EMISSION NEBULAE AS RADIO SOURCES

By B. Y. Mills,* A. G. Little,* and K. V. Sheridan*

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Summary

Attempts have been made to detect 14 bright emission nebulae at a wavelength of $3 \cdot 5$ m using a pencil-beam radio telescope with a beamwidth of 50 min of arc. Of these nebulae, six were probably observed in emission, seven were undetectable, and one, NGC 6357, was observed in absorption; radio isophotes were obtained for NGC 2237 and NGC 3372. Radio and optical data have been combined to estimate electron densities, masses, and sometimes the electron temperature of many of the nebulae. Values range from an electron density of 3 cm^{-3} and a mass of 3×10^6 solar masses for the outer regions of the 30 Doradus complex to an average electron density of 500 cm^{-3} and a mass of 20 solar masses for the Orion Nebula. Temperatures generally appear to be in the neighbourhood of 10,000 °K, except in the case of NGC 6357, for which 6500 °K is estimated.

I. Introduction

The role of the interstellar ionized hydrogen in producing metre wave radiation has not yet been satisfactorily determined. For instance, it has been claimed by Scheuer and Ryle (1953) that the gas produces, by virtue of its thermal emission, a band of intense radiation near the galactic centre; but Mills (1955) has shown that, although such a band of emission does exist, it is wider than the figure of 2° given by Scheuer and Ryle and its brightness temperature is too high to be reconciled with observations of the same region at much shorter wavelengths if thermal emission only is assumed. The present investigation was designed to throw some light on the problem by observation of the brightest emission nebulae accessible to the 1500 ft Sydney cross aerial.

Observations of 14 nebulae were made at a wavelength of $3 \cdot 5$ m: six were probably observed in emission, seven were undetectable, and one, NGC 6357, was observed in absorption. It is found that the nebulae emit and absorb radiation in the manner predicted by theory, and do not appear to be associated in any way with the non-thermal galactic radio sources. By combining radio and optical data it has been found possible to estimate electron densities, masses, and sometimes the electron temperature of many of the nebulae. It is not possible from these observations to determine the contribution that the thermal emission of ionized hydrogen makes to the general galactic radiation, but the agreement with theory suggests that detailed surveys at widely different wavelengths will allow this contribution to be deduced, probably in conjunction with the spatial distribution of the hydrogen throughout the Galaxy.

* Division of Radiophysics, C.S.I.R.O., University Grounds, Sydney.

II. Theory

The emission and absorption of radio waves by the process of free-free transitions in the ionized interstellar gas has been discussed by many authors. We will adopt some results given by Piddington (1951) and derive expressions useful for interpreting the present observations.

Consider a mass of ionized gas with uniform electron temperature T_e and optical thickness τ, situated in front of an extended emitting region of uniform brightness temperature T_b. The apparent excess temperature of the gas mass is given by

$$\begin{aligned}\Delta T &= T_e(1-\mathrm{e}^{-\tau})+T_b\mathrm{e}^{-\tau}-T_b \\ &= (T_e-T_b)(1-\mathrm{e}^{-\tau}). \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)\end{aligned}$$

The gas will therefore appear as an emitter for $T_e>T_b$ and as an absorber for $T_e<T_b$; with equal temperatures it is unobservable. The electron temperature in an H II region is known to be of the order of 10,000 °K, perhaps somewhat higher (see, for instance, Aller 1953). At 3·5 m the apparent brightness temperature near the galactic plane at longitudes within about 15° of the galactic centre is between 8000 °K and 20,000 °K (e.g. Mills 1955); consequently it might be expected that here individual emission nebulae will be observable in absorption, if at all. Elsewhere the brightness temperature is mainly below 2000 °K so that observations of H II regions in emission might be expected. Both these conclusions are supported by the present observations. At shorter wavelengths, with lower values of T_b, the gas might be expected to appear everywhere in emission and, conversely, in absorption at longer wavelengths.

