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Primary cosmic γ rays above 10^{12} eV

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Abstract. An analysis is made of the interactions of very energetic cosmic ray primaries with the universal black body radiation in extragalactic space. The γ rays from the initial π^0 mesons produce electron pairs in collisions with further black body photons and a γ–e cascade builds up through this interaction and the inverse Compton interaction. Results are given for the expected γ ray spectrum at the earth for a variety of assumptions about the magnitude of the primary spectrum and other parameters and comparison is made with upper limits to the γ ray intensity from experimental data.

One conclusion that arises immediately is that if the higher of the two primary proton energy spectra is correct then the extragalactic infrared energy density must be less than about $2\,\mathrm{eV\,cm^{-3}}$. In general the predicted γ to proton ratios are highest in the region of 3×10^{19} eV. They are mostly below present detection limits but should be detectable with the improved extensive air shower arrays at present being constructed.

1. Introduction

The well known lack of any significant anisotropy of primary cosmic rays of energy above about 10^{18} eV strongly suggests that these particles are of extragalactic origin (see, for example, the work of Karakula *et al* 1971). These energetic particles will interact with such matter and radiation fields as may be present in the Universe and, as a result, secondary particles and quanta will be generated which will arrive with the primary particles and thus be, in principle, detectable.

Insofar as the density of intergalactic matter is thought to be very low (and its magnitude is quite uncertain) we confine attention to the interaction of the extragalactic particles, assumed to be protons, with the radiation fields. A detailed examination is made of the problem of the γ rays resulting from the interactions of protons with extragalactic starlight and the 2·7 K black body radiation (Penzias and Wilson 1965) and their ensuing cascades; a brief discussion of the γ rays resulting from proton–black body radiation alone has already been given by the present authors (Wdowczyk *et al* 1971). The problem of the interaction of extragalactic protons with starlight alone has been considered by Hayakawa and Yamamoto (1963).

Attention is devoted particularly to estimating the intensity of primary γ rays as a function of energy above 10^{12} eV and to comparing it with the intensity of protons. At the highest energies, such γ rays could be recognized experimentally by virtue of the specific type of extensive air showers produced, and thus a check made of the validity of the initial assumptions. More likely, from an estimated upper limit to the observed γ ray intensity some limits can be set on extragalactic parameters. This aspect is discussed in the last section.

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2. Extragalactic radiation fields

A summary of the extragalactic radiation fields which affect cosmic ray primaries of the energies in question is given in figure 1. The different regions can be considered in turn.

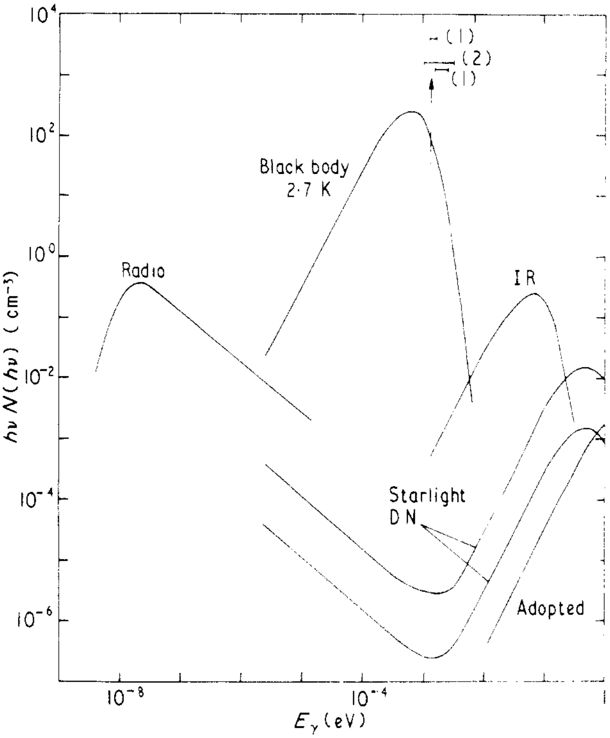

Figure 1. Extragalactic radiation fields. The horizontal bars represent possible infrared lines (1, Houck and Harwit 1969; 2, Muehlner and Weiss 1970). The arrow represents the position of the infrared line used in the calculations described in § 4.5. DN signifies Davidson and Narlikar (1966).

The 2·7 K black body radiation (Penzias and Wilson 1965) appears to be universal and may well be the relict radiation of the initial big bang predicted by Gamow. As yet, actual intensities, as distinct from upper limits, have only been determined on the low energy side of the maximum but the fact that there is such a good fit to the shape there (the curvature approaching the maximum is reproduced) gives confidence in the black body hypothesis. On the high energy side of the maximum there have been reports of higher intensities than would fit the 2·7 K spectrum and the existence of discrete lines has been suggested but there is some doubt about the measurements. For most of the present work these possible lines will be disregarded; an examination of their likely effect is given in § 4.5.

