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Explanations of the Spectral Shape in the Energy Range 10 ^{14}-10^{20} eV [and Discussion

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Explanations of the spectral shape in the energy range 10^{14}–10^{20} eV

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There is evidence suggesting an increase in slope of the energy spectrum of primary cosmic-ray nuclei at about 3×10^{15} eV. Alternative explanations are advanced for this change, related to diffusion of particles of galactic origin or black body cut-off effects for particles of extra-galactic origin.

At higher energies there appear to be particles of energy up to 10^{20} eV. The evidence will be examined critically and alternative explanations put forward for the spectral shape in this region.

1. Introduction

The fact that the sources of the cosmic radiation are obscure is well known. In the present work attention is devoted to examining the detailed shape of the primary spectrum above about 10^{14} eV and to examining its possible interpretations. The subject is a wide one in which many workers have made contributions. No attempt is made here to provide a comprehensive summary; instead attention is largely confined to models which have been studied recently by the Durham-Lodz group.

2. The experimentally measured primary energy spectrum

2.1. *General remarks*

With the exception of experiments using the Proton series of satellites (Grigorov *et al.* 1970), direct measurements of the primary spectrum have been confined to energies below a few times 10^{12} eV. Thus, the results of indirect measurements – mainly by way of the extensive air showers produced in the atmosphere – must be used at the higher energies (the problems posed by the Grigorov data will be considered later). A summary has recently been made by the author and his colleagues (Kempa, Wdowczyk & Wolfendale 1974) and the result is shown in figure 1.

In previous summaries (see, for example, Greisen 1965) it was concluded that the spectrum comprises a region below *ca.* 3×10^{15} eV where the integral exponent was -1.6 and one above with integral exponent -2.2. In figure 1, however, it is seen that there is some suggestion of a more complicated situation, namely, the presence of a 'bump' in the spectrum between 10^{14} and 10^{15} eV. Although the evidence in favour of the bump is not very strong (conversion from measured shower characteristics to primary energy is by no means a straightforward procedure) it must be considered as a distinct possibility: there is no *a priori* reason against it and, indeed, if the whole of the cosmic-ray spectrum is considered to be derived from sources of more than one type then something of this form might have been expected. If the spectrum of figure 1 is correct then the integral exponent is about -1.75 below *ca.* 3×10^{12} eV; about -1.0 between 2×10^{13} and 2×10^{14} eV and about -2.2 above 10^{16} eV.

Figure 2 shows the best line from figure 1 together with other measurements. The line marked Ryan, Ormes & Balasubrahmanyan (1972) refers to direct measurements using a balloon-borne

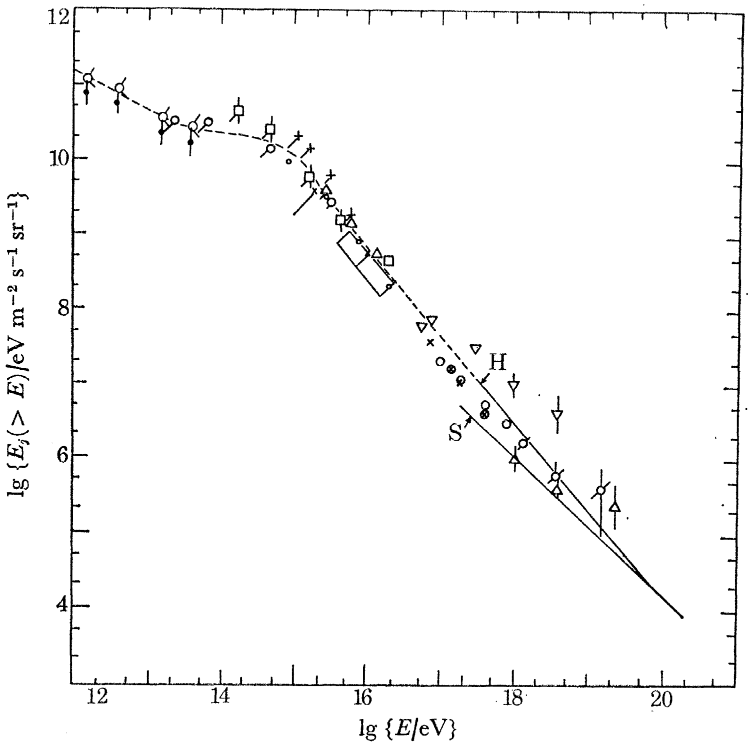


FIGURE 1. The integral spectrum of primary cosmic-ray nuclei (Kempa *et al.* 1974). The key to the experimental points is given in that work; briefly, the points below 2×10^{13} eV came from an examination of nuclear-active particle spectra as a function of atmospheric depth; H denotes the best line through the Haverah Park measurements of Edge *et al* (1973), S denotes the measurements of C. J. Bell *et al.* (1974). The dotted line is an estimate of the overall best line.

