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Modeling Synchrotron Emission from galaxies and the Extragalactic Radio Background

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Normal galaxies and radio galaxies are associated with star-formation and active galactic nuclei (AGN), respectively. These galaxies are considered to be the primary source of extra-galactic radio emissions permeating throughout the universe. The dominant mechanism responsible for this radio emission is synchrotron radiation due to relativistic electrons interacting with the galactic magnetic field. In this study, we calculate the radio spectra from these galaxies. We use observations from the source count population data, which influence the selection of the appropriate radio luminosity function. Finally, we calculate the intensity of the diffuse extra-galactic radio background using the ΛCDM cosmology.

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1. Introduction

The universe is filled with electromagnetic radiation, including radiation in the radio frequencies, which forms part of a diffuse background. At frequencies below $\sim$ 1GHz, Galactic emissions become important in the extragalactic radio background where the dominant mechanism is synchrotron emission due to ultra-relativistic electrons gyrating in magnetic fields [1]. The effects of synchrotron self-absorption and free-free absorption from hot ionized gas (mainly the HII regions) in the interstellar medium (ISM) become important at low frequencies [2]. The extragalactic radio sources are mainly normal galaxies characterized by radio luminosities in the range 10^{19} to 10^{25} W/Hz and radio galaxies with radio luminosities between 10^{22} and 10^{28} W/Hz, when observed at 1.4GHz [3,4,6]. The radio spectra of these galaxies are similar to a power-law, which is a special characteristic of synchrotron radiation. Studies in low frequency surveys indicate a steep power-law gradient for radio sources with a spectral index of $\alpha \sim 0.8$ [4].

Pioneered by Clark et al. [5], an estimate of the radio background was presented almost fifty years ago using data from the Radio Astronomy Explorer (RAE-1) sky survey. However, the intensity of the extragalactic radio background still remains unclear due to our position in the Milky Way galaxy which radiates at similar wavelengths [6]. Furthermore, uncertainties are also present in the radio source spectra, the infrared-radio correlation for normal galaxies and the evolution model of the local luminosity function [6,20]. To address this problem, statistical properties such as the radio source counts and the cosmology model are used as constraints.

In this paper, we analyse and update the methodology introduced by Protheroe and Biermann [6] using the appropriate luminosity function derived from recent observations and the radio spectra of our source population to establish an updated model for the extragalactic radio background.

2. The Radio Spectra

In the case of normal galaxies, we use recent data from the Alpha Magnetic Spectrometer (AMS) experiment, corresponding to observations made from earlier measurements [7-10] in the (0.5 - 1400) GeV energy range. The resulting electron spectrum is given by equation (5) of ref. [11] with a low energy cut-off at $\sim$ 8 GeV. We follow ref. [12] for the case of radio galaxies.

The synchrotron emission from the galaxies is modified by synchrotron self-absorption and free-free absorptions from HII regions in the ISM [1, 13]. Accordingly, the intensity of the radio emission follows by calculating the solution to the radiative transfer equation. This takes into account the synchrotron emission coefficient ϵ_ν^{sync}, the synchrotron self-absorption coefficient κ_ν^{sync} and the free-free absorption coefficient κ_ν^{ff}. For an isotropic distribution of viewing angles, we assume: a magnetic field strength of 9.0 ± 2.0 μG [20], $\sin\alpha = 0.8$, the temperature $T = 3 \times 10^5$ K , the electron density and ion density $n_e = n_i = 0.01$ cm^{-3}, the averaged gaunt factor $\bar{g}_{ff} = 1$. We calculate the synchrotron luminosity as given below:

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$$L_\nu = 4\pi A_{proj} \frac{\epsilon_\nu^{sync}}{\kappa_\nu^{ff} + \kappa_\nu^{sync}} \tag{2.1}$$

where the synchrotron emission, absorption and free-free absorption coefficients are given by

$$\epsilon_\nu^{sync} = \frac{\sqrt{3} q^3 B \sin\alpha}{2\pi m c^2} \int_o^\infty F(x) n(E) dE \tag{2.2}$$

$$\kappa_\nu^{sync} = -\frac{c^2}{8\pi\nu^2} \frac{\sqrt{3} q^3 B \sin\alpha}{2\pi m c^2} \int_o^\infty F(x) E^2 \frac{d}{d} \left[\frac{n(E)}{E^2}\right] dE \tag{2.3}$$

$$\kappa_\nu^{ff} = \frac{4e^6}{3mhc} \left(\frac{2\pi}{3km}\right)^{1/2} T^{-1/2} Z^2 n_e n_i \nu^{-3} (1 - \exp^{-h\nu/kT}) \bar{g}_{ff} \tag{2.4}$$

The function $F(x)$ is given by ref. [2]

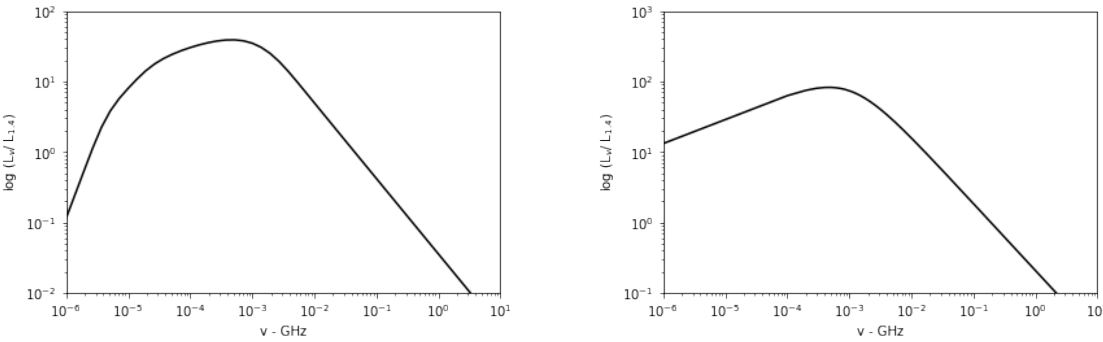

Figure 1: The normalized synchrotron radio spectrum to 1.4 GHz frequency of (a) normal galaxies and (b) radio galaxies in the radio region, for an isotropic distribution of viewing angles, neglecting the effects of synchrotron self-absorption.

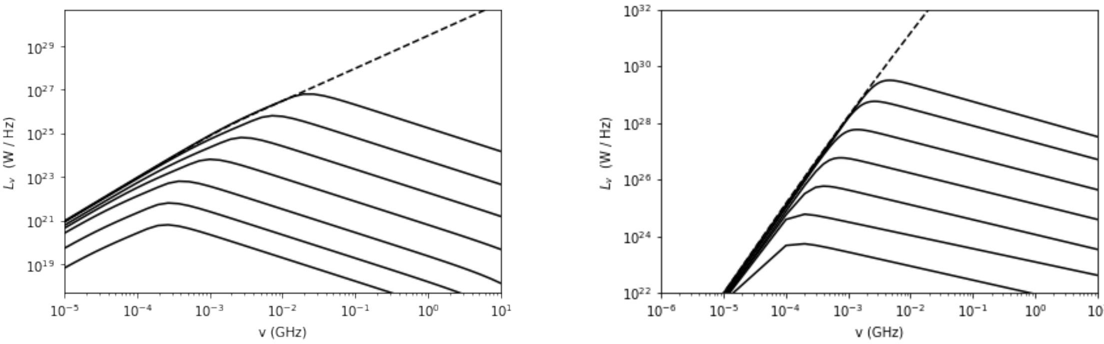

Figure 2: The average synchrotron radio spectra for (a) normal galaxies with 1.4 GHz luminosity $L_{1.4} = 10^{19}...10^{25}$ W/Hz and (b) radio galaxies with 1.4 GHz luminosity $L_{1.4} = 10^{22}...10^{28}$ W/Hz, including the effects of synchrotron self-absorption - solid curves. The dashed line shows the maximum luminosity of a completely self-absorbed source.

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The low-frequency cut-off changes when including the effects of synchrotron self-absorption (see Figures 1-2), in addition to the low energy cut-off in the electron distribution and the free-free absorption [2,6,23].

