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Cosmic rays from galactic and extragalactic sources

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Abstract. A model is presented in which the bulk of the cosmic rays comprises two components: one, from galactic sources (probably pulsars) and the other having a universal, ie extragalactic, origin. Attention is directed particularly towards the particles above about 10^{17} eV which, like those below 10^{14} eV, are proposed to be of universal origin, it is shown that if these particles have a production spectrum having constant exponent (differential value $= -2{\cdot}75$) then interaction with the black-body radiation gives a spectrum at the earth not inconsistent with observation. In this model the extragalactic sources of cosmic rays do not increase in total number or in intensity at high red shifts.

1. Introduction

In a preceding paper (Kempa *et al* 1974) attention was directed towards examining the possibility that the energy spectrum of primary cosmic rays might have a constant exponent over the whole range 10^{10}–10^{20} eV. This possibility arose because direct measurements in the range 5×10^{10}–2×10^{12} eV (by Ryan *et al* 1972) gave a spectrum which, if extrapolated, produced intensities not far from those actually measured in the region of 10^{18} eV. It is in this energy region that contemporary ground-based extensive air shower detectors of large area are producing what are thought to be rather reliable results (particularly the work of Edge *et al* 1973, Bell *et al* 1974) whereas much of the work at lower energies (10^{14}–10^{17} eV) arose from what are probably less reliable observations, largely at mountain altitudes. However, the analysis indicated that there is a good measure of consistency between the various measurements below 10^{17} eV and it appears that the argument of a constant exponent is not tenable. Instead, the data appear to indicate the presence of a distinct 'knee' in the spectrum such that the modulus of the spectral exponent falls, reaches a minimum at about 2×10^{14} eV, and then increases again to reach a near constant value above about 10^{17} eV. The constant value amounts to $\gamma_d \simeq -(3{\cdot}0$–$3{\cdot}2)$ and is clearly higher than the initial value of around $-2{\cdot}75$ measured below 10^{12} eV. The initial reduction in exponent had, in fact, been suggested by some of the authors (Wdowczyk and Wolfendale 1973) when considering the interpretation of cosmic ray data in relation to models of high energy interactions.

In the present paper an attempt is made to explain the spectral shape given above and various consequences are discussed.

2. The spectrum below 10^{17} eV

It was pointed out by Karakula *et al* (1974) that the spectrum of primary cosmic rays up to 10^{17} eV could be understood as a superposition of two components. These are,

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a part due to pulsars, which dominates at energies 10^{14}–10^{16} eV, and a part with constant differential spectral exponent $\gamma_d = -(2{\cdot}7–2{\cdot}75)$ throughout. The spectrum due to pulsars was obtained on the basis of the theory developed by Ostriker and Gunn (1969) coupled with experimental data on pulsar frequencies and an assumed residence time of cosmic rays in the galaxy of 10^6 yr (equal to the value that appears to be the case at lower energies). The total spectrum obtained in this way produced a remarkably good measure of numerical agreement when the constant slope part was normalized to the observations in the range 10^{10}–10^{12} eV (the intensities of the pulsar spectrum come only from the factors referred to earlier, no arbitrary normalization has been applied). It is, of course, possible that the agreement is fortuitous because the acceleration theory based on pulsars has, no doubt, imperfections and, furthermore, the assumption of an energy independent residence time is rather *ad hoc*. However, pulsars remain a definite contender for that energy region.

In the present paper we analyse the possibility that the two-component model can also give agreement with the highest energy end of the primary spectrum, namely with the region 10^{17}–10^{20} eV. The immediate question which arises is that of the origin of the component having constant slope. In the paper by Karakula *et al* (1974) it was mentioned, without detailed arguments, that this part may be due to some sort of acceleration in supernovae. This mechanism, which is effectively galactic, would however give rise to anisotropies of arrival directions, inconsistent with experiment, when extended to the highest energies (above $\sim 10^{18}$ eV), as was demonstrated by Karakula *et al* (1972).

In what follows we will examine the idea under the old assumption that the bulk of the cosmic rays are of universal origin (with the exception of a fraction from galactic pulsars, having an energy density $\simeq 2{\cdot}5 \times 10^{-3}$ eV cm^{-3}—or a class of source having a similar energy spectrum—in the range 10^{14}–10^{16} eV) and that they are protons. The advantage of the idea is well known: an immediate explanation of the observed high degree of isotropy, as is the objection: the very great energy in the universe carried by cosmic rays (nearly 1 eV cm^{-3} everywhere). Another potential difficulty arising in the highest energy region is the apparent lack of the expected effect of the 2·7 K black-body radiation which should cause considerable attenuation for protons above 5×10^{19} eV (Greisen 1966, Zatsepin and Kuzmin 1966). However, it will be shown that this difficulty is not insurmountable and, indeed, over the range 10^{18}–5×10^{19} eV the black-body radiation is instrumental in forming the correct spectral shape.

