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Cosmic ray origin above 10^{17} eV

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Abstract. An analysis is made of the implications of assuming an extragalactic origin for cosmic rays above 10^{17} eV. The effect of the black-body radiation on the propagation of extragalactic protons is examined in some detail and the expected spectral shape is derived for alternative assumptions about the origin and confinement of the particles. The possibility of distinguishing between various models using contemporary extensive air shower arrays is considered.

1. Introduction

In a previous paper (Strong *et al* 1974, to be referred to as I) we examined a possible model for the origin of the bulk of the cosmic radiation in which the particles (protons) were considered to come largely from galactic pulsars together with a universal component. On this model the universal component dominates above about 10^{17} eV and in the present paper we consider this region in more detail.

The need for extragalactic particles at the highest energies (above $\sim 10^{18}$ eV) is well known: it arises because of their apparent isotropy of arrival directions (as indicated by the measured directions of the resulting extensive air showers) whereas galactic particles would be expected to show a pronounced anisotropy. For example, Osborne *et al* (1973) using what is probably a reasonable model for the magnetic field in the galaxy showed that, if the primaries are protons, then the majority between 7×10^{17} eV and 10^{19} eV must be of extragalactic origin.

The usual objections to an extragalactic origin lie in the high energy density of cosmic rays in the universe which would result if the particles were 'uniformly' distributed and the apparent lack of the expected cut-off at about 6×10^{19} eV due to the effect of the universal black-body radiation (Greisen 1966, Zatsepin and Kuzmin 1966).

The first problem can be overcome in two ways: by assuming that only the more energetic primaries are extragalactic or by taking a model in which there is confinement in the galactic systems within the universe, eg the supercluster (Brecher and Burbidge 1972). Regarding the former, the summary by Wolfendale (1973) gives the following energy densities for the corresponding threshold energies: $1\ \mathrm{eV\,cm^{-3}}$ (10^8 eV), $3\times10^{-1}\ \mathrm{eV\,cm^{-3}}$ (10^{10} eV) and $10^{-2}\ \mathrm{eV\,cm^{-3}}$ (10^{12} eV). The last mentioned energy density would be regarded by many as not being too extravagant on a universal scale.

Turning to the effect of the black-body radiation, this will be considered in detail in the next section.

The form of the paper is first to examine the expected shape of the production spectrum and to follow this with a discussion of interactions with the black-body

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radiation. Then there is an examination of the predicted primary spectrum for various extragalactic source distributions together with a comparison with such experimental data as are available and an indication is given of the likelihood of experimental arrays allowing distinction to be made between classes of models.

2. The effect of the black-body radiation on the spectrum of extragalactic protons

2.1. Spectral form of the production spectrum

The measured spectra of various cosmic ray components, protons, electrons etc are observed to have the form $N(E)\,\mathrm{d}E = AE^{-\gamma_d}\,\mathrm{d}E$ with a differential exponent, $-\gamma_d$, roughly independent of energy over quite wide ranges of energy—at least several orders of magnitude. In consequence it has become conventional to regard the near constancy of γ_d as the norm and indeed, in I, it was shown that a production spectrum of extragalactic protons having a constant exponent over the very wide range 10^{10}–10^{20} eV could give some measure of explanation of the shape of the observed primary spectrum, which has γ_d nearly constant for about four decades below 10^{14} eV and again, with a different value, for 3 or 4 decades above 10^{16} eV.

As is well known, the Fermi-type acceleration mechanism (Fermi 1949), in which particles gain energy from collisions with moving 'clouds' of magnetized gas, gives rise to a production spectrum with an energy independent exponent. The essential prerequisites are as follows:

(i) an exponential rise in particle energy E with time t; the rate of increase of energy is $\mathrm{d}E/\mathrm{d}t = \alpha E$, giving $E = E_0 \exp \alpha t$;

(ii) an exponential distribution of periods for which the particles are accelerated before being lost, $w(t) = (1/T) \exp(-t/T)$; and

(iii) constant particle injection and acceleration conditions over the time necessary for a particle to acquire the maximum observed energy. The result is an energy spectrum of generated particles: $N(E) \propto E^s$ with $s = -[1+(1/\alpha T)]$.

