OBSERVATIONS AT 2700 MHz OF SELECTED PLANETARY NEBULAE

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Abstract

Observations at 2700 MHz of 74 planetary nebulae have been obtained with the Parkes 64 m radio telescope. Comparison is made with the optically determined Hβ intensity to obtain extinction coefficients in these directions.

I. INTRODUCTION

Radiofrequency observations of numerous planetary nebulae have been obtained by many investigators using a variety of equipment; an excellent compilation and bibliography has been given by Higgs (1971). The radio emission, which is relatively weak, is due to free–free transitions within the ionized hydrogen cloud. Consequently there is a relationship between the intrinsic luminosities at radio and optical frequencies, which can be used to determine the optical absorption to the nebula. In the present investigation the 64 m radio telescope at Parkes was used to obtain radio positions and 2700 MHz flux densities of 74 planetary nebulae south of declination $+27°$. These flux densities are compared with the optically determined Hβ intensities to obtain extinction coefficients for these nebulae. The preliminary results for 17 of the nebulae were given by Aller (1969*a*, 1969*b*).

II. OBSERVATIONS

The 2700 MHz parametric correlation receiver (Batchelor, Brooks, and Cooper 1968) has a system noise temperature of 100 K. With the 400 MHz bandwidth and an output time constant of 1 s the r.m.s. noise is equivalent to $0 \cdot 05$ f.u.‡ This is a considerably better sensitivity than was used in a previous Parkes survey of planetary nebulae by Slee and Orchiston (1965). However, many of the planetary nebulae are located near the Milky Way, where confusion generally imposes a higher limit than this.

Away from the galactic plane, where the confusion limit is about $0 \cdot 02$ f.u., correlation with an offset beam was used (mainly in the November 1968 observations). However, for most of the second and longer run (in June 1969), which involved the more confused regions, the offset feed was replaced by a cold load. In this configuration there was a small loss in sensitivity but this was more than compensated for by the integration of digitally-stored repeat scans (normally five to seven scans in both right ascension and declination through the optical position). Some typical

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‡ 1 flux unit (f.u.) = $10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$.

scans shown in Figure 1 illustrate the problems. An example of particularly bad confusion is shown in Figure 1(*b*), where it was difficult to draw a baselevel giving consistent intensities for the source from the two scans. The baselevel chosen for each scan is shown in these figures.

The telescope beamwidth ($8'\cdot 1$ arc), the pointing errors, and the flux density calibration were determined from observations on several point sources: PKS 0048−12 (1·4 f.u. at 2700 MHz), 3C 71 (3·3 f.u.), Hydra A (23·5 f.u.), PKS 1934−63 (11·5 f.u.), PKS 1309−22 (2·4 f.u.), and PKS 1932−46 (6·4 f.u.). These adopted flux densities are on the Parkes scale and probably contain errors no greater than $\pm 0\cdot 07$ f.u. $\pm 7\%$ (Ekers 1969).

