ADP-AT-96-1
Astroparticle Physics, in press

A new estimate of the extragalactic radio background and implications for ultra-high-energy gamma-ray propagation

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Abstract

We make a new estimate of the extragalactic radio background down to kHz frequencies based on the observed luminosity functions and radio spectra of normal galaxies and radio galaxies. We have constructed models for the spectra of these two classes of objects down to low frequencies based on observations of our Galaxy, other normal galaxies and radio galaxies. We check that the models and evolution of the luminosity functions give source counts consistent with data and calculate the radio background expected from kHz to GHz frequencies.

The motivation for this calculation is that the propagation of ultra-high energy gamma-rays in the universe is limited by photon-photon pair production on the radio background. Electromagnetic cascades involving photon-photon pair production and subsequent synchrotron radiation in the intergalactic magnetic field may develop. Such gamma-rays may be produced in acceleration sites of ultra-high energy cosmic rays, as a result of interactions with the microwave background, or emitted as a result of decay or annihilation of topological defects. We find that photon-photon pair production on the radio background remains the dominant attenuation process for gamma-rays from 3×10^{10} GeV up to GUT scale energies.

1 Introduction

The universe is not transparent to high energy gamma-rays due to interactions with low energy photons of the extragalactic radiation fields, the most important process being photon-photon pair production. For example, interactions in the cosmic microwave background radiation give a mean interaction length of less than 10 kpc at 10^6 GeV as has been known since soon after the discovery of the microwave background [1, 2]. The threshold for interactions on the microwave background is $\sim 10^5$ GeV, and at lower energies interactions on the infrared and optical backgrounds limit the transparency at TeV energies (e.g. [3, 4]) Other components of the extragalactic background radiation are discussed in the review of Ressel and Turner [5].

Above $\sim 10^{10}$ GeV interactions with the radio background become more important than the microwave background in limiting the transparency of the universe to gamma-rays and controlling any resulting electromagnetic cascades. Both the infrared and radio backgrounds are poorly known due to our location within our Galaxy which emits and absorbs at these wavelengths. The radio background was measured over twenty-five years ago [6], but the fraction of this radio background which is truly extragalactic, and not contamination from our own Galaxy, is still debatable. A theoretical estimate [7] was made about the same time which gave a quite different spectrum, particularly at low frequencies. In recent cascade calculations [8, 9, 10, 11] the estimate of ref. [6] has been used. It is this very uncertain radio background which will provide target photons for UHE γ-rays above $\sim 10^{10}$ GeV.

While gamma-ray astronomy is not currently undertaken at $\sim 10^{10}$ GeV energies, it is important to know the photon-photon mean interaction length at these energies because cascading involving gamma-rays at these energies occurs in top-down models for the origin of the highest energy cosmic rays. The highest energy cosmic rays have energies of 200 EeV [12, 13] and 300 EeV [14], and are well above the "Greisen-Zatsepin-Kuzmin cut-off" [15, 16] at 50 EeV in the spectrum of cosmic ray protons due to pion photoproduction in the microwave background, which is expected if the cosmic rays originate further than a few tens of Mpc (*e.g.*, [17, 18]). Of the various models proposed to account for the origin of these high energy cosmic rays [19, 18, 20, 21, 22], one of the more tantalizing speculations is that the highest energy cosmic rays may be ultimately due to the decay of supermassive X particles [23, 24, 25, 26], themselves radiated during collapse or annihilation of topological defects, remnants of an early stage in the evolution of the Universe. The X particles have GUT-scale masses of $\sim 10^{16}$ GeV or lower, depending on the theory, and decay into leptons and quarks at lower energies. The quarks themselves fragment into a jet of hadrons which, it is supposed, could produce the highest energy cosmic rays, although there is some debate as to whether a sufficiently large fraction of the energy of the defect could end up in high energy particles [27]. In any case, much of the radiation is likely to emerge in the electromagnetic channel and initiate an electromagnetic cascade in the ambient radiation field, in which collisions with radio photons play an important role.

In this paper we make a new calculation of the extragalactic radio background down to kHz frequencies based on the infrared luminosity function of normal galaxies recently determined from IRAS source counts, the observed radio–infrared correlation, and the luminosity function of radio galaxies, together with recent models for radio spectra of these objects. Finally, we calculate the mean free path for γ-rays in the extragalactic radio background radiation.

2 Calculation of radio background

The main contributions to the radio background will be from normal galaxies and radio galaxies and we will discuss the radio spectra of these objects down to kHz frequencies and construct models for their spectra. Using appropriate luminosity functions, we will then integrate over luminosity and redshift to obtain the radio background. This is very sensitive to the evolution of galaxies and we shall use radio and infrared source counts to constrain the evolution. We start by discussing the how the observed radio flux is related to the luminosity in an expanding universe.

The observed flux S_ν at frequency ν is related to the luminosity at frequency $\nu' = (1+z)\nu$ by

$$S_\nu = \frac{L_{\nu'}}{4\pi d_L^2}\frac{d\nu'}{d\nu} = \frac{L_{\nu'}(1+z)}{4\pi d_L^2} \tag{1}$$

where S_ν has units of W Hz^{-1} m^{-2}, L_ν has units of W Hz^{-1}, $d_L = (1+z)d_0$ is the luminosity distance, and d_0 is the physical distance at photon reception (m).

