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VLA OBSERVATIONS OF STELLAR PLANETARY NEBULAE[1]

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ABSTRACT

Coordinates, dimensions, 4885 MHz flux densities, and brightness temperatures of K3-2, NGC 6833, Ps 1, II 5117, Me 2-2, Hb 12, Vy 1-1, and M1-5 are reported. In two other cases, H3-29 and H3-75, confused, extended structure was detected in which the nebula could not be identified with certainty. He 2-467, M1-2, and Peterson's Hα object in M15 were also included in the observations but not detected with an upper limit of less than 10 mJy. The observations are compared with some of the previous optical and radio data, such as log $S(\mathrm{H}\beta)$. Distances are computed from the present data with standard assumptions. Corresponding linear radii range below 0.1 pc, among the smallest in previous distributions of radius.

Subject headings: interferometry — nebulae: planetary — radio sources: general

I. INTRODUCTION

The so-called stellar planetary nebulae (PN) may be expected to look like stars when a visual examination is made of the telescopic or photographic images. If no mention of angular extent is made in the *Catalogue of Galactic Planetary Nebulae* (Perek and Kohoutek 1967) or in subsequent work, one may assume that a nebula has never been resolved. But it is well known that the photographic or visual image of a slightly extended object may closely resemble the image of a slightly fainter star, especially at magnitudes too faint to reveal diffraction phenomena or in poor seeing. The VLA is capable of significantly improving the degree of resolution with which many PN have been examined.

Many PN have been cataloged with very rough coordinates. In some cases these have been too inaccurate to center the PN well enough in the beam of a single-dish radio telescope to obtain an accurate flux density (cf. Milne 1973). We have used the NRAO overlay program with the National Geographic–Palomar Observatory Sky Atlas to check all of the PN coordinates used in our VLA survey so as to be sure that the $64'' \times 64''$ synthesized fields of 128×128 cells contain the images identified on Perek and Kohoutek's (1967) finder charts. When the object has been detected on the VLA synthesized map, it gives coordinates that are accurate to the order of $\pm 1''$. Thus we report improved coordinates for several stellar PN.

The VLA is a very sensitive detector of PN that subtend solid angles comparable with or smaller than the synthesized half-power beamwidth (HPBW). The Higgs (1971) catalog compiled no satisfactory radio data for the objects which we report here, but we can relate our data to certain other observations. Aside from the good match of stellar PN to the data-taking capabilities of the VLA, an astrophysical motive for observing them is to examine the argument that, since PN expand, really small ones are exceptionally young, and angularly small PN are likely to be linearly small. Johnson (1977) has shown that the internal kinematics of a sample of stellar PN are not very distinguishable from the internal kinematics of more typically extended PN. This is quite different from the kinematics of HM Sge (Wallerstein 1978), an object which has been discussed as a very young planetary nebula, e.g., by Kwok and Purton (1979). The rich ultraviolet emission-line spectrum of HM Sge (Boggess 1978) is also quite different from the rather featureless ultraviolet continuum observed with the *IUE* satellite by one of us (H. M. J.) in Hb 12 and Vy 1-1. We open the question whether many stellar PN may not be young, but rather relatively old, having lost most of their original envelopes. Some slightly extended, and supposedly highly evolved, PN have been observed as infrared continuum sources (Cohen and Barlow 1974) and optical emission-line sources (Bond 1979).