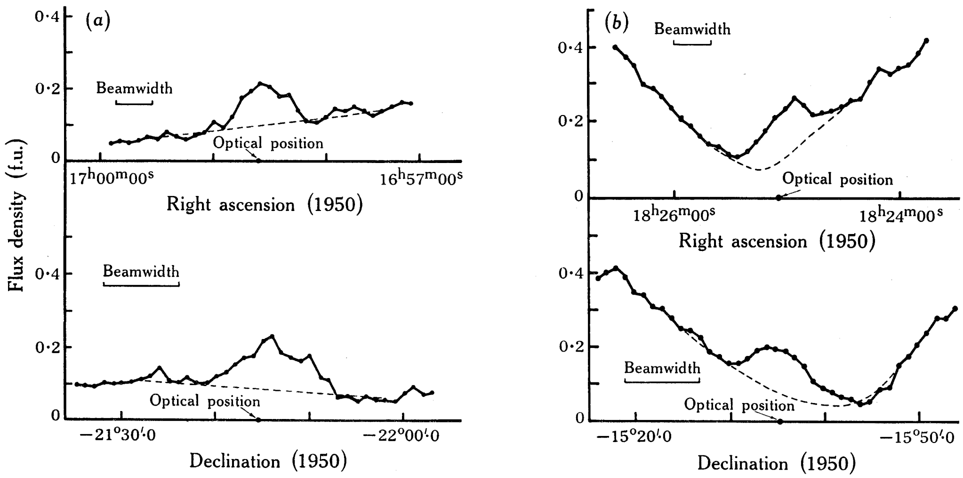

Fig. 1.—Averages of five scans through the optical positions of the two moderately weak planetary nebulae (*a*) IC 4634 (0·12 f.u.) and (*b*) M1−46 (0·11 f.u.). This figure illustrates the limitations set by confusion and sensitivity. The right ascension scans were made at declinations of (*a*) $-21°\,44'\cdot 6$ and (*b*) $-15°\,35'\cdot 0$, and the declination scans at right ascensions (*a*) $16^{h}\,58^{m}\,46^{s}$ and (*b*) $18^{h}\,25^{m}\,04^{s}$. In each case the optical position of the nebula is indicated. The baselevels chosen for each source are shown. The zero point on the flux density scale is arbitrary.

When account is taken of the effective integration time, the limit in the detection of these weak sources due to noise fluctuations is about 0·05 f.u. for a single scan, and after integrating five scans this limit is reduced to about 0·02 f.u., i.e. near the confusion limit away from the galactic plane. We have placed upper limits of 0·04 f.u. on the sources we did not detect. Estimates of the probable error in the flux density for each of the sources observed are given in Table 1. These errors apply to the flux density level of the source rather than to the particular source. They were obtained from a comparison of the flux densities measured from the right ascension and declination scans of sources in each flux density range. Telescope pointing errors were approximately $\pm 1'$ arc in both right ascension and declination. However, confusion and low signal-to-noise ratio in some cases imposed greater errors than those on the measured positions.

III. Results

The radio positions and flux densities determined from the observations are given in Table 1. We also list the differences between our radio positions and those of the optical nebulae. For most nebulae these are small: the r.m.s. difference is $\pm 0'\cdot 6$ arc in right ascension and $\pm 1'\cdot 1$ arc in declination, commensurate with the pointing errors of the telescope, and we believe that all of the sources in Table 1 are related to the nebulae.

The flux densities are generally close to the values obtained by other observers, and in particular they are in good agreement with the values obtained by Slee and Orchiston (1965) for 56 of the sources in Table 1. Five of the nebulae have significant angular diameters compared with the $8'\cdot 1$ beam and we have corrected the flux densities of those sources by using: for NGC 246, 6781, and 6853 the optical sizes quoted by O'Dell (1962); for NGC 6302 the radio size given by Reifenstein *et al.* (1970); and for NGC 7293 the broadening of our own scans. Note that the size deduced here for NGC 7293 ($9'\cdot 4 \times 9'\cdot 1$) is smaller than the optical diameter ($13'\cdot 4$) given by O'Dell (1962) and may account in part for our integrated flux density being lower than those given by Hughes (1967) ($1\cdot 74 \pm 0\cdot 28$ f.u.) and Slee and Orchiston (1965) ($1\cdot 60$ f.u.). The peak flux densities of these five sources are given in parentheses in Table 1.

Given the optically thin free–free radio flux density S_v ($\mathrm{W\,m^{-2}\,Hz^{-1}}$) and the electron temperature T_e (K) for an HII region, we can predict the Hβ flux density $F(\mathrm{H}\beta)_{\mathrm{pred}}$ sufficiently well by the approximate relation (Aller 1969*a*)

$$F(\mathrm{H}\beta)_{\mathrm{pred}} = S_{v,\mathrm{obs}} \times 10^{14}/(1\cdot 69 \times 10^{-4} T_e + 1\cdot 81) \qquad \mathrm{W\,m^{-2}}. \tag{1}$$

