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RADIO OBSERVATIONS OF COMPACT PLANETARY NEBULAE

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ABSTRACT

An attempt has been made to identify very young planetary nebulae from radio observations. Details of the observations at the Algonquin Radio Observatory and the Very Large Array are presented. Four nebulae which were previously designated as stellar are resolved using aperture synthesis techniques with angular resolution as high as 0."2. Two of the observed nebulae, SwSt-1 and M 3-38, exhibit characteristics expected of very young planetary nebulae. These two nebulae are compared to other planetary nebulae which are believed to be young, and the possibility that young planetary nebulae may have different spectral behavior in the radio is discussed.

Subject headings: nebulae: planetary — radio sources: general

I. INTRODUCTION

The mechanism by which planetary nebulae are formed is not well understood. In order to distinguish between different theories (e.g., wind versus sudden ejection), it is necessary to identify and study planetary nebulae that are still at the early stages of formation. Young planetary nebulae are expected to have the following characteristics:

1. *Small angular sizes.* The linear size of planetary nebulae is expected to be proportional to the age of the nebulae. Although the linear size is not directly measurable, the angular size can be determined from optical images. A large fraction of the planetary nebulae, e.g., in the catalog of Perek and Kohoutek (1967), remain unresolved to the resolution limit of several arc seconds. Modern techniques of radio aperture synthesis can achieve extremely high angular resolution, and, in some cases, surpass those of optical telescopes. This opens the possibility of investigating very compact (and presumably younger) planetary nebulae which were previously unresolved. The selection criteria based on angular size is, however, distance dependent and therefore quantitatively imprecise.

2. *High electron density.* The average electron density in the nebular shell is expected to decay as $t^{-\beta}$, where the value of β is dependent on the model of planetary nebulae evolution. In the conventional sudden-ejection model, $\beta = 3$, and, in the interacting-winds model of Kwok, Purton, and FitzGerald (1978), $\beta = 2$. In the optical region, there exist several emission-line ratios which are sensitive to electron densities. Results obtained by such methods are generally consistent to within a factor of 10. However, it is well known that optical emission lines are sensitive to local density fluctuations and, therefore, the derived density may not be a very reliable indicator of age.

3. *High emission measure.* Mean emission measures derived from radio observations represent an averaged property of the ionized region and may be a better indicator of the overall density structure of planetary nebulae. Furthermore, the emission measure having a time dependence of $t^{-\gamma}$ (where $\gamma = 2\beta - 1 = 3$ and 5 for the interacting-winds model and sudden-ejection model respectively) is more age sensitive. There are two well-known methods of estimating the emission measure (cf. Terzian and Dickey 1973):

   a) *From the critical frequency.* For most of the planetary nebulae observed to date, the critical frequencies are found to be less than 5 GHz, and the derived emission measures less than 10^8 cm^{-6} pc. Planetary nebulae with higher critical frequencies (and therefore higher emission measures) can, in principle, be discovered by observing at higher frequencies.

   b) *From the optically thin flux density and the angular size.* The current angular resolution limits of optical photographs are usually not good enough to allow identification of nebulae with high emission measure. In this respect, the technique of aperture synthesis is particularly useful.

In this paper, we report our search and study for planetary nebulae with the above characteristics, using a sample of planetary nebulae chosen for their optical stellar appearance.

II. OBSERVATIONS

We have surveyed 40 stellar planetary nebulae selected from the catalog of Perek and Kohoutek (1967). Positions were taken from Milne (1973, 1976). Observations were made in 1979 at the Algonquin Radio Observatory[1]

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[1] The Algonquin Radio Observatory is operated by the National Research Council of Canada, Ottawa, as a national radio astronomy facility.