II. VLA OBSERVATIONS

A subarray of up to 12 available elements of the VLA was used in generally good conditions for 6 hours on 1978 August 18 and for 11 hours on August 19 to observe 12 candidate stellar PN in the 4885 MHz continuum with 50 MHz bandwidth. The allotted

[1] The Very Large Array of the National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

observing time was distributed in alternate integrations of 5 minutes on NRAO standard calibrators and 15 minutes on PN, less slew time. The calibrators were 3C 138, 3C 286, P2134+00, BL Lac, and DA 611. These were chosen to be as near as possible to the nebulae. The antenna elevations were always greater than 10°, and the sequence of sources approximately maximizes (u, v)-plane coverage. Any given source was observed typically once per hour as many times as possible on either day. The nebulae actually observed were selected mostly to accommodate observing constraints from a much larger set of candidate stellar PN. In one field, that of Peterson's (1976) Hα object at the center of the globular cluster M15, another PN is known, Ps 1 or K648, and was detected. In two cases, H3-29 and H3-75, the synthesized field showed extended structure with dimensions of 10″ or more, which could not be interpreted in terms of a single brightness maximum. The (u, v)-plane coverage was also very narrow in these two cases, resulting in extensive sidelobes in the beam. The positions of maximum brightness and the maximum fringe amplitudes are quoted, but the designated nebulae could not be positively identified, and no conclusions can be drawn from the observations.

Standard programs developed by NRAO for reducing the raw data to synthesized maps, fringe visibilities, etc., were used at the VLA site. Badly behaved data, such as those containing large phase jumps, were deleted appropriately. We have condensed the results into the following information.

a) *Coordinates*

Except for Peterson's (1976) object, Table 1 lists the PN according to the Perek and Kohoutek (1967) catalog number and name, the coordinates of the peak of the VLA synthesized image precessed to 1950, the deviations of these coordinates from the reference coordinates, and the origin of the reference coordinates. The absolute proper motions of NGC 6833 and II 5117 amount to 0″.3 and 0″.5, respectively, in 28 years according to Cudworth (1974), but Table 1 does not include any proper-motion data. These reference coordinates were used to point the VLA and give the map center, except for Ps 1 which was located in a map centered on Peterson's object. Since Peterson reproduced his discovery plate without giving coordinates of the Hα object at the center of M15, we estimated them to be $\alpha = 21^h27^m34^s.0$, $\delta = +11°56''48''.0$ (1950). We comment that the M15 X-ray source (Bradt, Doxsey, and Jernigan 1979), the emission-line star Rosino No. 86 (Ford *et al.* 1978), and Peterson's Hα object do not appear in the map within their coordinate-error areas at an rms noise level around ± 1 mJy.

b) *Flux Densities*

The fringe amplitude data were calibrated by comparison with corresponding data from the calibration sources. Two methods were used to determine the flux densities of the PN. In method I the calibrated fringe amplitudes, averaged over 10 minute observing scans, were plotted as a function of w_λ, the projected antenna spacing: $w_\lambda = (u^2 + v^2)^{1/2}$. The spacings for which observations were available were generally between 2000 and 200,000 wavelengths. The curve was then extrapolated to zero spacing to estimate the unresolved fringe amplitude. In method II the flux density was determined from the map that was obtained for each nebula. To do this it is necessary to determine the ratio of the radio brightness integrated over the nebula to the corresponding quantity for a point source of unit flux density. The rather incomplete (u, v) coverage resulted in extensive sidelobes on the synthesized beam which made it impractical to derive the abovementioned ratio directly. As an approximation to it, the ratio of the areas of the nebular response and the beam, each at the half-power level, was used. The flux density values obtained by the two methods are given in Table 2. For the narrower nebulae the agreement is good, but becomes worse as the degree of resolution of the nebula at the shortest spacings increases. This reflects the fact that in these latter cases data are missing, and any attempts to compensate for this are of limited accuracy.