Ginzburg and Syrovatsky (1964) have examined a variant of the model in which fluctuation effects are included (such as fluctuations in path length of particles in regions of rising and falling magnetic fields). They conclude that the spectrum is, again, of power law form. These workers have also examined the spectral shape expected in the general situation of particles leaking from a confined plasma, such as a supernova shell or the central region of a radio galaxy. Arguments are presented for an equality of the energy densities in cosmic rays (W_c), magnetic field (W_H) and turbulent gas motion (W_T) and it is shown that the differential spectrum of particles leaving the system is $N(E) \propto E^{-2.5}$ (it is assumed that the actual injection spectrum has a steeper spectrum). If there is a divergence from equipartition such that the energy density in cosmic rays is some constant δ times the remainder then the spectral exponent becomes $-(2+\delta)$.

From what has been said, therefore, there is an *a priori* reason for adopting trial production spectra (ie spectra of cosmic rays escaping from the acceleration regions), which are of the simple power law form. Such an approach can be regarded as a conservative one although it is realized that different sources might well produce spectra with different exponents and for any one source there will be an energy above which the simple power law form breaks down. The simplest model for extragalactic particles is, therefore, one in which γ_d is constant over the whole range of energy, as was used in I, and has been referred to already.

2.2. Energy loss of protons in black-body photon interactions

A number of treatments have been carried out to determine the mean rate of energy loss of protons in the radiation field, by way of electron pair production and pion production. For the most important region, above 10^{19} eV, only the last mentioned is important and attention will be confined to it. So far, a number of workers have calculated the average fractional rate of energy loss, $(-1/E)(\partial E/\partial t)$, under various approximations. Figure 1 gives a comparison of the calculations. In this figure, the predictions have been converted to a standard temperature of 2·7 K where other temperatures had been adopted by the authors. It will be noted that the discrepancies are not large although it should be pointed out that, in view of the rapidly falling primary energy spectrum, a knowledge of the accurate shape of the energy loss curve is important.

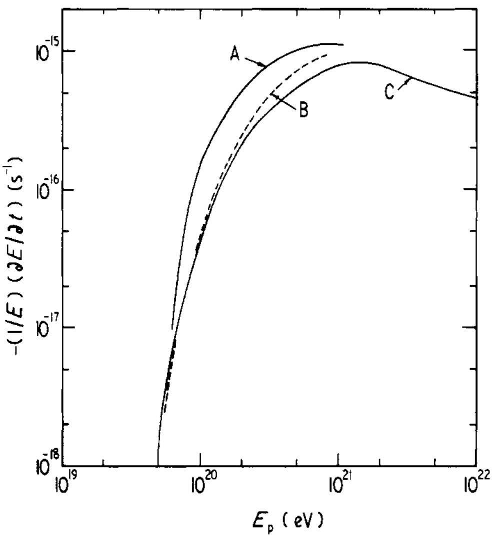

Figure 1. Comparison of the predictions of various authors for the fractional rate of energy loss of protons (by way of pion production) in the 2·7 K radiation field. A, Zatsepin and Kuzmin (1968); B, Adcock and Tkaczyk (1969); C, Stecker (1968).

We regard the work of Stecker (1968) for the mean rate of energy loss in pion production and that of Blumenthal (1970) for the mean energy loss in electron pair production as being most accurate and these will be adopted.

2.3. Effect of fluctuations on the resulting spectral shape

The object of the present work is to take a production spectrum of protons having a constant exponent and to calculate the expected spectral shape after the particles have passed through the universe, ie the expected shape of the primary spectrum at earth. It is assumed that the number and intensity of the sources are not dependent on the red-shift z. The expected shape neglecting fluctuations was considered in I; here fluctuation effects are included.

Fluctuation effects pervade the whole of cosmic ray physics, largely because of the presence of rapidly falling energy spectra, and the present situation of proton–black-body photon interactions is no exception. To our knowledge allowance for fluctuation effects has not been considered by previous authors.

Consider a source of protons at a distance x interaction lengths from the observer (the source being considered as a spherical shell with the observer at the centre). For continuous losses, $(-1/E)(\partial E/\partial x) = K$, then the intensity will change with x as

$$I(x) = I(0)\exp-(xK\gamma_{\mathrm{i}}) \tag{1}$$

where $-\gamma_{\mathrm{i}}$ is the exponent of the integral production spectrum.

