

THERMAL RADIO EMISSION FROM NORMAL GALAXIES

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Abstract. Thermal radiation from normal spiral galaxies may be detectable at centimeter and millimeter wavelengths. Predictions have been made assuming free-free radiation from H II regions at $T_e = 7000$ K, and a range of mean electron densities and radii.

1. Introduction

The observed radio spectra of normal galaxies are characteristic of the type of spectra found for non-thermal sources. However, thermal emission due to free-free transitions in ionized hydrogen regions inside normal galaxies also contributes to the radio radiation. Observations and theory suggest that the non-thermal radiation from normal galaxies is more intense than the thermal radiation by several orders of magnitude at radio frequencies below 5 GHz. At higher frequencies the contribution of the thermal radiation becomes important and perhaps it may even be the dominant source of energy at frequencies higher than 30 GHz.

This paper is a preliminary study in estimating the contribution of the thermal radiation from normal galaxies. Recently Hodge (1969) has completed the work 'An Atlas and Catalog of H II Regions in Galaxies'. This work is a search for H α -emission in ninety galaxies which led to the discovery of H II regions in sixty of them. Here we use Hodge's work for nine galaxies to estimate their thermal radio emission from the catalogued H II regions. In this study we also include the Andromeda galaxy (M31) using the H II data from Baade and Arp (1964), and M33 using the data by Sandage (1962), Courtès and Cruvellier (1965), and Carranza *et al.* (1968).

The predicted thermal radio spectra are then compared with the available radio observations. These observations are primarily from Mathewson and Rome (1963), Heesch and Wade (1964), De Jong (1966, 1967), Lang and Terzian (1969), Kuril'chick *et al.* (1970), and Whiteoak (1970). The radio observations for M31 are from Kraus *et al.* (1966), and Howard and Maran (1965).

2. Thermal Emission

The available data on emission nebulae in normal galaxies put some restrictions on the methods one can use to compute the thermal radio emission. The most reliable technique for computing the thermal radio emission is to use the recombination theory together with observed absolute fluxes of Balmer lines integrated over an entire galaxy. Terzian (1965, 1968) has shown that the ratio of the fluxes at a radio frequency ν and at H β for an optically thin thermal region is given as

$$\frac{S_\nu}{S_{H\beta}} = \frac{N_i}{N_p} \frac{T_e}{\langle b_4 \rangle} \frac{1.664 \times 10^{-19}}{e^{0.986 \times 10^4/T_e}} \ln \left(49.5 \frac{T_e^{3/2}}{\nu} \right) \quad (1)$$

where N_i/N_p is the ratio of the number of ions to protons and indicates the relative abundance of helium, which can be estimated to be 10 to 15%. T_e is the electron temperature which is of the order of 10^4 K, $\langle b_4 \rangle$ describes the departure from thermodynamic equilibrium for the $H\beta$ transition and it is equal to 0.20 (Burgess, 1958), and ν is the radio frequency. Clearly the dependence on frequency for an optically thin thermal source is very small. If we let $\nu = 5$ GHz, we find that

$$\frac{S_\nu}{S_{H\beta}} = 3.2 \times 10^{-14}. \quad (2)$$

Hence the thermal radio spectrum of a source can be computed if one has a knowledge of the $H\beta$ flux. Similarly a knowledge of the fluxes of other Balmer or Paschen lines may allow us to predict the thermal radio spectra (Pipher and Terzian, 1969).

Unfortunately the above method cannot be used for the present study because absolute Balmer line fluxes are not available for HII regions in normal galaxies. One should emphasize that such data will be extremely useful in computing the free-free emission from other galaxies.

In this preliminary study we compute the thermal radio spectra making use of the free-free emission theory together with the total number (and apparent area) of the emission regions in each galaxy measured from the work of Hodge. Since the measurement of emission region areas is a very uncertain quantity, we also compute thermal spectra by assuming certain mean sizes to the emitting regions.