TABLE 1

REFERENCE COORDINATES AND OBSERVED VLA COORDINATES OF PLANETARY NEBULAE

Catalog	Name	α_{ref}	(1950)	δ_{ref}	(1950)	$\alpha_{VLA} - \alpha_{ref}$	$\delta_{VLA} - \delta_{ref}$	(s) α_{VLA}	(″) δ_{VLA}	Origin of Reference Coordinates
28+5°1....	K3-2	18^h22^m	$25^s.1$	−01°32′	34″	−2″.0	−1″.5	$25^s.0$	32″.5	Kohoutek 1965
82+11°1...	NGC 6833	19 48	20.9	+48 50	01	−0.5	0.0	20.9	01.0	Perek and Kohoutek 1967
63−12°1...	He 2-467	20 33	42.6	+20 01	07	...	...	Not detected		Milne 1976
65−27°1...	Ps 1	21 27	34.52	+11 57	16.2	−2.4	−1.7	34.4	14.5	Klemola 1979[a]
89−5°1....	II 5117	21 30	36.8	+44 22	29	−0.5	−0.5	36.8	28.5	Perek and Kohoutek 1967
100−8°1....	Me 2-2	22 29	36.4	+47 32	46	+13.5	−9.0	37.7	37.0	Perek and Kohoutek 1967
111−2°1....	Hb 12	23 23	57.2	+57 54	24	+1.0	+0.5	57.3	24.5	Perek and Kohoutek 1967
118−8°1....	Vy 1-1	00 16	01.5	+53 35	41	0.0	−0.5	01.5	40.5	Perek and Kohoutek 1967
133−8°1....	M1-2	01 55	32.9	+52 39	15	...	...	Not detected		Perek and Kohoutek 1967
174−14°1...	H3-29	04 34	20.2	+24 57	00	+3.5[b]	−12.5[b]	...	...	Milne 1973
193−9°1....	H3-75	05 37	56.1	+12 19	47	+9.5[b]	+9.0[b]	...	...	Milne 1973
184−2°1....	M1-5	05 43	46.1	+24 20	59	−1.0	+1.5	46.0	00.5	Perek and Kohoutek 1967

[a] Misprint in Klemola (1979) gives declination incorrectly as +11°54′16″.2.

[b] Field confused and designated nebula not positively identified. Position given refers to point of maximum brightness.

TABLE 2

PLANETARY NEBULAE FLUX DENSITIES FROM VLA AND PREVIOUS RADIO DATA

	VLA			PREVIOUS		
NAME (1)	Method I (mJy) (2)	Method II (mJy) (3)	Mean (mJy) (4)	$S(\nu)$ (mJy) (5)	ν (GHz) (6)	Reference (7)
K3-2	38	40	39 ± 3			
NGC 6833	25	28	26 ± 3			
He 2-467	Not detected		< 10			
Ps 1	20	13	16 ± 4	4.4 3.3	2.7 8.1	Johnson 1976
Peterson	Not detected		< 3			
II 5117	184	213	198 ± 15			
Me 2-2	42	64	53 ± 11			
Hb 12[a]	43[a] 15[a] } 58	70	64 ± 6	27 79 123 181	2.7 8.1 10.6 22.2	Marsh, Purton, and Feldman 1976
Vy 1-1	28	58	43 ± 15			
M 1-2	Not detected		< 10			
H3-29	20[b]		20[b]			
H3-75	15[b]		15[b]			
M1-5	76	102	89 ± 13			

[a] Upper entry "core" component; lower, "halo" component.

[b] Field confused and designated nebula not positively identified. Value given refers to maximum fringe amplitude.

As a best estimate of the flux densities of the nebulae, the means of the values obtained by the two methods are given in column (4) of Table 2. The quoted errors are based on the scatter of the plotted fringe amplitude values or the difference in the results of methods I and II.

Table 2 continues with post-Higgs (1971) observations of flux density $S(\nu)$ at frequency ν, quoted from the reference in the final column.