For discontinuous losses, ie interactions which occur infrequently but in which there is a significant loss of energy, $-\Delta E/E = K\Delta x$, then the expression will be different. The distinction between the interaction length λ_{i} and the corresponding absorption length λ_{a} for a spectrum of integral exponent $-\gamma_{\mathrm{i}}$, is well known:

$$\frac{\lambda_{\mathrm{i}}}{\lambda_{\mathrm{a}}} = 1-(1-K)^{\gamma_{\mathrm{i}}} \tag{2}$$

where K is now the inelasticity in an individual interaction (eg Cranshaw and Hillas 1959, Ashton 1973). Application to the present situation yields:

$$I(x) = I(0)\exp\{-x[1-(1-K)^{\gamma_{\mathrm{i}}}]\}. \tag{3}$$

This formula is appropriate to the situation where the interaction length is constant; in fact it varies with energy, as can be seen in figure 1. Over a reasonable range of energy it can be written

$$\lambda_{\mathrm{i}}(E) = \left(\frac{E}{E_0}\right)^{-a}\lambda_{\mathrm{i}}(E_0), \tag{4}$$

where a and E_0 are constants, derived from figure 1, and the relations for the continuous and discontinuous processes are:

$$I(x) = I(0)\exp[-xK(\gamma_{\mathrm{i}}+a)] \tag{5}$$

$$I(x) = I(0)\exp\{-x[1-(1-K)^{\gamma_{\mathrm{i}}+a}]\}. \tag{6}$$

(As expected, (6) reduces to (5) if $K \ll 1$.)

The expressions can be applied to the case in point where cosmic rays are derived from extragalactic sources, distributed uniformly. It is convenient to work out the ratio of the expected intensity when fluctuations are included, I_{f}, to the result of the usual procedure where they are not, I_{nf}.

The ratio follows as:

$$R = \frac{I_{\mathrm{f}}}{I_{\mathrm{nf}}} = \frac{\int_0^\infty \exp\{-x[1-(1-K)^{\gamma_{\mathrm{i}}+a}]\}\,\mathrm{d}x}{\int_0^\infty \exp[-xK(\gamma_{\mathrm{i}}+a)]\,\mathrm{d}x} = \frac{K(\gamma_{\mathrm{i}}+a)}{1-(1-K)^{\gamma_{\mathrm{i}}+a}}. \tag{7}$$

(When $K \ll 1$, $R \to 1$, as required.)

Fluctuations in inelasticity coefficient must also be considered. These fluctuations can be seen most simply in the case of single pion production ($\mathrm{p}+\gamma \to \mathrm{p}+\pi^0$); for identical collisions, if the proton is emitted in the forward direction (in the C system) the elasticity is low whereas if it is in the backward direction it is high. Stecker (1968) has examined the interaction in some detail and has given the mean inelasticity $\overline{K}$ against effective photon energy (energy as seen by the proton). To sufficient accuracy the frequency distribution of K can be written as $f(K)$ = constant for $0 < K < 2\bar{K}$ and $f(K) = 0$ above $2\bar{K}$. Equation (2) must now be rewritten as

$$\frac{\lambda_i}{\lambda_a} = 1 - \int_0^1 (1-K)^{\gamma_i} f(K)\,\mathrm{d}K \tag{8}$$

$$= 1 - \frac{1-(1-2\bar{K})^{\gamma_i+1}}{2\bar{K}(\gamma_i+1)} \tag{9}$$

for the form of $f(K)$ adopted.

The final ratio is thus:

$$R = \frac{2\bar{K}^2(\gamma_i+a)(\gamma_i+a+1)}{2\bar{K}(\gamma_i+a+1)+(1-2\bar{K})^{\gamma_i+a+1}-1}. \tag{10}$$

3. Predicted proton spectra for various source distributions

3.1. Uniform density throughout the universe

An immediate problem that arises with extragalactic origins is to know the extent to which the particles are truly universal. In view of the lack of any specific information about the actual sources it is necessary to examine a variety of possibilities. Of these, the simplest is that the sources are distributed uniformly throughout the universe and that there is no red-shift dependence of source strengths or frequencies.

In the absence of fluctuations, for sources uniformly distributed throughout a radius R the intensity will be, from equation (1),

$$I(0, R) = \int_0^R I(x)\,\mathrm{d}x = I_0 \int_0^R \exp(-K\gamma_i x)\,\mathrm{d}x = \frac{I_0}{K\gamma_i}[1-\exp(-K\gamma_i R)]. \tag{11}$$

It was with the solution of this problem for a source distribution which was independent of red-shift z, but which had an energy loss factor K, which was a function of z (due to increase in black-body temperature) that the previous paper by the authors (I) was concerned.

