Diffuse γ rays from discrete extragalactic sources

1976 J. Phys. A: Math. Gen. 9 1553

(http://iopscience.iop.org/0305-4470/9/9/015)

J. Phys. A: Math. Gen., Vol. 9, No. 9, 1976. Printed in Great Britain. © 1976

Diffuse γ rays from discrete extragalactic sources

A W Strong, A W Wolfendale and Diana M Worrall
Physics Department, University of Durham, South Road, Durham DH1 3LE, UK

Received 7 April 1976

Abstract. An estimate is made of the fraction of the diffuse γ-ray background originating in discrete sources rather than intergalactic space. It is shown that 'normal' galaxies probably contribute about 4% of the γ-ray flux above 100 MeV. Radio galaxies can produce the bulk of the 1–10 MeV background if there is proportionality between their γ-ray and radio luminosities. Seyfert galaxies and clusters can account for most of the 100 MeV observations if the x-ray and γ-ray emissions are by the inverse Compton mechanism.

1. Introduction

Measurements with high flying balloons and satellite-borne detectors have shown the existence of a significant flux of extraterrestrial γ rays. Two components have been identified: a Galactic part, which shows a peak in the direction of the Galactic plane and an apparently isotropic part: the diffuse background.

The question of the origin of the diffuse background has aroused much discussion and a number of alternative theories have been put forward. The majority are cosmological and include production by way of:

(*a*) Cosmic ray interactions with intergalactic gas at large redshifts (Stecker 1969 and later papers, see Stecker 1975 for a summary).

(*b*) Interactions of nucleons and anti-nucleons at early epochs (Stecker 1971, Stecker and Puget 1972).

(*c*) Electrons generated in early epoch interactions of cosmic ray protons with the Universal black body radiation which cause γ rays to cascade through the Universe (Strong *et al* 1974, i.e. the present authors' group).

Attention had been drawn to the various physical processes underlying production of extragalactic γ rays in a classic paper by Morrison (1958) which predated the discovery of the diffuse background.

Preoccupation with cosmological explanations, at least for models (*a*) and (*b*), arose to a large extent because of the apparent presence of a 'shoulder' in the diffuse spectrum at about 1 MeV (see figure 1 for the experimental intensities). The point is that for production of γ rays by the way of π^0 meson decay the differential energy spectrum has a peak at $m(\pi^0)c^2/2$, i.e. about 70 MeV; this can clearly be displaced down to about 1 MeV by assuming production largely at redshifts approaching $z = 100$. It is necessary then to assume that the bulk of the radiation below 1 MeV, which can have a smoothly falling spectrum, arises from some other source. In model (*c*) no shoulder is predicted but the model gives a prediction in absolute terms and it is interesting that it is rather close to observation (but not as close as for (*a*) and (*b*) which are effectively normalized).

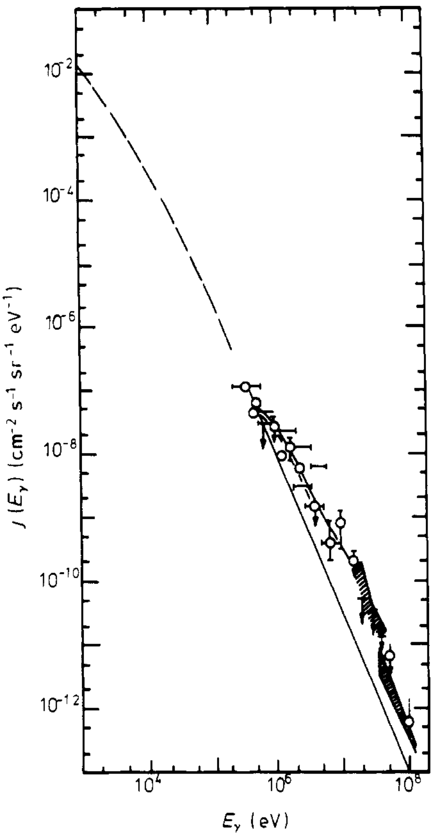

Figure 1. Collection of data on background x rays (broken curve) and γ rays (hatched area) taken from the summaries of Pinkau (1975) and Stecker (1975). Not all the measured intensities above 10^5 eV are shown; only a representative selection is given. The full line is the extrapolation of the x-ray spectrum.

There are other, alternative, explanations for the background, but in the present work we concentrate on the situation of extragalactic origin.

A very brief report of some of the ideas in this paper has been published already (Strong *et al* 1976).

2. Basis of the model

The factors which led to the consideration of the present model are twofold.

(*a*) It is possible that the apparent shoulder in the integral spectrum at about 1 MeV is not real and the true spectrum may vary quite smoothly over the whole energy region; see figure 3 for our estimate of the likely extreme limits to the spectrum. The problem is that the range 1–10 MeV is a particularly difficult energy region in which to make accurate measurements and the history of studies in this range shows intensity estimates which have fallen as time has progressed. The difficulties have been stressed recently by Daniel and Lavakare (1975) who conclude that the evidence for the 'shoulder' is poor.

(*b*) The contribution at 100 MeV from 'normal' galaxies alone is found to be about 4% of the observed flux. The studies of x-ray emissivities of various types of galaxy, summarized by Schwartz and Gursky (1973), Boldt (1974) and Rowan-Robinson and Fabian (1975) and others, have indicated values very much higher than our own for certain types of galaxy. These workers have examined the possibility of the x-ray diffuse background being interpreted in terms of the integrated sum from such sources. Here we make a similar analysis for the γ-ray case. (Very recent observations by Grindlay *et al* 1975a, of γ rays above 3×10^{11} eV from Cen A have added confidence to our analysis.)