3. Spectral shape expected for universal cosmic rays

The re-examination of the idea of a universal origin stems from the realization that, with the exception of the possible 'bump' in the region 10^{14}–10^{16} eV, the whole primary spectrum can be explained in terms of a production spectrum having a constant exponent throughout (and roughly equal to its directly measured value below 10^{12} eV). The observed shape of the spectrum above 10^{18} eV then arises because of the effect of interactions with the black-body radiation, primarily the effect of electron pair production in γ_{bb}–p interactions, which starts at about 10^{18} eV.

It should be remarked at this stage that some measure of explanation of the primary spectrum (assuming it to have $\gamma_d = -2{\cdot}6$ to $E_p = 3 \times 10^{15}$ eV and $\gamma_d = -3{\cdot}2$ above this energy) comes if, following Hillas (1968), it is assumed that the primaries originated mainly at large red shifts when the black-body temperature was much above the present

2·7 K. The 'kink' at 3×10^{15} eV then arises because of electron pair production at early epochs. Strong *et al* (1973) have, in fact, shown that the energy released into electron pairs can produce a 'cascade' in the universe which gives rise to an isotropic γ ray background spectrum not far from the experimentally observed spectrum. However, in the present work we present the results of an *alternative* suggestion—that the sources, which are of necessity extragalactic, do not have a strong red shift dependence. In this model, the observed γ rays would then need to come from some other mechanism.

If we assume that sources of cosmic rays do not vary in total number or intensity up to red shifts $z \sim 1$ and that the spectra at production can be described by a power law with a single exponent then, as a result of the modulation by interactions with the black-body radiation, the spectrum can be calculated if the attenuation length of the protons is known as a function of energy and if a value of the Hubble constant is adopted. A number of authors have calculated the fractional rate of energy loss per unit time, from which the attenuation length can be derived directly (eg Hillas 1968, Stecker 1968, Kuzmin and Zatsepin 1968, C Adcock 1970, private communication, Blumenthal 1970, Berezinsky *et al* 1973). The difference between the various treatments is small; for example, for the important case of pion production the energy at which the attenuation length is 10^{28} cm varies from 5·0 to $6{\cdot}5 \times 10^{19}$ eV when the calculated values are standardized to a temperature of 2·7 K (some were given for 3 K). In the calculations we have used the data of Blumenthal (1970) for electron pair production, and that of Stecker (1968) for pion production. No allowance has been made for the effect of a possibly significant energy density of infrared radiation (Berezinsky *et al* 1973, give the fractional rate of energy loss for an energy density of 0·1 eV cm^{-3}, assumed universal). If such an energy density were in fact present it would make the onset of pion production less dramatic (it is most important in the energy range 5×10^{18}–3×10^{19} eV); it is likely that the suggested model would still be a possibility if $|\gamma_d|$ were a little smaller. The fractional rates of energy loss adopted in the present work are shown in figure 1.

It is appropriate to comment at this stage on the significance of fluctuations in proton–photon collisions. Although negligible for electron pair production it is likely that they are important for pion production, particularly not far above threshold

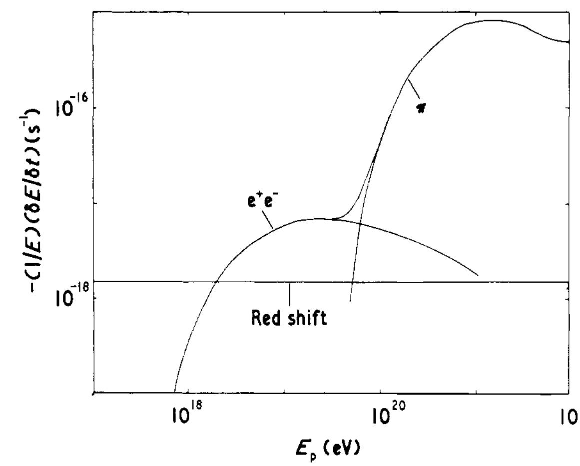

Figure 1. Fractional rate of energy loss of protons on the black-body radiation (T = 2·7 K) adopted in the present work. The curve for electron pair production is from the calculations of Blumenthal (1970) and that for pion production is from Stecker (1968).

