Lecture Notes

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GALACTIC RADIO SOURCES. I

by

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In the course of the early surveys of radio sources, it was found that there was a marked difference in the properties of those sources with $|b| > 10°$ and those with $|b| < 10°$. The sources at low galactic latitudes in general were strong, and had large (> 5') diameters. With further work it became clear that the majority of sources with $|b| < 10°$ were sources within our galaxy and were of two types: Those with flat spectrum were HII regions and those with nonthermal spectrum were apparently remnants of supernovae. This first lecture will be concerned with the thermal sources.

The concept of a region of ionized gas associated with an early type (O or B) star was first introduced by B. Strömgren (1939). He considered the case in which the hot central star is completely surrounded by an isothermal hydrogen cloud of uniform density. The central star emits ultraviolet radiation which maintains the interstellar material in the ionized state. It will now be shown, following Würm (1958), that the radius of the ionized region depends upon the density of the interstellar medium and the spectral type of the star.

The modified Saha (ionization equation) for a point at distance s parsecs from the star, whose color temperature is T, is

$$\frac{N_p N_e}{N_H} = C_1 \frac{e^{-\bar{\tau}_\upsilon}}{s^2} \qquad (1)$$

where N_p, N_e, and N_H are the densities of protons, electrons, and hydrogen atoms, respectively, in cm^{-3}. $e^{-\bar{\tau}_\upsilon}$ is a factor which corrects for the extinction of the starlight over the distance s, and

$$C_1 = 10^{-(0.51 + \theta\chi_1)} T^{3/2} \left(\frac{T_e}{T}\right)^{1/2} \Gamma(T,T_e) \qquad (2)$$

with T_e the electron temperature of the nebula

$$\theta = \frac{5040}{T}$$

$$\chi_1 = 13.59 \text{ ev}$$

$\Gamma(T,T_e)$ a function tabulated by Würm

Let the fraction of all hydrogen which is ionized be x. Then, if the total hydrogen density is N

$$N = N_p + N_H$$

$$N_e = N_p = xN$$

$$N_H = (1-x)N$$

and

$$\frac{x^2}{1-x} N = \frac{C_1}{s^2} e^{-\bar{\tau}_\nu} \qquad (3)$$

The optical depth is given by

$$d\bar{\tau}_\nu = (1-x) N \bar{a}_\nu \cdot 3.08 \cdot 10^{18} \, ds \qquad (4)$$

where $\bar{a}_\nu$ is the mean absorption coefficient at the Lyman continuum limit. The mean absorption coefficient has been tabulated by Eberlein (1955).

From equations (3) and (4)

$$e^{-\bar{\tau}_\nu} d\bar{\tau}_\nu = \frac{N^2}{C_1} x^2 s^2 \cdot 3.08 \cdot 10^{18} \bar{a}_\nu \, ds \qquad (5)$$

By substituting in equations (5) and (3), respectively, the quantities

$$y = e^{-\bar{\tau}_\upsilon} \quad (1 \geq y \geq 0) \tag{6}$$

$$dz = \frac{N^2}{C_1} \cdot 3.08 \cdot 10^{18}\, a_\upsilon s^2 ds \tag{7}$$

$$(z = 0 \text{ for } s = 0)$$

get the solution, in the form of two simultaneous equations.

$$\left.\begin{aligned} \frac{dy}{dz} &= -x^2 \\ \frac{1-x}{x^2} &= \alpha \frac{1}{y} z^{2/3} \end{aligned}\right\} \tag{8}$$

with $\alpha = \left(\dfrac{9}{N\, C_1\, (3.08 \cdot 10^{18}\, \bar{a}_\upsilon)^2} \right)^{1/3}$

For a given value of α, these equations may be integrated numerically, and a solution for the variation of electron density with distance from the exciting star determined. It is found that in general the degree of ionization remains high, i.e., $x \sim 1$ out to a distance given by $z \sim 1$, after which it drops very quickly towards zero. This critical radius, the radius of the Strömgren sphere, is obtained from equation (7)

$$s_o = \left(\frac{3\, C_1}{N^2 \cdot 3.08 \times 10^{18}\, \bar{a}_\upsilon} \right)^{1/3}$$

This is frequency written

$$U = s_o N^{2/3} \tag{9}$$

where now U is a function of the exciting star alone. The following table gives, for $N = 1\ cm^{-3}$, the radius of the HII region as a function of the spectral type of the central star. The stellar parameters have been taken from Pottasch (1956).

