PAPER 33

HYDROGEN EMISSION NEBULAE AS RADIO SOURCES

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This talk is based largely upon the centimetre-wave observations of hydrogen emission nebulae made with the Naval Research Laboratory 50-ft. paraboloidal reflector at 3·15 cm. [1], at 9·4 cm. [2], and at 21 cm. [3]. After the detection of the first individual bright galactic nebulae at 9·4 cm. a systematic search was made to detect other hydrogen emission nebulae, principally with the aid of the catalogue of emission nebulae obtained by Sharpless [4] from 48-inch Schmidt plates at Mount Wilson and Palomar Observatories. An interesting correlation between radio detectability and nebular classification by optical size and brightness was found, in spite of the fact that optical extinction was not taken into account. The Sharpless catalogue lists 140 classified emission nebulae, of which sixty-five of the brightest were scanned with the radio antenna beam. Of these, twelve nebulae were detected and measured. They can be grouped as follows.

The catalogue contains seventeen emission nebulae in the optically brightest class, of five classes, of which the five largest nebulae were detected as radio sources. Their average optical angular size was 50′ and their average centimetre-wave emission measure was 48,300 parsecs. cm.$^{-6}$ averaged over the 26′ circular antenna beam. It is assumed that 72 % of the true brightness temperature is measured when a uniformly bright source covers the main lobe and the neighbouring side lobes because of the spill-over effect, and that $A_1(2) = 19{\cdot}2$ and $T_e = 10^4$ degrees in the free-free emission formula.

The catalogue contains nine nebulae in the second brightest class and the five largest of these were also detected. Their average size was 110′ and their average emission measure was 27,000 parsecs. cm.$^{-6}$.

The two remaining nebulae that were detected are in the third brightness class and have an average size of 150′ and average emission measure of 10,600 parsecs. cm.$^{-6}$.

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The maximum size of nebulae in the 4th and 5th brightness classification is only 60′ and none were detected.

We see here systematic relationships between optical brightness class, angular size, and radio flux density (which is proportional to the beam emission measure). The brighter the nebula the smaller is the critical size required for radio detectability; and the brighter the nebula the greater is the radio flux density in spite of smaller average size.

These relations indicate that a common radio emission process is responsible for the observed radio flux; the proportionality between the radio and optical brightnesses suggests a thermal emission process.

Additional support for the radio-optical proportionality for emission nebulae was found in the correlation between the logarithm of the radio flux density and the magnitude in hydrogen-alpha light for seven nebulae measured by Shajn, Hase and Pikelner [5] and corrected by us for optical extinction.

Boggess [6] has measured calibrated intensity isophotes of four galactic emission nebulae (NGC 6523, 6514, 6611 and 6618) in several colours including H_α light from which he predicted the centimetre-wave thermal flux densities at the earth after making corrections for optical extinction and assuming an electron temperature in the nebulae of 10,000° K. When these were compared with the measured 9·4 cm. flux densities the latter were too large by factors of 1·5, 1·1, 1·9 and 2 for the four nebulae, respectively. He attributed these discrepancies to inadequate extinction data.

A revised evaluation, following the method of Boggess, has been made of the comparison between the H_α measurements by Boggess and the measured 9·4 cm. wave-length flux densities under the assumption of purely thermal radio emission. The chief features of this new evaluation are that the H_α brightness and emitting area was averaged over the antenna beam rather than using the entire nebula or the bright inner 'nucleus', and that Dr Nancy Roman has kindly derived for us absorption corrections for these nebulae based on extinction data recently published [7].

Furthermore when a 65% antenna gain efficiency (which includes the 72% spill-over effect mentioned above) is used and an allowance is made for a variation in electron temperature between the limits of 10,000 and 15,000° K., and for the 2° uncertainty in the radio antenna temperature measurements (which introduces uncertainties of 30, 50, 40, and 8% in radio flux density for the above four nebulae, respectively) we find the range of values in the predicted and observed radio flux values in M.K.S. units multiplied by 10^{25} given in Table 1.

The upper and lower predicted flux densities correspond to electron temperatures of $1\cdot5 \times 10^4$ and $1\cdot0 \times 10^{4\circ}$, respectively (see Boggess, thesis, for the effect of temperature). The agreement is good except for NGC6523, which fails to accord by a factor of 1·2. This is the nebulae for which Boggess obtained good agreement but he considered only the bright inner 'nucleus' which is appreciably smaller than the antenna beam and the entire nebula, the largest of the four, is larger than the beam but radiates 75% of its H_α flux from a region within 12′ of its central brightness peak. Nevertheless this 20% discord is too small to be considered as significant evidence against purely thermal radio emission, and for the other three nebulae the accord is excellent.

Table 1

NGC	Predicted	Observed
6514	6– 7	5–14
6523	26–31	12–22
6611	9–10·5	8–19
6618	52–61	53–62

Boggess did not measure the Orion Nebula, NGC 1976, because of the difficulty of eliminating the effect of the strong continuous radiation due to the presence of interstellar dust within the nebula. It is possible to estimate the expected upper limit of its radio emission from its H_α magnitude of 5·8 compared to 8·2 for NGC6618 as measured by Shajn, Hase and Pikelner. However, it is estimated that the absorption correction for NGC6618 is 2·5 magnitudes and is small for NGC 1976. Therefore, it is not unexpected that both at 9·4 cm. and 3·15 cm. wave-length the radio flux density is about 40 % greater for NGC6618.