To relate our measurements to the physical properties of the nebulae, we determine the optical depth τ from an expression for the absorption coefficient which is applicable at low electron densities, thus:

$$\left.\begin{aligned}\varkappa &= \frac{n^2}{f^2T_e^{3/2}}\times 9\cdot 70\times 10^{-3}\ln\left(\frac{3kT_e}{2hf}\times 10^{-6}\right), \\ \tau &= \int \varkappa \mathrm{d}s,\end{aligned}\right\} \quad \ldots\ldots \quad (2)$$

where n is the electron density, f the frequency in Mc/s, and k and h are Boltzmann's and Planck's constants respectively.

The logarithmic term varies slowly with frequency and temperature; it may be considered invariant over a wide range. Inserting physical constants and assuming an electron temperature of 10,000 °K in the logarithmic term, we have for the optical thickness at wavelengths near 3·5 m,

$$\tau_{(3\cdot 5\mathrm{m})}=\int\varkappa\mathrm{d}s=\frac{5\cdot 0\lambda^2}{T_e^{3/2}}\times EM, \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where the emission measure, EM, is conventionally defined as $\int n^2\mathrm{d}l$, l being the path length through the gas measured in parsecs, and the wavelength λ is measured in metres. At a wavelength near 10 cm the numerical constant is only slightly different, thus:

$$\tau_{(0\cdot 1\mathrm{m})}=\frac{3\cdot 8\lambda^2}{T_e^{3/2}}\times EM. \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

The apparent flux density of an emission nebula at constant temperature is obtained from equation (1) by applying the Rayleigh-Jeans formula, thus

$$S=\frac{2k}{\lambda^2}(T_e-T_b)\int(1-e^{-\tau})d\Omega. \qquad (5)$$

Two simplified forms arise if τ is either large or small; thus for large τ,

$$S=\frac{2k}{\lambda^2}(T_e-T_b)\Omega, \qquad (6)$$

and for small τ,

$$S=\frac{2k}{\lambda^2}(T_e-T_b)\Omega\tau. \qquad (7)$$

Substituting equations (3) and (4) in (7) we have two useful expressions for the apparent radio emission of a transparent nebula:

$$\left.\begin{aligned} S_{(3\cdot5\mathrm{m})}&=3\cdot3\times10^{-26}\frac{\overline{EM}}{T^{\frac{1}{2}}}\varphi^2\left(1-\frac{T_b}{T_e}\right),\\ S_{(0\cdot1\mathrm{m})}&=2\cdot5\times10^{-26}\frac{\overline{EM}}{T^{\frac{1}{2}}}\varphi^2\left(1-\frac{T_b}{T_e}\right),\end{aligned}\right\} \qquad (8)$$

where φ is the angular diameter of the nebula measured in degrees.

It is often convenient to assume a model consisting of uniform spherical distribution of fully ionized hydrogen; we must then integrate the emission measure throughout the sphere. The resulting expressions are, for small τ,

$$\left.\begin{aligned} S_{(3\cdot5\mathrm{m})}&=2\cdot2\times10^{-26}\frac{n^2l}{T^{\frac{1}{2}}}\varphi^2\left(1-\frac{T_b}{T_e}\right),\\ S_{(0\cdot1\mathrm{m})}&=1\cdot7\times10^{-26}\frac{n^2l}{T^{\frac{1}{2}}}\varphi^2\left(1-\frac{T_b}{T_e}\right),\end{aligned}\right\} \qquad (9)$$

where l is the diameter of the sphere, in parsecs.

The total mass in solar mass units of such a model may be estimated from the observations of apparent flux density as follows:

$$M=4\times10^6T_e^{\frac{1}{4}}.d^{5/2}.\varphi^{3/2}.S^{1/2}\left(1-\frac{T_b}{T_e}\right)^{-\frac{1}{2}}, \qquad (10)$$

where d is the distance to the gas mass in parsecs: the sum total of uncertainties involved does not warrant differentiating between flux densities at different wavelengths. It is interesting that the electron temperature has very little effect on the derived mass.

Equation (10) is usually not strictly applicable to a real nebula because electron densities are not uniform. With sufficient data the use of more sophisticated models may be justified, but at present a judicious choice of φ enables the order of mass to be estimated with an accuracy which is reasonably high by astrophysical standards.