3. The Luminosity function

Diverging from Protheroe [6], where the infrared-radio correlation is valid for normal galaxies with $L_{60\,\mu\mathrm{m}} < 10^{23}$ W/Hz, we follow the relation given by Yun et al. [14] valid for $L_{60\,\mu\mathrm{m}} \approx 10^{23}$ - $10^{25.5}$ W/Hz for a correlation between the radio luminosity at 1.4 GHz and the infrared luminosity at 60 μm. This relation is given by [1]

$$L_{1.4GHz} = 1.16 \times 10^{-2} L_{60\,\mu\mathrm{m}} \tag{3.1}$$

The luminosity function is described as the luminosity distribution of the radiative source objects per luminosity interval, and can therefore be used to study the properties of a specific group of galaxies [17,18]. The luminosity function $\rho(L_\nu, z)$ evaluated at redshift z for the luminosity at ν is given by:

$$\rho(L_\nu, z) = \frac{g(z)}{f(z)} \rho_0 \left(\frac{L_\nu}{f(z)}, 0 \right) \tag{3.2}$$

where $g(z)$ and $f(z)$ are the density evolution function and luminosity evolution function respectively. The local luminosity function $\rho_0(L_{\nu'})$ with redshift $z = 0$ as adapted from Hacking et al. [16], for the parameters given in Table (1), has a best fit curve given by equation (3.3), according to the data published by Mauch [18] from the NRAO VLA Sky Survey (NVSS).

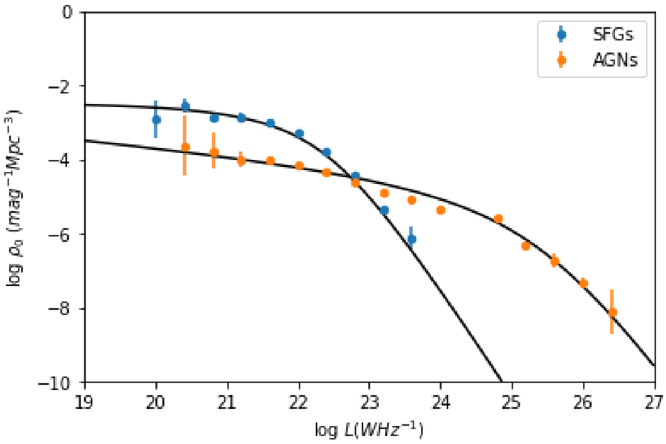

Figure 3: The local luminosity function at $\nu = 1.4GHz$ for SF galaxies and AGN galaxies. Figure adapted from [16]. Data given by [18].

$$\log \rho_0 \left(L_{60}\right) = Y - \left[B^2 + \frac{\log(L_{60} - X)^2}{W} \right]^{1/2} - 1.5 \log L_{60} + 28.5 \tag{3.3}$$

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Table 1: Local luminosity function parameters

Galaxy Class	**W**	**X**	**Y**	**B**
SFGs	0.65	22.4	3.1	1.8
AGNs	0.75	25.5	5.47	2.3

4. IR-Radio Counts and The Diffuse Extragalactic Radio Background

Another way to distinguish the galaxy class population and address the change in the cosmological evolution of the galaxy, is through the analysis of radio source count models described by the observed flux density weighted by $S^{5/2}$. Observing the changing gradient is indicative of this property. Figure (4), shows a dominant presence of radio galaxies at $\log(S/\mathrm{Jy}) >$ -3 characterized by a gentle rise of radio source counts for $-3 < \log(S/\mathrm{Jy}) < 0$. An earlier study [16] suggests that this behavior implies that there is a large population of radio sources at high redshift. At low flux densities ($\log(S/\mathrm{Jy}) < -3$), normal galaxies dominate the radio source count population. Assuming a cold dark matter ΛCDM cosmology model (normalized densities: dark energy $\Omega_\Lambda = 0.7$, baryonic and cold dark matter $\Omega_m = 0.3$ and the parameter $h = H_0/(100\ \mathrm{km}^{-1}\mathrm{s}^{-1}\mathrm{Mpc}^{-1})$, the source count model is obtained by integrating the luminosity function over the redshift. The resulting equation is given as [6]

$$n(S_\nu) = \int dz \frac{dV_c}{dz} \frac{d_L^2(z)}{1+z} \rho(L_{\nu'}, z) \tag{4.1}$$

given that the observed flux S_ν at frequency ν is expressed as

$$S_\nu = \frac{1+z}{4\pi d_L^2(z)} L_{\nu'} \tag{4.2}$$

where d_L is the luminosity distance.