The flux density of a radio source is normally given as

$$S_\nu = \frac{2k\nu^2}{c^2} \int_{\Omega} T_b d\Omega \quad (3)$$

where k is Boltzmann's constant, c is the velocity of light, T_b is the brightness temperature, and Ω is the solid angle of the source. If one assumes constant brightness for a source, then letting $\Omega = A/D^2$ where A is the projected area of the source and D is its distance, we can then write

$$S_\nu = \frac{2k\nu^2}{c^2} \frac{T_b A}{D^2}. \quad (4)$$

The brightness temperature is obtained from the solution of the equation of radiative transfer as $T_b = T_e(1 - e^{-\tau_\nu})$, where τ_ν is the optical depth. Since the thermal radio emission will only be important at the very high frequencies where generally $\tau_\nu \ll 1$, we can approximate $T_b \approx T_e \tau_\nu$, and the last expression becomes

$$S_\nu = \frac{2k\nu^2}{c^2} \frac{AT_e \tau_\nu}{D^2}. \quad (5)$$

The optical depth for thermal emission can be derived from the free-free absorption coefficient (Oster 1961, Terzian 1968) as

$$\tau_\nu = \frac{9.78 \times 10^{-3}}{\nu^2 T_e^{3/2}} \ln \left(4.95 \times 10^7 \frac{T_e^{3/2}}{\nu} \right) \int N_e^2 ds \quad (6)$$

where N_e is the electron density in cm^{-3} and ν is the frequency in units of Hz. One can assume that the HII regions inside a galaxy are spherical and have uniform electron densities, so that $\int N_e^2 ds = N_e^2 s$ where s is the diameter of a single emission region in a galaxy. If A is the total projected area of emission regions in a galaxy and N is the total number of such regions, then $A/N = \pi (s/2)^2$, and $s = 2(A/\pi N)^{1/2}$, so that

$$N_e^2 s = 2N_e^2 \left(\frac{A}{\pi N} \right)^{1/2} \tag{7}$$

Using Equations (6) and (7) with (5) we finally have

$$S_\nu = \frac{3.91 \times 10^{-2} k}{c^2 (\pi)^{1/2}} \frac{A^{3/2}}{D^2 (N)^{1/2}} \frac{N_e^2}{(T_e)^{1/2}} \ln \left(4.95 \times 10^7 \frac{T_e^{3/2}}{\nu} \right) \tag{8}$$

The last expression can now be used to compute the thermal radio spectra of normal galaxies. The distances for the galaxies are taken from Roberts (1969) and van den Bergh (1968). The values for N are those given by Hodge (1969), Baade and Arp (1964) for M31, Sandage (1962) and Courtès and Cruvellier (1965) for M33.

TABLE I
Number of HII regions in galaxies and distances

Galaxy	Type	Distance (Mpc)	Number of HII regions
M31	Sb	0.69	688
M33	Sc	0.69	369, 101
NGC 628	Sc	7.8	193
NGC 2403	Sc	3.2	109
NGC 2903	Sc	7.0	74
NGC 3368	Sa	7.3	3
NGC 3627	Sb	7.3	25
NGC 3628	Sb	7.0	18
NGC 4449	Irr	3.3	81
NGC 5457	Sc	3.5	189
NGC 6946	Sc	4.1	39

Table I gives the distances to the galaxies and the number of HII regions in each of them. In the case of M33 Sandage has reported 369 emission nebulae and Courtès and Cruvellier 101. The latter work includes primarily the HII regions which were photographically resolved. In order to make use of Equation (8) one has to assume values for T_e and N_e . From extensive research on emission nebulae in our own galaxy we find that $T_e \approx 7000 \text{ K}$ with a variation of a few thousand degrees. Mean values for N_e are more difficult to estimate; however, we know that in extreme cases N_e may have values of $\sim 1 \text{ cm}^{-3}$ to $\gtrsim 10^6 \text{ cm}^{-3}$ (as in compact HII regions). For the average regions, however, the range in N_e can be taken to be 10 cm^{-3} to 100 cm^{-3} .

In practice it is extremely difficult to measure reliable areas for most of the emission regions in other galaxies because of the limited resolution of the optical photographs. Nevertheless, we have tried to measure the total area of HII regions given by Hodge

for several galaxies and have applied the results in Equation (8). The results were very unrealistic. In particular the mean sizes of the emission regions were found to be several hundred parsecs in size as compared to 10–80 parsec for the sizes of normal H II regions in our own galaxy. However, one can argue that at distances of 3 to 7 Mpc we detect only the giant H II regions.