2.1 Normal galaxies

In calculating the radio flux of normal galaxies, we shall use the 60 micron luminosity, L_{60}, and an observed correlation between the luminosities at 1.4 GHz, $L_{1.4}$, and at 60 micron. We may then write

$$S_\nu = \frac{(L_{\nu'}/L_{1.4})(L_{1.4}/L_{60})L_{60}(1+z)}{4\pi d_L^2}. \quad (2)$$

We use the observed correlation between the luminosities at 1.4 GHz and at 60 micron given by Condon [28]

$$L_{1.4} = 1.69 \times 10^{-3}(2.58 + 1.67^\alpha)L_{60} \quad (3)$$

where both L_{60} and $L_{1.4}$ have units W Hz^{-1}, and α is the spectral index at 60 micron. Hacking et al. [29] give the distribution of spectral indices at 60 micron which can be approximated by a gaussian distribution with mean, $\langle\alpha(L_{60}, z)\rangle$ given by equation 2 of [29], and standard deviation $\sigma = 0.5$, and we integrate over this distribution of α in our calculation.

To obtain the ratio $(L_{\nu'}/L_{1.4})$ we need to know the spectrum of normal galaxies in the radio region from GHz down to kHz frequencies. This spectrum is poorly known, and so we shall model the spectrum based on observations of the Galaxy and other galaxies above $\sim$ 50 MHz together with an estimate of the effect of free-free absorption. In the Galaxy, the observed spectrum is a power-law, $I_\nu \propto \nu^{-\alpha}$, with spectral index $\alpha \approx 0.9$ at high frequencies, and $\alpha \approx 0.4$ at low frequencies [30]. If the emission from the Galaxy were observed from outside the Galaxy it would be modified by free-free absorption by the warm and hot ionized components of the interstellar medium, and by synchrotron self-absorption. Free-free absorption by the warm component may be expected to be patchy as based on observations of external galaxies [31, 32, 33, 34]. However, this patchy absorption is apparently not the cause of the observed downturn of the radio spectra of galaxies, but rather the losses experienced by the cosmic ray electrons at low energies.

The gamma-ray emission of the Galaxy demonstrates that the low energy spectrum of cosmic ray electrons is modified by ionization and bremsstrahlung losses below about 400 MeV, and cuts off below about 50 MeV [35]. Models can be constructed that explain both the radio as well as the gamma-emission from the Galaxy. Such models then have an approximate spectrum of cosmic ray electrons as follows

$$n_e(E) \propto \begin{cases} (E/400\ \mathrm{MeV})^{-2.8} & >\ 400\ \mathrm{MeV} \\ (E/400\ \mathrm{MeV})^{-1.8} & <\ 400\ \mathrm{MeV} \\ (\ 50\ \mathrm{MeV}/400\ \mathrm{MeV})^{-1.8} & <\ 50\ \mathrm{MeV} \end{cases} \tag{4}$$

There has to be a low energy cutoff in the electron spectrum, such as exists in low energy protons ([36]); such a cutoff arises from the extreme losses in ionization and heating of the interstellar medium on the one hand, but we also need to note that energetic electrons can be accelerated in Supernova remnant shocks only at those energies for which their Larmor radius exceeds that of the thermal protons in a shock ([37]), and that corresponds to a few tens of MeV. Below this energy the electrons gain and lose energy by interaction with plasma waves ([38]).

We use the electron spectrum of Equation 4, a magnetic field of 6 microgauss [39], and apply the standard formulae for obtaining the emission coefficient (W m^{-3} Hz^{-1} sr^{-1}) for synchrotron radiation

$$\varepsilon_\nu = \frac{1}{2} c_3 B \langle \sin\theta \rangle \int_0^\infty n_e(E) F(x) dE \tag{5}$$

where $x = \nu/\nu_c$,

$$\nu_c = \frac{3}{2} \nu_g \langle \sin\theta \rangle \gamma^2, \tag{6}$$

ν_g is the electron cyclotron frequency, $\langle \sin\theta \rangle = 0.785$ for isotropic electrons, and c_3 and the function $F(x)$ are given in ref. [40]. The amount of absorption by the hot component of the interstellar medium will also depend on viewing angle. We assume a density of 0.01 cm^{-3} and a scale height of 1 kpc [41], a temperature of 3×10^5 K and radial extent of 15 kpc giving pathlengths through the galaxy ranging from 2 to 30 kpc. Since the radio synchrotron radiation is observed to originate in approximately the same volume, we solve the equation of radiative transfer for the case of the emission and absorption coefficients being independent of position throughout this volume. The intensity is then

$$I_\nu = \frac{\varepsilon_\nu}{\kappa_\nu} [1 - \exp(-\tau_\nu)], \tag{7}$$

where ε_ν is the synchrotron emission coefficient and κ_ν and τ_ν are the free-free absorption coefficient and optical depth. For a given viewing angle we model the spectrum in this way neglecting synchrotron self-absorption. Assuming an isotropic distribution of viewing angles, we obtain the average spectrum in the radio region shown in Figure 1(a).

Synchrotron-self-absorption will be important at very low frequencies if the spectrum is not cut off by other processes. Following Longair [30] the flux at frequency ν from a self-absorbed synchrotron source may be approximated by

$$S_\nu \approx \frac{2m_e}{3\nu_g^{1/2}} \Omega \nu^{5/2} \tag{8}$$

where m_e is the electron mass and Ω is the solid angle subtended by the source. For a source at distance d this implies a luminosity $L_\nu = 4\pi d^2 S_\nu$ at frequency ν and solid angle $\Omega = A_{\rm proj}/d^2$, where $A_{\rm proj}$ is the projected area of the source normal to the line of sight, we obtain

$$L_\nu \approx \frac{2m_e}{3\nu_g^{1/2}} 4\pi A_{\rm proj} \nu^{5/2} \tag{9}$$

for a self-absorbed source. For a typical galactic magnetic field of a few micro-gauss (6 microgauss in the solar neighborhood [39]) and typical dimensions of the synchrotron emitting region of normal galaxies (radius $\sim$ 15 kpc, height $\sim$ 1 kpc) we find synchrotron self-absorption to be important for $L_{1.4} > 10^{20}$ W Hz^{-1}.