At lower photon energies there is the extragalactic radio background. A number of measurements have been made and the line drawn in figure 1, designated Clark *et al* (1970), is derived from experimental measurements; this line is close to the results of the other workers. The fall off in intensity below 10^{-8} eV is a prominent feature of the analysis of Clark *et al*; it has been accepted by us, although it should be pointed out that some other workers who have examined the problem have assumed that the fall off does not occur until a much lower energy. Also shown in the figure are limiting background spectra predicted by Davidson and Narlikar (1966) for a range of evolutionary models. It is interesting to note that the observed radio background is of higher intensity than that predicted.

The expected spectrum in the optical region has also been calculated by Davidson and Narlikar and the range of intensities is shown in figure 1. The energy densities are about 10^{-2} and 10^{-3} eV cm^{-3} respectively. Values quoted in the literature vary widely; for example, Godreich and Morrison (1964) quote 10^{-1} eV cm^{-3} whereas Ginzburg and Syrovatsky (1964) quote 10^{-3} eV cm^{-3}. In the present work we follow Felten (1966) and adopt 10^{-2} eV cm^{-3}. The spectral shape has been derived from interaction lengths given by Jelley (1966), and corresponds to a dilute black body.

In addition to the spectrum in the optical region there is the possibility of an excess of infrared continuum radiation (produced, perhaps, in the nuclei of Seyfert galaxies). Encrenaz and Partridge (1969) have given the interaction length against energy for such an infrared field having energy density $2{\cdot}4\times10^{-2}$ eV cm^{-3} and we have adopted this magnitude; the approximate spectral distribution is also given in figure 1. In fact this may be an overestimate of the actual situation but its effect on the calculations to be reported is minimal.

3. Interaction of photons with the radiation fields

3.1. Interaction length

Photons produced in extragalactic sources will interact with the photons of the radiation fields to produce pairs of particles when the energy available is above the threshold. For a head on collision of a photon of energy E_γ with a photon of energy E_b the cross section for production of pairs of particles each of mass m is given by:

$$\sigma_1 = \pi r_0^2\left(\frac{m}{\omega}\right)^2\left\{2\ln\left(\frac{2\omega}{m}\right)-1\right\} \qquad \text{for } \omega \gg m \text{ (ie in the extreme relativistic region)}$$

and

$$\sigma_2 = \pi r_0^2\left(1-\frac{m^2}{\omega^2}\right)^{1/2} \qquad \text{for } \omega \text{ close to } m \text{ (ie in the classical region).}$$

In these expressions (see, for example, Jauch and Rohrlich 1955)

$$\omega = \surd(E_\gamma E_b) \qquad \text{and} \qquad r_0 = \frac{e^2}{mc^2}.$$

Clearly the most important process is electron pair production but at a sufficiently high value of E_γ production of muon pairs sets in and eventually the cross sections for the two processes are the same. Figure 2 shows the corresponding interaction lengths $\lambda(\lambda = 1/n\sigma$, where n = number of 'target' photons per unit volume). The accurate form of the cross section has been used for each case and integration over collision angles and the energy spectrum of the target photons has been made. To illustrate the effect of angle and energy spectrum the variation of λ with E_γ is also given for head on collisions with photons of energy 6×10^{-4} eV, the mean photon energy for the 2·7 K radiation.

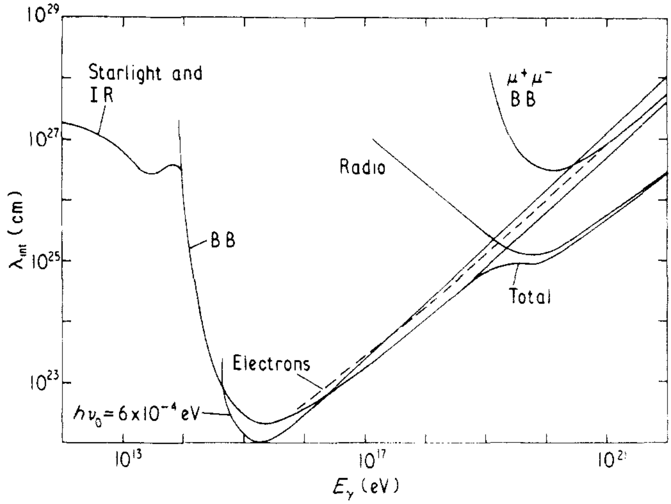

Figure 2. Interaction length against photon energy for collisions of energetic photons with photons of the various radiation fields. Unless stated otherwise the process concerned is electron pair production: e^+e^-.