The difference between the predicted and measured Hβ flux is interpreted as arising from optical space absorption, the extinction coefficient c being given by

$$c = \log_{10}\{F(\mathrm{H}\beta)_{\mathrm{pred}}/F(\mathrm{H}\beta)_{\mathrm{obs}}\}. \tag{2}$$

The values of c derived using equations (1) and (2) are given in column 8 of Table 1. The Hβ flux densities used were from O'Dell (1963*a*, 1963*b*, 1963*c*), Aller and Faulkner (1964), or Webster (1969). Generally we have chosen the electron temperature from the optical spectroscopic data, i.e. the [OIII] ratio of nebular to auroral line intensity. Where no data are available we have adopted $T_e = 10\,000$ K as a typical value.

The derived extinctions are generally lower than those obtained by Cahn and Kaler (1971) from a similar radio–Hβ comparison. There is an average systematic difference of $0\cdot 16$ between the two sets of results. The radiofrequency flux densities at 3000 MHz which they deduced from available data are comparable with our measured values and it seems that most of the difference is due to Cahn and Kaler's adoption of an electron temperature of 5000 K whilst we have used temperatures near 10 000 K. This would produce a difference of $0\cdot 12$ in extinction.

From recent photoelectric measurements of the lines and continuum in the planetary nebula NGC 7027, Mathews and Miller (1972) found no justification for these low hydrogen recombination temperatures. In fact both the lines and the continuum can be explained using the temperatures determined from the [OIII] lines. We believe that temperatures as low as 5000 K are unlikely and that therefore Cahn and Kaler's extinction coefficients represent upper limits.

All the evidence points to planetary nebulae being thermal sources and therefore the treatment given here is suitable; however, the occasional large extinction coefficients might imply that there could be some confusion with nonthermal sources. Le Marne (1969), for example, found a confusing source only 1′ arc away from NGC 6537. The general difficulties arising from confusion, particularly confusion with nonthermal sources, are much reduced in a 5000 MHz survey of planetary nebulae which will be described in a later paper.