Because synchrotron self-absorption will determine the shape of the low frequency part of the spectrum of normal galaxies we now give a more accurate treatment. The absorption coefficient is given by

$$\kappa_\nu = \frac{c^2 c_3}{2\nu^2} B \sin\theta \int_0^\infty E^2 \frac{d}{dE}\left[\frac{n_e(E)}{E^2}\right] F(x) dE, \tag{10}$$

and where the source is self-absorbed the intensity will be given by the source function

$$\frac{\varepsilon_\nu}{\kappa_\nu} = \frac{\nu^2 \int_0^\infty n_e(E) F(x) dE}{c^2 \int_0^\infty E^2 \frac{d}{dE}[n_e(E)/E^2] F(x) dE}. \tag{11}$$

The maximum luminosity at frequency ν is then

$$L_\nu = 4\pi A_{\rm proj} \frac{\varepsilon_\nu}{\kappa_\nu}. \tag{12}$$

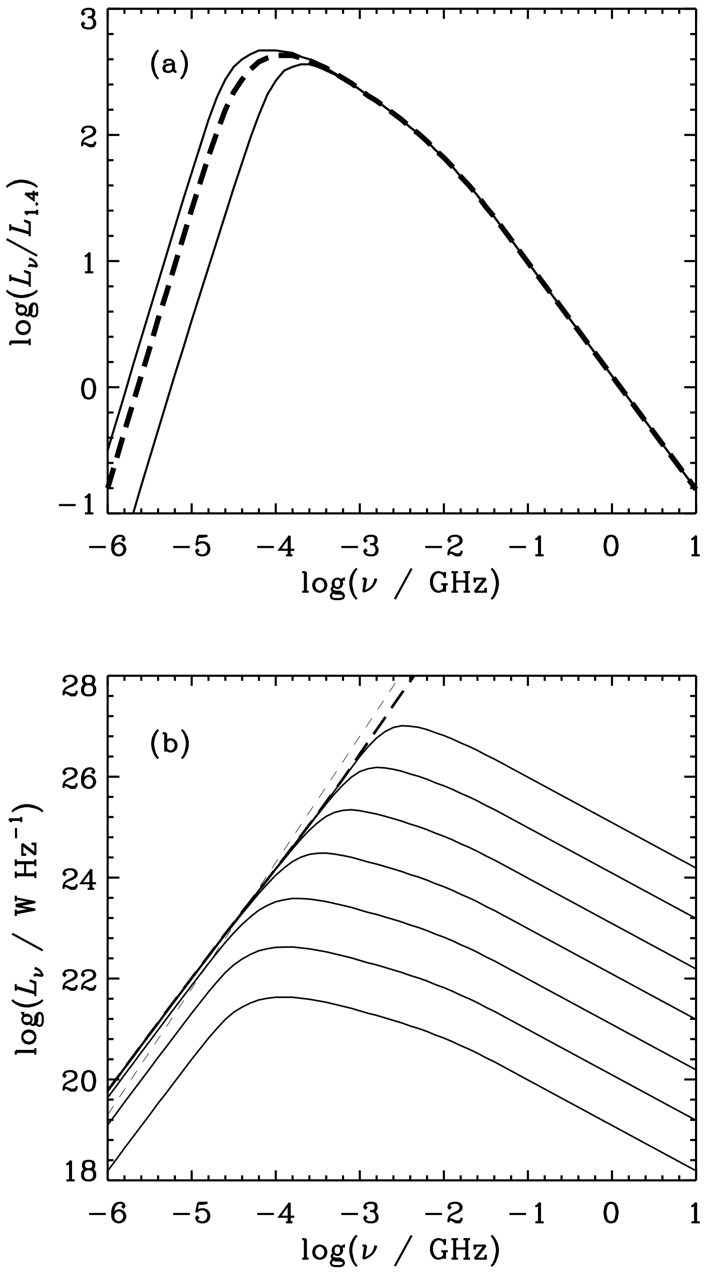

Figure 1: (a) Model radio spectrum for normal galaxies neglecting synchrotron self-absorption. Solid lines show the range of spectra for viewing angles 0° (top, face-on) and 90° (bottom, edge-on); dashed line shows average spectrum assuming isotropic distribution of viewing directions. (b) Average spectra for normal galaxies with luminosity $L_{1.4} = 10^{19} \ldots 10^{25}$ W Hz^{-1} including the effects of synchrotron self-absorption. Dashed lines show spectrum of completely self-absorbed source: long dashes – accurate treatment, short dashes – approximate treatment.

This is plotted as the long-dashed line in Figure 1(b) where average spectra of normal galaxies are also shown for a range of luminosities. The approximate result (Equation 9) is also shown (short-dashed line) and is seen to give a reasonable approximation to the more accurate treatment above. In summary, we note that all three effects, synchrotron self-absorption, free-free absorption in the hot medium, and a low energy cutoff of the electron spectrum, contribute to cut off the spectrum at kHz to MHz frequencies.

The 60 micron luminosity function, $\rho(L_{60}, z)$, is the number of sources at redshift z per unit co-moving volume at 60 micron luminosity L_{60} per unit of luminosity. It has units of Mpc^{-3} (W Hz^{-1})$^{-1}$. We use the local luminosity function, $\rho_0(L_{60})$, based on the local visibility function given by Hacking et al. [29]. The local luminosity function is obtained from equation 3 of [29]

$$\begin{aligned} \rho_0(L_{60}) &= 2.94 \times 10^{28} 10^{Q}, && (13) \\ Q &= Y - \left[B^2 + \left(\frac{\log L_{60} - X}{W} \right)^2 \right]^{1/2} - 2.5 \log L_{60}, && (14) \end{aligned}$$

where $B = 1.51, W = 0.85, X = 23.96$, and $Y = 5.93$, assuming $H_0 = 100$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ (note: in [29] Y appears to be incorrectly given as 6.93).