Also shown is the interaction length for electrons, by way of the inverse Compton effect. with black body photons.

It can be seen from figure 2 that the black body radiation dominates over most of the energy range of interest although radio is the most important radiation for the very highest energies encountered ($E_\gamma \gtrsim 3\times10^{19}$ eV). It should be noted that the importance of the radio flux arises because of its comparatively high intensity (figure 1); if the radio intensity were in fact an extrapolation of either of the Davidson and Narlikar predictions it would have very little significance for high energy γ ray attenuation. If the lower predicted intensity in the optical region (10^{-3} eV cm^{-3}) were correct it, too, would not be of importance.

3.2. The interaction processes

The angular distribution of the electrons in the process $\gamma+\gamma \rightarrow e^+ + e^-$ and the consequent energy distribution of the particles in the laboratory system is a function of ω, in such a way that as ω increases there is increased peaking of the distribution forwards and backwards in the centre of mass (CM) system and the mean energy of the more energetic electron is an increasing fraction of the incident photon energy. The problem has been examined in detail by Allcock and Wdowczyk (1972) and by Bonometto and Lucchin (1971). The results of the former workers show that $\langle E_e/E_\gamma\rangle$ is 0·83, 0·93, 0·96 and 0·97 for $\alpha = 2\times10^6$, 10^7, 10^8 and 10^9 respectively, where $\alpha = 2E_eE_b/m$ for a head on collision.

In the absence of magnetic fields, at least of strength above about 10^{-10} G, the electrons will interact with the radiation field to produce further photons by the inverse Compton effect (a discussion of the effect of possible extragalactic fields is given in § 4.4). There is again an increasing fraction of energy going to the particle as energy increases and $\langle E_\gamma/E_e\rangle$ is 0·53, 0·67, 0·80 and 0·84 for $\alpha = 2\times10^6$, 10^7, 10^8 and 10^9 respectively (Allcock and Wdowczyk 1972). Here $\alpha = 2E_bE_e/m$ for a head on collision.

The large ratios at high α values mean that the photon energy is degraded only slowly and both Allcock and Wdowczyk, and Bonometto and Lucchin have drawn attention to the consequent long attenuation length for photons in the region of 10^{18} eV. The former workers show that the ratio of attenuation length to sum of the interaction lengths for pair creation (PC) and inverse Compton effect (ICE) increases from 2·1 at 10^{16} eV to about 6·0 at 10^{19} eV (the figures referring to use of attenuation length in calculating the residual energy of γ rays). The 'total' interaction length allowing for both the black body radiation and the radio background is given in figure 2, as is the interaction length of electrons in the black body radiation.

4. Interaction of the extragalactic proton component with the radiation fields

4.1. The extragalactic proton spectrum

As mentioned in § 1 there is strong evidence in favour of cosmic rays above 10^{17} eV or so being of extragalactic origin. Until recently it was thought that there was an upturn to the primary spectrum at about 3×10^{18} eV and it was tempting to identify this as due to the entrance of extragalactic particles with a spectrum similar to that of (presumed) galactic particles below the first 'kink' at 10^{15} eV. Recent work by Hillas and collaborators (Hillas *et al* 1971, Andrews *et al* 1971) has thrown doubt on the existence of the upturn and accordingly we have calculated for alternative primary spectra with and without the upturn. These two spectra are denoted 'A' and 'B' in figure 3, 'A' referring to the summary of Greisen (1966) and 'B' to the more recent measurements of Andrews *et al* (1971). 'A' essentially represents, now, an upper limit to the likely primary spectrum.

If spectrum B is in fact correct it is a little difficult to see why the observed primary spectrum is so smooth in view of its being a composite of the two individual spectra. However, fluctuations in shower development and consequent lack of uniqueness in the relationship between observed extensive air shower characteristics and primary particle energies will smooth out small discontinuities in the spectrum.

In the calculations it is assumed that the equilibrium primary spectrum in space is given by A (or B) extrapolated without change of slope to higher energies. This is of course an assumption and an important one in view of the large contribution to the energetic γ rays in question from protons in this very high energy region and means that the production spectrum is significantly flatter than that measured. Accurate calculations have been made for spectrum A and the results for B found by a relaxation method.