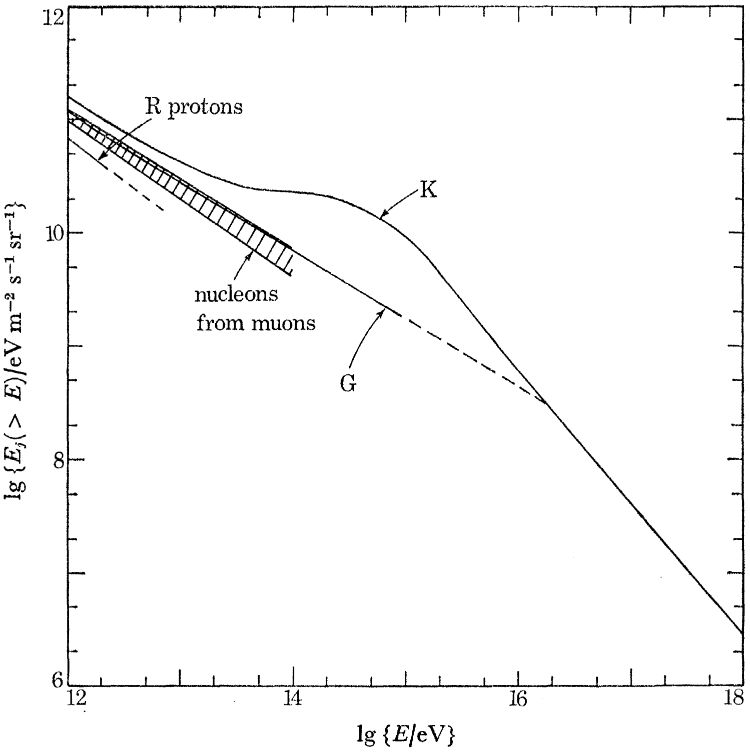


FIGURE 2. The integral spectra of primary nuclei, nucleons and protons from various experiments and treatments. See the text for details. R, Ryan *et al.* (1972); K, Kempa *et al.* (1974); G, Grigorov *et al.* (1970).

ionization spectrometer. Only the data for protons are shown – the line for all nuclei will be higher by a factor of about 2.2. 'Nucleons from muons' refers to a preliminary analysis by Erlykin & Wolfendale (1974) in which it is assumed that 'scaling' is valid in high energy interactions (Feynman 1969) at all energies. Conversion to a spectrum of nuclei requires an increase of intensity by about 1.7 if the composition remains unchanged from 10^{10} to 10^{14} eV. Neither the spectrum from Ryan *et al.* nor that from the muon data is inconsistent with the best line of Kempa *et al.*; the small discrepancy for the muon-derived spectrum at 10^{14} eV is easily explained in terms of a modest breakdown in the scaling model (Wdowczyk & Wolfendale 1973).

The spectrum given by Grigorov *et al.* (1970) is a different case. The data shown refer already to nuclei and it can be seen that there is a difference of a factor of 5 at 10^{15} eV. The Grigorov spectrum does indeed flatten a little at energies above 10^{13} eV but by no means sufficiently. The main reason for disregarding the Grigorov spectrum has been that the measurements indicate that above 10^{12} eV the flux of protons drops dramatically and that their place is taken by heavy nuclei. Such a change in composition would raise difficulties in explaining the constancy of the muon charge ratio (Daniel *et al.* 1974) and, furthermore, the discrepancy with the e.a.s. intensities would be even more dramatic because the latter intensities were calculated assuming an unchanged composition – heavy nuclei would need even higher primary intensities.

In the present work the spectrum of Grigorov is regarded as a lower limit to the actual situation.

2.2 *Conclusions about the form of the primary spectrum*

The best line of Kempa *et al.* complete with bump, should perhaps be regarded as giving an upper limit to the intensities in the region 10^{14}–10^{15} eV. The well-used spectrum of Greisen (1965) with its 'kink' at 3×10^{15} eV can be regarded as the 'middle way' and the spectrum formed by Grigorov's form to 2×10^{16} eV and the line of Kempa *et al.* at higher energies is the lower limit.

The important region above 10^{18} eV is considered in a later section.

2.3 *Anisotropies of arrival direction*

Although strictly out of place under the heading of spectral shape the question of the measured anisotropy is an important one if an effort is to be made to determine the origin of the primaries. Dickinson & Osborne (1974) have recently summarized the available data and have concluded that no significant anisotropy has been detected at any energy. Their upper limits to the anisotropy, $\delta = (I_{\max}-I_{\min})/(I_{\max}+I_{\min})$, are: 10^{-3}, 1.5×10^{-3} and 10^{-2} at primary energies 10^{13}, 10^{15} and 10^{17} eV.