The 60 micron luminosity function at redshift z is

$$\rho(L_{60}, z) = \frac{g(z)}{f(z)} \rho_0 \left(\frac{L_{60}}{f(z)} \right) \tag{15}$$

where $g(z)$ and $f(z)$ are density and luminosity evolution functions. According to Gregorich et al. [42], $g(z)$ and $f(z)$ given in table 1 of Condon [43] are consistent with IRAS source counts.

The intensity (W Hz^{-1} m^{-2} sr^{-1}) from all sources is obtained by integration over redshift and 60 micron luminosity:

$$I_\nu = \frac{1}{4\pi} \int dz \frac{dV_c}{dz} \frac{(1+z)}{4\pi d_L^2} \int dL_{60}\, \rho(L_{60}, z) \left(\frac{L_{\nu'}}{L_{1.4}} \right) \left(\frac{L_{1.4}}{L_{60}} \right) L_{60} \tag{16}$$

where dV_c (m^3) is the element of co-moving volume.

2.2 Radio galaxies

The intensity due to steep-spectrum radio galaxies is obtained in a similar way using the radio luminosity function at 1.4 GHz

$$I_\nu = \frac{1}{4\pi}\int dz \frac{dV_c}{dz}\frac{(1+z)}{4\pi d_L^2}\int dL_{1.4}\,\rho(L_{1.4},z)\left(\frac{L_{\nu'}}{L_{1.4}}\right)L_{1.4}. \qquad (17)$$

We obtain the radio luminosity function from the visibility function of "monsters" obtained by Condon [43] from the Auriemma et al. [44] data for elliptical galaxies (visibility function parameters $B = 2.3$, $W = 0.75$, $X = 26.1$, and $Y = 5.47$ for $H_0 = 50$ km s^{-1} Mpc^{-1}). Condon [45] shows that the 1.4 GHz source counts favour strong luminosity evolution by a factor ~ 16 at $z \sim 0.8$.

For the ratio $L_{\nu'}/L_{1.4}$ we follow Falcke & Biermann [46] in assuming the electrons responsible for the synchrotron radiation are $e^\pm$ from $\pi \to \mu \to e$ decay, the pions being produced as secondaries in interactions of energetic protons with ambient matter. Energetic protons may be accelerated in radio galaxies to a power-law spectrum by shock acceleration [19, 18]. We make the usual assumption that the electrons will be in energy density equipartition with the magnetic field, protons, etc., and radiate in an environment of typically 10 to 100 microgauss (see e.g. ref. [47]). The electron spectrum on production has a low-energy cut-off at $\gamma_c mc^2 \approx 100$ MeV (see e.g. [48]) giving rise to a break in the synchrotron spectrum at the break frequency

$$\nu_b = \frac{3eB_\perp}{4\pi mc}\gamma_c^2 \qquad (18)$$

where $\gamma_c \approx 200$ is determined by the pion rest mass and so corresponds to the low-energy cut-off of the electron energy distribution. Adopting a $B_\perp = 30$ microgauss gives rise to a break at ~ 5 MHz. Below this break frequency the spectrum will be $\nu^{1/3}$ (i.e. the asymptotic form of the synchrotron emission coefficient at low frequency for monoenergetic electrons [40]). For the spectrum above the break frequency we use the mean spectral index $\langle\alpha\rangle = 0.75$ suggested by Condon [43]. This spectrum is shown in Figure 2(a).

Because of the much higher luminosities of radio galaxies compared to normal galaxies, synchrotron-self absorption will be greater at low frequencies than in normal galaxies. Thus the contribution of radio galaxies to the radio background will be less at low frequencies than that of normal galaxies.

We may therefore use the approximate formula (Equation 9) with $A_{\rm proj} \sim (30\ {\rm kpc})^2$ and $B \sim 10$ microgauss to obtain the maximum luminosity, and modify the spectrum given in Figure 2(a). The resulting spectra are given in Figure 2(b) for various luminosities.

2.3 Infrared and radio source counts

There are uncertainties in the evolution of the luminosity functions of normal galaxies and radio galaxies, in the radio–infrared correlation used for normal galaxies, and in the models for the radio spectra we used. We therefore decided to calculate radio and infrared source counts and compare with observation to ensure that the evolution of the luminosity functions used in calculating the radio background is consistent with the source count data.

The number of sources with observed flux at frequency ν greater than S_ν is

$$N(> S_\nu) = \int dz \frac{dV_c}{dz} \int_{L_{\nu'}}^{\infty} dL_{\nu'}\, \rho(L_{\nu'}, z) \tag{19}$$

where

$$L_{\nu'} = \frac{4\pi d_L^2}{(1+z)} S_\nu. \tag{20}$$

Differentiating equation 19 with respect to S_ν we obtain

$$n(S_\nu) \equiv \frac{1}{4\pi}\frac{dN}{dS_\nu} = \int dz \frac{dV_c}{dz} \frac{d_L^2}{(1+z)} \rho(L_{\nu'}, z). \tag{21}$$

We use the same luminosity functions and other input we used in calculating the radio background to obtain the radio source counts at 1.4 GHz for normal galaxies and radio galaxies. Resulting radio source counts of normal galaxies and radio galaxies are shown in Fig. 3(a) for the case of i) no evolution and ii) evolution of the normal galaxy population according to table 1 of Condon [43], and pure luminosity evolution of the radio galaxy population according to $f(z) = (1+z)^4$ at all z. We compare the total source counts with data obtained by Condon [45].