4.2. Proton–photon interactions

Proton–photon collisions are of two types—electron pair production in the Coulomb field of the proton and γ–p nuclear interactions. The energy transferred to the electromagnetic component is similar in the two cases but whereas the γ from nuclear interactions extend to very high energies (10^{20} eV or so) those from the electrons in pair production are lower by a factor of about 10^3. Since we are interested mainly in the very energetic γ rays pair production will not be included at this stage but will be added in later (§ 4.3) when approximate results valid at lower energies are considered.

The characteristics of γ–p interactions measured at accelerators, as summarized by Stecker (1968), have been used in deriving the production spectrum of π^0 mesons and thence of γ rays in the proton–black body photon interactions (proton–radio photon interactions are of no consequence at the energies in question).

The production spectra of γ rays from the π^0 mesons for the two proton spectra are given in figure 3. At energies above about 10^{21} eV the slope is seen to be constant; this is a consequence of the adoption of a primary spectrum of constant slope $j(E_p) = AE_p^{-\gamma}$, a constant photonuclear cross section and a multiplicity law of the form E_p^{α}, well above threshold; the slope of the production spectrum then follows as E_γ^{-v} where $v = \{(2\alpha-\gamma)/(1-\alpha)\}$. In the present calculation we assume $\alpha = \frac{1}{4}$.

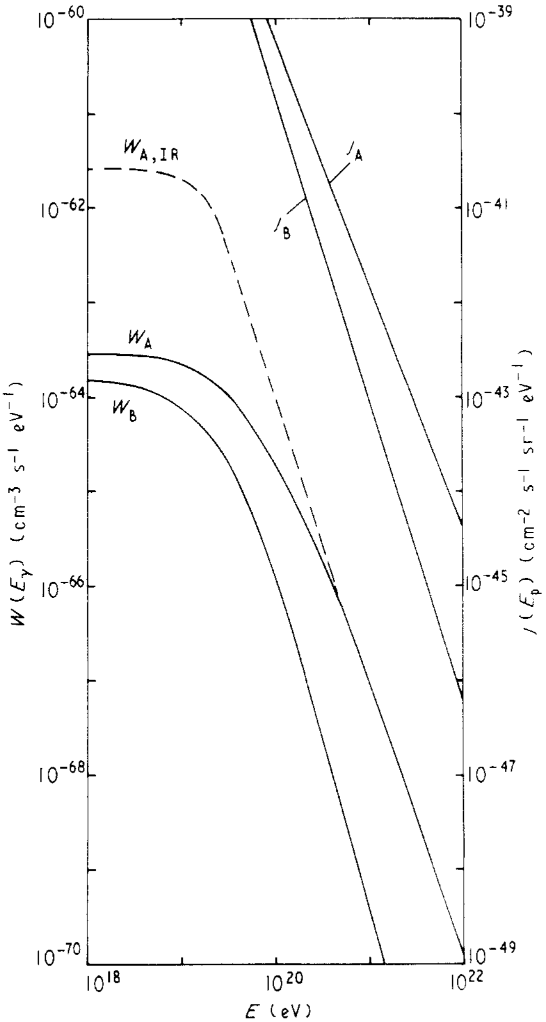

Figure 3. Primary proton spectra (j_A and j_B, right hand scale) and γ production spectra (W, left hand spectra). The broken curve refers to collisions with photons of an infrared line at $1{\cdot}35 \times 10^{-3}$ eV, having energy density 3·4 eV cm^{-3}, for spectrum A.

It is the energy contained in the production spectrum that is converted into lower energy γ rays (and electrons) and in the present calculations, in which interactions with matter are ignored, energy conservation indicates the order of magnitude of the photon spectra at the earth that may be expected. For spectrum A and γ from π^0 production the integrated rate of production of energy is

$$\frac{\partial E_c}{\partial t} \simeq 7\times 10^{-25}\,\mathrm{eV\,cm^{-3}\,s^{-1}}.$$

This is to be compared with a total production rate of about 2×10^{-24} eV cm^{-3} s^{-1}, including energy going into π^+ and π^- as well as π^0 mesons, and the production rate for electron pairs from direct p–γ interactions of approximately 4×10^{-25} eV cm^{-3} s^{-1}, all the values referring to primary spectrum A.

For spectrum B the rate of production of energy for γ from π^0 mesons is 6×10^{-26} eV cm^{-3} s^{-1} and the other values are similarly smaller.