It is useful to note that the form of the expected spectrum can be calculated approximately using the form of K as a function of proton energy $K(E)$ (eg figure 1 in I) and assuming a static universe. Thus, if we assume a uniform source density throughout a volume of radius R, then, from equation (11), the spectral shape attenuation factor is given approximately by

$$F_a(E) = \frac{K_0[1-\exp(-K(E)\gamma_i R)]}{K[1-\exp(-K_0\gamma_i R)]},$$

where K_0 is the value of K for red-shift alone.

Figure 2 shows a comparison of the accurate attention factor $F(E)$ derived in *I* with $F_a(E)$. As remarked in § 2.2, the calculations in I used the energy loss data given by Stecker (1968) and Blumenthal (1970).

The usefulness of the approximate relation is that a rough spectral shape for the expected primary spectrum can be determined rather easily for various circumstances, eg a changed value of the Hubble constant or primary nuclei heavier than protons.

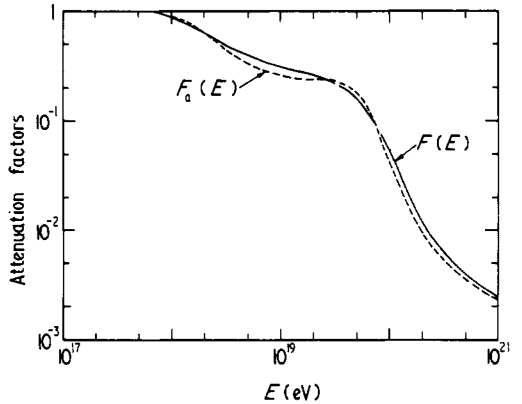

Figure 2. Comparison of accurate and approximate attenuation factors, $F(E)$ and $F_a(E)$, by which the differential production spectrum of protons should be multiplied to give the expected primary spectrum. Fluctuation effects are not included.

The accurate calculations referred to in I give rise to the primary spectrum shown in figure 3, for the case of a universal production spectrum having differential exponent $-2{\cdot}75$ (the spectrum is thus $F(E)E^{-2{\cdot}75}$). The correction factor for fluctuations (equation (10)) has been calculated for this situation (over most of the energy region of importance, $\bar{K} \simeq 0{\cdot}2$, although its exact value is not important), allowance having been made for the region below 6×10^{18} eV where continuous losses predominate. It can be seen that although the difference between the two treatments is not large it is significant, particularly in view of the fact that experimental data are becoming very sparse, as energy increases in this region.

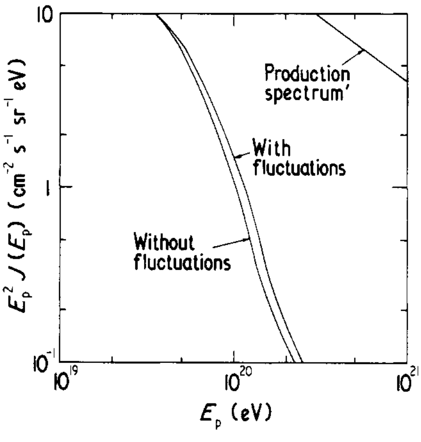

Figure 3. The differential spectrum expected for extragalactic protons where the sources are distributed uniformly throughout the universe. The effect of fluctuations in interaction points and in inelasticity is indicated.

3.2. Production density proportional to matter density

Perhaps a more reasonable assumption to make concerning the sources of extragalactic cosmic rays is to consider that they are grouped according to matter density. This means that, since the galaxy is in a 'local' assembly with a higher density of galaxies than the average universal density, the cosmic ray density will also be higher locally. It is clear that this idea cannot be pushed too far; because large anisotropies of arrival directions have not been seen it is necessary to assume that significant sources of very high energy cosmic rays are not to be found in our own galaxy or in the local group.