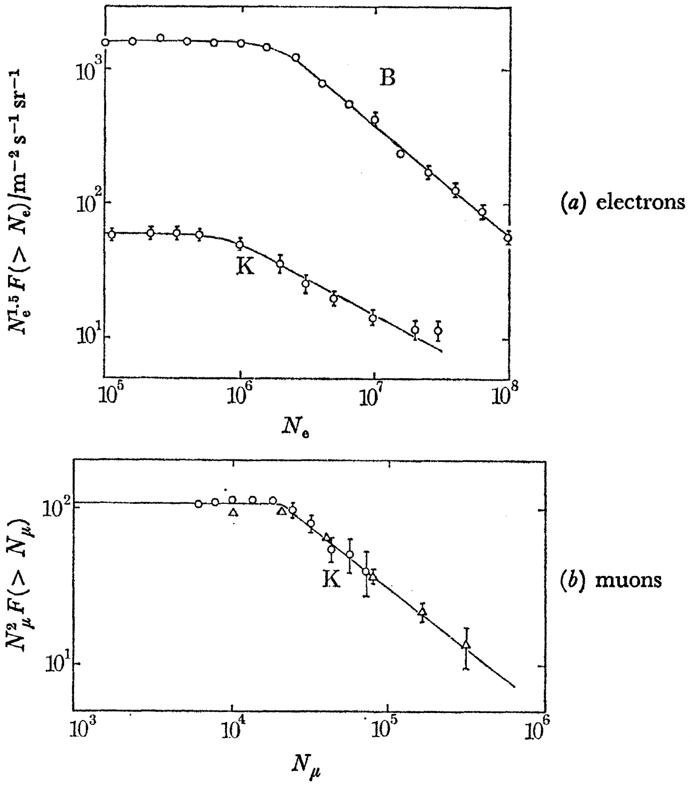
3. POSSIBLE EXPLANATIONS OF THE SPECTRAL SHAPE IN THE RANGE 10^{14}–10^{17} eV

3.1 *Galactic origin*

3.1.1. *Energy dependent diffusion*

Perhaps the most conservative approach to the origin of cosmic rays is to assume that the particles in question are generated in galactic sources with a constant spectral exponent and that the measured spectral shape is caused by a change in the diffusion coefficient with energy. This view has been advanced by many authors (e.g. Logunov & Terletskii 1956). The spectral shape most appropriate to such an explanation is that with a simple kink (§2.2) although a spectrum of the shape proposed by Kempa *et al.* (figure 1) could possibly also be accommodated. Whether or not there is an upturn, there certainly appears to be a rapid change of slope over quite a narrow range of energy. Figure 3 gives e.a.s. data which demonstrate the point rather clearly (data from these experiments have also contributed to the spectrum of figure 1).

The diffusion of cosmic rays in the Galaxy is a process of complexity and uncertainty, largely because of lack of adequate knowledge of the conditions (magnetic field distribution, etc.) in interstellar space. The problem has been treated by a number of authors. For example Skilling (1970, 1971) has studied the interaction of cosmic rays with resonant hydromagnetic waves in the interstellar plasma, a treatment that is particularly appropriate at energies below about 10^{13} eV. In the present work, where higher energies are concerned, interaction with the hydromagnetic waves would be expected to be small and, instead, interaction with larger scale magnetic field irregularities is more appropriate. The problem has been considered by the author and his colleagues (Bell, Kota & Wolfendale 1974) by taking data on the HI clouds which are known to exist in the interstellar medium (see Spitzer 1968, for a summary). In this treatment the radio astronomical measurements of Heiles (1967) and Ames & Heiles (1970), which give the frequency distribution of cloud radius (R) and corresponding hydrogen density (n_H), and the correlation of mean cloud field B_c with n_H from the work of Verschuur (1970), have been used to determine the frequency distribution of deflecting powers (B_cR) of the clouds. The result is the function shown in figure 4; the most probable radius is 2–3 pc (these small clouds are termed 'cloudlets' by Heiles). A difficult problem in this work is whether or not the



(*a*) electrons

(*b*) muons

FIGURE 3. (*a*) Integral size spectrum of electrons e.a.s. The data of Bradt *et al.* (B, 1965) refer to measurements at Mt Chacaltaya (atmospheric depth 540 g $\mathrm{cm^{-2}}$) and those of Khristiansen (K, 1972) are for sea level. (*b*) Integral size spectrum of muons in e.a.s. standardized to sea level.

distribution of clouds and cloudlets, which is only measured for a restricted region of the Galaxy, is sufficiently representative of the conditions in the Galaxy as a whole, or at any rate in the nearest several hundred parsecs. Bell *et al.* endeavoured to make some allowance for variations in number density distribution but considerable uncertainty remains.

Application of the results of figure 4 to the situation in a section of the local spiral arm some 2 kpc in length gives cosmic-ray lifetime versus proton momentum as shown in figure 5 ($B_1 = 0$).

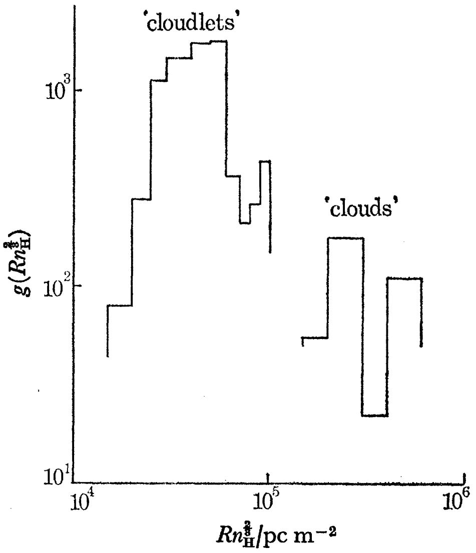


FIGURE 4. Frequency distribution of scattering powers ('power' $\propto RB$ i.e. $\propto Rn_{\mathrm{H}}^{\frac{2}{3}}$) for interstellar clouds. The data come from measurements by Heiles (1967), Ames and Heiles (1970) and Verschuur (1970).