Flux density measurements at radio wavelengths are similar in the information they provide to the standard Hα brightness measurements; both are directly proportional to emission measure and are related similarly to electron temperature. However, the radio measurements are unaffected by optical obscuration, which is usually a serious source of uncertainty in the Hα measurements, and, moreover, they yield additional information at metre and decametre wavelengths where most nebulae are more or less opaque. As against this, the resolution of a radio telescope is always vastly inferior to its optical counterpart and usually it is quite incapable of determining the brightness distribution across a nebula. A combination of radio and optical observations is therefore likely to yield considerably more information than either alone; this will become apparent in the subsequent detailed discussion of the observations.

III. Observations

Attempts were made to observe 14 bright emission nebulae including several which have been detected at centimetre wavelengths by Haddock, Mayer, and Sloanaker (1954) and Hagen, McClain, and Hepburn (1954), using the 50 ft N.R.L. paraboloid. Our observations are summarized in Table 1 together with some physical properties of the nebulae obtained by combining these with other radio and optical observations; they are discussed in detail below. Two of the nebulae, NGC 2237 and NGC 3372, were sufficiently large

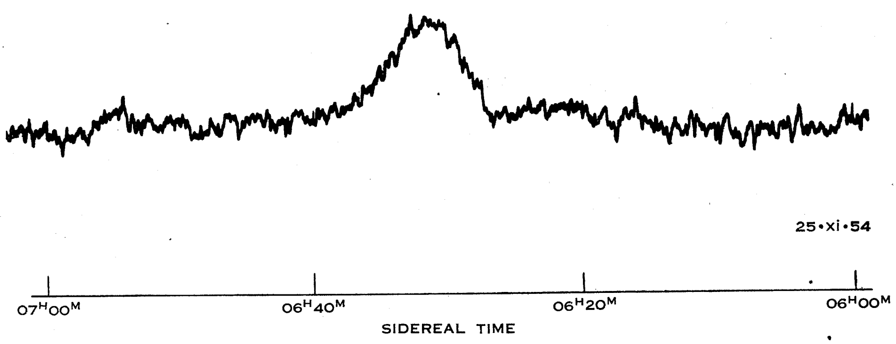


Fig. 1.—Facsimile of a record taken at the position of NGC 2237.

and intense to warrant drawing their radio isophotes. These are shown in Plate 1 in comparison with photographs of the nebulae to the same scale; the isophotes are not corrected for aerial smoothing and the half-power contour of the aerial response pattern is shown. In Figure 1 is reproduced a facsimile of a record taken at the position of NGC 2237, showing the extent of the superimposed random noise fluctuations which limit the accuracy of the radio isophotes.

30 Doradus

Details of the observations at $3 \cdot 5$ m of this nebula in the Large Magellanic Cloud have already been published (Mills 1955). The flux density of the whole emission complex is $5 \cdot 5 \times 10^{-25}$ W m^{-2} (c/s)$^{-1}$ and it is estimated that the flux density of 30 Doradus itself is about 3×10^{-25} W m^{-2} (c/s)$^{-1}$, the remainder