c) *Angular Dimensions*

The degree of resolution of the present PN observations is not sufficient to avoid arbitrary modeling in the results to determine angular dimensions. However, plots of the maximum fringe amplitude on the (u, v)-plane suggest no evidence of noncircular asymmetry in NGC 6833, II 5117, Me 2-2, Hb 12, and Vy 1-1, all of which were observed over a significant range of position angles. The models we have used are a circularly symmetric uniform disk and a thin ring, each of angular diameter θ. For the disk model the fringe visibility $V(w_\lambda) = [2J_1(\pi w_\lambda \theta)/\pi w_\lambda \theta]$, and θ can be estimated from $w_{\lambda 0.5}$, the spacing in wavelengths at which $V(w_\lambda) = 0.5$, by $\theta = 1.45 \times 10^5 w_{\lambda 0.5}{}^{-1}$ arcseconds. Similarly, for the ring model $V(w_\lambda) = J_0(\pi w_\lambda \theta)$, and $\theta = 9.99 \times 10^4 w_{\lambda 0.5}{}^{-1}$ arcseconds. These well-known relationships may be found in Bracewell (1965) and Balick and Terzian (1976). Table 3 summarizes the results for the above parameters derived from computer-plotted fringe visibilities, $V(w_\lambda)$. We note that the shape of the $V(w_\lambda)$ function is nearly linear, which is more nearly consistent with a thick ring than with a thin ring or uniform disk. Previous information is also cited in Table 3.

d) *Brightness Temperature and Other Parameters*

The uniform disk model can also be used to estimate the brightness temperature T_b, since the flux density per steradian is $2kT_b\lambda^{-2}$, where k is Boltzmann's constant and λ is the wavelength. For a frequency of 4885 MHz and an assumed electron temperature $T_e = 10^4$ K, $T_b = 74S\theta^{-2}$, where the flux density S is given in mJy units and θ is given in arcseconds. Values of T_b are given in Table 4, based on the results in Table 3. The brightness temperature can provide an estimate of the mean emission measure over a nebula since $T_b = T_e[1 - \exp(-\tau)]$, where τ is the optical depth. The emission measure can be derived from τ by means of the usual formulae for free-free emission, summarized, for example, by Thompson (1974). In units of cm^{-6} pc emission measure is $-8.6 \times 10^7 \ln(1 - 10^{-4}T_b)$, again for a frequency of 4885 MHz and $T_e = 10^4$ K. Column (3) of Table 4 gives emission measures derived in this manner.

The emission measure provides an indicator of the degree of expansion of a nebula. Mean values of emission measure for well-known PN are given by Terzian and Dickey (1973), and peak values by Terzian, Balick, and Bignell (1974). The emission measures in Table 4 correspond to the mean over the solid angle of the disk model that we use, and they should be roughly comparable with values intermediate between two cases which are considered by Terzian and Dickey. The highest emission measure in Table 4, that for II 5117, is at least twice that of NGC 7027. Lower values, of the order of 10^6 cm^{-6} pc, are more nearly comparable to that of NGC 7662, for example, In at least one case, that of Hb 12, the situation is not so simple. The emission measure of

TABLE 3

PLANETARY NEBULA DIMENSIONS FROM VLA AND PREVIOUS DATA

Name	VLA $w_{\lambda 0.5}$ (wavelengths)	VLA Disk θ (″)	VLA Ring θ (″)	Previous Diameter	Previous Criterion	Previous Reference
K3-2	4.7×10^4	3.1	2.1	Stellar	Direct photograph	Kohoutek 1965
NGC 6833	1.9×10^5	0.74	0.51	Stellar	Pg spectrum	Kaler, Aller, and Czyzak 1976
Ps 1	4.2×10^4	3.5	2.4	1″.0	Visual	O'Dell, Peimbert, and Kinman 1964
II 5117	1.1×10^5	1.3	0.91	...	...	...
Me 2-2	1.0×10^5	1.4	0.96	Stellar	Visual	Merrill 1941
Hb 12[a]	1.9×10^5 / 2.1×10^4	0.8 / 6.9	0.53 / 4.8	$\lesssim 1''$	Radio interf.	Marsh, Purton, and Feldman 1976
Vy 1-1	2.3×10^4	6.2	4.3	...	...	...
H3-29	...	...	...	20″	Disk unlike stellar images on Palomar Schmidt print	
H3-75	...	...	...	20″–27″	Uniform disk on Palomar Schmidt print	
M1-5	6.4×10^4	2.3	1.6	...	...	...