It will be noted that the mean lifetime below $\sim 10^{16}$ eV/*c* is only about 10^4 years, a value almost certainly too small (see later) and, furthermore, above 10^{17} eV the 'geometrical limit' is reached, where the trajectories are virtually straight and very large anisotropies would be expected. Such anisotropies are not observed so that the model is unacceptable in the present form. Bell *et al.* point out that the presence of a large scale coherent field acting along the axis of the spiral arm, such as has been shown to exist in fact by a variety of measurements (see Karakula, Osborne, Roberts & Tkaczyk 1972, for a summary), improves the situation considerably. Figure 5 shows the effect of imposing a uniform axial field of magnitude B_1; the likely reversal of this field in crossing the galactic plane and the dependence of field on distance above the plane are not expected to alter the results appreciably. Measurements indicate that the effective value of B_1 is about 3×10^{-10} T. Inspection of figure 5 shows that the predicted kink in the spectrum will be at 5×10^{15} eV/*c*, not far from the 'observed value'. (Figure 2 shows that the position of the 'kink' is almost certainly in the range 5×10^{14}–2×10^{16} eV/*c*. The earlier work, such as follows from the data of figure 3, gave 3×10^{15} eV/*c* for the position.)

A further prediction of this model is that the lifetime of the protons below 10^{15} eV/*c* should be about 3×10^5 years, a value closer to the 2×10^6 years inferred from experimental data on the relative frequencies of various nuclear species at *ca.* 10^{10} eV/*c*. Some more comments are necessary on the question of lifetime before proceeding. Implicit in the calculated lifetime of 2×10^6 years is the assumption that the bulk of the matter traversed by particles is in interstellar space. In fact, a significant amount (and perhaps nearly all) may be traversed in comparatively high density regions close to the sources themselves. Thus the 2×10^6 years could be an overestimate (on the other hand, Dickinson & Osborne (1974) present arguments which could lead to the opposite conclusion). A further important point is the recent conclusion by Ramaty, Balasubrahmanyan & Ormes (1973) and others that the mean mass of material traversed by particles is falling with increasing energy above *ca.* 10^{10} eV. This argument appears well founded so that at the energies in question here ($> 10^{14}$ eV) the lifetime could well be less than 10^6 years and may indeed be close to the present prediction.

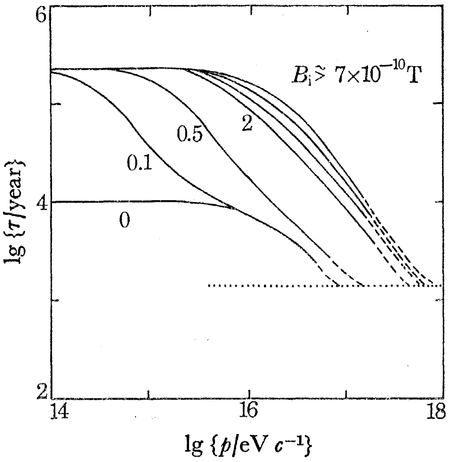


FIGURE 5. Mean lifetime against momentum for protons in a section of the local spiral arm. B_i is the magnitude of the mean longitudinal magnetic field.

Continuing to higher momenta, the fall-off in lifetime above 10^{16} eV/c would give a spectrum having a change in exponent not too far from that indicated in figure 1, at least as far as 5×10^{17} eV/c where the geometrical limit would cause a flattening in the spectrum if, as has been assumed so far, the sources have production spectra with constant exponents. A problem arises as the geometrical limit is approached: large anisotropies are predicted, but not observed.

The conclusion with respect to diffusion is that use of astronomical data gives directly a lifetime which is not inconsistent with experiment and a kink position rather close to observation but that the production spectrum must fall rather rapidly above *ca.* 5×10^{17} eV/c and some other (near isotropic) source distribution take over.

3.1.2. *Pulsar origin*

It is possible that pulsars give a significant contribution to the flux of primary cosmic rays, and indeed, it is attractive to attribute the 'bump' at *ca.* 10^{14} eV to pulsar-accelerated particles. This idea has been considered in detail by Karakula, Osborne & Wdowzcyk (1974) and by Wdowzcyk (1974) in these proceedings. The topic is not treated further in this section but will be returned to, briefly, later.