A more acceptable assembly is the supercluster (Brecher and Burbidge 1972), and this will be considered. A number of authors have given surveys of astronomical data for the supercluster. For example, Ginzburg and Syrovatsky (1964) quote a volume of 10^{77} cm^3 (oblate spheroid: 30 Mpc major axis, 6 Mpc minor axis) containing 10^4 galaxies and with a mass density about 20 times the universal density of galaxies. On this scale, the distance to the important Virgo cluster of galaxies is 11 Mpc. A more recent value comes from de Vaucouleurs (1970) who obtains a distance modulus for M87 (in Virgo) corresponding to 18 Mpc. Using the latest data of Allen (1973), who adopts a value of the Hubble constant, $H = 60\,\text{km s}^{-1}\,(\text{Mpc})^{-1}$, the mass density appears to be about 0·5 galaxies Mpc^{-3} compared with the mean universal value of about 0·02 galaxies Mpc^{-3}, ie a factor 25 higher.

Adopting the most recent values, the average linear dimension over which the higher density acts is about 20 Mpc, ie about 0·4% of the Hubble radius. Coupled with the factor of 25 for the 'local' density this would mean that, in the absence of attenuation, approximately 10% of the primaries would come from sources within the supercluster. Although this is a small contribution at energies below 10^{19} eV, at higher energies it achieves greater importance because of the smaller attenuation caused by black-body interactions for the more local sources. Calculations have been made for two supercluster fractions: 13% and 6%, which bracket the 10% just mentioned and which probably encompass the correct value. Attenuation appropriate to a sphere of radius 20 Mpc has been allowed for. This would refer to sources distributed roughly uniformly through the supercluster.

The importance of the enhancement from the supercluster at energies above 10^{20} eV is seen to be very marked.

At this point it should be remarked that although small ($\simeq 10\%$) the contribution of supercluster particles to the general flux below 10^{18} eV might be expected to give rise to a significant anisotropy in arrival directions because of the off-central position of the galaxy in the supercluster. However, the effect of the galactic magnetic field is almost certainly to smear out such an anisotropy in this energy region.

3.3. Effect of magnetic fields

It is conceivable that there are significant magnetic fields in the universe in general and the supercluster in particular, which act so as to trap cosmic rays significantly. For example, a field of 10^{-7} G causes a proton of momentum 10^{20} eV/c to have a radius of curvature of 1 Mpc. If field irregularities within the supercluster were such as to give mean free paths for diffusion of the order of 0·3 Mpc then within the supercluster, of radius about 20 Mpc, the lifetime of a particle would approach H_0^{-1}. If these irregularities could scatter particles of momentum as high as 10^{20} eV/c then all particles would have essentially the same lifetime and the expected spectrum would be the same as that for no trapping at all, ie a rapid fall of intensity above 8×10^{19} eV/c (figure 4), the point being that the random path followed by the particles would give the required length for significant pion production by interaction with the black-body radiation.

Brecher and Burbidge (1972) have examined the problem of supercluster origin in some detail. At the time of their work, it was thought that there was a flattening in the

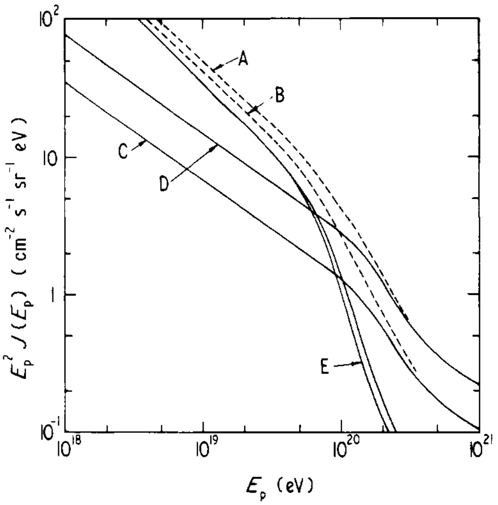

Figure 4. Differential proton spectra expected for extragalactic protons where the source density is proportional to the density of galaxies. Two supercluster fractions are considered: 13 % and 6 %. It seems likely that the correct fraction is in this range. An effectively uniform distribution of sources throughout a sphere of radius 20 Mpc is assumed. A, total (13 % supercluster); B, total (6 % supercluster); C, 6 % supercluster; D, 13 % supercluster; E, universal.

primary spectrum at about 10^{18} eV/c and they interpreted this as indicating that higher energy particles were of truly universal origin, those of lower energy being largely of origin in the Virgo supercluster. The region below 10^{16} eV/c corresponded essentially to slow diffusion of particles within the supercluster and the region 10^{16}–10^{18} eV/c to more rapid diffusion. The authors showed that the mean free path for intra-supercluster scattering could well give a transition momentum of 10^{16} eV/c and the whole model therefore had a certain appeal. The contemporary view, however, is that there is no appreciable flattening above 10^{18} eV/c (eg Edge *et al* 1973) and so the model loses an attractive feature. Despite this, the possibility still remains that there is a transition from trapping to inefficient trapping at some momentum p_1 below 10^{20} eV/c in which case the calculations reported here are not valid.