The procedure is first to examine the energy spectrum of γ rays in our own Galaxy and to calculate the total emissivity as a function of energy. The diffuse background contribution from 'normal' galaxies can then be estimated to fair accuracy. Next follows the less certain estimate of the likely contributions from other astronomical objects, specifically: radio and Seyfert galaxies and clusters of galaxies.

3. Spectrum of Galactic γ rays and the total emissivity

3.1. Energy spectrum

The low intensities of γ rays has meant that there is some uncertainty about the exact form of the energy spectrum just as in the diffuse case. Figure 2 gives a summary of the data. The best measurements are those by Fichtel *et al* (1975) from the SAS-II data and these authors state that, taking their measurements in conjunction with some others,

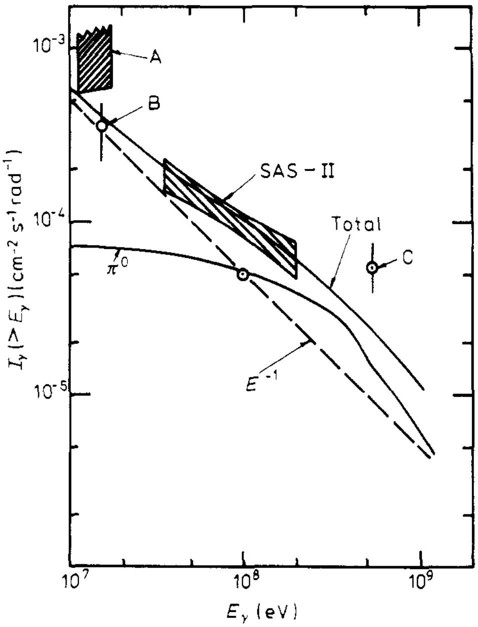

Figure 2. Integral spectrum of Galactic γ rays. The points marked A, B and C are from Helmken and Hoffman (1973), Share *et al* (1974) and Sood *et al* (1974) respectively. Other data, not shown, give comparable intensities in the region 30–100 MeV but do not add greatly to our knowledge of the spectral shape.

the energy spectrum is consistent with a two-component model of a π^0-decay type spectrum and a differential power law of the form $j(E_\gamma) = AE_\gamma^{-2\cdot 0}$. The latter would presumably be identified with an inverse Compton effect (ICE) source—i.e. γ rays from electron–starlight collisions—together with a contribution from bremsstrahlung. Calculations of the contribution to the total γ-ray flux from ICE have in fact been made by a number of authors (Cowsik and Voges 1974, Beuermann 1974, Dodds *et al* 1975, and others). The last mentioned authors show that it is possible to have as much as 50% of the γ rays above 100 MeV coming from ICE interaction if the cosmic ray intensity is allowed to peak in the region of a Galactocentric distance of 4 kpc as appears to be necessary in some interpretations of the γ-ray flux (e.g. Puget and Stecker 1974, Strong 1975, Strong and Worrall 1976).

In figure 2 we give the adopted Galactic spectrum; it is derived assuming that 50% of the intensity above 100 MeV is derived from π^0 production and 50% from ICE and bremsstrahlung.

3.2. *Total Galactic emissivity*

A derivation of the total γ-ray output of the Galaxy relies on knowledge of the distribution of γ-ray emissivity. Kraushaar *et al* (1972) used their own satellite measurements to make an approximate estimate of $1\cdot 8 \times 10^{42}$ γ rays of energy above 100 MeV per second. Using the more recent SAS-II data and a radial distribution of emissivity Strong and Worrall (1976) calculate a value of $1\cdot 3 \times 10^{42}$ γ rays per second.

The spectral shape of γ rays leaving the Galaxy will be similar to that in figure 2 but not identical to it. The reason for the discrepancy is that although the π^0 and bremsstrahlung contributions vary with Galactocentric distance R in the same way (assuming that the electron to proton ratio is independent of R) the ICE contribution increases with falling R because of the increase in starlight intensity. However, the spectral intensities shown in figure 2 at 10 MeV may well be somewhat overestimated (see the recent work of Kniffen *et al* 1975) and insofar as an accurate treatment would increase the low energy intensities the form shown in the figure for the spectral shape at the earth is probably quite close to the overall Galactic emission spectrum.

4. Calculation of the expected γ-ray background

4.1. *Methods of calculation*

Two methods are used to calculate the contribution from a particular class of sources.

(*a*) If we know the γ-ray emissivity $q(E_\gamma)$ of a member, we multiply it by the density of sources of the same emissivity which will make up the class. The diffuse background at the earth, $j(E_\gamma)$, from the class of sources must depend on the cosmological model adopted and any evolutionary effects; however, in the absence of the latter we have

$$j(E) = \frac{k\overline{\eta q_\gamma}}{4\pi}\left(\frac{H_0}{c}\right)^3$$

where η is the density of sources in units of number per volume $(c/H_0)^3$ and k is the factor dependent on the cosmological model employed. For a deceleration parameter $q_0 \simeq 0$ and a spectrum of the form $q(E_\gamma) \propto E_\gamma^{-2}$ it follows that $k = \frac{1}{2}$, and this is the value to be used. We adopt $H_0 = 50$ km s^{-1} Mpc^{-1}, giving $j(E_\gamma) = 1{\cdot}3 \times 10^{-58}\overline{\eta q}(E_\gamma)$. Similarly, for integral spectra, $j(>E_\gamma) = 1{\cdot}3 \times 10^{-58}\overline{\eta Q}(>E_\gamma)$. The quantity $\overline{\eta q}(E_\gamma)$ can be calculated by assuming that the γ-ray emissivity is proportional to some property of the object for which the density function for the class of sources is known.