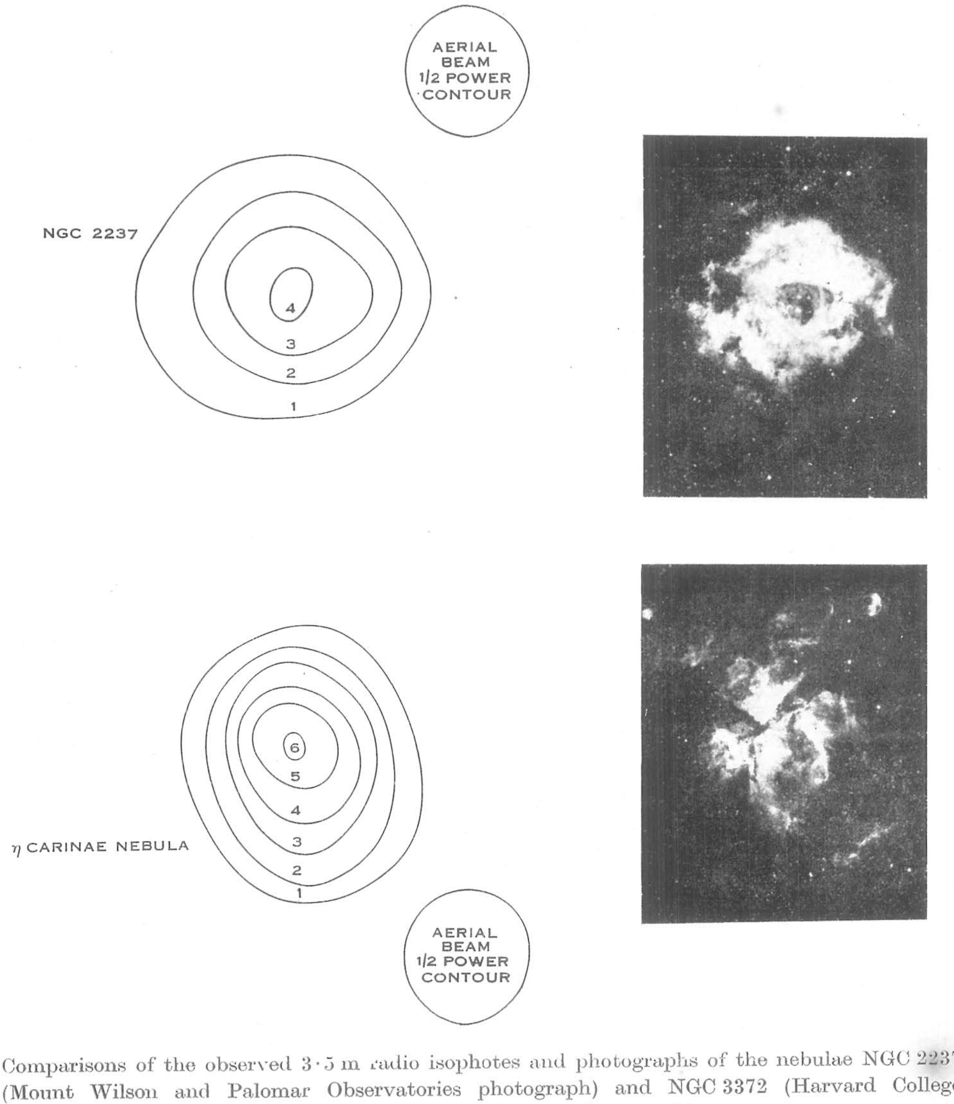
TABLE 1

EMISSION NEBULAE: FLUX DENSITY AND DERIVED QUANTITIES

Nebula	Apparent Flux Density at 3·5 m (W m^{-2} $(c/s)^{-1} \times 10^{-26}$)	Electron Temperature (°K)	Average Electron Density (cm^{-3})	Mass (⊙)	Remarks
30 Doradus complex	55	10,000*	30 Doradus 40; Neighbouring regions .. 3	4×10^6; 3×10^6	Electron density and mass are both very uncertain
NGC 2237	130	10,000	14	8000–10,000	Electron temperature and density are based on optical data: agreement with radio observations is good
NGC 3372 (η Carinae Nebula)	150	10,000*	14	3000	Electron density and mass are probably lower limits
M42 (Orion Nebula)	37	10,000*	500	20	Electron density and mass are derived from flux density measurements at different wavelengths.
IC 2177	15	—	—	—	Identification uncertain
NGC 2264	8	—	—	—	Identification uncertain
NGC 3324	<20	10,000*	<40	<7000	
NGC 6188	<10	~10,000	—	—	Undetectable although all are strong sources at centimetre wavelengths; electron temperatures must be close to the background temperature, in all cases of the order of 10,000 °K
NGC 6334	<20	~10,000	—	—	
M16	<20	~10,000	—	—	
M17	<10	~10,000	—	—	
M8	<30	~10,000	—	—	
M20	<50	~10,000	—	—	
NGC 6357	−85	6,500	37	1500	Observed in absorption

* Value assumed.

EMISSION NEBULAE AS RADIO SOURCES



Comparisons of the observed 3·5 m radio isophotes and photographs of the nebulae NGC 2237 (Mount Wilson and Palomar Observatories photograph) and NGC 3372 (Harvard College Observatory, Boyden Station photograph).