3.2. *Extra-galactic origin*

3.2.1. *Energy density considerations*

The advantage of assuming that the bulk of cosmic rays are of extragalactic origin is that it is then easy to understand the reason for their high degree of isotropy. The disadvantage is that the energy density of the primaries, *ca.* 1 eV cm^{-3}, is high and, if it pertains to the Universe it will represent an energy density exceeded only by matter itself. However, it should be pointed out that the primary intensity falls off rapidly with increasing energy and with it the energy density. Wolfendale (1973) quotes the energy densities given in table 1. There would appear to be little objection on energy density grounds to primaries of energy above 10^{12} eV or so being of extra-galactic origin.

3.2.2. *Enhanced cosmic-ray emission at early epochs*

Hillas (1968) has pointed out that the kink in the primary spectrum at 3×10^{15} eV could be explained if the primaries were produced predominantly at very early epochs (red shifts *ca.* 15). At these early times the universal black-body radiation was at a higher temperature and electron pair production from p–γ collisions would occur at lower energies than is the case at the present epoch. A suitable choice of parameters enables a production spectrum with constant integral exponent $\gamma_1 = -1.6$ to give the presently observed spectrum with its transition to $\gamma_1 = -2.2$ above 3×10^{15} eV.

TABLE 1. ENERGY DENSITY OF PRIMARY COSMIC RAYS

threshold energy/eV	10^{10}	10^{12}	10^{14}	10^{16}	10^{18}
energy density/eV cm^{-3}	3×10^{-1}	2×10^{-2}	7×10^{-4}	10^{-5}	3×10^{-8}

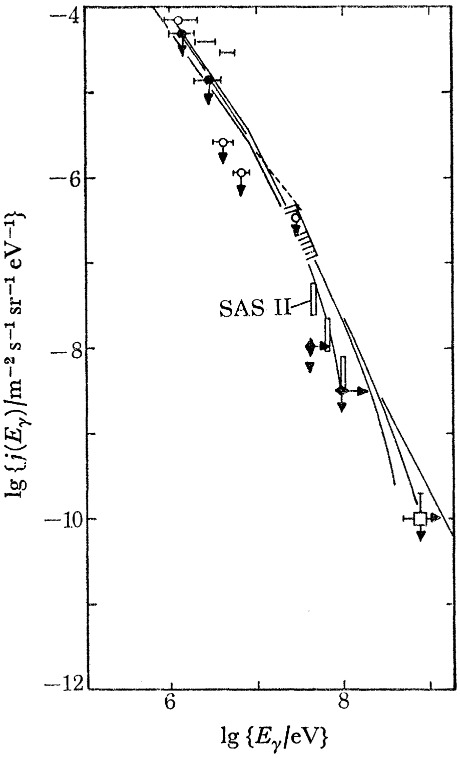


FIGURE 6. Comparison of observed and predicted isotropic intensity of γ-rays (Strong *et al.* 1974*a* – see this work for references to the experimental points and the significance of the different curves). New experimental intensities added are those from the SAS II experiment (Kniffen *et al.* 1973) and are represented by vertical boxes. The vertical extent of the boxes comprises a factor of 1.5 due to the then uncertainty in calibration.

Strong, Wdowczyk & Wolfendale (1973, 1974*a*) have examined the problem in more detail and have calculated the flux of γ-rays which would be expected to ensue from the cascade of electrons and γ-rays in space. The calculations assume that the density of non-stellar matter (i.e. matter not condensed in stars) is low enough so that a negligible amount of energy is lost by the cascade. This amounts to assuming an average density less than 3×10^{-9} atom cm^{-3}.

In fact, the density expected by averaging galactic gas over the whole of the Universe is about 2×10^{-9} atom cm^{-3} so that the present assumption requires a virtual vacuum between galaxies ($\rho \ll 10^{-9}$ atom cm^{-3}); such an assumption might appear unreasonable but there is, as yet, no evidence against it.

Using the primary spectrum with a kink at 3×10^{15} eV (and assuming that the primaries are virtually all protons) Strong *et al.* calculate that the total energy in the γ-ray spectrum will be about 1.7×10^5 eV cm^{-2} s^{-1} sr^{-1}. This is simply the energy taken out of the primary spectrum, i.e. that contained between spectral forms with $\gamma_1 = -1.6$ and $\gamma_1 = -2.2$ beyond 3×10^{15} eV. The mode of calculation is to consider the interaction between the initial electron pairs and the black-body radiation, by way of the inverse Compton effect and electron pair production in γ-ray – starlight photon interactions. The resulting predicted γ-ray spectrum is given in figure 6. It will be noticed that there is some uncertainty in the predictions due to problems concerning lack of detailed knowledge of the extra-galactic starlight spectrum and computational difficulties. However the divergencies are rather small where most of the experimental data are to be found.