(*b*) If the γ-ray emissivity $q(E_\gamma)$ of an object is assumed to be proportional to emissivity in another part of the electromagnetic spectrum I_ν then a knowledge of the total extragalactic intensity in this part of the spectrum enables the background flux of γ rays to be predicted. If the radio emissivity of individual galaxies is taken, then we expect the contribution to the γ-ray diffuse background flux ($j(E_\gamma)$ to be proportional to the contribution to the radio background I_ν from the class of sources, such that

$$j(E_\gamma) = \frac{q(E_\gamma)}{L_{\rm R}(\nu)} I_\nu.$$

Unlike method (*a*), this has the advantage of including evolutionary effects. There is evidence presented by Paul *et al* (1976) for proportionality between the 150 MHz radio emission and the γ-ray emissivity of the Galaxy and we confirm that there is a rough and ready correspondence. The 150 MHz radiation is almost certainly generated by electrons of energy in the region of 1 GeV moving in interstellar magnetic fields of the order of several microgauss and much of the γ-ray component above 100 MeV comes from collisions between protons of several GeV and nuclei in the interstellar medium. Insofar as electrons and protons of similar energy are probably distributed in a similar fashion both in this Galaxy and in others a rough proportionality between $q(E_\gamma)$ and $L_{\rm R}(\nu)$ would be expected.

4.2. *The contribution from normal galaxies*

4.2.1. *Calculation using method (a)*

(i) *γ-ray emission proportional to total luminosity.* At energies greater than 100 MeV, π^0 emission dominates over other production mechanisms in the Galaxy (figure 2). A proportionality between luminosity and γ-ray emissivity is justified by the fact that we expect a rough correlation between the numbers of stars and cosmic ray sources.

Luminosity functions for galaxies have been given by several authors (e.g. Kiang 1961, Shapiro 1971, Huchra and Sargent 1973, Shectman 1973). The distribution of Shectman gives a value for ηL (photographic) of $3{\cdot}3 \times 10^{19}$ $L_\odot$ per 'unit' volume and the other luminosity functions give values close to this.

The absolute photographic luminosity of our Galaxy is calculated to be $L_{\rm Gal} = 6 \times 10^9$ $L_\odot$. This estimate uses the value for the absolute visual magnitude as seen from the direction of the Galactic pole outside the Galaxy given by Allen (1973): $M_{\rm v} = 20{\cdot}5$. A correction for absorption of $0{\cdot}36$ cosec $b_{\rm II}$ magnitudes (Allen 1973) is applied to give the mean value for the absolute luminosity integrated over all inclinations (this correction, a factor of 1·65 in luminosity is necessarily approximate).

We therefore find $\eta L/L_{\rm Gal} = 5{\cdot}5 \times 10^9$. Using the SAS-II measurement of Fichtel *et al* (1975) of $j_{\rm obs}(E_\gamma > 100\ {\rm MeV}) = 1{\cdot}9 \times 10^{-5}$ cm^{-2} s^{-1} sr^{-1} and the Galactic γ-ray emissivity $Q(E_\gamma > 100\ {\rm MeV}) = 1{\cdot}3 \times 10^{42}$ γ rays s^{-1} as given by Strong and Worrall (1976) the γ-ray intensity follows as $j_\gamma(>100\ {\rm MeV}) = 9{\cdot}2 \times 10^{-7}$ cm^{-2} s^{-1} sr^{-1}, or 5% of the observed background.

(ii) *γ-ray emission proportional to neutral hydrogen mass.* If the density of cosmic ray protons in the GeV region is the same in all galaxies then the γ-ray emissivity will be proportional to the mass of neutral hydrogen in the Galaxy, or more accurately, the total mass of gas. The mean density of HI for galaxies, $\overline{\eta M_H}$ is given by Rowan-Robinson and Fabian (1975) as $9\times10^{18}\ M_\odot$ per 'unit' volume and the mass of gas in the Galaxy is quoted to be $4\times10^{9}\ M_\odot$ per 'unit' volume. Using the same values for Q and j_{obs} as before, we calculate $j_\gamma(>100\,\text{MeV})=4\times10^{-7}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$, or 2% of the observed background.

4.2.2. Calculation using method (b). The ratio $q(E_\gamma)/L_R(\nu)$ for the Galaxy is found by comparing the intensities of the γ rays and radio waves from the surveys of the Galaxy (Fichtel *et al* 1975, Landecker and Wielebinski 1970, respectively); this ratio does not vary greatly with direction in the plane (where the bulk of the radiation is certainly of Galactic rather than extragalactic origin) and is equal to $1{\cdot}2\times10^{-7}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,\text{K}^{-1}$ at 150 MHz. The contribution to the radio background due to normal galaxies has been estimated by Longair (1971) as corresponding to a brightness temperature of 4 K at 178 MHz and Schmidt (1972) estimates 0·48 K at 408 MHz. For a Galactic radio spectral index −0·75, these values give, respectively, 6·4 K and 6·7 K at 150 MHz ($T\propto\nu^{-2\cdot75}$) and, taking the mean with the ratio of γ-ray intensity to 150 MHz radio intensity referred to earlier, the γ-ray intensity is: $j_\gamma(>100\,\text{MeV})=8\times10^{-7}\,\text{cm}^{-2}\,\text{sr}^{-1}\,\text{s}^{-1}$, i.e. 4% of the background.

4.2.3. Summary of estimates for normal galaxies. All the estimates: 5%, 2% and 4% give similar values for the contribution to the background, so we can be fairly confident that such objects provide about 4% above 100 MeV, and possibly more when correlations between cosmic ray and gas densities are considered. This value can be contrasted with the 0·5% calculated by Rowan-Robinson and Fabian (1975) for the contribution from normal galaxies to the x-ray background. The difference in percentages manifests itself in the fact that the spectrum of Galactic γ rays (figure 2) is flatter than that of the diffuse background (figure 1).

The expected contribution to the diffuse γ-ray background, based on the observed γ-ray spectrum of our Galaxy is shown in figure 3.