The calculated source counts are dominated by the radio galaxy contribution at high S_ν and by normal galaxies at small S_ν. As can be seen, in both

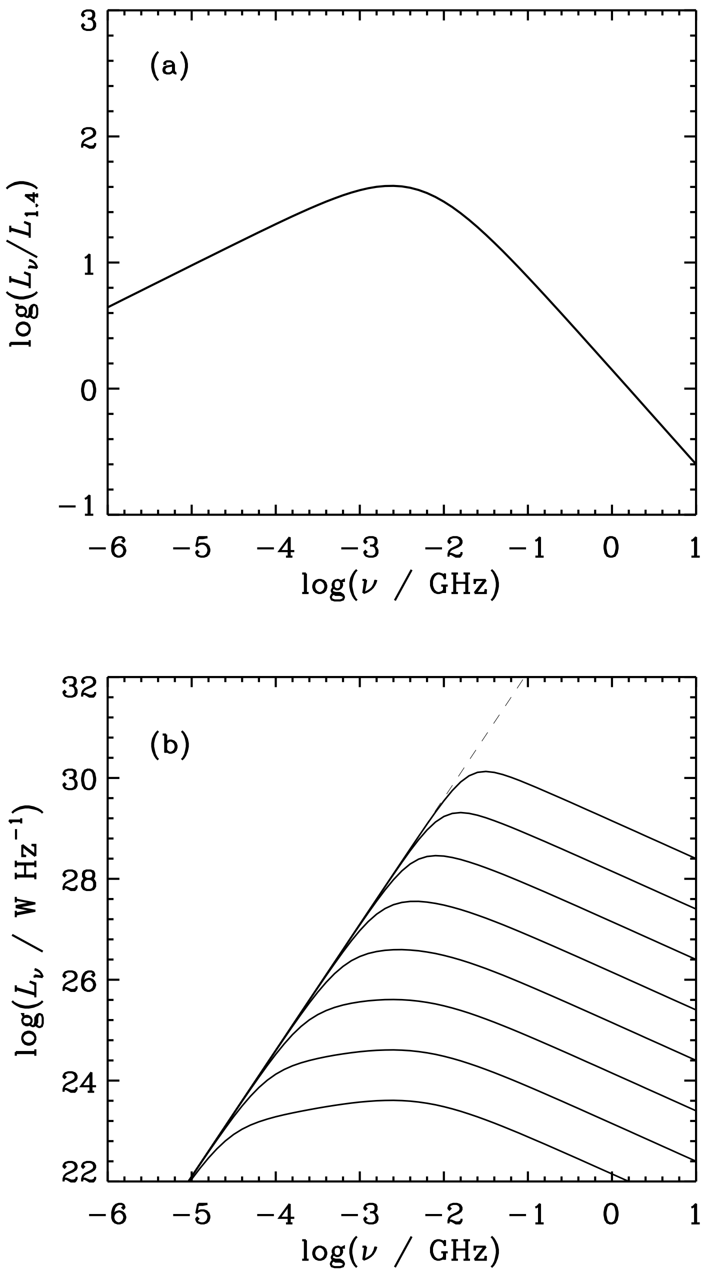

Figure 2: (a) Model radio spectrum for radio galaxies neglecting synchrotron self-absorption. (b) Average spectra for radio galaxies with luminosity $L_{1.4} = 10^{22} \ldots 10^{29}$ W Hz^{-1} including the effects of synchrotron self-absorption. Dashed line shows spectrum of completely self-absorbed source.

cases, the predicted source counts fall well below the data for the case of no evolution and are well above the data for the evolution models assumed. We note that the evolution of normal galaxies according to table 1 of Condon is also approximately pure luminosity evolution with $f(z) = (1+z)^4$. Our approach to this problem is to set $g(z) = 1$ and modify the luminosity evolution to fit the source counts. We assume luminosity evolution of the form

$$f(z) = \begin{cases} (1+z)^4 & z < z_0 \\ (1+z_0)^4 & z \geq z_0, \end{cases} \tag{22}$$

and we adjust z_0 to fit the data. We find the best fit is given by $z_0 = 0.8$ for both normal galaxies and radio galaxies. The resulting radio source counts of normal galaxies and radio galaxies are shown in Fig. 3(b) and are seen to be in good agreement with the data. As a further check, we have calculated the 60 micron source counts due to normal galaxies for the case of no evolution, evolution of the normal galaxy population according to table 1 of Condon [43], and the evolution model described above which fits best the radio source counts. The results are shown in Figure 4 where we see that the evolution model we adopt gives as good a fit as table 1 of Condon [43].

We note that by omitting data with statistical errors larger than 20% in Figure 4 (data with large error bars were included in the original plot of Gregorich et al. [42]) we see that for fluxes between 0.3 and 3 Jy both models predict source counts which are higher than the data. Whether this is an indication of a new source population contributing at $S_\nu < 0.3$ Jy (perhaps AGN), or some systematic effect affecting the data, remains to be seen. However, Gregorich et al. [42] argue that their data favour the evolution model of Condon [43] rather than no evolution, and our adopted evolution model gives as good a fit to these data as Condon's. We therefore proceed to calculate the mean free path for interactions of γ-rays in our calculated radio background for two possible cases: (a) no evolution of the normal galaxy population (we assume a new source population below 0.3 Jy which does not contribute significantly to the radio background); and (b) evolution of the normal galaxy population (we assume the sources with $S_\nu < 0.3$ Jy are still normal galaxies).