Comparison of prediction with observation does not yet allow firm conclusion to be drawn because of divergences between the different sets of experimental points. A further point to be considered is that the initial proton spectrum, which gives the energy going into γ-rays, is not certain. Calculations for the upper and lower spectra referred to in §2.2 yield energy flows of 3.3×10^5 eV cm^{-2} s^{-1} sr^{-1} and 2.7×10^4 eV cm^{-2} s^{-1} sr^{-1} respectively. These can be compared with the value of 1.7×10^5 eV cm^{-2} s^{-1} sr^{-1} for the 'middle' spectrum referred to earlier. An estimate can be made of the energy flow actually observed by drawing a 'best line' through the experimental points and integrating. A problem arises in selecting a lower energy limit for the integration. Inspection shows a point of inflexion near 1 MeV and this energy has been used for the limit – it seems likely that lower energies (X-rays) are generated by some other process. The resulting energy flow is very approximately 8×10^4 eV cm^{-2} s^{-1} sr^{-1}.

In conclusion, the experimental isotropic γ-ray intensities are certainly of the order of magnitude of those expected on the proposed model; when more precise proton and γ-ray spectra are available it should be possible to make a firm decision on its validity.

3.3. *Mixed galactic and extra-galactic origin*

3.3.1. *General remarks*

A compromise solution to the origin problem would be to assume that the particles are derived from both galactic and extra-galactic sources. In so far as the Sun emits particles of energy as high as 10^{10} eV during solar flares, other stars and the Sun itself presumably contribute a significant very low energy flux. Other evidence in favour of a galactic contribution is the presence of electrons (and positrons) of energy up to 10^{12} eV, which cannot be of extra-galactic origin, and of very heavy nuclei. The observed high degree of isotropy (see §2.3) makes it almost obligatory to assume that primaries in the range 7×10^{17} eV and 10^{19} eV arise from extra-galactic sources (Osborne, Roberts & Wolfendale 1973), unless the nuclei are very heavy.

A 'reasonable' model would, perhaps, be one in which particles below about 10^{17} eV are galactic and those above are extra-galactic. However, in what follows we examine a model in which most particles are extra-galactic with a galactic contribution (from pulsars) mainly between 10^{14} and 10^{16} eV. As will be seen this model has certain attractive features.

3.3.2. *Pulsar and universal origin* (*no supercluster enhancement*)

Strong, Wdowczyk & Wolfendale (1974*b*) have recently shown that the primary energy spectrum of figure 1 can be explained in a straightforward way if it is assumed that there are protons produced throughout the Universe with a production spectrum having a constant exponent $\gamma_1 = -1.75$ to which are added pulsar-accelerated particles in the manner suggested by Ostriker & Gunn (1969). As remarked in § 3.1.2, the pulsar component has been considered by Karakula *et al.* (1974) and Wdowczyk (1974). It is perhaps remarkable that near absolute agreement with observation results from taking the Ostriker & Gunn predictions together with the residence time (10^6 years) derived from the 'direct' measurements at 10^{10} eV. In fact, as was mentioned in § 3.1.1, the actual lifetime is very uncertain and the agreement may be fortuitous.

Of greater interest is the possibility of the universal component. The usual objection to this idea is that there should be considerable distortion of the spectrum due to interactions with the 2.7 K black-body photons (Greisen 1966; Zatsepin & Kuzmin 1966). However, as will be seen, the black-body interactions can be instrumental in forming the correct spectral shape.

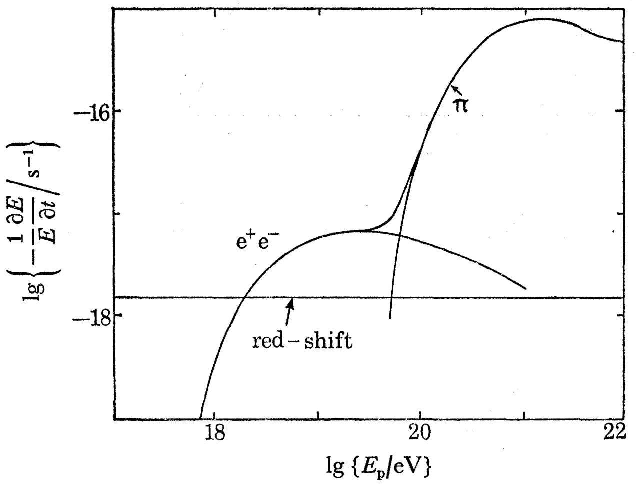


FIGURE 7. Fractional rate of energy loss of protons on the black-body radiation ($T = 2.7$ K). The curve for electron pair production comes from the calculations of Blumenthal (1970) and that for pion production is from Stecker (1968). The red-shift loss relates to a Hubble constant of 50 km s^{-1} Mpc^{-1} (Abell 1971).

Figure 7 shows the fractional energy loss of protons on the black-body radiation at the present epoch and the effect of the red shift. Strong *et al.* (1974*b*) have applied these data to protons originating at a constant rate in the Universe independent of red shift z and with the spectral exponent actually observed below 10^{12} eV and derived the spectrum shown in figure 8.

It is interesting to note that the predicted spectrum above *ca.* 5×10^{12} eV is rather close to the summary spectrum of figure 1 until about 7×10^{19} eV.

The important high energy region is examined in more detail in figure 9.