TABLE 1

FLUX DENSITIES OF COMPACT PLANETARY NEBULAE

PK Catalog No., Name	$S_{5\,\mathrm{GHz}}$ (mJy)	$S_{10.6\,\mathrm{GHz}}$ (mJy)	Optical Size (arcsec)	N_e (10^4 cm^{-3})	Comments
118 − 8°1, Vy 1–1	43 ± 15[a]	14 ± 11	...	...	...
133 − 8°1, VV 8		-1 ± 7	<0.5[j]	>10[b] >1000[c,d]	...
193 − 9°1, H3–75	<15[a] 24 ± 8[e]	3 ± 6	...	...	confused[a]
184 − 2°1, M 1–5	89 ± 13[a]	75 ± 4	...	2.8 ± 0.3[b]	...
211 − 3°1, M 1–6	100 ± 13[e]	86 ± 10	<5[j]	1.9[f]	low excitation[f]
212 + 4°1, M 1–9	36 ± 12[g]	30 ± 5	...	1.6[h]	moderate excitation[h]
234 − 0°1, M 1–15	...	46 ± 12	<1[j]	...	confused
226 + 5°1, M 1–16	28 ± 5[e] 30 ± 8[g]	28 ± 4	3[j]	0.8[h]	moderate excitation[h]
228 + 5°1, M 1–17	25 ± 11[g]	26 ± 7	3[j]	1.5[h]	moderate excitation[h]
353 + 8°1, MyCn 26	16 ± 10[e]	6 ± 6	<5[j]	...	...
018 + 20°1, Na 1	<15[e]	21 ± 3	...	1.1[h]	moderate excitation[h]
356 + 4°1, M 2–11	16 ± 10[e]	21 ± 6	<10[j]	...	...
356 + 4°2, M 3–38	20 ± 10[e]	36 ± 10	<25[j]	...	...
358 + 5°2, M 3–40	30 ± 10[e]	11 ± 6	<10[j]	...	...
358 + 3°1, M 3–10	20 ± 15[e]	41 ± 8	3.5[j]	...	confirmed PN[i]
357 + 2°1, Ap 1–1	<12[e]	-12 ± 3	<9[j]	...	...
358 + 3°6, H1–20	49 ± 8[e]	22 ± 4	4.5[j]	...	...
000 − 2°1, Bl 3–13	10 ± 5[e]	-8 ± 16	...	...	confirmed PN[i]
000 − 2°4, M 2–21	...	35 ± 19	<10[j]	...	...
358 − 4°1, H1–46	40 ± 10[e]	35 ± 4	<10[j]	...	...
000 − 2°2, M 3–20	40 ± 10[e]	26 ± 5	...	...	confused, confirmed PN[i]
008 − 1°1, M 1–40	...	185 ± 4	<5[j]	...	...
003 − 4°1, Ap 1–10	<10[e]	-15 ± 16	<10[j]	...	...
001 − 6°2, SwSt-1	...	171 ± 20[k]	<2[l]	...	...
002 − 6°2, H1–63	20 ± 10[e]	-3 ± 22	<5[j]	...	...
008 − 4°1, M 2–39	8 ± 5[e]	9 ± 33	3.3[j]	...	...
007 − 6°2, Vy 2–1	40 ± 10[e]	29 ± 4	<7[j]	...	...
028 + 5°1, K3-2	39 ± 3[a]	32 ± 5	...	...	...
043 + 11°1, M 3–27	...	4 ± 5	...	>10[b] 400[c] 200[d]	
032 + 5°1, K3-4	21 ± 5[e]	15 ± 4	12.5[j]	...	...
010 − 6°1, IC 4732	56 ± 10[g]	50 ± 33	3[j]	...	...
016 − 4°2, M 1–56	23 ± 10[e]	-19 ± 11	<10[j]	...	...
003 − 17°1, Hb 8	8 ± 7[e]	12 ± 12	<5[j]	...	...
027 − 9°1, IC 4846	50 ± 9[g]	45 ± 7	...	1.2 ± 0.5[b]	...
042 − 6°1, NGC 6807	22 ± 7[g]	31 ± 5	...	...	...
082 + 11°1, NGC 6833	26 ± 3[a]	18 ± 2	Stellar	8.5 ± 1.5[b]	...
071 − 2°1, M 3–35	...	169 ± 28	<5[j]	8 ± 3[b] 2.0[f]	moderate excitation
065 − 27°1, K648	16 ± 4[a]	16 ± 5	1[j]	0.26 ± 0.06[h]	...
089 − 5°1, II 5117	198 ± 15[a]	238 ± 5	...	...	...
100 − 8°1, Me 2–2	53 ± 11[a]	40 ± 3	...	1.8 ± 1[b]	...

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[a] 4.9 GHz, Johnson, Balick, and Thompson 1979.
[b] Barker 1978.
[c] Adams 1975.
[d] Ahern 1978.
[e] Milne 1979.
[f] Kondrat'eva 1979.
[g] Milne and Aller 1975.
[h] Kondrat'eva 1978.
[i] Allen 1979.
[j] Perek and Kohoutek 1967.
[k] Purton *et al.* 1981.
[l] Westerlund and Henize 1967.

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(ARO) at 10.6 GHz. The low flux levels of most objects made scanning impractical, and the method of wagging (where main and reference beams are alternately pointed at the source for periods of 20–30 s) was used. Because most of the sources are near the galactic plane, the inclusion of confusing sources in our 2'.7 beam was a distinct possibility. In cases of doubt, simple 5 point maps were made to sort out possible background confusion.

From the above planetary nebulae, we have selected six, plus HBV 475 (which has been suggested as a possible protoplanetary nebula), for observation at VLA[2] on 1980 March 24. Observations were made using a subarray of up to 22 antennas at 4.885 GHz and up to 18 antennas at 15.035 GHz under good conditions. The maximum baseline was ~ 23 km, providing a resolution of ~ 0".5 and ~ 0".2 at 5 and 15 GHz respectively. Standard NRAO calibrators were observed between ON source observations of ~ 5 minutes. To optimize the (u, v) coverage, each source was observed four times at different hour angles. The data were edited until satisfactory phase and amplitude closure on the calibrators were obtained.