TABLE 1

2700 MHz OBSERVATIONS OF PLANETARY NEBULAE

(1) Nebula	(2) Designation*	(3) Radio position (1950) R.A. h m s	(4) Radio position (1950) Dec. ° ′	(5) Optical − radio position R.A. (min of arc)	(6) Optical − radio position Dec. (min of arc)	(7) Flux density S_{2700} (f.u.)	(8) Extinction coeff. c	(9) Comments
NGC 246	118 − 74°1	00 44 31	−12 08·4	−0·2	−0·1	0·26(0·23) ± 0·08		
NGC 1535	206 − 40°1	04 11 54	−12 51·4	0·0	−0·3	0·17 ± 0·06	0·29	
J320	190 − 17°1					0·05 ± 0·02	0·40	
IC 418	215 − 24°1	05 25 07	−12 43·5	−0·2	0·2	1·61 ± 0·16	0·16	
NGC 2022	196 − 10°1	05 39 20	09 04·6	0·1	−0·7	0·12 ± 0·05	0·40	
IC 2165	221 − 12°1	06 19 23	−12 57·1	−0·3	−0·8	0·23 ± 0·08	0·79	
J900	194 + 2°1	06 23 02	17 50·3	−0·1	−0·9	0·17 ± 0·06	0·90	
NGC 2392	197 + 17°1	07 26 11	21 00·8	0·0	0·3	0·28 ± 0·10	0·15	
VV 68	235 + 1°1					0·05 ± 0·02		
NGC 2440	234 + 2°1	07 39 41	−18 05·2	−0·4	−0·1	0·42 ± 0·10	0·56	
NGC 2438	231 + 4°2	07 39 32	−14 37·7	−0·2	0·8	0·10 ± 0·04	0·47	
NGC 2610	239 + 13°1		−15 57·5		−1·1	0·04 ± 0·02	0·43	
M3 − 6	254 + 5°1					⩽ 0·04		
IC 2448	285 − 14°1	09 06 33	−69 43·6	−0·1	−0·6	⩽ 0·06	⩽ 0·0	
NGC 2792	265 + 4°1	09 10 34	−42 12·1	−0·0	−1·2	0·13 ± 0·05	0·83	
NGC 2818	261 + 8°1					< 0·04	< 0·5	
NGC 2867	278 − 5°1	09 20 04	−58 05·2	−0·1	−0·9	0·27 ± 0·09	0·45	
A33	238 + 34°1					< 0·04		R.A. scans only
IC 2501	281 − 5°1	09 37 22	−59 51·4	−0·6	−0·3	0·26 ± 0·08	0·52	
NGC 3132	272 + 12°1	10 04 56	−40 11·5	−0·4	−0·3	0·24 ± 0·08	0·00	
NGC 3195	296 − 20°1	10 10 01	−80 37·0	−0·2	−0·1	0·02 ± 0·02	−0·20	
NGC 3211	286 − 4°1	10 16 12	−62 25·2	−0·1	−1·0	< 0·04	< 0·3	Confused
NGC 3242	261 + 32°1	10 22 22	−18 23·0	−0·2	−0·4	0·87 ± 0·10	0·19	
IC 2621	291 − 4°1	10 58 22	−64 57·2	−0·3	−1·8	0·15 ± 0·06		
VV 60	290 + 7°1	11 26 22	−52 39·5	−1·2	0·2	0·08 ± 0·03		
NGC 3918	294 + 4°1	11 47 50	−56 54·0	−0·5	−0·3	0·82 ± 0·10	0·32	
NGC 4361	294 + 43°1	12 21 52	−18 30·5	0·3	−0·1	0·17 ± 0·06	0·0	
NGC 5189	307 − 3°1	13 29 55	−65 42·3	−0·2	−1·1	0·33 ± 0·10		
NGC 5307	312 + 10°1	13 47 54	−50 56·9	0·0	−1·4	0·11 ± 0·04	0·60	
IC 4406	319 + 15°1	14 19 11	−43 55·8	0·6	0·5	0·15 ± 0·06	0·35	
NGC 5882	327 + 10°1	15 13 26	−45 27·5	−0·2	−0·0	0·39 ± 0·10	0·37	
VV 124	342 + 27°1	15 19 23	−23 27·8	0·5	0·8	0·08 ± 0·03	0·65	
VV 73	322 − 2°1					< 0·04		Confused
Sp 1	329 + 2°1		−51 21·2		−0·1	0·11 ± 0·04	1·03	Confused
NGC 6072	342 + 10°1	16 09 40	−36 05·7	0·3	−0·6	0·16 ± 0·08	0·96	
IC 4593	25 + 40°1	16 09 23	12 11·5	−0·2	0·6	0·11 ± 0·04	0·01	
NGC 6153	341 + 5°1	16 28 00	−40 08·0	0·3	−0·2	0·70 ± 0·10	1·05	
NGC 6210	43 + 37°1	16 42 21	23 53·1	0·6	0·2	0·33 ± 0·10	0·00	
IC 4634	0 + 12°1	16 58 34	−21 46·3	0·5	1·6	0·12 ± 0·06	0·37	
NGC 6302†	349 + 1°1	17 10 20	−37 02·7	0·5	−0·2	3·06(2·84) ± 0·25		
NGC 6309	9 + 14°1	17 11 14	−12 51·4	0·5	0·3	0·14 ± 0·06	0·66	
NGC 6326	338 − 8°1	17 16 49	−51 41·8	0·0	−0·3	0·15 ± 0·06	0·51	Confused

TABLE 1 (*Continued*)