($E_p \simeq 5\times10^{19}$ eV) both through fluctuations in distance between interactions and through fluctuations in inelasticity. As will be seen later, the energy at which pion production becomes important is crucial in deciding whether the particles above 10^{19} eV or so are of universal origin or not and we intend to look into the fluctuation problem in detail in a later publication.

In the calculations reported here, spectra with $\gamma_d = -2{\cdot}65$, $-2{\cdot}70$ and $-2{\cdot}75$ were taken and in each case the spectrum was normalized to an integral intensity $j(>10^{12}\,\text{eV}) = 1{\cdot}2\times10^{-5}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$. The 'latest' value of the Hubble constant: $50\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ was adopted (Abell 1971). The acceleration parameter q_0 was assumed to be zero.

Writing the fractional energy loss of figure 1 as

$$f(E) = \frac{1}{E}\frac{\delta E}{\delta t}$$

the problem reduces to solving the equation

$$\frac{\delta J}{\delta z}+\frac{\delta}{\delta E}\left(J\frac{\delta E}{\delta z}\right) = AE^{-\gamma}\frac{\delta t}{\delta z}$$

where

$$\frac{1}{E}\frac{\delta E}{\delta z} = \frac{1}{1+z}+(1+z)^3 f(E(1+z))\frac{\delta t}{\delta z}$$

for the present epoch: $z = 0$.

The differential spectrum is shown in figure 2 for the whole range of energy for one value of $\gamma_d(-2{\cdot}75)$ to show the effect of the black-body radiation. The pulsar contribution from the work of Karakula *et al* (1974) is also indicated, together with a rough

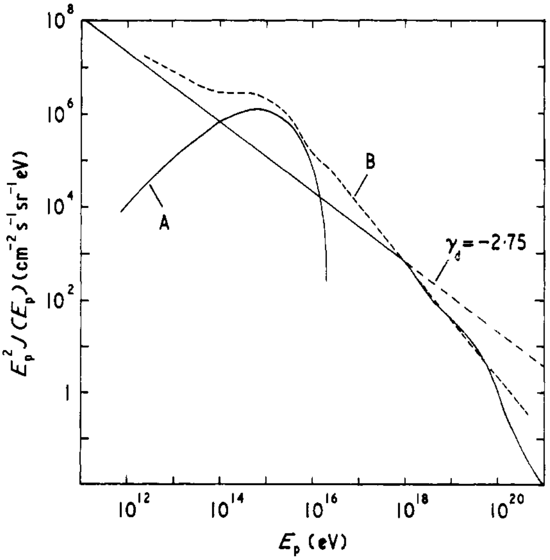

Figure 2. The derived 'universal' component of the primary proton spectrum for a production spectrum having $\gamma_d = -2{\cdot}75$. The production spectrum itself is also shown, together with the contribution from pulsars (A) according to Karakula *et al* (1974) and a 'best line' (B) drawn through the experimental data summarized by Kempa *et al* (1974). The energy density in the pulsar contribution is about $2{\cdot}5\times10^{-3}$ eV cm^{-3}.

indication of the 'best line' through the whole of the experimental data reported by Kempa *et al.* This figure indicates how the pulsar component (or a galactic component having similar energy spectrum) and the black-body modified universal component act together to give roughly the measured spectrum.

Integral spectra are shown in figure 3, where intensities from the summary given by Kempa *et al* (1974) are also given. The significance of these intensities is discussed in the caption to the figure.

Bearing in mind that the best estimates of the primary spectrum above 10^{17} eV are probably those from Sydney and Haverah Park (S and H), figure 3 indicates that best agreement is obtained with $\gamma_d = -2{\cdot}75$. This value is in remarkable agreement with the value of $-2{\cdot}75 \pm 0{\cdot}03$ directly measured by Ryan *et al* (1972) up to 10^{12} eV.