In order to calculate the source count model and consequently the intensity of the radio background, we need to consider the redshift evolution model of the luminosity and the density. We assume the luminosity evolution functon and the density evolution function as given by Condon [24] where

$$f(z) = (1+z)^x, g(z) = (1+z)^y \tag{4.3}$$

for the best-fitting parameters $x = 4$ and $y = 0$. The proposed source count model (see Figure 4) agrees with earlier data from Condon [23] and recently from de Zotti [1]. Integration over redshift for the luminosity evolution, yields the intensity from the radio sources as

$$I_\nu = \frac{1}{4\pi} \int\int dz dL_{\nu'} S_\nu \frac{dV_c}{dz} \left(\frac{L_{\nu''}}{L_{1.4}}\right) \rho(L_{\nu'}, z) \tag{4.4}$$

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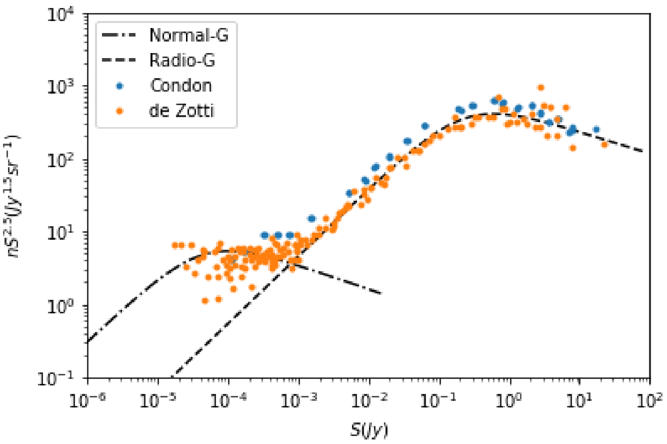

Figure 4: The weighted source counts $S^{2.5}n(S)$ of normal galaxies and radio galaxies tested against data from [1,23].

where the ratio $L_{\nu''}/L_{1.4}$ is given from the galaxy spectrum in Figure (1). The infrared-radio correlation in equation (3.1) is included when calculating the intensity for the normal galaxies evaluated for 60 μm luminosity L_{60}. We evaluate the radio galaxies at 1.4 GHz luminosity $L_{1.4}$. The background intensity model in Figure (5) shows that normal galaxies contribute more to the extragalactic radio background when compared to the radio galaxies at low frequencies.

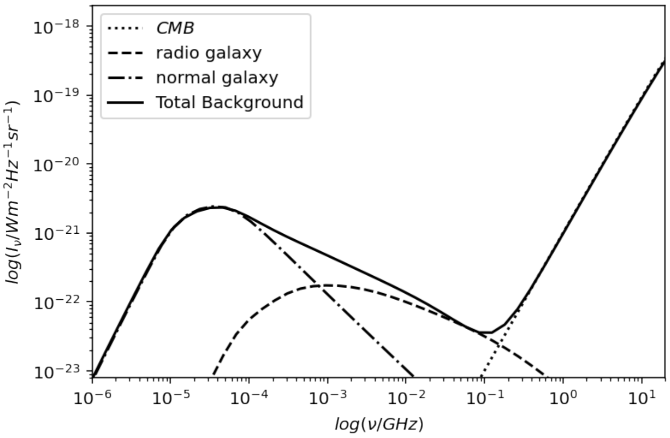

Figure 5: The extragalactic radio background intensity with contributions from the normal galaxies, radio galaxies and the cosmic microwave background (CMB).

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