# OBSERVATIONS OF 23 PLANETARY NEBULAE AT 408 MHz*

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Various observers (e.g. Slee and Orchiston 1965; Davies *et al.* 1967; Hughes 1967; Thompson and Colvin 1967; Thompson, Colvin, and Stanley 1967; Kaftan-Kassim 1968) have so far detected nearly 100 planetary nebulae at high radiofrequencies ($\geqslant$ 3 GHz). In this range, the nebulae have been shown to be optically thin, their spectra being almost flat. Wherever possible, the radio flux densities have been compared with hydrogen recombination line observations.

Low frequency ($<$ 500 MHz) observations are of considerable interest because some planetary nebulae show appreciable self-absorption in this region. Provided that a radio flux density measurement can be made at an optically thick frequency, and that Balmer line isophotes are available, estimates may be made of the electron temperature $T_e$. However, suitable radiofrequency observations have proved to be difficult to obtain and to be subject to serious confusion errors, for reasons discussed in earlier papers (e.g. Kaftan-Kassim 1966; Le Marne 1966; Ficarra 1967; Terzian 1967; Barbieri and Ficarra 1968).

The present high resolution ($\sim 3'$ arc) observations at 408 MHz were made at the Molonglo Radio Observatory. Of the sources previously observed at high frequencies, 23 of those south of $\delta = 20°$ were investigated and 12 were detected. In each case several transits of the source were recorded digitally on magnetic tape using 3 sec sampling intervals, and the digital data were then added and suitably smoothed. The flux densities given are based on the Wyllie (1969) scale, reference sources used being PKS 0023−26, 0157−31, 0218−02, 0235−19, 0347+05, 0859−25, 0947+14, 1005+07, 1040+12, 1143−48, 1309−22, 1416+06, 1640−15, and 2144+15.

The results, together with those of Thompson, Colvin, and Stanley (1967) and Kaftan-Kassim (1968), which are the most comprehensive of the sets of high frequency observations, are summarized in Table 1. The flux densities at 408 MHz are believed to have a standard error of about 10%. Because of the low flux densities of most of the planetary sources, the standard error in the positions is large ($\sim 10''$ arc). Hence an identification has been suggested only when the position of the radio source is within $20''$ arc of the optical position listed in either Thompson, Colvin, and Stanley (1967) or Thompson and Colvin (1967). For each case in which an upper limit is placed on the 408 MHz flux density, there is no radio source above that limit within $1'$ of the optical position.

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The excitation temperature of a nebula may be measured directly if the nebula is both (1) optically thick at 408 MHz and (2) resolved by the 3′ pencil beam (Mills and Shaver 1968). None of the planetary nebulae so far observed satisfy both of these conditions. However, IC 418 satisfies (1), having a mean optical depth of about 10 at 408 MHz. Hence the brightness distribution can be approximated by a disk whose height is equal to $T_e$. The estimation of $T_e$ then depends only on the flux value (0·17 f.u.) used and on the outer dimensions of the nebula. Le Marne and Shaver (1969) have used this method to estimate $T_e$ at 12 500°K. The outer dimensions of the nebula were estimated by correcting the observed Hβ intensity profile of Wilson and Aller (1951) as completely as possible for smearing effects in the optical observations.

Table 1

OBSERVATIONS OF 23 PLANETARY NEBULAE

| Source* | Flux Density (f.u.) 408 MHz† | 3 GHz‡ | 5 GHz§ | Source* | Flux Density (f.u.) 408 MHz† | 3 GHz‡ | 5 GHz§ |
|---|---|---|---|---|---|---|---|
| NGC 246 | <0·09 | 0·15 | 0·11 | NGC 6369 | 0·90 | 1·56 | 2·32 |
| IC 418 | 0·17 | 1·41 | 1·76 | NGC 6445 | 0·36 | 0·27 | 0·37 |
| SH2−267[a] | 0·50 | <0·30 | 0·35 | NGC 6537[b] | <0·10 | 0·54 | 0·59 |
| NGC 2346 | <0·06 | <0·10 | 0·14 | NGC 6572[c] | <0·20 | 0·92 | 1·20 |
| NGC 2440 | 0·25 | 0·31 | 0·36 | NGC 6629 | 0·12 | — | 0·24 |
| M3−4 | <0·06 | 0·13 | — | NGC 6741 | <0·10 | 0·26 | 0·36 |
| NGC 3242 | 0·60 | 0·72 | 0·85 | NGC 6781 | 0·40 | 0·37 | 0·25 |
| NGC 4361 | 0·24 | 0·22 | 0·21 | NGC 6818 | 0·29 | 0·34 | 0·30 |
| NGC 5882 | <0·13 | 0·34 | 0·40 | NGC 6891 | <0·10 | — | 0·05 |
| NGC 6072 | <0·13 | 0·11 | — | NGC 6905 | <0·11 | — | 0·10 |
| NGC 6153 | 0·25 | 0·51 | 0·69 | NGC 7009 | 0·31 | 0·62 | 0·76 |
| IC 4634 | <0·06 | 0·15 | 0·16 | | | | |

* Notes on individual sources: (a) The radio source is extended with respect to the 408 MHz aerial beam, the equivalent Gaussian half-power source diameter being about 3′ arc. (b) A radio point source of 0·40 f.u. is observed at $18^h 02^m 11^s$, −19° 50′·6, about 1′ arc to the north-west of the optical position of NGC 6537. (c) The upper limit of 0·2 f.u. for NGC 6572 is derived from facsimile records only, as digital data were not recorded for this source.