[a] Upper entry "core" component; lower, "halo" component.

7.7×10^7 in Table 4 corresponds to a turnover frequency of 3–4 GHz in the spectrum (Terzian and Dickey 1973), whereas the flux density values of Marsh, Purton, and Feldman (1976) in Table 2 show that the spectrum is still increasing up to 22 GHz. Evidently our analysis based on a uniform disk model is invalid in this case. Marsh, Purton, and Feldman found two other cases of stellar PN, HD 167362 (1−6°2) and Vy 2-2 (45−2°1) which similarly exhibit steeply rising spectra above 10 GHz. Wright and Barlow (1975), Panagia and Felli (1975), Olnon (1975), and Marsh (1975) have discussed the production of such spectra. The core-halo structure derived for Hb 12 suggests a possible $n_e \propto r^{-2}$ law of electron density n_e as a function of nebular radius r which has been derived for objects which exhibit an approximately +2/3 spectral index. As further evidence of high electron densities, Aurière, Laques, and Leroy's (1978) failure to detect Peterson's (1976) Hα object in [O III] λλ4959–5007 suggests that the object is of too high density for the forbidden radiation, if not too low in ionization. In the case of II 5117 a further measurement at 15.035 GHz by one of us (A. R. T.) with the VLA gives a flux density of 0.2 ± 0.01 Jy, so for this nebula the spectrum appears to flatten off at high frequencies like a typical PN.

If the objects of Table 4 are optically thin at 6 cm, it is possible to predict Hβ flux densities, compare the predictions with observed values, and deduce the extinctions at Hβ (λ4861). We quote log S(Hβ) values from Perek and Kohoutek (1967) in Table 4 and give the predicted 6 cm continuum flux densities. For Ps 1, log S(Hβ) is from O'Dell, Peimbert, and Kinman (1964). The numerical relation is $S(4885\ \text{MHz}) = 2.97 \times 10^{-14} S(\text{H}\beta)s$ for an electron temperature of 10^4 K (Thompson 1974). The fifth column of Table 4 shows that M1-2 should have been detectable with the VLA. II 5117 appears to be heavily obscured at Hβ by dust, and the remaining PN are moderately obscured. It is also possible, although rather unlikely, that the differences between the predicted and observed flux densities could result from high optical depth at 6 cm wavelength. This is the indeterminateness in the prediction of extinction from Hβ.

In the last two columns of Table 4 we have applied Milne and Aller's (1975) formula for radio distance

TABLE 4

ADDITIONAL PARAMETERS DERIVED FROM VLA AND OPTICAL DATA

Name (1)	VLA T_b (K) (2)	Emission Measure cm^{-6} pc ($T_e = 10^4$ K) (3)	log S(Hβ) (cgs) (4)	Predicted S (mJy) (5)	Predicted $S(\nu)$ / Observed $S(\nu)$ (ν = 4885 MHz) (6)	Radio Distance (kpc) (7)	Disk Model Radius (pc) (8)
K3-2	300	2.6×10^6	...	...	...	9.1	0.07
NGC 6833	3500	3.7×10^7	−11.22	18	0.69	23	0.04
Ps 1	100	8.6×10^5	−11.93	3.5	0.22	10	0.09
II 5117	8300	1.5×10^8	−11.71	5.8	0.029	11	0.04
Me 2-2	2000	1.9×10^7	...	...	...	14	0.05
Hb 12[a]	5900 / 26	7.7×10^7 / 2.2×10^5	−10.96	33	0.52	6.7	0.013 / 0.11
Vy 1-1	80	6.9×10^5	−11.49	9.6	0.22	5.9	0.09
M1-2	...	...	−11.21	18	>1.8	...	...
M1-5	1200	1.1×10^7	...	...	...	9.2	0.05

[a] Upper entry "core" component; lower, "halo" component.