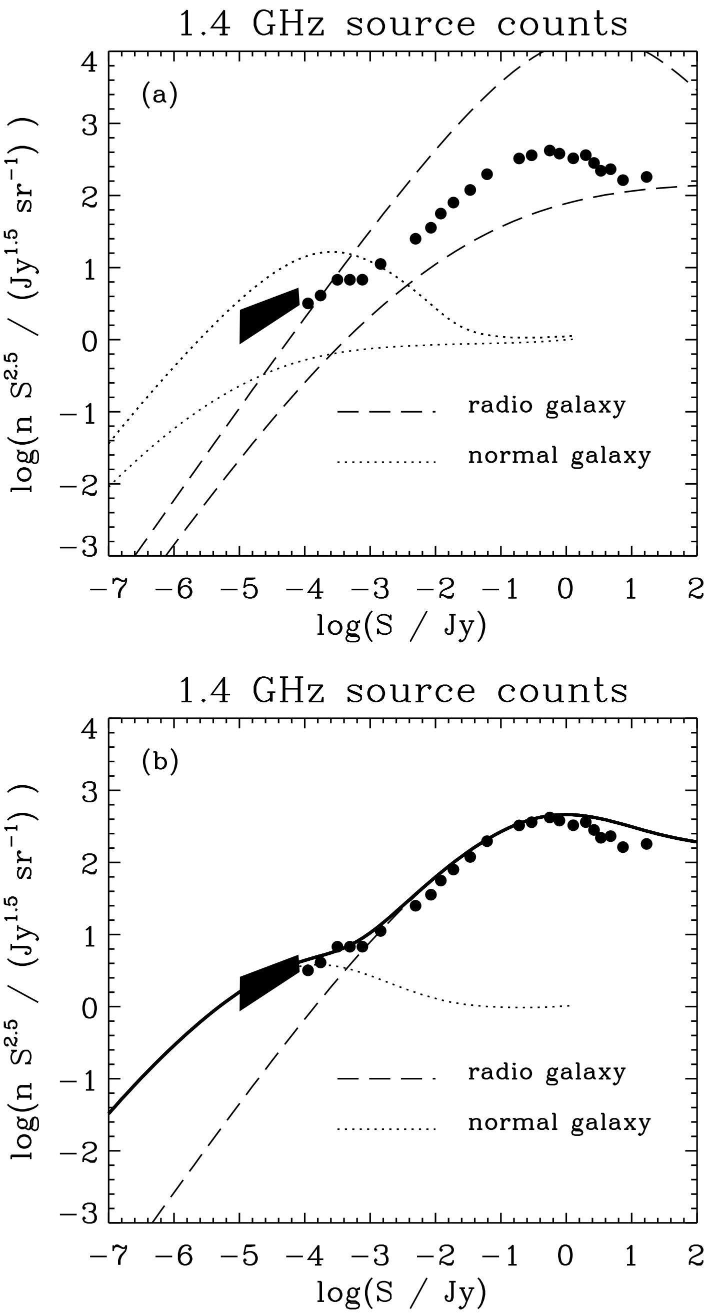

Figure 3: Contributions of normal galaxies (dotted curves) and radio galaxies (dashed curves) to the total extragalactic radio source counts at 1.4 GHz (solid curve). (a) Lower curves are for no evolution and upper curves are for evolution of normal galaxies according to table 1 of Condon [43] and pure luminosity evolution of radio galaxies described by $(1+z)^4$ at all z. (b) Best fitting pure luminosity evolution as described in the text; solid curve gives the total source count. Data are from ref. [45].

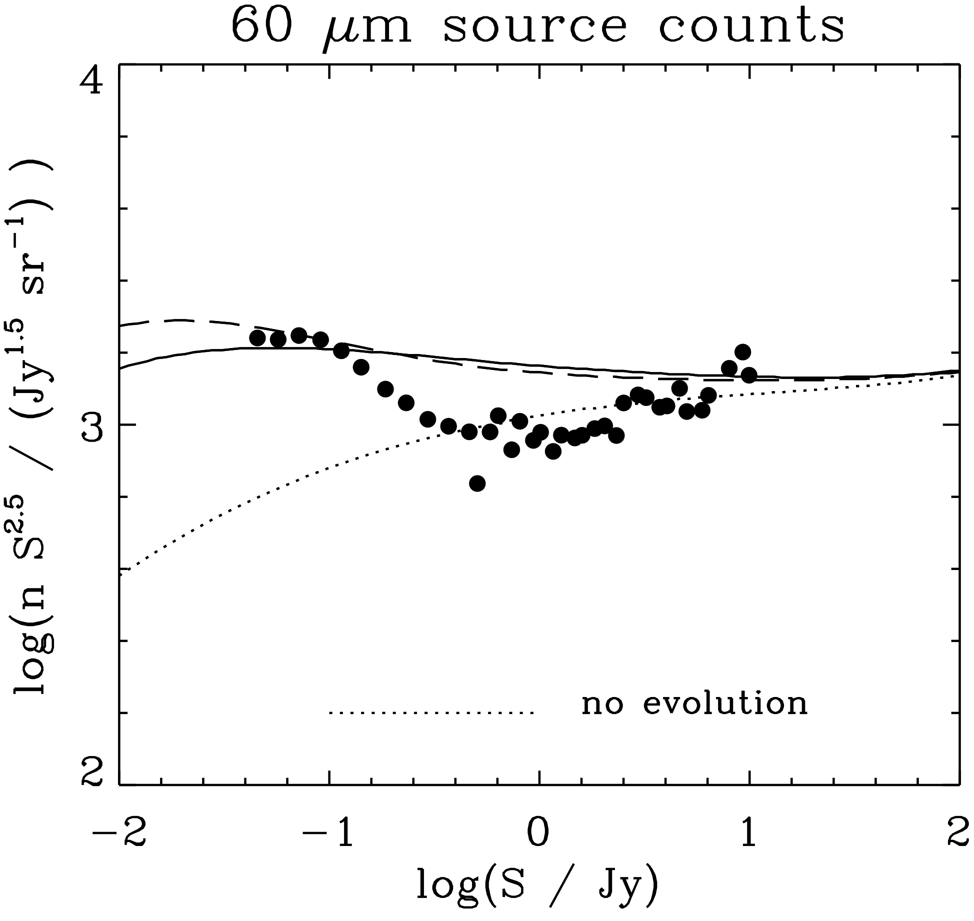

Figure 4: Contributions of normal galaxies to the 60 micron source counts for no evolution (dotted curve), evolution according to table 1 of Condon [43] (dashed curve), and with pure luminosity evolution as described in the text (solid curve). Data are points with error bars smaller than 20% from the summary in Figure 2 of ref. [42].