SPORADIC E AT BRISBANE

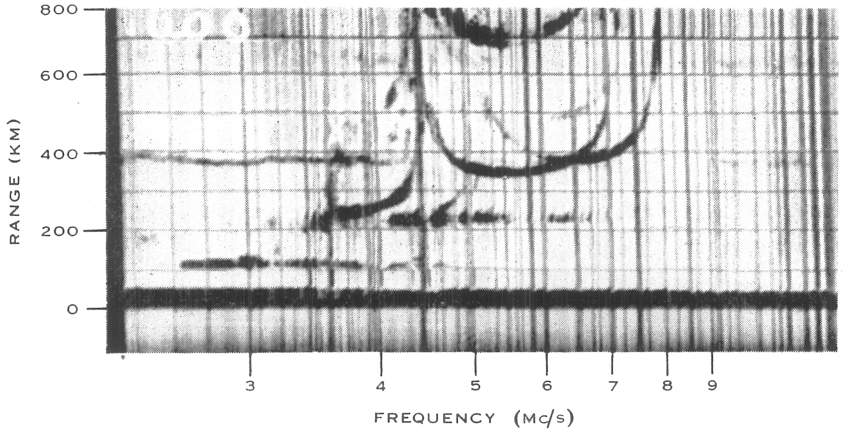


Fig. 1.—$P'f$ record showing $f_mE_s > fE_s$.

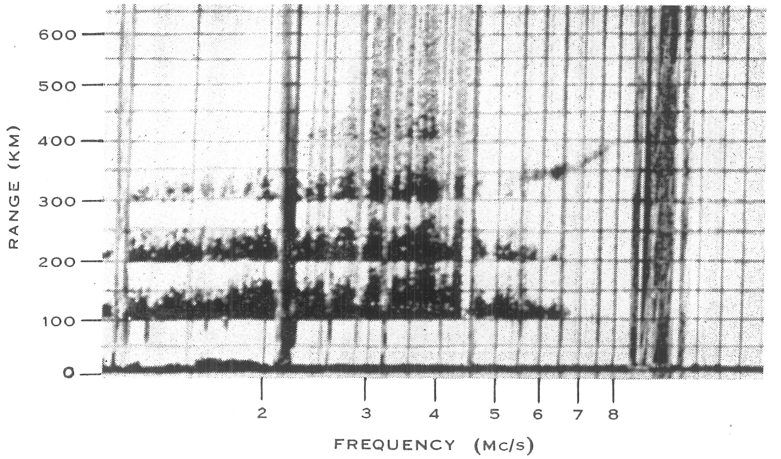


Fig. 2.—$P'f$ record showing range spreading (index 4).

being made up by the neighbouring emission regions mainly to the south. The flux density of 30 Doradus may be estimated independently on the assumption that at a wavelength of $3 \cdot 5$ m the nebula is opaque, has an angular size of 15 min of arc, an electron temperature of 10,000 °K, and the background temperature is 500 °K. The resulting flux density is $3 \cdot 2 \times 10^{-25}$ W m^{-2} (c/s)$^{-1}$ in good agreement with the radio data, suggesting that these assumptions are probably substantially correct. Measurements of the nebula at a wavelength of 50 cm have been made by Piddington and Trent (1956) ; they find a source of flux density $4 \cdot 5 \times 10^{-24}$ W m^{-2} (c/s)$^{-1}$ at the position of the emission complex. It should eventually be possible to combine the radio data to derive reliable values for electron density and temperature in the nebula and surrounding regions. This would be quite a straightforward procedure if the Hα brightness distribution were available, but in the absence of such data there is little point in a detailed analysis. Both radio observations could be reproduced by a model consisting of a dense spherical concentration 200 pc in diameter and with uniform electron density of 40 cm^{-3}, contiguous with a uniform spheroidal concentration 600 pc in diameter and 200 pc thick with an electron density of 3 cm^{-3}, all at a uniform electron temperature of 10,000 °K. The corresponding masses of the gas concentrations are 4×10^6 and 3×10^6 solar masses.