(1) Nebula	(2) Designation*	(3) Radio position (1950) R.A. h m s	(4) Radio position (1950) Dec. ° ′	(5) Optical − radio position R.A. (min of arc)	(6) Optical − radio position Dec. (min of arc)	(7) Flux density S_{2700} (f.u.)	(8) Extinction coeff. c	(9) Comments
M1−25	4+4°1		−22 05·6		−1·5	0·04±0·02		
Hb 5	359−0°1		−29 56·8		−2·0	0·16±0·06		Dec. scans only
NGC 6445	8+3°1	17 46 14	−20 01·6	0·9	1·8	0·36±0·10	1·41	
NGC 6537	10+0°1	18 02 14	−19 52·6	0·4	1·6	0·64±0·10	1·85	
NGC 6563	358−7°1		−33 52·3		−0·7	0·12±0·06	0·49	Confused in R.A.
NGC 6565	3−4°5					0·10±0·04	0·72	Confused
NGC 6572	34+11°1	18 09 39	06 50·3	0·6	−0·1	1·15±0·10	0·29	
NGC 6567	11−0°2		−19 07·3		1·7	0·35±0·10	0·92	Confused
NGC 6578	10−1°1	18 13 14	−20 27·4	0·9	−0·5	0·06±0·03	0·98	Confused
IC 4699	348−13°1					<0·04		
NGC 6629	9−5°1	18 22 41	−23 15·7	−0·1	1·7	0·27±0·09	0·80	
M1−46	16−1°1	18 25 00	−15 35·2	0·9	0·2	0·11±0·04		
IC 4732	10−6°1	18 30 50	−22 41·3	1·0	0·2	0·10±0·04	0·88	
M1−59	23−2°1	18 40 35	−09 07·2	0·2	−0·5	0·13±0·05	0·95	
IC 4776	2−13°1	18 42 35	−33 27·2	0·2	3·1	0·05±0·03		Dec. uncertain
NGC 6741	33−2°1	19 00 00	−00 28·9	0·7	−0·8	0·35±0·10	1·24	
NGC 6751	29−5°1	19 03 17	−06 03·8	−0·3	−0·5	0·04±0·02	0·20	
M1−67	50+3°1	19 09 21	16 45·0	−1·0	1·3	0·29±0·10	−0·54	
NGC 6778	34−6°1	19 15 51	−01 41·1	−0·2	−0·3	<0·04	<0·6	
NGC 6781	41−2°1	19 16 01	06 25·9	0·5	0·8	0·34(0·32)±0·10	1·19	
NGC 6790	37−6°1	19 20 22	01 25·7	0·8	−1·0	0·16±0·06	0·34	
NGC 6803	46−4°1	19 28 52	09 57·0	0·5	−0·2	0·05±0·03	0·60	Confused
NGC 6804	45−4°1	19 29 17	09 05·7	−1·2	1·2	0·25±0·09	1·08	
NGC 6807	42−6°1	19 32 03	05 30·4	0·9	3·8	0·03±0·03	0·63	Doubtful obs.
NGC 6818	25−17°1	19 41 08	−14 16·6	0·4	0·1	0·33±0·10	0·00	
NGC 6853	60−3°1	19 57 25	22 35·1	0·4	−0·2	1·81(1·21)±0·20	0·17	
NGC 6886	60−7°2	20 10 34	19 50·5	−0·7	−0·1	0·11±0·04	0·97	
NGC 6891	54−12°1	20 12 52	12 33·1	−0·8	−0·3	0·10±0·04	0·09	
IC 4997	58−10°1	20 17 52	16 34·5	0·4	0·3	0·10±0·04	−0·23	
NGC 6905	61−9°1	20 20 07	19 56·2	0·7	0·6	0·04±0·02	−0·12	
NGC 7009	37−34°1	21 01 26	−11 34·3	0·3	0·4	0·78±0·10	0·09	
NGC 7293	36−57°1	22 26 53	−21 06·5	0·6	3·2	1·32(0·57)±0·20	0·00	

* Designation from Perek and Kohoutek (1967).

† NGC 6302 is probably not a true planetary nebula (see Minkowski and Johnson 1967; Oliver and Aller 1969). A few additional recent results are given by Milne *et al.* (1969) and Reifenstein *et al.* (1970).

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