Returning to spectrum A and assuming a residence time for photons in the Universe of $T = 13\times 10^9$ yr, $= 3{\cdot}9\times 10^{17}$ s, the integrated γ ray energy is

$$\int E_\gamma I(E_\gamma)\,\mathrm{d}E_\gamma = \frac{1}{4\pi}\frac{\partial E_c}{\partial t}cT \simeq 7\times 10^{2}\,\mathrm{eV\,cm^{-2}\,s^{-1}\,sr^{-1}}.$$

Similarly, the energy density is $T\,\partial E_c/\partial t \simeq 3\times 10^{-7}$ eV cm^{-3}. To set the scale of these energies, the energy carried by the diffuse x ray and γ ray background (see, for example, the summary by Ipavich and Lenchek 1970) is about 6×10^5 eV cm^{-2} s^{-1} sr^{-1} for $10^3 < E_\gamma < 10^7$ eV. Thus, the present energy is several orders of magnitude below that carried by x rays and low energy γ rays, most of which is presumably provided by processes within our own galaxy.

Despite the comparatively small magnitude of the energy the γ rays generated by the ultra-energetic protons may have significance and offer the possibility of detection because after cascading the energy spectrum may conceivably give intensities relative to the primary protons themselves which are appreciable in restricted energy regions.

The spectrum that may be calculated immediately, without complication, is that of first generation γ rays. This follows directly as $I_1(E_\gamma) = (W(E_\gamma)/4\pi)\lambda(E_\gamma)$. This spectrum for case A is given in figure 4. If extragalactic magnetic fields are such that the electrons resulting from PC radiate the majority of their energy as magnetic bremsstrahlung before ICE is able to take place then this represents the sole source of very energetic γ rays.

4.3. Photon cascading in space in the absence of magnetic fields

As remarked in § 3, the effect of ICE following pair creation is to cause the generation of a photon cascade. The diffusion equations have been solved using the data given in the previous figures with the resulting γ ray spectra shown in figure 4. Spectra are shown both for the situation where the radio background is ignored (the situation in our earlier paper: Wdowczyk *et al* 1971) and where it is included. The effect of inclusion is seen to be a reduction in γ ray intensity above 4×10^{19} eV and some enhancement below it. The enhancement comes from the extra cascading of the photons produced with energy above this value in the radio radiation. A useful parameter characterizing the cascades is the effective maximum distance R_0 from which photons produced with a particular energy E reach the earth with energy above some threshold energy E_t. For $E_t = 10^{18}$ eV, $R_0 = 6\times 10^{26}$ cm and 5×10^{27} cm for $E = 10^{20}$ eV and 10^{21} eV. (In fact the values of R_0 refer to the length of photon path; when electron paths are included the distances should be multiplied by about 2·7.) It is clear from these values that cosmological distances are not quite reached and evolutionary effects need not be considered.

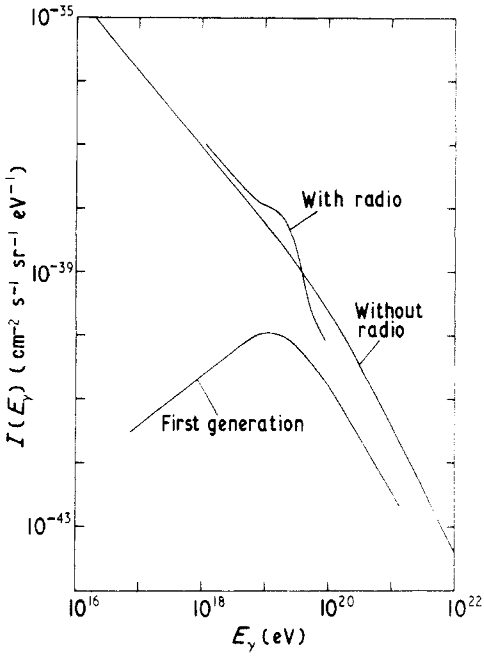

Figure 4. Predicted γ ray spectra in the high energy region for primary spectrum A.

Figure 5 shows the spectrum of γ rays over the whole energy range for which calculations have been made ($E > 10^{12}$ eV) and includes experimental data on very low energy quanta (x rays) so that the scale of the predicted γ intensities can be appreciated. The γ rays resulting from electrons produced directly in p–γ interactions (§ 4.2) have been included in the estimated spectrum.

4.4. Photon cascading in space in the presence of magnetic fields

4.4.1. Strength of field necessary to invalidate the previous calculations. If a magnetic field is present, of sufficient magnitude, the electrons produced in PC will lose much of their energy through synchrotron radiation before they have had opportunity to undergo ICE and the high energy cascade will be virtually terminated. Instead of very energetic γ rays there will instead be generated γ rays of much lower energy, typically about 10^{12} eV. The magnitude of this intensity will be considered later.

