources must thus be relatively local, certainly lying within 200Mpc.

Evidence for anisotropy in the arrival directions of the highest energy events (figure 7) appears at variance with any reasonable model of Galactic origin, and it has become popular[6,7,37-39] to consider the possibility that highest energy particles are produced by sources within the Virgo cluster. A major drawback of this hypothesis is that the energy requirements for such sources are very large. To maintain the observed local energy density of $\sim 10^{-8}$ eV cm^{-3} throughout the Local Supercluster when the 3K-limited lifetime is $\sim 10^{8}$y requires an energy input, into 10^{20}eV particles and above, of $\sim 5 \times 10^{41}$erg s^{-1}. Additionally the sources would have to pump vast quantities of energy into lower energy cosmic rays, as much as 10^{46}erg s^{-1} into cosmic rays >1GeV if the high energy spectral shape ($\gamma = 1.3 \pm 0.1$) persists to lower energies. Such an energy output is about 10^{6} times that of our own Galaxy in cosmic rays whereas the number of similar galaxies in the Virgo cluster may only be $\sim 10^{3}$.

A particularly interesting and detailed discussion of this problem has been given by Giler et al[40] in a development of some earlier ideas of Wdowczyk and Wolfendale[41]. They have made a detailed study of a model in which the sources of the particles lie in the Virgo cluster and in neighbouring clusters. Two diagrams from their paper are shown in figure 10. The spectral shape at the highest energies can be reproduced by the multi-cluster model with a large diffusion coefficient ($3 \times 10^{35}\ E_{19}^{1.5}$ cm^2 s^{-1}) though a better description of the anisotropy data is provided by the model in which the Virgo cluster contains the most significant sources. A test between the two models may be possible when

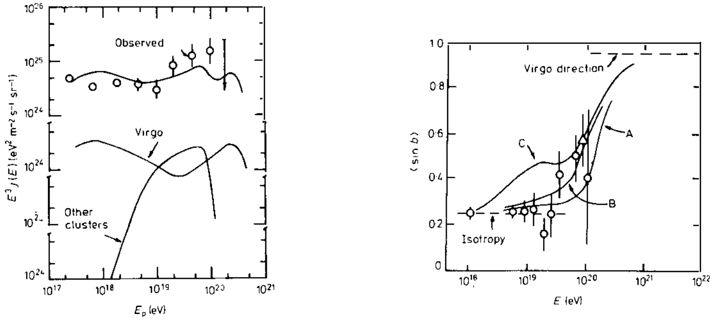


Figure 10 Results of calculations of the Virgo cluster and multi-cluster models of Giler et al[40]. The left hand diagram shows the fit to the spectral shape achieved with the multi-cluster model (clusters within 100Mpc) in which the diffusion coefficient is energy dependent, $D = 3 \times 10^{35}\ E_{19}^{1.5}$ cm^2 s^{-1} (E in units of 10^{19}eV). The right hand diagram shows the variation of $\langle \sin b'' \rangle$ predicted by models: A, Virgo cluster only, $D = 5 \times 10^{33}\ E_{19}^{\frac{1}{2}}$ cm^2 s^{-1};
B, Virgo cluster alone, $D = 1.58 \times 10^{34}\ E_{19}$ cm^2 s^{-1};
C, Virgo plus other clusters, $D = 3 \times 10^{35}\ E_{19}^{1.5}$ cm^2 s^{-1}. The open circles are from[1], the triangle is a smaller sample of Yakutsk data than that of[23] which is shown in figure 7. The diagrams are figures 7 and 9 of reference (40).

data on the spectra and anisotropy in the Southern Hemisphere ($\delta<0^0$) become available. On the Virgo hypothesis it seems clear that a smaller anisotropy than seen in the Northern Hemisphere would be expected together with a less pronounced flattening of the spectrum. This arises because of the well-known concentration of galaxies in the northern Galactic hemisphere[42]. Predictions based on the multi-cluster model require more detailed knowledge of the positions, sizes and distances of Galactic clusters than are presently available.