based on the assumption of a constant nebular mass (specifically 0.16 $M_\odot$) radiating as a gas that is optically thin at 6 cm and with the following parameters: electron temperature = 10^4 K, fraction of the nebula volume filled with radiating gas = 0.6, number abundance ratio of He/H = 0.11, and fraction of doubly ionized helium atoms = 0.5. (In Milne and Aller the radius rather than diameter is called θ.) The uniform disk model for the derivation of angular diameters leads to the use of a cylindrical model with an axial length equal to 4/3 of its radius so that its volume equals the volume of a sphere of the same radius. The assumption of optical thinness gives an upper limit on distance and linear radius for nebulae that are actually optically thick.

Arp (1965) gives the independent distance of M15, the globular cluster in which Ps 1 occurs, as 10.5 kpc. In order to achieve a consistent distance for the "core" and "halo" of Hb 12, the ratio of the masses is made a free parameter. By keeping the sum equal to 0.16 $M_\odot$, the mass of the core is 0.010 $M_\odot$ and its mean density is 43 times the mean density of the halo. The high T_b found for II 5117 suggests that the tabulated distance and radius may be upper limits for it. The linear radii of the sample of Table 4 fall in a narrow range which starts somewhat below the lower limit of the radii of more general samples of PN that have been discussed by O'Dell (1962), Seaton (1966), and Cahn and Kaler (1971). Those discussions are based on models of PN that are optically thin in the Lyman continuum.

e) *Further Notes on Selected Objects*

The failure to detect He 2-467 and M1-2 with the VLA may be correlated with an optical peculiarity of these two objects that is not known to be present in the other objects that have been observed with the VLA. Lutz *et al.* (1976) have observed a G-type stellar spectrum with the recombination spectrum of He 2-467, and O'Dell (1966) and others have observed a G2 supergiant spectrum in M1-2 (sometimes known as VV 8). M1-2 is unresolved to a diameter of less than 0″.5 (Perek and Kohoutek 1967), and He 2-467 is also "stellar" according to Lutz (1977). Radio detection selects against sufficiently dense and optically thick PN.

Extensive but inconclusive discussions of the optical spectra of one or both of these objects are given by Arkhipova, Noskova, and Gapborov (1974), Zipoy (1975), Adams (1975), and Lutz (1977). He 2-467 is sufficiently dense so as not to show either forbidden-line radiation or detectable radio flux density.

Bond (1976) identifies H3-29 with GL Tau, and suggests that it is probably a nebular variable rather than a true PN. The star is classified "Ins?" in the *General Catalogue of Variable Stars* (Kukarkin *et al.* 1969), where Hα emission and a small emission nebula with bright N_1, N_2 lines are noted.

III. CONCLUSIONS

We have observed a very incomplete sample of so-called stellar PN, i.e., about a dozen among several times as many that are not noted as optically resolved by Perek and Kohoutek (1967). The present results suggest that the objects are near the minimum of the range of linear radii of well-known PN, and not apparently small merely on account of great distance. Hb 12 has a spectrum and structure consistent with a high central-emission measure and monotonic decrease in electron density with radius. Measurements at other frequencies are required to extend these conclusions to other PN. Whether any of the stellar PN are remnants of old nebulae, as suggested in § I, cannot presently be determined. Distances and radii of such remnants would be greatly overestimated because we have assumed that the objects have average PN masses. For predicted distances of several kiloparsecs, there is some hope of being able, in the future, to examine the spectra at 21 cm for expected galactic absorption features, and thereby test such a mass-distance assumption. Nondetection of certain objects in a larger sample would suggest the need of further tests for combination spectra, i.e., the presence of a cool stellar spectrum with the nebular emissions. Stellar PN are inhomogeneous even in our limited sample. The optical data for our sample appear to us to be insufficient to proceed to any evolutionary scheme for them. Theoretical study is needed to predict the circumstellar structures of newly ejected envelopes and nearly exhausted envelopes; further VLA observations are needed to enlarge the sample and to investigate the structures in greater detail.

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