† Present observations.

‡ Thompson, Colvin, and Stanley (1967).

§ Kaftan-Kassim (1968).

Earlier estimates of the temperature of IC 418 (Menon and Terzian 1965; Khromov 1966; Thompson 1967) were based on flux densities at $\geqslant$ 750 MHz, and are therefore more model dependent. In particular it was shown that incomplete restoration of the Hβ profile leads to low estimates of $T_e$. The present value agrees well with the 11 200°K derived by Kaler (1966) from optical observations.

Recently Thompson (personal communication) has derived very low ($\sim$ 3000–4000°K) values of $T_e$ for NGC 7009 and 3242. His calculations used upper limits to the 408 MHz flux densities given by Barbieri and Ficarra (1968), the limits being 0·2 f.u. for NGC 7009 and 0·3 f.u. for NGC 3242. The present observations (0·31 and 0·60 f.u.) for these sources suggest that the nebulae are still relatively optically thin at 408 MHz and that the actual electron temperatures are significantly higher than Thompson's estimates.

The planetary nebulae NGC 6369, 6741, and 7009 are not sufficiently optically thick at 408 MHz for the present methods to be used to derive useful lower limits to their electron temperatures. Any estimates of $T_e$ made would be dependent on assumed models of the opacity distribution at 408 MHz, and would consequently be very uncertain.

For NGC 3242, 6369, 6445, and 7009, the present observations also exceed upper limits to the 408 MHz flux densities published in an earlier paper (Le Marne 1966). These upper limits, as well as those given by Barbieri and Ficarra, were obtained from fan beam observations. The present observations using a 3′ pencil beam show that, in some regions of the sky, fan beam observations have been more seriously confused than previously thought.

It is to be noted that the present identifications are additional to the five southern planetary nebulae (Wray 1966) of large angular area (> 3 sq min of arc) detected at 408 MHz by Le Marne and Lyngå (1968).

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## *References*


Barbieri, C., and Ficarra, A. (1968).—Observations of planetary nebulae at 408 MHz. *Memorie Soc. astr. ital.* (in press).

Davies, J. G., Ferriday, R. J., Haslam, C. G. T., Moran, M., and Thomasson, P. (1967).—*Mon. Not. R. astr. Soc.* **135**, 139.

Ficarra, A. (1967).—*Nuovo Cim.* B **52**, 267.

Hughes, M. P. (1967).—*Astrophys. J.* **149**, 377.

Kaftan-Kassim, M. A. (1966).—*Astrophys. J.* **145**, 658.

Kaftan-Kassim, M. A. (1968).—*Astrophys. J.* **155**, 469.

Kaler, J. B. (1966).—*Astrophys. J.* **143**, 722.

Khromov, G. S. (1966).—*Soviet Astr.* **9**, 705.

Le Marne, A. E. (1966).—*Observatory* **86**, 148.

Le Marne, A. E., and Lyngå, G. (1968).—*Observatory* **88**, 248.

Le Marne, A. E., and Shaver, P. A. (1969).—*Proc. astr. Soc. Aust.* **1**, 216.

Menon, T. K., and Terzian, Y. (1965).—*Astrophys. J.* **141**, 745.

Mills, B. Y., and Shaver, P. A. (1968).—*Aust. J. Phys.* **21**, 95.

Slee, O. B., and Orchiston, D. W. (1965).—*Aust. J. Phys.* **18**, 187.

Terzian, Y. (1967).—*Astr. J.* **72**, 443.

Thompson, A. R. (1967).—*Astrophys. Lett.* **1**, 25.

Thompson, A. R., and Colvin, R. S. (1967).—*Astrophys. J.* **150**, 345.

Thompson, A. R., Colvin, R. S., and Stanley, G. J. (1967).—*Astrophys. J.* **148**, 429.

Wilson, O. C., and Aller, L. H. (1951).—*Astrophys. J.* **114**, 421.

Wray, J. D. (1966).—A study of Hα emission objects in the Southern Milky Way. Dissertation at Evanston, Illinois.

Wyllie, D. V. (1969).—*Mon. Not. R. astr. Soc.* **142**, 229.