The 'normal' galaxy contribution will be higher if we consider the effect of the enhanced emission from a galaxy which contains a very recent supernova. At early stages a supernova envelope is so dense that much of the particle energy is dissipated in nuclear collisions from which γ rays will result. Rough calculations give an upper limit to the energy in γ rays (mainly concentrated in the first ten years) as about 10^{49} erg. If supernovae occur at an average frequency of 1 per 25 years per galaxy, the maximum extra γ-ray yield will be of the order of $1{\cdot}3\times10^{40}\,\text{erg}\,\text{s}^{-1}$. The corresponding 'static' value for our own Galaxy is about $10^{39}\,\text{erg}\,\text{s}^{-1}$ (§ 3) so that clearly if the efficiency of the process described were more than a few per cent then the contribution from prompt supernovae would be of the same order as that of the Galaxy.

The next facet of 'normal' galaxies to be considered is that of the likely range of cosmic ray energy densities and of spectral exponents in other galaxies. Ginzburg and Syrovatskii (1964) use radio data to estimate energy densities for a number of normal galaxies and these are not far from that in the Galaxy; more important, however, is the range of exponents. The exponent of the radio spectrum α (i.e. the exponent in the expression $I_\nu=A\nu^\alpha\,\text{W}\,\text{m}^{-2}\,\text{sr}^{-1}\,\text{Hz}^{-1}$) is related to the exponent of the electron spectrum in a galaxy and there is a fair amount of information on the relevant values. Confining analysis to a fixed frequency of about 100 MHz (the exponents vary somewhat with frequency) attention should be directed to the summary of Allen (1973)

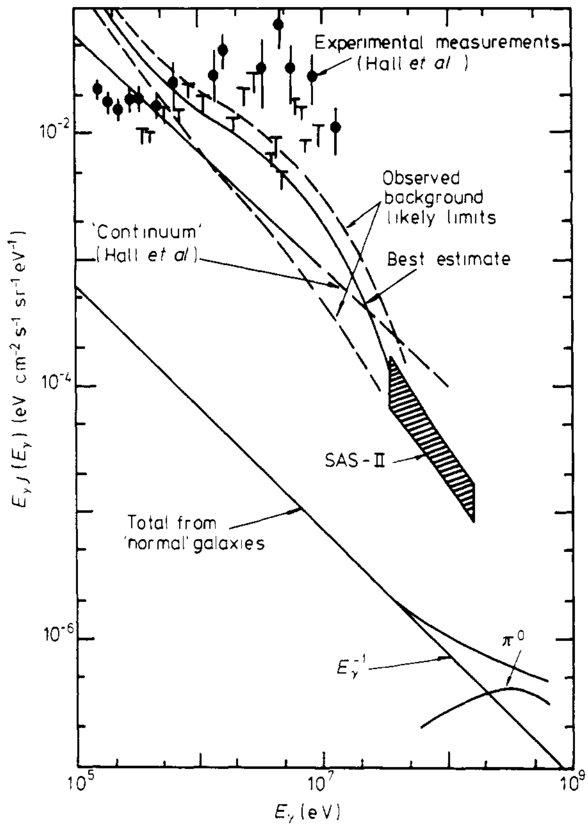

Figure 3. Comparison of observed γ-ray background with the contribution from radio galaxies for an evolutionary model and that from 'normal' galaxies. The limits to the observed background need explanation; the upper limit and the 'best estimate' follow from the data of figure 1, the lower limit also uses measurements by Daniel *et al* (1972) (see also the summary by Pinkau 1975). The 'SAS-II' data are those of Fichtel *et al* (1975). The radio galaxy contribution is calculated from the data of Hall *et al* (1975) for Cen A converted to a predicted background using the method described in the text. Although Hall *et al* indicate a number of finite line intensities for Cen A above 1 MeV they claim line emission only at 1·6 MeV and 4·5 MeV, the other intensities being less than one standard deviation above zero (Meegan, private communication).

which shows that although the mean value for galactic sources is $\alpha = -0{\cdot}71$, the mean for extragalactic sources is $-1{\cdot}05$ (the value for the Galaxy as a whole is approximately $-0{\cdot}75$). Thus, the electron spectra in other galaxies are probably, on average, somewhat steeper than in our own. The implication for γ rays from π^0 production (by protons) is not great but there is considerable relevance for γ rays from electrons (by way of bremsstrahlung and ICE). These processes dominate in the range 1–30 MeV so that here we might expect a γ-ray spectrum from extragalactic sources significantly steeper than indicated in figure 3. For example, with $\alpha = -1{\cdot}05$ the exponent of the electron spectrum will be $-3{\cdot}1$, (compared with $-2{\cdot}5$ for the Galactic value of $\alpha = -0.75$) so that the exponent for the γ rays produced by way of ICE will be $-2{\cdot}05$ and that of bremsstrahlung will be $-3{\cdot}1$ under the assumption that the electron spectrum has a constant exponent over the energy range in question. In fact there will no doubt be a variation of electron exponent with energy and the exponent of the bremsstrahlung γ rays will be reduced; however, the overall γ-ray spectrum will still be steeper than that of Galactic γ rays and more in agreement with observation.

4.3. *The contribution from radio galaxies*

4.3.1. Calculation using method (a). Calculations using method (a) will necessarily provided only a lower limit, since radio galaxies exhibit strong evolution.