3 The radio background and interactions of γ-rays

The contributions to the extragalactic radio background intensity from normal galaxies, radio galaxies, and the cosmic microwave background, together with the total estimated radio background intensity are plotted in Figure 5. Our result is compared with the total extragalactic radio background intensity estimated from observations by Clark et al. [6] and with a theoretical estimate made several years ago by Berezinsky [7]. We note that with our adopted model for the radio spectrum from normal galaxies, the normal galaxies dominate the background as suggested by their dominance in source counts at low flux density levels ([49]).

Photon-photon interactions are described in [50] and references therein. The mean interaction length, λ, of a photon of energy E is given by,

$$[\lambda(E)]^{-1} = \frac{1}{8E^2}\int_{\varepsilon_{\min}}^{\infty} d\varepsilon \frac{n(\varepsilon)}{\varepsilon^2}\int_{s_{\min}}^{s_{\max}(\varepsilon,E)} ds\, s\sigma(s), \tag{23}$$

where $n(\varepsilon)$ is the differential photon number density of photons of energy $\varepsilon = h\nu$,

$$n(\varepsilon) = \frac{4\pi}{hc}\frac{I_\nu}{h\nu}, \tag{24}$$

and $\sigma(s)$ is the total cross section for photon-photon pair production [51] for a centre of momentum frame energy squared given by

$$s = 2\varepsilon E(1 - \cos\theta) \tag{25}$$

where θ is the angle between the directions of the energetic photon and the background photon, and

$$\begin{aligned} s_{\min} &= (2m_e c^2)^2, && (26)\\ \varepsilon_{\min} &= \frac{(2m_e c^2)^2}{4E}, && (27)\\ s_{\max}(\varepsilon, E) &= 4\varepsilon E. && (28) \end{aligned}$$

The interaction length for photon-photon pair production in the radio background is plotted in Fig. 6 along with those for competing processes

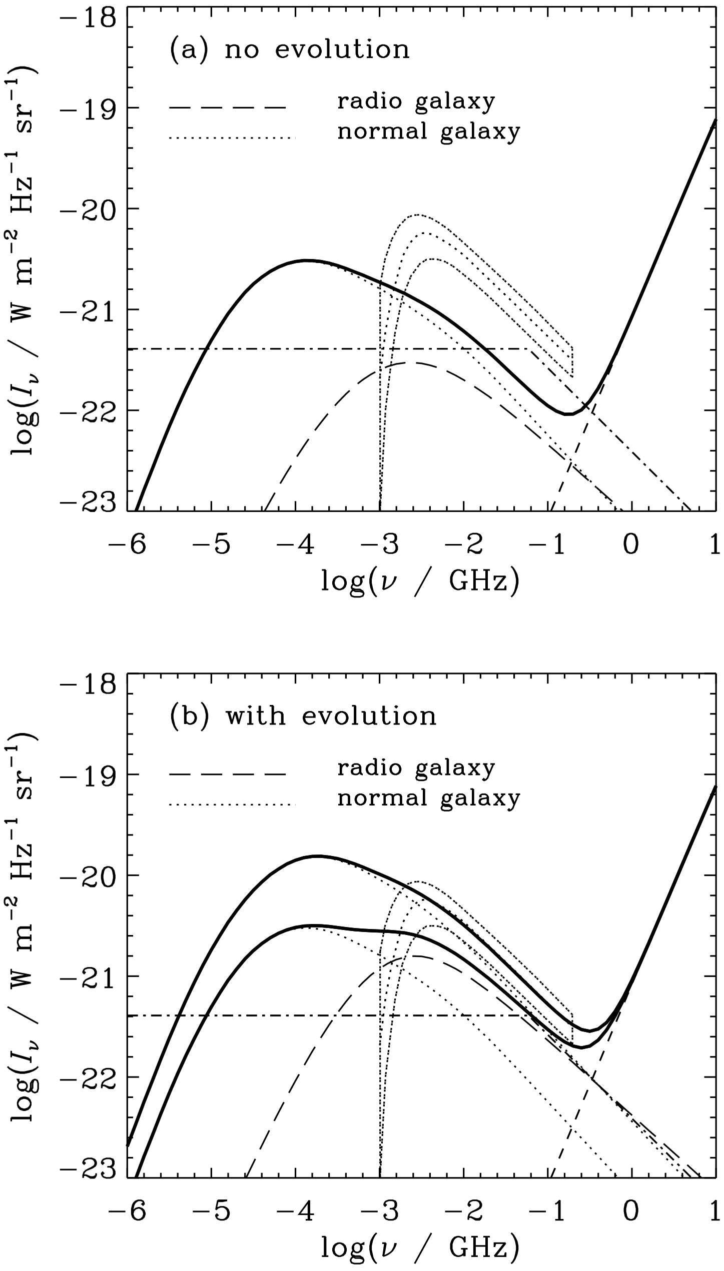

Figure 5: Contributions of normal galaxies (dotted curves), radio galaxies (long dashed curve), and the cosmic microwave background (short dashed curve) to the extragalactic radio background intensity (thick solid curves) for (a) no evolution and (b) with pure luminosity evolution as described in the text (upper curves), and with pure luminosity evolution only for radio galaxies (lower curves). Dotted band give an observational estimate of the total extragalactic radio background intensity [6] and the dot-dash curve gives an earlier theoretical estimate [7].

and other radiation fields [8]. We also show the mean interaction length for the radio spectrum based on direct observations together with attempts at subtraction of the effects of galactic absorption and background [6].