NGC 2237

This nebula is easily resolved and isophotes are shown in Plate 1 ; maximum emission occurs at a position of $06^{h}\,29^{m} \cdot 6$, $+5°\,01'$ (1950). Minkowski (1949) has studied the nebula and deduced the physical state of the gas : he has recently revised this result (Minkowski 1955) and, based on his new data, a model has been assumed which consists of a uniform sphere 35 pc in diameter with an electron density of 14 cm^{-3} at a temperature of 10,000 °K located at a distance of 1400 pc. At decimetre wavelengths this model would give a flux density of $2 \cdot 2 \times 10^{-24}$ W m^{-2} (c/s)$^{-1}$ and at $3 \cdot 5$ m an apparent flux density of $1 \cdot 6 \times 10^{-24}$ W m^{-2} (c/s)$^{-1}$, in reasonably good agreement with the present observations and also with a measurement of Ko and Kraus (1955), who found a flux density of $2 \cdot 0 \times 10^{-24}$ W m^{-2} (c/s)$^{-1}$ at a wavelength of about 1 m. However, Piddington and Trent (1956) quote a flux density of 4×10^{-24} W m^{-2} (c/s)$^{-1}$ at a wavelength of 50 cm for a source which they identify with the nebula. If this is correct the model assumed must be wrong. The occurrence of small dense regions within the nebula could perhaps explain the discrepancy. The mass of the model is 8000 solar masses and the mass corresponding to the measurement of Piddington and Trent is about 10,000 solar masses. The shape of the isophotes in Plate 1 is consistent with an absence of emission from the centre of the nebula, but the resolution is inadequate to establish this beyond doubt.

NGC 3372 (η *Carinae Nebula*)

Of the emission nebulae observed, this is the most prominent radio source and it is also easily resolved by the aerial. Isophotes are shown in Plate 1 ; the position of maximum emission is $10^{h}\,43^{m} \cdot 4$, $-59°\,31'$ (1950). Unfortunately no optical data relating to emission measures or brightness distributions are available and it could not be separately resolved in the 50 cm survey by Piddington and Trent; consequently no reliable estimates can be made of the physical state of the system. The central concentration is clearly much more pronounced than in NGC 2237, which is evident also from the photographic appearance. If the nebula is assumed transparent at $3 \cdot 5$ m with electron temperature 10,000 °K, background temperature 2000 °K, and at a distance of 1100 pc equal to that of the presumed exciting star, η Carinae, we find an r.m.s. electron density of 14 cm^{-3} and a corresponding mass of about 3000 solar masses. These are likely to be lower limits, however, because it is probable that the central portion of the nebula is opaque at this wavelength.

M42 (Orion Nebula)

This nebula offers perhaps the best opportunities for a detailed analysis since it has been studied extensively both at radio and optical wavelengths. However, optical measurements appear to differ widely, presumably because of the great variations in density across the nebula and the large amount of obscuration in the region. It is difficult to assess the significance of these differences, consequently we will in this paper attempt to deduce some properties of the nebula almost entirely from the radio observations.

The observations of the nebula are rather more uncertain than those already described because of the possibility of interference from the intense radio source Taurus-A which culminates at nearly the same time. However, it is considered that such interference is not likely to be serious. The position obtained is $05^{\mathrm{h}}\ 32^{\mathrm{m}} \cdot 6$, $-5°\ 23'$, displaced by a few minutes of arc from the position given by Haddock, Mayer, and Sloanaker (1954) observing at $9 \cdot 4$ cm; but this is to be expected as the electron density is not constant over the nebula. If it is assumed that the nebula is optically thick at $3 \cdot 5$ m and has an electron temperature of 10,000 °K, an "effective angular diameter" may be estimated from the flux density measurement, by substitution in equation (6) of Section II. This diameter is 16 min of arc, which is consistent with a slight widening of the apparent response pattern of the aerial from 50 to about 53 min of arc when observing the source. Accordingly we shall assume a uniform spherical model of diameter $1 \cdot 4$ pc, corresponding to the nebula distance of 300 pc. The flux density at $9 \cdot 4$ cm is $4 \cdot 5 \times 10^{-24}$ W m^{-2} (c/s)$^{-1}$ leading to an electron density of about 500 cm^{-3} and a mass of about 20 solar masses.