Schmidt (1972) gives density–luminosity data at 500 MHz for radio galaxies separate from other extragalactic objects. From these data, assuming q_γ to be proportional to radio luminosity, L_R, at 500 MHz we estimate, for a Hubble constant of 50 km s^{-1} Mpc^{-1},

$$\frac{\overline{\eta_R q_\gamma}}{\bar{q}_\gamma}=\frac{\overline{\eta_R L_R}}{\bar{L}_R}=3{\cdot}7\times10^5 \qquad \text{and} \qquad \bar{L}_R=3{\cdot}5\times10^{25}\ \mathrm{W\ Hz^{-1}}.$$

If a radio galaxy gives a γ-ray flux at the earth of $F(E_\gamma)$ and a 500 MHz flux of $F_R(\nu)$ then the arguments of § 4.1 show that the estimated contribution to the γ-ray background from radio galaxies will be

$$j(E_\gamma)=1{\cdot}3\times10^{-58}\eta\frac{F(E_\gamma)}{F_R(\nu)}\bar{L}_R.$$

The only radio galaxy to have quoted flux limit for γ rays above 100 MeV appears to be M87 with a SAS-II value (Fichtel *et al* 1975) of $j(>100\ \mathrm{MeV})<10^{-6}\ \mathrm{cm^{-2}\ s^{-1}}$. The 500 MHz radio flux is $F_R(\nu)=450$ Jy (Jansky $\equiv 10^{-26}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$) giving a contribution to the background from radio galaxies of less than $3{\cdot}7\times10^{-6}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}$, that is less than 19% of the measured intensity.

Unfortunately, no other upper limits have been given for radio galaxies in the γ-ray region above 100 MeV, although observations of Cen A up to 10 MeV have been made by Hall *et al* (1975) and γ rays above 3×10^{11} eV have almost certainly been detected from the same object (see Grindlay *et al* 1975a).

In the x-ray region, Uhuru (Giacconi *et al* 1974) have only observations for four radio galaxies; M87, Cen A, 3C405 and 3C129 (in the case of M87 the Uhuru value is only an upper limit to the Galactic nucleus emission since the x-ray diameter is approximately 200 kpc).

In view of the fact that there is an absence of observations in the γ-ray energy region of major interest here, we have to resort to model predictions. The shortage of radio galaxies for which there are x-ray observations makes it statistically meaningless to search for correlations between the x-ray flux and fluxes at other wavelengths for this class of object. A model has been given by Grindlay (1975) for Cen A which is based on the Compton-synchrotron mechanism. As in most models for radio galaxies and Seyferts, the x-ray emission is assumed to come only from the central nucleus ($<10^{-2}$ arc sec). The radio flux is synchrotron emission and the x rays come from inverse Compton scattering of the electrons on the synchrotron photon field. Grindlay finds that consistency with the data from radio to x-ray wavelengths and the one observation at 3×10^{11} eV requires a two-component model.

Assuming a 500 MHz radio flux from Cen A of $F_R(\nu)=2300$ Jy we find that $j(E_\gamma)=0{\cdot}7F(E_\gamma)$. Figure 4 shows the observations and predictions.

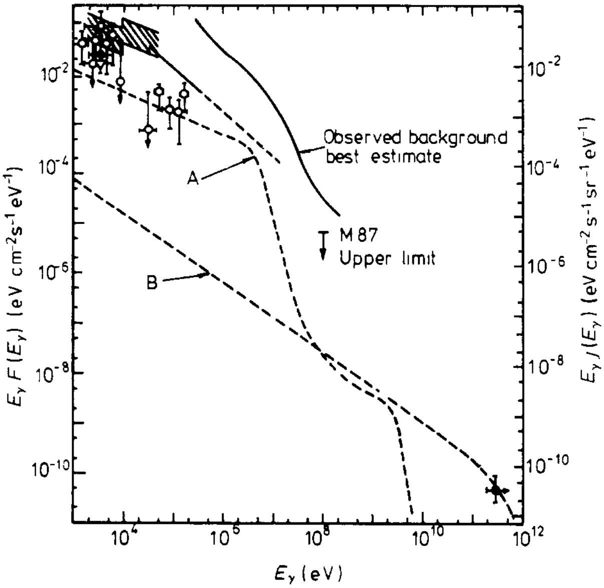

Figure 4. Comparison of observed background with the contribution from radio galaxies for a non-evolutionary model. Note the different scales (right and left): the left-hand scale is for the Cen A flux and the right-hand scale is for the background γ-ray intensity. See text, § 4.4, for explanation. Key to Cen A flux values: ○ Lampton *et al* (1972); ■ Grindlay *et al* (1975a); □ Grindlay *et al* (1975b); —— — — —— Hall *et al* (1975), the full line is a power law through the observed fluxes where the errors are small and the broken line is an extrapolation when the errors are large; ◆ Giacconi *et al* (1974); ▽ Tucker *et al* (1973); ▨ Winkler and White (1975); broken lines marked A and B are predictions from the model of Grindlay (1975) for components A and B for Cen A, see the text for details.

The right-hand ordinate gives the contribution to the background flux. A line through the diffuse background observations is shown for comparison and also the upper limit provided by M87. As the Grindlay model stands, the prediction for 100 MeV is only of the order of $2{\cdot}2\times10^{-8}$ eV cm^{-2} s^{-1} sr^{-1} eV^{-1} and the expected radio galaxy contribution to the background at 100 MeV is only about 0·1%. In order to produce a large flux at around 100 MeV we need either: (*a*) the synchrotron component A to turn over at about $10^{15\cdot3}$ Hz as opposed to 10^{14} Hz (see figure 1 of Grindlay 1975), implying that the inverse Compton component, A, turns over at about 10^8 eV, as would be the case if there were large scale optical absorption; or (*b*) the synchrotron component B (not shown in the figure) to extend to 10^8 eV instead of cutting off at 10^5 eV.

It is not possible to test (*b*) above by comparison with other radio galaxies as there is a lack of observations in the high energy x-ray/γ-ray region. However, the optical emission from other radio galaxies (e.g. M87) has been investigated; so far giving no great encouragement. Large scale absorption of the optical photons must be postulated.