For the reasons given above we have eliminated the parameter A from Equation (8) and assumed several mean radii for the individual H II regions in other galaxies. Thus, thermal radio spectra were computed by using $A^{3/2} = r^3 (\pi N)^{3/2}$ in Equation (8), where r is the mean radius of an H II region.

3. Results

A series of computations of thermal spectra was performed with wide ranges in r , N_e and T_e . As can be seen from the previous section, the dependence of T_e on the spectrum when $\tau_v \ll 1$ is very small, hence, we have taken $T_e = 7000$ K for the results reported below.

Table II and Figure 1 show the main results of the computations. In Table II we compare the observed radio emission at $\lambda 3$ cm and $\lambda 3$ mm wavelengths (these are extrapolated fluxes; references for radio observations are given in Section 1) with the theoretically predicted pure thermal radiation. The computed flux densities due to thermal radiation in Table II are those at $\lambda 3$ cm. The thermal spectra are almost independent of wavelength when $\tau \ll 1$ and the fluxes at $\lambda 3$ cm are essentially the same

TABLE II

Flux densities at $\lambda 3$ cm, $\lambda 3$ mm, extrapolated from the observed spectra, compared with predicted thermal fluxes

Galaxy	3 cm (obs.)	3 mm (obs.)	Flux Density (10^{-26} W m $^{-2}$ Hz $^{-1}$) ^a		
			Thermal (1)	Thermal (2)	Thermal (3)
M31	1.50	0.11	0.32	60.5	505.0
M33 ^b	0.31	0.03	a) 0.169 b) 0.046	32.5 8.9	271.3 74.3
NGC 628	0.025	0.003	0.0007	0.135	1.13
NGC 2403	0.15	0.07	0.0023	0.448	3.75
NGC 2903	0.07	0.009	0.0003	0.063	0.53
NGC 3368	0.002	0.00002	0.00001	0.002	0.02
NGC 3627	0.14	0.03	0.0001	0.020	0.17
NGC 3628	0.11	0.02	0.00008	0.015	0.13
NGC 4449	0.05	0.004	0.0016	0.314	2.62
NGC 5457	0.06	0.007	0.0036	0.691	5.77
NGC 6946	0.30	0.05	0.0005	0.97	0.81

^a Computed thermal fluxes are at $\lambda 3$ cm. The thermal spectra are almost flat at this wavelength region so that the $\lambda 3$ mm fluxes are essentially the same as those at $\lambda 3$ cm.

^b a) 369 H II regions, b) 101 H II regions, (see text for observed flux).

Thermal (1) $\langle N_e \rangle = 20$ cm $^{-3}$, $\langle r \rangle = 10$ pc.

Thermal (2) $\langle N_e \rangle = 70$ cm $^{-3}$, $\langle r \rangle = 25$ pc.

Thermal (3) $\langle N_e \rangle = 100$ cm $^{-3}$, $\langle r \rangle = 40$ pc.