IC 2177

The radio emission shows considerable structure near this emission complex and until isophotes of the whole region become available it is not possible to make any certain identifications. However, there appears to be a source centred on $07^{\mathrm{h}}\ 03^{\mathrm{m}} \cdot 6$, $-10°\ 40'$ (1950) extending for about a degree in a roughly north-south direction; it may probably be identified with the main nebulosity of the area. An estimate of the physical state of the system is not possible with the present inadequate data.

NGC 2264

This is a relatively faint nebula surrounding a cluster of stars. The radio source is very weak and is in a region of irregular background variation so that the identification is uncertain. Furthermore, insufficient observations are available at adjacent declinations to fix the position with any accuracy: it is estimated as $06^{h}\,36^{m}\cdot5\pm1^{m}$, $+10^{\circ}\pm\frac{1}{2}^{\circ}$ (1950), which is sufficiently close to the centre of the nebula to warrant suggesting a possible identification. The estimated flux density is also uncertain because of difficulties in allowing for the angular size of a weak source. A diameter of $\frac{1}{2}^{\circ}$ was assumed, comparable with the size of the nebula.

NGC 3324

This is a small and not particularly bright nebula in a region of fairly high and irregular background temperature; failure to detect it is therefore not surprising. Assuming an angular size of 15′, a distance of 3000 parsecs corresponding to that of the exciting star GC 14621, an electron temperature of 10,000 °K, and a background temperature of 3000 °K, we may deduce from equation (**9**) that the electron density is less than 40 cm^{-3} and the mass less than 7000 solar masses.

NGC 6188, NGC 6334, M16, M17

These nebulae are all in regions with background temperatures of the order of 10,000 °K. In no case could excess radiation be detected and in one case, M17, there is some suggestion of a slight absorption, but further observations are required to verify this. All the nebulae have been observed at shorter wavelengths by one or more of several observers (Haddock, Mayer, and Sloanaker 1954; Hagen, McClain, and Hepburn 1954; McGee, Slee, and Stanley 1955): it is possible to infer from the failure to observe them at $3\cdot5$ m that electron temperatures are generally in the neighbourhood of 10,000 °K and that there is little, if any, non-thermal radiation emitted by the nebulae.

M8, M20

Both these nebulae, particularly M20, occur close to an intense non-thermal source, 17–2A (Mills 1952), which has a position of $17^{h}\,57^{m}\cdot4$, $-23^{\circ}\,25'$ (1950). No evidence for any effect, either in absorption or emission, can be found at the nebulae positions. An association with the source 17–2A therefore appears unlikely.

NGC 6357

This is the only nebula studied which shows clear evidence of an absorption effect. Tracings of records made on adjacent declinations straddling the nebula are shown in Figure 2: the position of maximum absorption is estimated as $17^{h}\,22^{m}\cdot0$, $-34^{\circ}\,09'$ (1950) in very good agreement with the position of the nebula given by Bok, Bester, and Wade (1954), that is $17^{h}\,21^{m}\cdot7$, $-34^{\circ}\,07'$ (1950). Measurements of the nebula at a wavelength of $9\cdot4$ cm have been made by Haddock, Mayer, and Sloanaker who quote the identical position that we obtain. If we assume an angular size of $63'\times43'$ as given by Bok, Bester, and Wade and a flux density at $9\cdot4$ cm of $4\cdot0\times10^{-24}$ W m^{-2} $(c/s)^{-1}$, it follows that at a wavelength of $3 \cdot 5$ m the nebula must be optically thick, that is, $e^{-\tau} \simeq 0$. In these circumstances we may use equation (**6**) to derive the electron temperature, but it is more illuminating to analyse the data directly in terms of brightness temperatures.