Of particular significance in the figure is a comparison of the prediction with the data of the Haverah Park experiment in so far as the Haverah Park spectrum accords well with the summary of figure 1. It can be seen that although most of the points agree well, the last point is significantly higher than predicted. However, three facts need to be borne in mind:

(i) zero counts in higher energy cells reduce the significance of the difference,

(ii) experimental errors in energy determination (Edge *et al.* 1973; Strong *et al.* 1974*b*) cause a flattening of the expected spectrum,

(iii) fluctuations in interaction point in the Universe and in the inelasticity of the proton–black-body photon interaction cause a small displacement to higher energy of the point at which the predicted spectrum starts to dip steeply.

Concerning the last mentioned point, Strong, Wdowczyk & Wolfendale (1974*c*) give the spectrum shown in figure 10; the effect of fluctuations is to cause the energy at which the intensity falls by a factor 2 over that expected for an extrapolation of the spectrum below 10^{19} eV

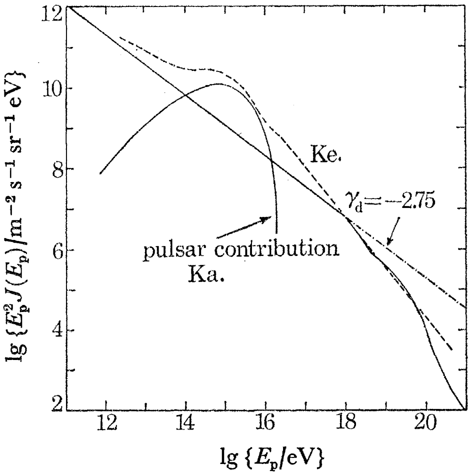


FIGURE 8. Comparison of the spectrum of figure 1 with a component derived from pulsars (Ka., Karakula *et al.* 1974) and one of universal origin (Ke., Kempa *et al.* 1974), the latter having a constant exponent with $\gamma_d = -2.75$ at production.

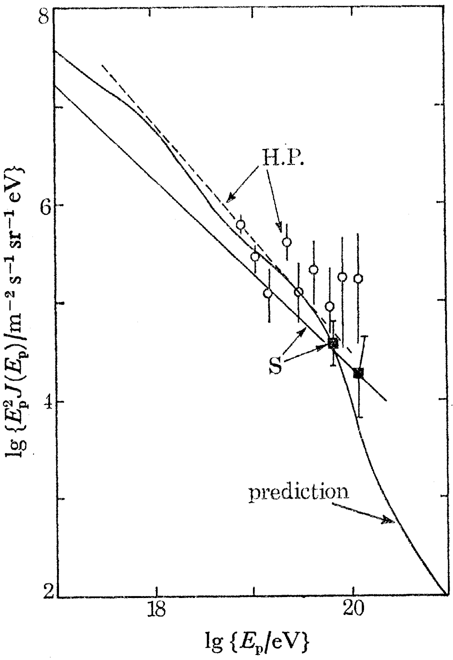


FIGURE 9. Comparison of the prediction of figure 8 with the experimental intensities determined by Edge *et al.* (1973) at Haverah Park (H.P.), and by C. J. Bell *et al.* (1974) at Sydney (S). The predicted spectrum has been calculated for a universal origin of energetic particles with a constant density of sources.

to higher energies, $E_{\frac{1}{2}}$, to increase from 7.9 to 9.2×10^{19} eV. Although such a displacement in energy is small it is important in view of the fact that the predicted intensity is falling so rapidly.

It can be concluded at this stage that the highest energy data are not inconsistent with expectation although if later measurements should confirm the trend exhibited by both the Haverah Park and Sydney data for a spectrum with no change in exponent then the conclusion would need to be reversed (however, see later). The weakest point in the argument is probably the energy region 3×10^{16}–3×10^{17} eV, where the predicted intensity appears to be significantly less than observed (see figure 8). It is possible that this region is filled by pulsar-accelerated heavy nuclei – the spectrum of such particles would be expected to be similar to that for protons, but displaced to higher energy. There is the possibility of checking this hypothesis by examination of the mass composition over the range 10^{14}–10^{17} eV. In fact, measurements of composition would be useful at all energies but, as is well known, such measurements are very difficult and have not yet proved possible.