An alternative situation is that the model is not appropriate and that the actual photon spectrum is smooth over the whole range 10^4 to 10^{11} eV. In this case a contribution of the order of 50% at 100 MeV might be expected.

In conclusion, the analysis using method (*a*) gives a lower limit (i.e. without evolution) of around 5% for $3\times10^5 < E_\gamma < 3\times10^6$ eV (figure 4) with a negligible contribution above 10^7 eV if the Grindlay model is correct or a large contribution if a smooth spectrum is adopted.

4.3.2. Calculation using method (*b*). The approach here is to assume proportionality between the radio emission and that of γ rays for radio galaxies. Three situations are considered: the proportionality is taken from observations on normal galaxies, on M87 and on Cen A. Longair (1971) estimates that the powerful radio galaxies produce a background of 16–19 K at 178 MHz, giving a total, inclusive of normal galaxies, of 20–23 K compared with Bridle's (1967) observed value of 30 ± 7 K. Similarly, Schmidt (1972) gives 1·5 K at 408 MHz for objects other than normal galaxies, giving a total of 2·0 K compared to Bridle's (1967) value of 2·8 K. The above estimates are based on source counts extrapolated using the evolutionary models derived from the counts. Adopting these values gives $j_\gamma(>100\ \mathrm{MeV}) = 3{\cdot}4\times10^{-6}$ and $2.8\times10^{-6}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}$, i.e. about 17% and 14% of the background respectively.

The SAS-II upper limit for the M87 flux of $1{\cdot}0\times10^{-6}\ \mathrm{cm^{-2}\ s^{-1}}$ (>100 MeV) can be combined with its 178 MHz flux of 970 Jy and the background intensity at 178 MHz of $1{\cdot}9\times10^{22}\ \mathrm{W\ m^{-2}\ sr^{-1}\ Hz^{-1}}$ (20 K) to give $j_\gamma(>100\ \mathrm{MeV}) < 2\times10^{-5}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}$, a value not incompatible with the observed value.

Turning now to Cen A, the galaxy from which a continuum of γ rays has been observed in the range 1–10 MeV by Hall *et al* (1975) with line emission at 1·6 MeV and 4·5 MeV, the data can again be used to predict the intensity of the diffuse γ-ray background. If the observed flux is denoted by $F(E_\gamma)\ \mathrm{cm^{-2}\ s^{-1}\ eV^{-1}}$ then, using Longair's estimate for the radio background from radio galaxies and the 178 MHz flux from Cen A of 4800 Jy, we find $j(E_\gamma) = F(E_\gamma)\times3{\cdot}6$. This is a factor of 4·4 higher than the estimate for the case with no evolution under the present assumptions. The observations of Hall *et al* now imply a contribution from radio galaxies in the 1–10 MeV range comparable with observations and this is indicated in figure 3. It is seen that the 'continuum' measurement gives intensities within the experimental limits and the spectral lines at 1·6 MeV and 4·5 MeV extend to even higher values.

To conclude this discussion of radio galaxies, we see that there is a discrepancy of about 5 between the predictions from a model including evolution and those from a model without evolution for our assumptions. Since we know from source count observations that radio galaxies show evolution we prefer method (*b*) and therefore conclude that radio galaxies should be a principal contributor to the γ-ray background in the 1–10 MeV range; they may even account for the whole of the observed background in this region.

4.4. *The contribution from Seyfert galaxies*

Estimates of the contribution from Seyfert galaxies must be very model dependent because there are as yet no observations of γ rays from Seyferts. Attention is restricted to the model for Seyferts suggested by Bergeron and Salpeter (1971, 1973, to be referred to as BS) in which the nucleus is envisaged as containing a central source of relativistic electrons which produce the IR radiation by synchrotron emission; the x rays and γ rays then result from first- and second-order Inverse Compton scatterings respectively. (Third-order scattering is negligible owing to the fall-off in the Klein–Nishina cross section.) The following relation between infrared, x-ray and γ-ray luminosity follows:

$$L_\gamma/L_x = L_x/L_{IR}.$$

Only two Seyferts, NGC 4151 and NGC 1275, have been detected in x rays. Fortunately L_{IR} (10μm) for NGC 4151 ($6{\cdot}8\times10^{42}$ erg s^{-1}) is close to the mean value for Seyferts, $\overline{L_{IR}}$ (10μm), and therefore we assume that L_γ for NGC 4151 is an appropriate average for Seyferts. $\overline{L_{IR}}$ (10μm) was calculated from data on 18 Seyferts and related galaxies given by Rieke and Low (1972). To try to remove the bias towards objects with high luminosity we note that the maximum distance to which a source can be seen $d_m \propto L^{1/2}$, and hence the volume observed $V_m \propto L^{3/2}$. The best estimate of $\bar{L}$ is therefore given by $\bar{L} = \Sigma L^{-1/2}/\Sigma L^{-3/2}$.

The method is invalid unless the sample is complete, i.e. includes all objects down to a limiting flux density. This is clearly far from the case with our small sample; however, $\bar{L}$ will still be estimated correctly provided that the sample is unbiased in the choice of the distances of objects—and this condition is probably fulfilled.

The expression gives a value $\bar{L}_{IR} = 3\times10^{42}$ erg s^{-1} for the sample chosen. This is close to the lower end of the scale of luminosity, showing that the powerful sources like NGC 1275 are unimportant in comparison with the more numerous weaker sources.

The total IR luminosity for NGC 4151 is $5{\cdot}7\times10^{43}$ erg s^{-1} (Rieke and Low 1975) and L_x (2–6 keV) $= 3\times10^{42}$ erg s^{-1} (Kellogg *et al* 1973). We therefore have $L_\gamma = 1{\cdot}6\times10^{41}$ erg s^{-1}.