It is clear that the electron temperature of a nebula observed in absorption must normally be less than the brightness temperature measured at its position ;* in the present case the brightness temperature is 7800 °K. The estimated maximum calibration error in this part of the sky is ± 20 per cent., or 1600 °K ; accordingly we conclude that the electron temperature of the nebula is probably less than 7800 °K and almost certainly less than 9400 °K. An estimate of the

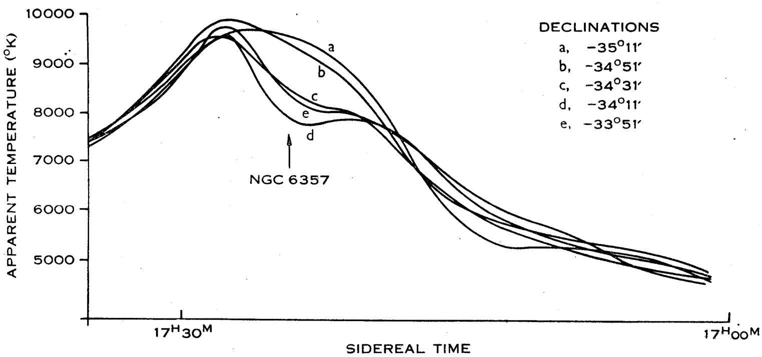


Fig. 2.—Tracings of records at declinations straddling the nebula NGC 6357, superimposed to display the effect of absorption.

actual temperature may be obtained from the following equation, derived from equations (**1**) and (**5**) of the preceding section :

$$T_e = T_a - (T_0 - T_a)\left(\frac{\Omega_0}{\Omega_n(1 - e^{-\tau})} - 1\right) - \alpha D, \quad \ldots\ldots\ldots \quad (\mathbf{11})$$

where T_a is the brightness temperature at the nebula position ; T_0 is the temperature which would have been observed in the absence of the nebula, estimated by interpolation ; Ω_0 is the equivalent solid angle of the nebula when smoothed by the aerial beam ; Ω_n is the actual solid angle of the nebula ; α is a measure of the density of galactic radio emission in units of temperature per unit distance measured in the direction of the nebula ; and D is the distance to the nebula.

We take the following values :

$T_a = 7800$ °K,

$T_0 = 8800$ °K,

$\Omega_0 = 3 \cdot 6 \times 10^{-4}$ steradians,

$\Omega_n = 1 \cdot 9 \times 10^{-4}$ steradians (corresponding to a size of $63' \times 43'$),

$e^{-\tau} \simeq 0$ (consistent with the measurements of flux density at $9 \cdot 4$ cm),

$\alpha \simeq 0 \cdot 5$ °K/parsec (estimated from the integrated brightness through the Galaxy),

$D = 1000$ parsecs (distance of the assumed exciting star $-34°11671$).

* If both the nebula and background are irregular with comparable scale factors this conclusion is not necessarily true, but it appears safe to ignore such a possibility here.

The corresponding electron temperature is 6500 °K, substantially lower than the value of 10,000 °K usually assumed for such nebulae. It would be interesting to attempt to check this abnormally low value by optical spectral measurements. With this value of T_e and the flux density obtained at 9·4 cm, we find an electron density of 37 cm^{-3} and a mass of 1500 solar masses. With these parameters it is surprising that the nebula is not more prominent optically; probably the large amount of obscuration in the region is responsible.

IV. Conclusions

A significant deduction from the observations is that ordinary emission nebulae emit radio waves as the result of their high electron temperature by the process of free-free transitions. There is no indication whatsoever that they have an association with the more intense non-thermal galactic radio sources. Accordingly it appears quite safe to apply the well-known theory of this process in determining the properties of the ionized interstellar gas. Detailed high resolution surveys of the Milky Way at widely different frequencies should enable the distribution and the physical state of the gas to be determined. A crude distance scale is available for individual distant gas concentrations by estimation of the background temperature, T_b, from observations at different wavelengths; this may well be of use in determining a three-dimensional model of the distribution. It is essential that all surveys should be complete and of high resolution, as a casual inspection of our records reveals a complicated structure along the length of the southern Milky Way; until the records are analysed in detail it is not possible to estimate the resolution actually required.

Finally, the importance of quantitative optical studies of emission nebulae is obvious; particularly in the extremely rich southern fields. Apart from the possibility of deriving physical properties of the nebulae, independent estimates of optical extinction may also arise from comparisons between the radio and optical data.

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