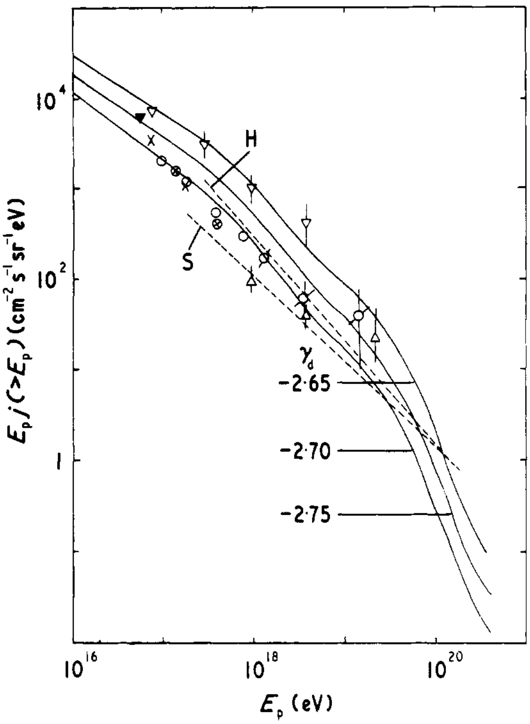

Figure 3. The integral spectrum above 10^{16} eV computed for three values of γ_d. The experimental points are from the summary of Kempa *et al* (1974). It should be pointed out that some, at least, of the spread in experimental points arises from the use of different models to convert from the measured quantity (lateral distribution of muons, electrons, etc) to the primary proton spectrum. It will be noticed that, apart from the work of Linsley (1973) the slopes of the various spectra are rather similar.

○ Krasilnikov (1973), as recalculated by Kempa *et al* (1974); ⊗ Clark *et al* (1963); △ Linsley (1973, Volcano Ranch data of 1963, preliminary re-analysis by Linsley); ▽ Aguirre *et al* (1973, and a later preprint). ▼ La Pointe *et al* (1968); S Sydney experiment (Bell *et al* 1974); H Haverah Park experiment (Edge *et al* 1973); × Khristiansen *et al* (1972).

4. Detailed discussion of the spectral shape at the highest energies

The experimental observations by the two largest EAS devices (Haverah Park and Sydney) show that the spectrum is consistent with the assumption of a constant slope up to the highest energy measured ($\sim 10^{20}$ eV). The question then arises: to what extent are the observations inconsistent with the spectrum expected on the basis of the present hypothesis? The situation is illustrated in figures 4 and 5. In figure 4 the experimental data are compared with direct predictions of the hypothesis and in figure 5 some allowance is made for inaccuracies in the shower size determination. The standard deviations for a logarithmic gaussian distribution (which was assumed as the distribution of errors in shower size determination) were taken as 0·10, 0·167, 0·25 for curves 1, 2, 3 respectively.

It can be seen in the figures that the experimental results are hardly in contradiction with the predicted spectrum without considering errors in size determination (see also the work by Edge *et al* 1973, on the effect of errors on the derived spectrum; similar analyses have been made by many other authors for other spectra; eg by Hayman and Wolfendale 1962 for muon spectra).

Where errors are included ($\sigma \sim 0{\cdot}25$ appears to us to be not unreasonable for the biggest showers) then the agreement between prediction and observation is quite good, particularly for the Haverah Park data.

5. Conclusions

It is apparent from what has been said that the primary cosmic ray spectrum can be described by the two-component model discussed here. Further precise measurements

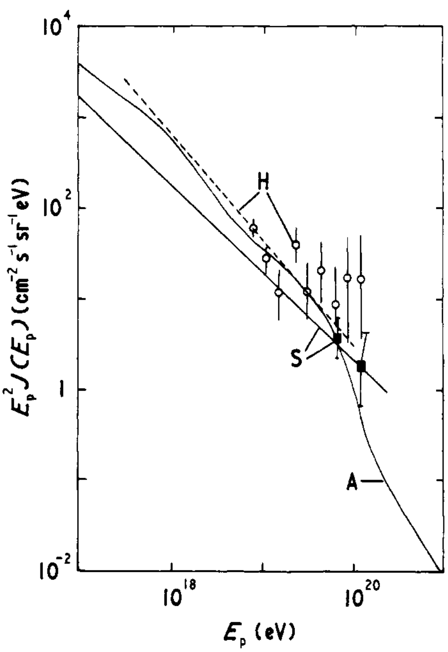

Figure 4. Comparison of the observed (H and S) and predicted (A) differential spectra. H and S refer to Haverah Park and Sydney; the open circles and the broken line come from the work of Edge *et al* (1973). The Sydney measurements are from the work of Bell *et al* (1974). In both cases the points at high energies alone are shown; at lower energies, where the statistical errors are small, the points lie along the respective straight lines.

The line marked A is the spectrum from the present work with $\gamma_d = -2{\cdot}75$. No allowance has been made for the effect of errors of measurement of shower energies.