Taking $\eta = 5\times10^7$ per 'unit' volume (from Schmidt 1971) we find a γ-ray background energy flux of 700 eV cm^{-2} s^{-1} sr^{-1}, compared with an observed energy flux in the 30–200 MeV range of 5000 eV cm^{-2} s^{-1} sr^{-1}. This estimate for Seyferts is conservative since $L_\gamma \propto L_x^2$ and we have included only the x-ray flux in the 2–6 keV range and the spectrum is quite flat (index −0·7) (Kellogg *et al* 1973); an increase from 700 to 5000 eV cm^{-2} s^{-1} sr^{-1} for the predicted flux is quite likely. The γ rays will be produced mainly at energies of order $E_\gamma \sim \epsilon_x^2/\epsilon_{IR}$ where ϵ_{IR} and ϵ_x are the mean energies of the IR and x-ray photons. The IR maximum probably occurs near 100μm ($\epsilon_{IR} \sim 10^{-2}$ eV) (Rieke and Low 1975) and $\epsilon_x \sim 1$ keV so that $E_\gamma \sim 100$ MeV.

We conclude that if the BS mechanism is correct, Seyferts may contribute most of the 100 MeV background. Alternative models involving x rays from supernova remnants however (Harwit and Pacini 1975) would give a much lower γ-ray flux.

4.5. The contribution from clusters of galaxies

Rowan-Robinson and Fabian (1975) have considered the contribution to the x-ray background expected from Abell clusters. They conclude that the likely contribution at 10^{18} Hz (4·1 keV) is in the range 5–7% for no evolution and 22–65% for an evolutionary factor of the form $\exp\{5[1-(1+z)^{-1}]\}$. If the inverse Compton mechanism (ICE) is the dominant x-ray production process then we expect a significant contribution to the background at γ-ray energies since the spectral slope will be smaller than that of the background for an electron spectrum similar to that of the Galaxy. However, thermal bremsstrahlung may well be in the x-ray production mechanism in which case the γ-ray contribution will be negligible.

The hypothesis that ICE is the dominant x-ray and γ-ray production mechanism for clusters would be supported if either spectra from individual clusters were found to be power laws, or a correlation were to be found between the radio and x-ray luminosities for clusters. It is unfortunate that present x-ray observations of individual clusters on the whole give equally good fits to power law and thermal spectra. Conclusions reached from an analysis of the spectral data from the Uhuru satellite are that best fits are given by power law spectra for the Virgo cluster (Kellogg *et al* 1972) and the Perseus cluster (Forman *et al* 1972), and equally by a power law or thermal spectrum in the case of Coma (Forman *et al* 1972). Data from the Copernicus experiment for both the Perseus (Fabian *et al* 1974) and Centaurus (Mitchell *et al* 1975) clusters can be fitted equally well by power law or thermal spectra.

In the majority of x-ray cluster sources, up to about 25% of the emission is from a central massive galaxy. This x-ray emission is most likely ICE from the nuclei of these galaxies (see discussions of radio galaxies and Seyferts), but from spectral information we cannot come to a firm decision as to how much of the bulk of cluster emission is ICE.

A correlation between the radio and x-ray luminosities of clusters would be suggestive of an ICE x-ray flux and synchrotron radio flux from the same electron spectrum. Kellogg *et al* (1973) searched for a correlation, but with too few statistics to come to a firm conclusion. Owen (1974) claims a correlation for ten x-ray sources identified with Abell clusters between the x-ray and 1400 MHz radio flux but in a comparison of the 10 MHz radio luminosity with the 10^{12} MHz x-ray luminosity for 18 Abell clusters, Rowan-Robinson and Fabian (1975) find no general correlation.

It is therefore not possible to say whether ICE or bremsstrahlung dominates and we must await further observations before attempting a firm estimate of the cluster contribution to the γ-ray diffuse flux.

5. Conclusions

We have shown that normal galaxies provide only about 4% of the diffuse γ-ray background, at least at 100 MeV, with perhaps up to as much again from galaxies which have had recent supernovae. The observations of Cen A together with an evolutionary model suggest that radio galaxies can produce the 1–10 MeV background if the γ-ray and radio luminosities are proportional. Seyfert galaxies and clusters may be able to account for the 100 MeV observations if the x-ray and γ-ray emissions are by the inverse Compton mechanism.

Firmer conclusions must now await more experimental data from specific objects and hence a better understanding of the models of production of energetic quanta.

Acknowledgments

The authors wish to thank Dr M Rowan-Robinson, Dr A C Fabian and Mr D Dodds for helpful comments and criticisms.

The Science Research Council is thanked for provision of a Research Council Studentship to DMW and the 1851 Commission for the award of a Fellowship to AWS.

References

Allen C W 1973 *Astrophysical Quantities* (London: Athlone Press)
Bergeron J and Salpeter E E 1971 *Astrophys. Lett.* **9** 121–4.
——— 1973 *Astron. Astrophys.* **22** 385–406

Beuermann K P 1974 *Proc. 9th ESLAB Symp., Frascati, Ed. ESRO* SP-106 pp 259–63

Boldt E 1974 *High Energy Particles and Quanta in Astrophysics* eds F B McDonald and C E Fichtel, (Cambridge, Mass.: MIT Press) p 368

Bridle A H 1967 *Mon. Not. R. Astron. Soc.* **136** 219–40

Cowsik R and Voges W 1974 *Proc. 9th ESLAB Symp., Frascati, Ed. ESRO* SP-106 pp 229–39

Daniel R R, Joseph G and Lavakare P J 1972 *IAU/COSPAR Symp.* 55 (Dordrecht: Reidel)

Daniel R R and Lavakare P J 1975 *Proc. 14th Int. Conf. on Cosmic Rays, Munich* vol. 1 (Munich: Max Planck Institut für extraterrestriche Physik) pp 23–8

Dodds D, Strong A W, Wolfendale A W and Wdowczyk J 1975 *J. Phys. A: Math. Gen.* **8** 624–35