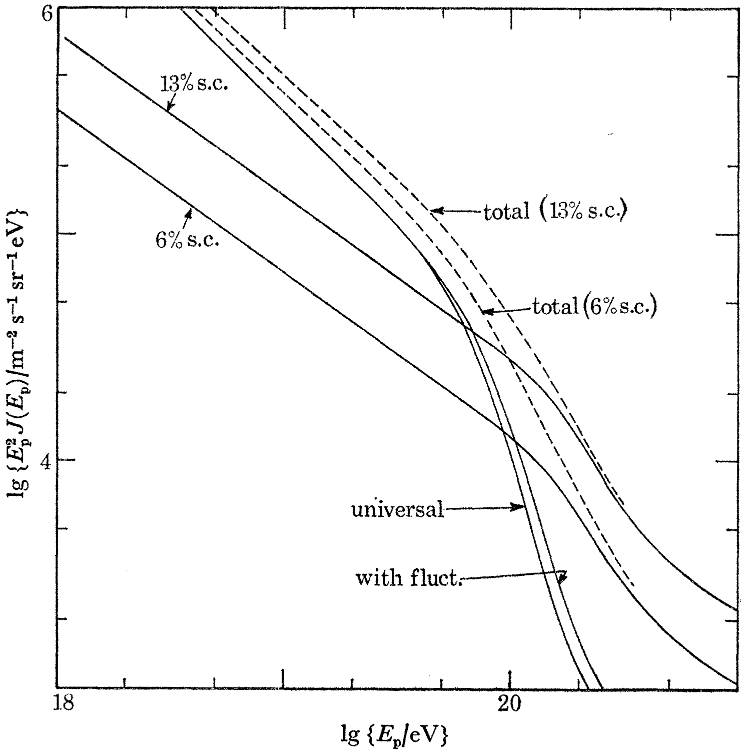


FIGURE 10. Predicted primary spectra for models in which the particles arise from extra-galactic sources. The 'universal' spectrum refers to the situation where the density of sources is uniformly distributed over the Universe; the effect of fluctuations is indicated for this situation. The dotted lines relate to the case where there is enhanced density of sources in the supercluster. The percentages refer to the ratio of the supercluster contribution to the rest of the Universe. For comparison with experimental data the spectra below 10^{18} would need to be normalized one to the other.

3.3.3. *Universal origin with supercluster enhancement*

Returning to the very highest energies, it is possible to reduce the predicted fall off in primary intensity above 6×10^{19} eV even with particles of universal origin if it is assumed that the extra-galactic sources are not uniformly distributed. For example, it would appear reasonable to assume that the particles are generated in particular types of galaxy (our own Galaxy not being of this type) which are distributed in the Universe in a manner proportional to the distribution of galaxies in general. If this is the case then the fact that we reside in a 'local' assembly of galaxies with a higher density of galaxies than the average universal density means that the cosmic-ray density will also be higher locally. A further consideration is the possibility of significant magnetic fields being present locally, which can cause trapping; this effect will be considered later. The absence of detectable anisotropies means that the local group of galaxies is probably not represented – a more acceptable region is the local supercluster (the Virgo supercluster; de Vaucouleurs, 1953). A number of authors have given surveys of astronomical data for the supercluster. Very recently Allen (1973) has summarized the data, using a value for the Hubble constant $H = 60$ km s^{-1} Mpc^{-1}: the distance to the important Virgo cluster is 19 Mpc and the average density appears to be about 0.5 galaxies Mpc^{-3}, compared with a mean universal value of *ca.* 0.02 galaxies Mpc^{-3}. The local density is thus some 25 times the average value and if the average linear distance over which this higher density acts is 20 Mpc, i.e. *ca.* 0.4 % of the Hubble radius, this means that, in the absence of any attenuation, about 10 % of the extra-galactic particles will come from the supercluster. Although this is a small fraction at energies below 10^{19} eV, at higher energies it achieves great importance because of the smaller attenuation caused by the black-body interactions. Calculations are presented in figure 10 for two supercluster fractions: 13 and 6 % (with respect to the contribution from outside the supercluster) which bracket the fraction derived earlier and which probably encompass the correct value. In the calculations, uniform production throughout a volume of radius $\approx$ 20 Mpc round the Galaxy has been assumed. The characteristic energy $E_{\frac{1}{2}}$ (see §3.3.2) is now higher: 1.6×10^{20} eV for 13 % supercluster contribution and 1.1×10^{20} eV for 6 % contribution.

When more extensive experimental data are available it should be possible to examine the hypothesis of supercluster enhancement by detecting very energetic primaries from specific energetic sources such as M87, i.e. to detect strong anisotropies.

Finally, some remarks are necessary about the possibility of significant magnetic fields in the supercluster. If the field is sufficient to ensure essentially complete trapping with a lifetime independent of energy then the situation is roughly that appropriate to simple universal origin (figure 19). This occurs because multiple traversals build up the necessary length of trajectory to produce black-body interactions. The average field necessary for such trapping is about 10^{-11} T. Such a field is probably much higher than is actually present. If a field is present, of smaller magnitude, then the spectral shape will be more complicated, showing an extra increase in intensity as one proceeds back to lower energies and trapping begins. An alternative explanation of the bump at 10^{14}–10^{15} eV is, in principle, possible in this way although the reduction in intensity below 10^{14} eV is difficult to understand, unless it is related in some way to difficulties in entry into the Galaxy by extra-galactic particles.

4. CONCLUSIONS

A variety of suggestions have been put forward in order to explain the measured shape of the cosmic-ray spectrum. That such a variety is possible is due to uncertainty in both the experimental data on cosmic rays and astronomical data. Hopefully, with continual improvements in each, it will be possible to choose between the models before too long.

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Discussion

E. W. Kellermann (*Department of Physics, Leeds University*). Professor Wolfendale has only mentioned the possible influence of composition of primaries on the shape of the spectrum. Could he give some more quantitative information? Have such calculations been carried out?

A. W. Wolfendale. Calculations are being carried out at present.