4 Conclusion

Motivated by a new interest in electromagnetic cascades through the universe at extremely high energies, we have made a new calculation of the extragalactic radio background radiation down to kHz frequencies. The main contribution to the background is from normal galaxies and is uncertain due to uncertainties in their evolution. The 60 micron source counts from IRAS above 0.3 Jy appear consistent with no evolution provided there is a new source population (possibly AGN) contributing below 0.3 Jy. An alternative interpretation of the data is that there is strong evolution of normal galaxies giving agreement with the source counts above 3 Jy and below 0.1 Jy (but not for $0.1 < S_\nu < 3$ Jy). This gives rise to a factor of 5 uncertainty in the radio intensity at kHz frequencies, and this translates to a factor of 5 uncertainty in the mean free path at 10^{12} GeV. If there is a new source population contributing to the infrared source counts it may also be important in determining the infrared background which limits the transparency of the universe to TeV energy gamma rays. Clearly, it is vital to determine the nature of the sources which dominate the 60 micron counts below 0.3 Jy.

We calculated the radio background for the two assumptions about the evolution of normal galaxies, and in both cases the background we obtain exceeds previous estimates at low frequencies. By examining Fig. 6 we find that for the radio background calculated in this paper photon-photon pair production on the radio background is the dominant interaction process for photons over four or five decades of energy from $3 \times 10^{10} - 5 \times 10^{10}$ GeV to $10^{15} - 5 \times 10^{15}$ GeV, above which double pair production on the microwave background dominates. We estimate the mean free path to be $\sim 1 - 5$ Mpc at 10^{12} GeV. Using the radio background estimated by Clark [6] photon-photon pair production on the radio background would only be important only up to 10^{13} GeV, and the mean free path at 10^{12} GeV would be a factor of $3 - 10$ larger. This difference will be very important in electromagnetic cascades initiated by particles with energies up to the GUT scale produced at topological defects.

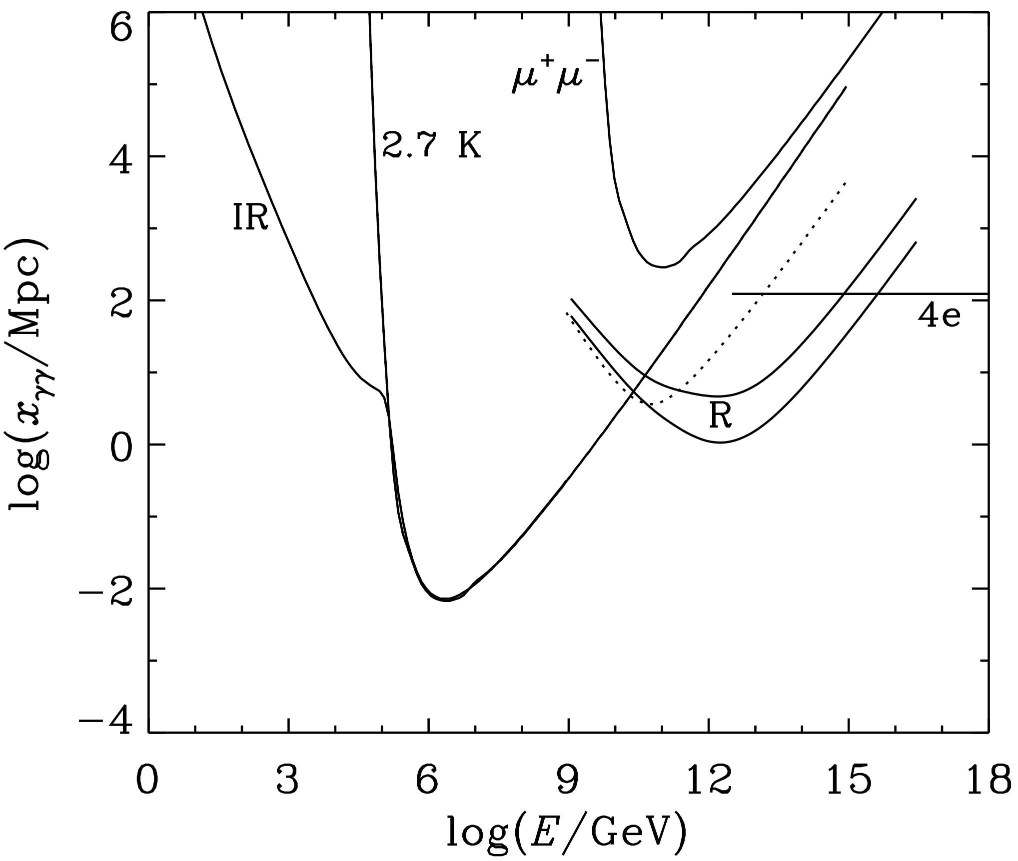

Figure 6: The mean interaction length for pair production for γ-rays in the Radio Background calculated in the present work (solid curves labelled R: upper curve – no evolution of normal galaxies; lower curve – pure luminosity evolution of normal galaxies) and in the radio background of Clark [6] (dotted line). Also shown are the mean interaction length for pair production in the microwave background (2.7K), the infrared and optical background (IR), and muon pair production ($\mu^+\mu^-$) and double pair production (4e) in the microwave background [8].

5 Acknowledgment

P.L. Biermann wishes to thank Reinhard Schlickeiser and Andy Strong for intense discussions of the cosmic ray electrons in the Galaxy. We also thank Bram Achterberg, Tom Gaisser, Hinrich Meyer and Matthew Whiting for detailed comments on the manuscript, and Henning Seemann for help with the preparation of the paper. The research of R.J. Protheroe is funded by a grant from the Australian Reseach Council.

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