Fabian A C, Zarnecki J C, Culhane J L, Hawkins F J, Peacock A, Pounds K A and Parkinson J H 1974 *Astrophys. J. Lett.* **189** 59–63

Fichtel C E, Hartman R C, Kniffen D A, Thompson D J, Bignami G F, Ogelman H, Ozel M F and Tumer T 1975 *Astrophys. J.* **198** 163–82

Forman W, Kellogg E, Gursky H, Tananbaum H and Giacconi R 1972 *Astrophys. J.* **178** 309–16

Giacconi R, Murray S, Gursky H, Kellogg, E, Schreier E, Matilsky T, Koch D and Tananbaum H 1974 *Astrophys. J. Suppl.* **237** 27, 37

Ginzburg V L and Syrovatskii S I 1964 *The Origin of Cosmic Rays* (Oxford: Pergamon)

Grindlay J E 1975 *Astrophys. J.* **199** 49–53

Grindlay J E, Helmken N F, Hanbury Brown R, Davis J and Allen L R 1975a *Astrophys. J. Lett.* **197** 9–12

Grindlay J E, Schnopper H, Schreier E J, Gursky H and Parsignault D R 1975b *Astrophys. J. Lett.* to be published

Hall R D, Meegan C A, Walraven G D, Djuth F T, Shelton D H and Haymes R C 1975 *Proc. 14th Int. Conf. on Cosmic Rays, Munich* vol. 1 (Munich: Max Planck Institut für extraterrestriche Physik) pp 84–8

Harwit M and Pacini F 1975 *Astrophys. J. Lett.* **200** 127–9

Helmken H and Hoffman J 1973 *Nature, Phys. Sci.* **243** 6–8

Huchra J and Sargent W L W 1973 *Astrophys. J.* **185** 433–43

Kellogg E, Gursky H, Tananbaum H, Giacconi R and Pounds K 1972 *Astrophys. J. Lett.* **174** 65–9

Kellogg E, Murray S, Giacconi R, Tananbaum H and Gursky H 1973 *Astrophys. J. Lett.* **185** 13–6

Kiang T D 1961 *Mon. Not. R. Astron. Soc.* **122** 263–78

Kniffen D A, Bignami G F, Fichtel C E, Thompson D J and Cheung C Y 1975 *Proc. 14th Int. Conf. on Cosmic Rays, Munich*, vol 1 (Munich: Max Planck Institut für extraterrestriche Physik) pp 40–5

Kraushaar W L, Clark G W, Garmire G P, Borken R, Higbit P, Leong C C and Thorsos T 1972 *Astrophys. J.* **177** 341–63

Lampton M, Margon B, Bowyer S, Mahoney W and Anderson K 1972 *Astrophys. J. Lett.* **171** 45–50

Landecker T L and Wielebinski R 1970 *Aust. J. Phys., Astrophys. Suppl.* **16** 1–30

Longair, M S 1971 *Rep. Prog. Phys.* **34** 1125

Mitchell R J, Charles P A, Culhane J L, Davison P J N and Fabian A C 1975 *Astrophys. J. Lett.* **200** 5–8

Morrison P 1958 *Nuovo Cim.* **7** 858–65

Owen F N 1974 *Astrophys. J. Lett.* **189** 55–8

Paul J, Cassé M and Cesarsky C J 1976 *Astrophys. J.* submitted for publication

Pinkau K 1975 *Origin of Cosmic Rays* eds J L Osborne and A W Wolfendale (Dordrecht: Reidel) pp 335–70

Puget J L and Stecker F W 1974 *Astrophys. J.* **191** 323–9

Rieke G H and Low F J 1972 *Astrophys. J. Lett.* **176** 95–100

——— 1975 *Astrophys. J. Lett.* **200** 67–9

Rowan-Robinson M and Fabian A C 1975 *Mon. Not. R. Astron. Soc.* **170** 199–217

Schmidt M 1971 *Nuclei of Galaxies* ed D J K O'Connell (Amsterdam: North Holland) pp 395–401

——— 1972 *Astrophys. J.* **176** 288–301

Schwartz D and Gursky H 1973 *Proc. Gamma Ray Astrophys. Symp. Goddard Space Flight Centre, NASA* (Greenbel)

Shapiro S 1971 *Astron. J.* **78** 291–3

Share G H, Kinzer R L and Seeman N 1974 *Astrophys. J.* **187** 511–9

Schectman S A 1973 *Astrophys. J.* **179** 681–98

Sood R K, Bennett K, Clayton P G and Rochester G K 1974 *ESLAB Symp. on γ-Ray Astronomy, Frascati, Ed. ESRO* SP-106 pp 217–20

Stecker, F W 1969 *Astrophys. J.* **157** 507–14

——— 1971 *Cosmic Gamma Rays* (Baltimore, Maryland: Mono Book Corporation)

Stecker F W and Puget J L 1972 *Astrophys. J.* **178** 57–76

Stecker F W 1975 *Origin of Cosmic Rays* eds J L Osborne and A W Wolfendale (Dordrecht: Reidel) pp 267–334

Strong A W 1975 *J. Phys. A: Math. Gen.* **8** 617–23
Strong A W, Wdowczyk J and Wolfendale A W 1974 *J. Phys. A: Math. Gen.* **7** 120–34
Strong A W and Worrall D M 1976 *J. Phys. A: Math. Gen.* **9** 823–7
Strong A W, Wolfendale A W and Worrall D M 1976 *Mon. Not. R. Astron. Soc.* **175** 23–7
Tucker W, Kellogg E, Gursky H, Giacconi R and Tananbaum H 1973 *Astrophys. J.* **180** 715–24
Winkler P F and White A E 1975 *Astrophys. J. Lett.* **199** 139–42