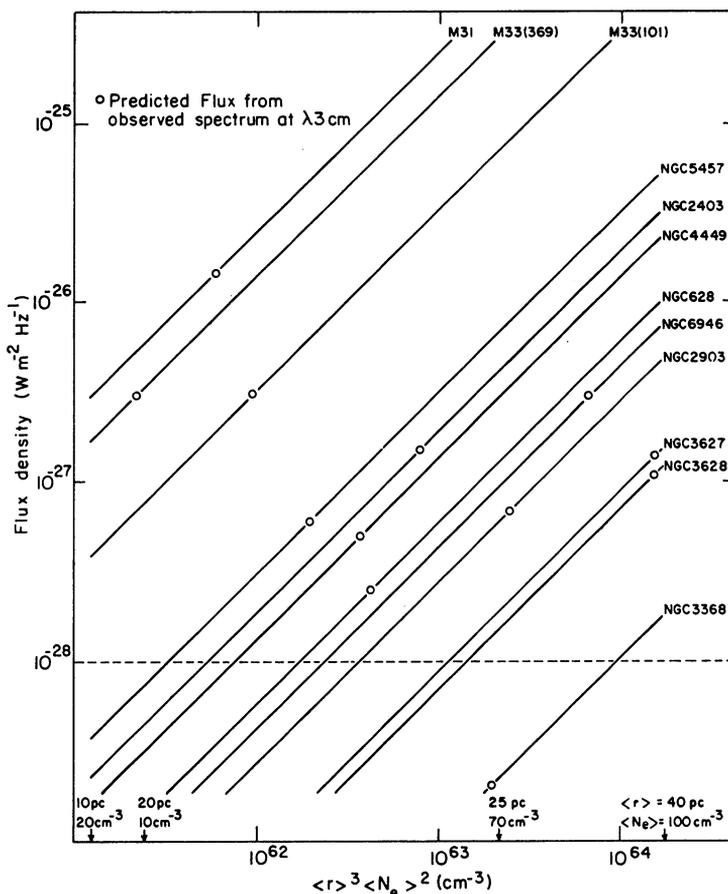


Fig. 1. Predicted flux densities due to thermal radiation for a number of galaxies as a function of $\langle r \rangle^3 \langle N_e \rangle^2$. $\langle r \rangle$ is the mean radius of the HII regions and $\langle N_e \rangle$ is the mean electron density. The dashed line indicates the lower limit of detectability for a radio source with present-day instrumentation. The circles on each curve show the predicted flux for the corresponding galaxies at $\lambda 3$ cm extrapolated from their observed spectra.

as those at $\lambda 3$ mm. Three cases of computed thermal spectra are given in Table II with regard to mean radii and mean densities of the HII regions; (1) $\langle N_e \rangle = 20 \text{ cm}^{-3}$, $\langle r \rangle = 10 \text{ pc}$; (2) $\langle N_e \rangle = 70 \text{ cm}^{-3}$, $\langle r \rangle = 25 \text{ pc}$; (3) $\langle N_e \rangle = 100 \text{ cm}^{-3}$, $\langle r \rangle = 40 \text{ pc}$.

The data on $\langle N_e \rangle$ and $\langle r \rangle$ for our own galaxy can be obtained from Murdin and Sharpless (1968). These authors have compiled more than seventy emission regions and their data indicate that $\langle N_e \rangle \sim 70 \text{ cm}^{-3}$ and $\langle r \rangle \sim 25 \text{ pc}$. One can clearly note that if the mean population of HII regions in other spiral galaxies is similar to our own, then case (2) in Table II shows that the radio radiation of the thermal regions is in general of the same order as the radio non-thermal radiation at $\lambda \lesssim 3 \text{ cm}$. One also notes that a comparison of the predicted thermal radiation with the observations may put a limit on the mean values of r and N_e (actually on the product $\langle r \rangle^3 \langle N_e \rangle^2$).

Figure 1 shows the relationship between flux density due to thermal radiation (at $\lambda 3$ cm, $T_e = 7000$ K) and the parameter $\langle r \rangle^3 \langle N_e \rangle^2$ for the HII regions in eleven galaxies. The dashed line represents the low flux density limit for a detectable radio source with the present-day available instrumentation.

The arrows show four examples of combinations of $\langle r \rangle$ and $\langle N_e \rangle$. The open circles indicate the flux densities from the observed spectra of the galaxies (extrapolated to $\lambda 3$ cm). As an example, if $\langle r \rangle = 20$ pc and $\langle N_e \rangle = 10 \text{ cm}^{-3}$ for M33, where Sandage reports 369 HII regions, then we see that the flux due to the HII regions is of the same order as the flux due to the non-thermal radiation ~ 0.3 f.u. (Recent observations of M33 by Terzian and Pankonin (1971, in preparation) show a flux at $\lambda 3$ cm of ~ 4 f.u.)

One should emphasize that these computations include only the free-free radiation from normal HII regions. No attempt has been made to include the so called 'background' thermal component, which appears in our own galaxy, and which is probably due to ionization of the neutral hydrogen by low energy cosmic rays.

As a conclusion, we have shown that thermal radiation from normal spiral galaxies may be important at centimeter wavelengths, and certainly very important at millimeter wavelengths. More accurate predictions can be made if one obtains integrated absolute fluxes of Balmer or Paschen lines of normal spiral galaxies.

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