Although the model just described successfully explains features associated with the highest energy cosmic rays it predicts that the direction of anisotropy of 10^{18} - 10^{19}eV particles should lie above the Galactic plane (figure 10) rather than below it as is found experimentally (figure 8). The origin model can be reconciled with observations if the primaries which reach us from southern Galactic latitudes have undergone some preferential acceleration, perhaps as a result of having spent a substantial part of their lives within the Local Group of galaxies, the centre of which lies in a direction 22^0 below the Galactic plane. The possibility of intergalactic acceleration, suggested originally by Cocconi[43], has been revived more recently in the context of shock acceleration by Blandford and Ostriker[35]. It is not being suggested here that particles receive all of their energy in intergalactic space. Rather it is being proposed that the anisotropy arises because particles receive a boost of energy, ΔE, leading to an anisotropy of $(\gamma + 1)\,\frac{\Delta E}{E}$, where γ is the slope of the integral energy spectrum. Galactic winds and the motion of massive gas clouds, such as those of the Magellanic stream[44], may generate the necessary shocks in the medium of the Local Group.

If a heavy mass composition is eventually established as being more probable than the proton dominated composition supposed in the above discussion then the observations between 10^{18} and 10^{19}eV could be reconciled with a Galactic origin. A cosmic ray gradient caused by inefficient trapping within the Galactic magnetic field would result in an anisotropy in a direction orthogonal to the local magnetic field and the gradient. The direction of the observed excess is consistent with a field direction of $\ell^{II}\sim 90^0$, $b^{II}\sim 0^0$ provided the sun lies in the direction towards the inner boundary of the local spiral arm as it may do[45].

5. Summary and Future Experiments

The conclusions which have been reached above as to the origin of cosmic rays are:-

1. 10^{12} - 2.10^{17}eV : It is likely that the majority of these particles are

accelerated in sources which lie within our own Galaxy. The levels of anisotropy observed from 10^{15} to 2.10^{17}eV are much larger than expected on any extragalactic theory of origin and since there is evidence from studies of γ-ray data that 10^9 - 10^{10}eV cosmic rays are Galactic it would be surprising if particles of intermediate energy had a different origin. Furthermore a number of plausible Galactic models have been devised[46-49] which, though differing in their assumptions, lead to predictions for the amplitude of anisotropy in rough agreement with experiment.

It should be borne in mind, however, that a mixture of an isotropic extragalactic component and an anisotropic Galactic component could be present at any energy. For example the observed anisotropy near 10^{17}eV might arise from a Galactic component which had a 100% 1st harmonic amplitude (a point source produces a 200% amplitude) and an isotropic extragalactic component which comprised ∿98% of the total intensity.

2. 2.10^{17}-10^{19} eV : It is not clear at the present time whether cosmic rays in this energy band originate dominantly from within our Galaxy or outside of it. If the major mass component is established to be hydrogen then it will be hard to sustain the view that the majority of the particles originate within our Galaxy.

3. >10^{19}eV : The evidence for anisotropy in a direction nearly normal to the Galactic plane, coupled with the difficulty of accelerating particles to these energies in any known structure within our Galaxy, makes it probable that the particles observed are of Galactic origin. The continuation of the spectrum to just beyond 10^{20}eV, however, requires that the sources lie within 200Mpc and probably closer.

What experiments need to be undertaken to test these conclusions? At the highest energies the major needs are for data from the Southern Hemisphere, which should come shortly from the Sydney experiment[35] and for a three-to-tenfold increase in statistics which may be achieved by the University of Utah's Fly's Eye experiment[50] in the near future. If 10^3km^2 of collecting area could be monitored for 10 years only about 5 events with E>10^{21}eV would be expected from an extrapolation of the known rate at 10^{20}eV. Between 10^{17} and 10^{19}eV high statistics experiments in which it is possible to measure the arrival direction pattern of individual mass components are being discussed and preliminary data of this type may come from the recently commissioned large array in Japan[51]. At lower energies the Nagoya group has plans to extend their high counting rate, small air shower experiments to energies above 10^{14}eV[52] while between 10^{15} and 10^{17}eV experiments currently running at Haverah Park enable an interesting region to be surveyed with current technology. Below 10^{17}eV however, the smallness of the showers makes it hard to see how mass assignments can be made efficiently for individual events.

Of immense benefit to the interpretation of existing data would be theoretical effort aimed at pinning down likely acceleration regions. In particular the enormous power required to be input to high energy cosmic rays and the acceleration of particles to 10^{20}eV pose challenging problems for astrophysicists.

Acknowledgements

I am grateful to the organizers of the 1st Moriond Astrophysics meeting for inviting me to attend and for the financial support which helped to make it possible. I would like to thank my co-authors of reference (32) for permission to quote our results prior to publication, and Jeremy Lloyd-Evans for lively and helpful discussions. The continuing support for air shower studies at Haverah Park given by the Science Research Council is gratefully acknowledged.

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