Table I

Spectral Type	S_o (pc)
05	100
07	70
B0	25

The amount of radio emission originating in a Strömgren sphere of this type is easily computed from the equations of the emission, as given previously. For an isothermal nebula, the brightness temperature is

$$T_b(\nu) = T_e\ (1 - e^{-\tau_\nu}) \qquad (10)$$

with $$\tau_\nu(s) = \int k_\nu\ ds$$

and $$k_\nu = 9.776 \times 10^{-15}\ \frac{N_e^{\ 2}}{\nu^2 T_e^{\ 3/2}}\ \ln\left[49.5\ \frac{T_e^{3/2}}{\nu}\right]$$

$$= R_\nu\ N_e^{\ 2}\ T_e^{\ -3/2}$$

It has been found that the electron temperature in most HII regions lie in the range 5000°K to 15000°K. Values of R_ν for a temperature $T_e = 1 \times 10^4$°K are given, for various frequencies, in Table II.

Table II

Frequency ν Mc/s	$R_\nu \cdot \nu^2$ cgs	R_ν cgs
8000	0.0852	1.33×10^{-21}
3000	0.0948	1.05×10^{-20}
1400	0.102	5.22×10^{-20}
960	0.106	1.15×10^{-19}
400	0.115	7.15×10^{-19}

Let the nebula subtend a solid angle Ω. The radio flux S_ν may then be derived from the brightness temperature by means of the relation

$$S_\nu = \frac{2k\nu^2}{c^2} \int T_b \, d\Omega \tag{11}$$

The quantity $\int N_e^2 \, ds$ has been defined by Strömgren as the emission measure E, and is usually quoted in units of cm^{-6} pc. Thus

$$\int N_e^2 \, ds = 3.08 \times 10^{18} E \tag{12}$$

$$\tau_\nu = 3.08 \times 10^{18} R_\nu E \, T_e^{-3/2} \tag{13}$$

and, if $\tau_\nu \ll 1$

$$T_b = 3.08 \times 10^{18} R_\nu \, T_e^{-1/2} E \tag{14}$$

$$S_\nu = 0.850 \, R_\nu \, T_e^{-1/2} \lambda^{-2} \int E d\Omega \tag{15}$$

with E in cm^{-6} pc, λ in cm, S in wm^{-2}/cps, T_b and T_e in °K, and R_υ in cgs units, as in Table II.

Therefore, if an HII region is observed with a radio telescope of high resolution, so that the brightness temperature is measured, equation (14) may be used to determine the emission measure, and the electron density distribution as well, if a model of the nebula is assumed. Such a procedure has been followed by Terzian (1964) for 4 regions. If the resolution is poor, so that only a total flux is measured, then equation (15) can be used to obtain a mean emission measure, averaged over the nebula. Measurements of the latter type have been made, for example, of planetary nebulae (Menon and Terzian, 1965).

The relationship between the radio flux and the excitation of the HII region is seen by comparison of equations (15) and (9). The quantity $\int E d\Omega$ is related to U directly, since

$$\int_\Omega E d\Omega = \int_A \int_S N_e^2 \, ds \, \frac{dA}{R^2}$$

$$= \int_v \frac{N_e^2 \, dv}{R^2}$$

$$= \frac{\frac{4}{3} \pi U^3}{R^2}$$

where R is the distance from the observer to the nebula, in pc. Therefore, from (15)

$$U = \sqrt[3]{\frac{0.281 \, R^2 \, T_e^{1/2} \, \lambda^2 \, S_\upsilon}{R_\upsilon}} \qquad (16)$$