It is conceivable that the model of Brecher and Burbidge is still correct, ie efficient trapping within the supercluster below about 10^{16} eV/c and reduced efficiency for trapping and thus a steeper spectrum above 10^{16} eV/c. In this case, however, an *ad hoc* explanation of the actual change of spectral shape (a change of γ_d of about 0·6) is necessary. Furthermore, with a negligible contribution from outside the supercluster large anisotropies might be expected to occur, above about 10^{19} eV/c, where the galactic field 'smearing' should be small, and these are not seen.

4. Comparison with experimental data

4.1. *Anisotropies of arrival directions*

The general problem of anisotropies is outside the scope of the present work but a few remarks will be made. As was mentioned in I, there is no firm evidence for an anisotropy of arrival directions at any energy and the present region, ie above 10^{17} eV, is no exception. Returning to the situation in which extragalactic magnetic fields are absent, it should be possible to distinguish between the truly universal model and one in which there is supercluster enhancement, by searching for discrete sources in the supercluster (eg in the Virgo cluster). As already remarked, the effect of galactic magnetic fields, which are known to be present, probably precludes the identification of the contribution ($\sim 10\%$) from the supercluster below about 10^{19} eV/c but at higher momentum such identifications should be possible.

The studies that have been made (eg by Linsley and Watson 1974) do not show any positive identifications but the statistical accuracy is not yet good enough to pronounce for, or against, supercluster enhancement. The main problem is that, as can be seen from figure 4, the supercluster dominates only above about 10^{20} eV.

4.2. Shape of the energy spectrum

This problem was considered in some detail in I and it was concluded that the experimental data presently available, although not inconsistent with a primary spectrum of constant slope to at least 10^{20} eV, were probably not inconsistent with a truly universal shape (figure 4). This arose because of problems concerned with both random and systematic errors in primary energy determination. In the present work, where the inclusion of fluctuations delays, slightly, the energy at which the fall off in intensity should become noticeable, the conclusion is reinforced.

With increased precision of energy determination and improvement in statistical accuracy it should be possible to distinguish between the 'universal' model and '10% supercluster' model. With a somewhat smaller improvement in accuracy distinction should be possible between a spectral shape with accurately constant exponent (such

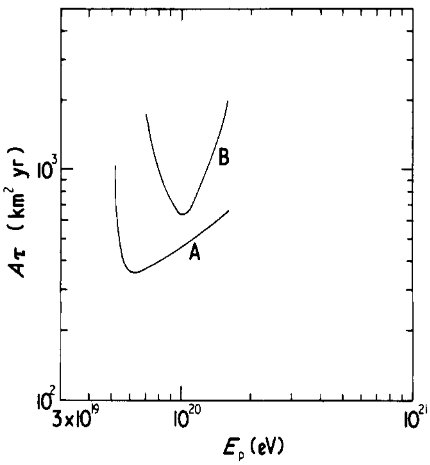

Figure 5. Product of area and running time of EAS arrays, $A\tau$, necessary to enable a distinction to be made between primary spectra having: (i) a constant exponent; and (ii) a variable exponent appropriate to a uniform distribution throughout the universe (figure 3). Two situations are considered: A, $\sigma = 0$, corresponding to no error in primary energy determination; B, $\sigma = 0{\cdot}17$, corresponding to an error distribution with logarithmic standard deviation equal to 0·17.

as would result from a non-universal black-body radiation and production spectrum having constant exponent) and the shape for universal origin.

Figure 5 shows the product of area and running time needed for ground level extensive air shower arrays to distinguish between the universal spectrum of figure 4 and a spectrum having constant exponent (the '13% supercluster' spectrum would need somewhat longer exposures). Bearing in mind that the Sydney array—the largest in existence at present—has an array of about 100 km^2 it is apparent that a definitive answer to the problem will probably not appear for some years yet.

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