A particle of charge Ze rest mass M, and energy E, moving in a field having a perpendicular component of magnitude $B_\perp$, radiates energy at a rate

$$-\frac{\partial E}{\partial t} = \frac{2}{3}\frac{(Ze)^4}{m^2c^3}B_\perp^2\left(\frac{E}{mc^2}\right)^2.$$

For electrons this reduces to

$$-\frac{\partial E}{\partial t} = 0{\cdot}98 \times 10^{-3} B_\perp^2\left(\frac{E}{mc^2}\right)^2 \qquad \text{eV s}^{-1}$$

that is

$$-\frac{\partial E}{\partial x} = 3{\cdot}3 \times 10^{-14} B_\perp^2\left(\frac{E}{mc^2}\right)^2 \qquad \text{eV cm}^{-1} \text{ for } B_\perp \text{ in gauss.}$$

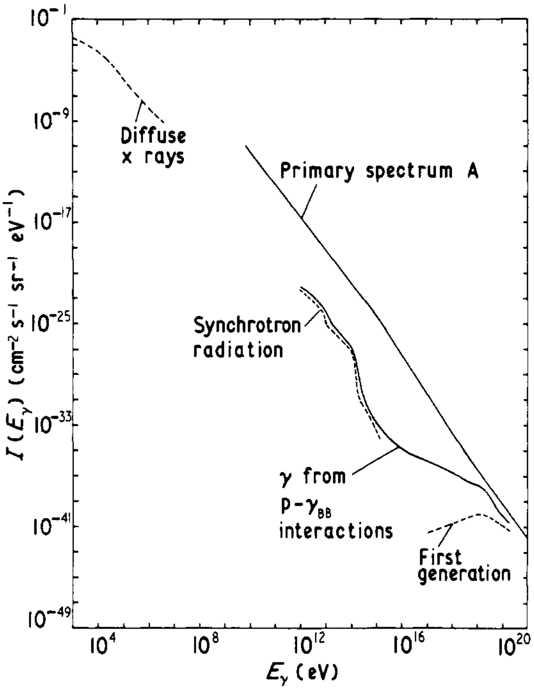

Figure 5. γ ray spectra over whole energy range. The diffuse x ray data are from the summary by Ipavich and Lenchek (1970). The predicted spectra refer to primary spectrum A.

If this is to be less than say 10 % of the electron energy in an interaction length λ then we need $B_\perp^2 < 7{\cdot}9 \times 10^{23}/E\lambda$ (E in eV and λ in cm). Substituting the appropriate value of λ gives limiting values of $B_\perp$ as approximately 3×10^{-12}, 2×10^{-11} and 1×10^{-10} G for $E = 10^{21}$, 10^{20} and 10^{19} eV respectively.

4.4.2. Synchrotron radiation produced in extragalactic magnetic fields. If extragalactic fields are present, of magnitude bigger than the limits given above, then synchrotron radiation from the electrons causes a significant low energy γ intensity. Using the nomenclature given in § 4.4.1, the spectral distribution of the radiation from an electron has a frequency distribution peaking at ν_m given by

$$\nu_m \simeq 0{\cdot}29\nu_c = 0{\cdot}07\frac{eB_\perp}{mc}\left(\frac{E}{mc^2}\right)^2 = 4{\cdot}6 \times 10^{-6} B_\perp E^2$$

with $B_\perp$ in gauss and E in electron volts (see, eg Ginzburg 1969). Using electron energy spectra derived from figure 3 an approximate estimate of the synchrotron spectrum has been derived for $\langle B_\perp \rangle = 10^{-9}$ G. It should be noted that there is the implicit assumption that the field is sufficiently random that the same extragalactic proton spectrum can be used as adopted previously.

The production spectrum of the synchrotron radiation has been taken together with the interaction lengths given in figure 2 and the cascade problem has been solved to give the resultant spectrum shown in figure 5. Calculations have not been made below 10^{12} eV because the interaction lengths are approaching the Hubble radius (figure 1) and evolutionary effects will surely be important under these conditions.

4.5. The effect of intense infrared lines

Any additional radiation fields will produce further absorption of energy and a higher γ ray intensity and associated with this there must be a higher source intensity of energetic cosmic rays to maintain the observed primary proton intensity.

Very energetic sources (eg Seyfert galaxies) are known to be sources of infrared radiation, strongly peaked at around 0·1 mm, and such radiation can be interpreted as coming from the synchrotron radiation of electrons; Setti and Woltjer (1970) have shown that energy densities of order 2 eV cm^{-3} are not unreasonable and indeed there is some experimental evidence (Houck and Harwit 1969) for an energy density of about 3·4 eV cm^{-3} and $\overline{h\nu} \simeq 1{\cdot}35 \times 10^{-3}$ eV. Values as high as around 10 eV cm^{-3} would appear possible.