Equation (16) shows that for a classical Strömgren region, in which the entire amount of ultraviolet energy radiated by the exciting star (or stars) is absorbed by the nebula, the absolute radio flux $4\pi R^2 S_\upsilon$ is proportional to the stellar ultraviolet flux, as measured by the quantity U. The most common application of this relationship is in the determination of whether the HII region is a Strömgren zone or not. Thus, if the U-value computed from the radio flux is smaller than that computed from the spectral type of the exciting star, then it can be concluded that the HII region is density bounded, and that some of the stellar ultraviolet escapes the nebula. An alternative is to assume that the HII region is a Strömgren zone, and from the radio flux and the spectral type of the exciting star, deduce the distance of the object.

It is worthwhile to note briefly the relation between the optical emission lines and the radio continuum emission. The prominent lines which are observed are the Balmer series of hydrogen, as well as the forbidden lines of [OII], [OIII], and N[II]. The latter are of importance in the cooling of the nebula. The volume emissivity of the Balmer lines can be given in general by

$$j_{n_2} = N_n \, A_{n_2} \, h \, \upsilon_{n_2} \qquad (17)$$

where A_{n_2} is the Einstein transition coefficient and N_n is the number of atoms in the n^{th} level, given by

$$N_n = f(T) \, n^2 \, e^{\chi_n/kT} \, N_p \, N_e \qquad (18)$$

Here χ_n is the ionization potential from the quantum state n. Thus, the emissivity is a function of the product $N_p \, N_e$, just as in the case of the rf emission, and the ratio of the fluxes is therefore independent of structure and distance. Comparison of the optical and radio fluxes have been used to verify the theory of the recombination of hydrogen in HII regions.

The recently discovered rf line of 5000 MHz is a transition between upper levels in the hydrogen atom, and is therefore governed by these same rules.

There are now about 50 HII regions identified as radio sources, and many more should be found in future high resolution surveys such as the one proposed by Mezger. The most complete study of the emission from HII regions is still that of Westerhout (1958) in which approximately 25 of the brightest nebulae have been observed. More recent surveys have been made by Wilson (1963) and Wilson and Bolton (1960). From the radio observations, and with the assumption of a model for each region, Westerhout was able to estimate the emission measure, the electron density, and the total mass for each nebula detected. The range in values of the emission measure is from 10×10^3 to 1000×10^3 cm^{-6} pc, in total mass from 50 to 10,000 solar masses.

There are more detailed observations for a much smaller number of sources. A good example of such work is Menon's (1961) study of the Orion Nebula. Because the brightness temperature distribution was actually resolved, Menon was able to construct a model of the electron density distribution as a function of the distance from the center of the nebula. The optical depth at a distance s from the center is related to the brightness by the equation

$$\tau(s) = \frac{T_b(s)}{T_e} \qquad (19)$$

Then, by assuming that the nebula is spherically symmetrical and composed of concentric shells (22 in this case), the emission distribution, and hence the electron density distribution is derived from equation (17). The solution of the problem is unique. For Orion, Menon finds that the electron density is a maximum at the center, with a value $N_e = 2 \times 10^3$ cm^{-3}, and decreases towards the edge, where $N_e \sim 10$ cm^{-3}. The total mass of the nebula on the basis of this model is about 100 solar masses.

That such observations as these can be of much value in the interpretation of the physical conditions within the HII regions is perhaps best illustrated by reference to Menon's (1962) further work on Orion. Here it is shown that the radial distribution of electron density is quite similar to the radial distribution of stars. Such a correspondence is to be expected only if ionization has taken place very recently, within a time of less than, say, 10^6 years. Since within the Orion Nebula cluster there are stars whose gravitational contraction times are at least of the order of 10^6 years, it appears therefore that star formation within the cluster has been proceeding for a period of at least 10^6 years. Moreover, the formation of the exciting stars must have taken place after the collapse of the cloud from which the cluster as a whole was formed. Thus, the radio observations have been instrumental in raising a number of important questions about the process of star formation.

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