The evidence presented so far for a purely thermal radio emission from galactic emission nebulae has been based upon the theoretically expected proportionality between H_α and centimetre-wave intensities and, as has been discussed above, this evidence is favourable. However, it is possible to present additional evidence, independent of optical measurements, in the form of radio spectra. Fig. 1 shows the measured radio flux density in M.K.S. units for NGC 1976 at five different wave-lengths embracing a 100 to 1 range. The three short wave-length points were measured at the Naval Research Laboratory, the point at 1·2 metres was obtained by Kraus and Ko (private communication) and at 3·5 metres by Mills (reported by Pawsey [8]). The symbol at 1·4 metres indicates the upper limit set by Baldwin from the failure to detect this nebula [9]. The double set of marks at 3·15 and 9·4 cm. wavelength indicate the observed and corrected flux densities. The correction was made for the fact that the antenna beam

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is smaller than or comparable to the radio source size. The amount of the correction is determined directly from the percentage broadening of the drift curve (obtained as the 13′ diameter source drifts through the 9′.5 or 26′ antenna beam), and is not too sensitive to the assumed shape of the radio brightness distribution.

The solid curve is the theoretical thermal spectrum based entirely upon the apparent source size estimated from the broadening of the drift curves

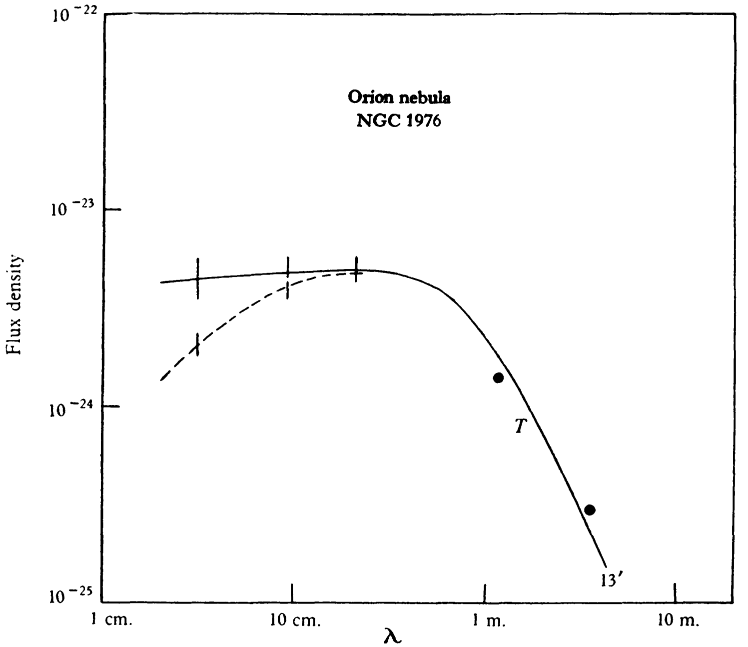

Fig. 1. Observed and computed spectrum of the Orion nebula.

and the measured flux densities at 3·15 or 9·4 cm. wave-length. The good agreement at the longer wave-lengths is strong evidence favouring a thermal model of the Orion nebula. The emission measure at 3·14 cm. averages 465,000 parsecs. cm.$^{-6}$ over its 9′.5 beam using the same antenna parameters as used with the 9·4 cm. beam mentioned above and with $A_1(2) = 17$. This is of the same order as the optically determined values [10].

Theoretical thermal spectra have also been obtained for NGC 6618 and 6357, based upon a source diameter of 8′ and 17′, respectively, and are in fair agreement with observed flux densities at four wave-lengths embracing a 50 to 1 range.

The radio source Cygnus X has been mapped at 9·4 cm. with a 26′

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beam. It has been found to consist of two principal maxima, one located near the star γ Gygni which is surrounded by hydrogen emission nebulosity and the other maximum at about $2^\circ.5$ farther east and $0^\circ.5$ farther north located at a faint un-catalogued emission nebulosity in the heavily reddened Cygnus rift region. The flux densities from the γ Cygni nebulosity at 9·4 and 21 cm. give similar emission measures of 18,600 and 13,600 parsecs.cm.$^{-6}$ respectively, when averaged over their respective beams, thereby indicating thermal emission (the 55′ beam at 21 cm. measures a somewhat lower value as would be expected from the isophotes found with a 26′ beam). Piddington and Minnett [11] obtained a flat radio-spectrum for Cygnus X at longer wave-lengths and suggested it was due to the thermal emission from the γ Cygni nebulosities or from the whole spiral arm in the direction of Cygnus. Their flux density is too high for either the γ Cygni region or the spiral arm alone because their broad antenna beam included both maxima in Cygnus X as well as part of the underlying background from the spiral arm.

REFERENCES

[1] Haddock, F. T. and McCullough, T. P. *A.J.* **60**, 161, 1955.
[2] Haddock, F. T., Mayer, C. H. and Sloanaker, R. M. *Ap. J.* **119**, 456, 1954. *Nature*, **174**, 176, 1954.
[3] Hagen, J. P., McClain, E. F. and Hepburn, N. *Proc. I.R.E.* **42**, 1811, 1954.
[4] Sharpless, S. *Ap. J.* **118**, 362, 1953.
[5] Shajn, G. A., Hase, W. F., and Pikelner, S. B. *Astr. Zhur.* **31**, 105, 1954.
[6] Boggess, A., Thesis, University of Michigan, 1954.
[7] Morgan, W. W., Harris, D. L. and Johnson, H. L. *Ap. J.* **118**, 92, 1953. Morgan, W. W., Code, A. D. and Whitford, A. E. *Ap. J.* Supp. Ser. II, no. 14, 1955.
[8] Pawsey, J. L. This publication, paper 18, p. 130.
[9] Baldwin, J. E. *Observatory*, **73**, 155, 1953.
[10] Greenstein, J. L. This publication, paper 32, p. 179.
[11] Piddington, J. H. and Minnett, H. C. *Aust. J. Sci. Res.* A, **5**, 17, 1952.