It is possible that the whole assembly of '2·7 K' radiation and the 'lines' in the region of 10^{-3}–10^{-2} eV form a grey body flux corresponding to $T \simeq 8$ K but in what follows we examine the effect of a single line (or fairly narrow spectrum) with 3·4 eV cm^{-3} at $1{\cdot}35 \times 10^{-3}$ eV. The γ ray production spectrum is shown in figure 3 and rate of production of energy is

$$\frac{\partial E_c}{\partial t} \simeq 9 \times 10^{-24} \text{ eV cm}^{-3}\text{ s}^{-1}.$$

With the quite high energy density of infrared radiation adopted the energetic photon interaction lengths are somewhat shorter than for the 2·7 K radiation and the minimum is displaced to lower energy. Values are: 10^{23} cm, 2×10^{21} cm, 7×10^{22} cm and 4×10^{24} cm at $E_\gamma = 3 \times 10^{14}$ eV, $7{\cdot}5 \times 10^{14}$ eV, 10^{17} eV and 10^{19} eV respectively.

The γ ray spectrum has been calculated using the methods described in the previous sections with the result shown in figure 6.

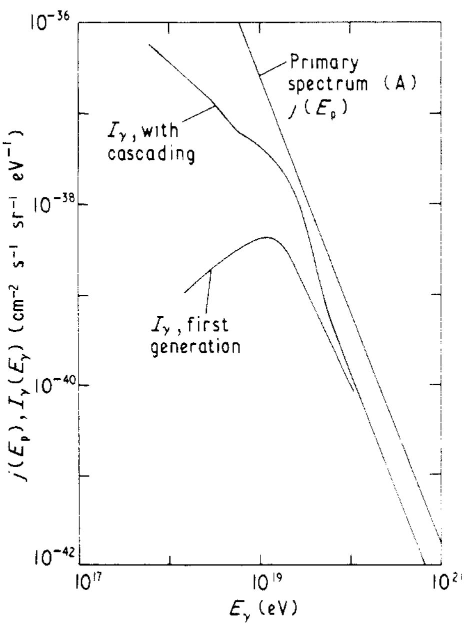

Figure 6. Predicted γ ray spectra in the high energy region for primary spectrum A and an infrared line with 3·4 eV cm^{-3} at $\overline{h\nu} = 1{\cdot}35 \times 10^{-3}$ eV.

5. Comparison of the various predictions for the γ ray intensity

5.1. General remarks

As has been remarked already, insofar as the models adopted do not involve interactions between photons (or electrons) and matter, leading to irreversible energy losses, the same initial proton spectrum and the same energy going into very energetic γ rays must result in γ ray spectra after cascading having the same total energy. What is dependent on the model is the spectral shape. Thus, for very small values of $\langle B_\perp \rangle$ there will be a significant flux of very energetic γ rays ($E_\gamma \gtrsim 10^{18}$ eV) whereas if $\langle B_\perp \rangle$ is significant only the 'first generation' is operative and the very energetic γ rays are few. Below 10^{15} eV, however, the fluxes are not very dependent on field strength and this is where the bulk of the energy lies.

5.2. Ratio of intensities of gamma rays and protons

It is apparent from figure 5 that although the predicted absolute intensities of γ rays are comparatively high in the region of 10^{12} eV, the experimentally important quantity, the γ/p ratio, is highest above about 10^{18} eV and attention will be devoted to this region. Figure 7 shows the ratios for some of the choices of parameters.

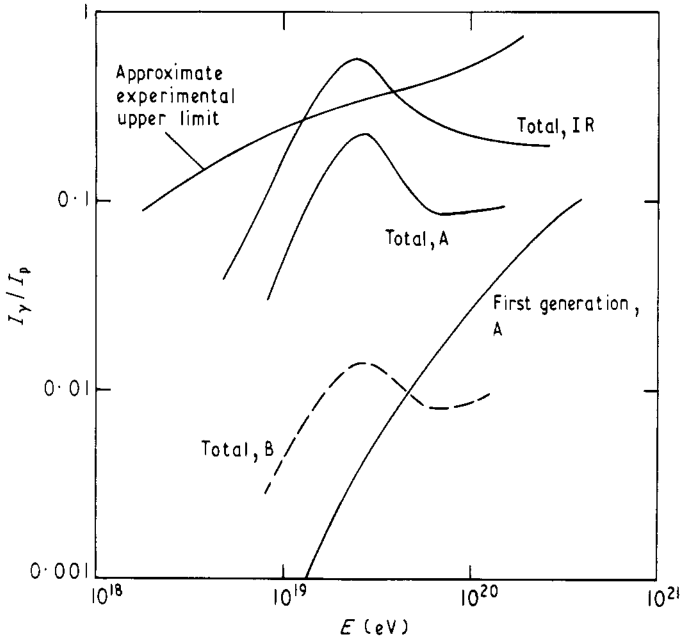

Figure 7. Ratio of intensities of γ rays and protons against energy.