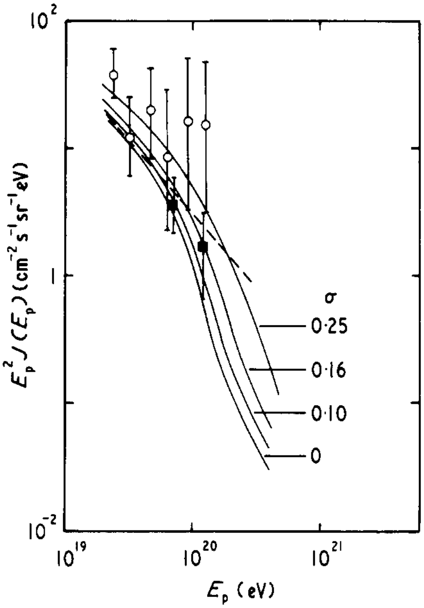

Figure 5. Comparison of the observed and predicted differential spectra above 10^{19} eV. The key to the experimental points is the same as that in figure 4.

The theoretical curves correspond to various values of σ, the standard deviation for the logarithmic gaussian distribution representing the uncertainty in shower energy measurement.

extending to somewhat higher energies than at present will be necessary before the idea of a universal origin for the particles above about 10^{17} eV can be rejected (by observation of the predicted fall-off intensity).

In fact, the idea of a universal origin may be even more difficult to disprove, for the following reason. In our calculations we have assumed that the distribution of sources of energetic particles is uniform over the universe but this may not be the case. If the sources (very energetic radio-galaxies?) follow the distribution of normal galaxies then the local groupings of galaxies ($\sim 10^4$ galaxies in the 'supergalaxy', of volume $\simeq 10^3$ Mpc^3) would give rise to particles of negligible attenuation below about 2×10^{20} eV. The result would be a smaller reduction in predicted intensity above 5×10^{19} eV than derived here. This problem will be examined in detail in a later publication.

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References

Abell G 1971 *Bull. Am. Astron. Soc.* **3** 49
Aguirre C *et al* 1973 *Proc. 13th Int. Conf. on Cosmic Rays, Denver* (Denver: University of Denver) pp 2598

Bell C J *et al* 1974 *J. Phys.* A: *Math., Nucl. Gen.* **7** 990–1009
Berezinsky V S, Grigoreva S I and Zatsepin G T 1973 *Proc. 13th Int. Conf. on Cosmic Rays, Denver* (Denver: University of Denver) pp 603–9
Blumenthal G R 1970 *Phys. Rev.* D **1** 1596–602
Clarke G *et al* 1963 *Proc. 8th Int. Conf. on Cosmic Rays, Jaipur* vol 4 (Bombay: TIFR) pp 9–23
Edge D M *et al* 1973 *J. Phys.* A: *Math., Nucl. Gen.* **6** 1612–34
Greisen K 1966 *Phys. Rev. Lett.* **16** 748–50
Hayman P J and Wolfendale A W 1962 *Proc. Phys. Soc.* **80** 710–28
Hillas A M 1968 *Can. J. Phys.* **46** S623–6
Karakula S, Osborne J L, Roberts E and Tkaczyk W 1972 *J. Phys.* A: *Gen. Phys.* **5** 904–15
Karakula S, Osborne J L and Wdowczyk J 1974 *J. Phys.* A: *Math., Nucl. Gen.* **7** 437–43
Kempa J, Wdowczyk J and Wolfendale A W 1974 *J. Phys.* A: *Math., Nucl. Gen.* **7** 1213–21
Khristiansen G B *et al* 1972 *Proc. 3rd Eur. Symp. on EAS, Paris*
Krasilnikov D D 1973 *Proc. 13th Int. Conf. on Cosmic Rays, Denver* (Denver: University of Denver) pp 2393–7
Kuzmin V A and Zatsepin G T 1968 *Can. J. Phys.* **46** S617–9
La Pointe *et al* 1968 *Can. J. Phys.* **45** S68
Linsley J 1973 *Proc. 13th Int. Conf. on Cosmic Rays, Denver* (Denver: University of Denver) p 2506
Ostriker J P and Gunn J E 1969 *Astrophys. J.* **157** 1395–417
Ryan M J *et al* 1972 *Phys. Rev. Lett.* **28** 985–8
Stecker F W 1968 *Phys. Rev.* **21** 1016–8
Strong A W, Wolfendale A W and Wdowczyk J 1973 *Nat. Phys. Sci.* **241** 109–10
Wdowczyk J and Wolfendale A W 1973 *J. Phys.* A: *Math., Nucl. Gen.* **6** 1594–611
Zatsepin G T and Kuzmin V A 1966 *Sov. Phys.–JETP* **4** 114–7