6. Possibility of detecting very energetic primary γ rays

6.1. Effect of γ rays on shower characteristics

The expected character of extensive air showers produced by primary photons has been examined in detail by a number of workers, principally the Lodz group (eg Wdowczyk

1966). Clearly, the showers produced will be deficient in muons and nuclear active particles and indeed it was thought for some years that the muon-poor showers observed by the Lodz and Chacaltaya groups (eg Gawin *et al* 1963, Suga *et al* 1963) at energies in the region of 10^{15} eV were examples of such showers. Subsequent work has thrown doubt on this interpretation, and others have been put forward in terms of X particle production (Catz *et al* 1971) and primary electrons (Ramaty and Lingenfelter 1971) but the problem is still not solved. It is interesting to note in this context that the present predictions give a minimum in the γ/p ratio in the energy region in question.

The phenomena to be observed in an EAS array when struck by a γ initiated shower depend on its response characteristics. The different types can be dealt with in turn.

(i) Array sensitive to all particles and without ability to distinguish between muons and electrons.

The muon density in a shower falls off with distance from the axis at a faster rate than the electron density. Thus, the onset of γ rays would be signified by an increase in the rate of fall of particle density with distance, that is, the 'lateral structure function' would steepen.

(ii) Array sensitive to muons alone (Sydney experiment, Bell *et al* 1971).

The calculations of Wdowczyk (1966) and Braun and Sitte (1966) indicate that for a primary energy of 10^{19} eV a γ ray shower would yield only about 10% of the number of muons in a proton initiated shower. The effect of this would be to cause a large difference in apparent rate of showers between a muon-only array and an all-particle array, if particle energy were calculated in the usual way.

(iii) Array sensitive to energy flow (Haverah Park experiment, Andrews *et al* 1971).

As with case (i) the lateral structure function would steepen after the onset of γ rays.

6.2. *Upper limit to γ/p ratio from present experimental data*

An analysis has been made of the experimental data referred to in § 6.1 together with that from the Volcano Ranch experiment (Linsley 1963). From a comparison of the Sydney and Haverah Park data it can be concluded that the primaries are not all γ rays at any energy in the range 10^{17}–10^{20} eV: if anything, the Sydney intensities are a little higher at the highest energies (in contrast to what would be expected for primary γ) although there are problems of primary energy determination.

All the experiments show an increasing steepness of the average structure function with increasing shower size but such a behaviour is expected for conventional proton primaries because the mean height of origin of the muons diminishes as the primary energy rises. There is no evidence for an unusual increase in mean steepness.

Where a small flux of γ rays would be expected to show up is in the individual lateral distributions and in individual μ/e ratios. No such data have been reported, as yet, at energies above 10^{18} eV and there is thus a need for such information.

What information there is on the mean values of various parameters has been used to estimate an upper limit to the γ/p ratio; this is shown in figure 7.

7. Conclusions

7.1. *'Low' level of extragalactic infrared radiation*

It has been shown that if cosmic rays above 10^{18} eV are extragalactic in origin, if the 2·7 K radiation is universal, if extragalactic magnetic fields are negligible and if the primary spectrum is close to what we regard at present as the upper limit then a comparatively large amount of energy goes into γ radiation ($\simeq 2\times 10^{-7}$ eV cm^{-3}). The initial γ rays, derived from π^0 mesons produced in proton–black body photon interactions, and their cascade progeny, give rise to a significant γ ray intensity at the earth and one which is only just below the experimental limits at present available. Such intensity levels will be detectable before long.

For the more likely primary spectrum B the γ ray intensities are about a decade smaller and detection will be correspondingly more difficult. However, these too would appear to be eventually detectable.

7.2. *'High' level of extragalactic infrared radiation*

Calculations have been made for an additional flux of infrared radiation of energy density 3·4 eV cm^{-3} carried by photons of $1{\cdot}35\times 10^{-3}$ eV. Such an energy density has been suggested by Houck and Harwit (1969). With the 2·7 K radiation and spectrum A, a γ ray intensity higher than that allowed by experiment results. Thus, if the other assumptions are correct an upper limit can be put on the infrared energy density; interpolation yields a value for this limit of about 2 eV cm^{-3}. If, on the other hand magnetic fields are appreciable so that only first generation γ rays are operative above 10^{18} eV the upper limit that can be set is about 10 eV cm^{-3}.

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