The calibrated visibility data were then transformed to a map, which was subjected to the CLEANing process. The best-fit elliptical Gaussian components were then found, both from the CLEANed map, and in the transform domain using the calibrated visibility data. Flux densities, positions, and angular sizes were derived from the results of these fittings. Estimates of the flux densities were also obtained from the summation of the CLEANed components. Since all our objects are small in angular size, maps of low resolution were also made so that the integrated flux can be inferred from the peak flux values as well. In one case (SwSt-1), the flux density was high enough to use the "self-calibration" procedure, in which the externally calibrated data are used as a model to predict the phase observed by each antenna at each time interval. The data are adjusted for several iterations until optimal agreement between model and observed values is obtained.

III. CALCULATION OF EMISSION MEASURES

Results of our ARO measurements at 10.6 GHz are given in Table 1, together with 5 GHz measurements previously published by Milne and Aller (1975), Milne (1979), and Johnson, Balick, and Thompson (1979). Comparing the flux densities at two frequencies, we find most nebulae to be optically thin above 5 GHz. An upper limit to the emission measure can be obtained from equation (6) of Terzian and Dickey (1973):

$$\langle E \rangle_I = \frac{\nu_c{}^2 T_e{}^{3/2}}{\zeta(\nu_c)} ,$$

where ν_c is the critical frequency in MHz, T_e is the electron temperature (assumed to be 10^4 K), and $\zeta = 9.776 \times 10^{-15} \ln (49.5 T_e{}^{3/2}/\nu)$. For most sources, $\nu_c < 5$ GHz, i.e. $\langle E \rangle_{\rm I} < 9 \times 10^7 \text{ cm}^{-6}$ pc, with possible exceptions of SwSt-1, M 3–10, M 3–38, and Na 1. These objects were followed up by observations at the VLA.

In Table 1, optical angular sizes and electron density are also listed wherever information is available in the literature. If the electron density is used as a criterion for the selection of young planetary nebulae, there are only three objects given in Table 1 with densities $> 10^5 \text{ cm}^{-3}$. Two of these (VV 8, M 3–27) were below the detection limit of ARO, and the third (NGC 6833) was found to be optically thin at 5 GHz.

Some objects (e.g., H 1–20) seem to have a negative spectral index; this could be the result of poor signal-to-noise or the presence of confusion.

For objects observed at the VLA, the emission measures were estimated using both methods: ν_c was used to derive $\langle E \rangle_{\rm I}$ as outlined above; and another estimate ($\langle E \rangle_{\rm II}$) was obtained from the flux density (S_ν) and the measured angular size (θ),

$$\langle E \rangle_{\rm II} = \frac{\int E(\theta, \phi) d\Omega}{\Omega} \quad \text{(Terzian and Dickey 1973)}$$

$$= \frac{6.3 \times 10^{-7} S_\nu T_e{}^{1/2}}{\zeta \theta^2} \text{ cm}^{-6} \text{ pc} ,$$

where S_ν and θ are in units of janskys and arc seconds respectively. Results are given in Table 2.

TABLE 2

VLA OBSERVATIONS OF POSITIONS, FLUX DENSITIES, AND ANGULAR SIZES OF PLANETARY NEBULAE

Name	$\alpha_{\rm VLA}$ (1950)	$\delta_{\rm VLA}$ (1950)	$S_{4.885 \rm GHz}$ (mJy)	$S_{15.035 \rm GHz}$ (mJy)	Angular Diameter (arcsec)	$\langle E \rangle_{\rm I}$[a] (cm^{-6} pc)	$\langle E \rangle_{\rm II}$[b] (cm^{-6} pc)
Na 1	17h10m14s.43	−03°12'29".0	23 ± 1	<25	5	$<9 \times 10^7$	4×10^5
M 3–38	17 17 54.20	−29 00 03.4	25 ± 2[c], 15 ± 1[d]	34 ± 5[c], 26 ± 4[d]	<0.3[d], ~10[e]	$>9 \times 10^7$ [d]	2×10^8 [d], 7×10^4 [e]
M 3–10	17 24 10.61	−28 25 22.0	44 ± 1	38 ± 5	1.2	$<9 \times 10^7$	2×10^7
SwSt-1	18 12 58.64	−30 53 11.8	130 ± 3	207 ± 11	0.8	2×10^8	2×10^8

[a] $\langle E \rangle_{\rm I}$ determined from ν_c.

[b] $\langle E \rangle_{\rm II}$ determined from S_ν and θ.

[c] Core and halo.

[d] Core only.

[e] Halo only.

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

TABLE 3

NONDETECTIONS AT THE VLA

Name	α (1950)	δ (1950)	$S_{4.885\,\mathrm{GHz}}$ (mJy)	$S_{15.035\,\mathrm{GHz}}$ (mJy)
VV 8	$01^{\mathrm{h}}55^{\mathrm{m}}32^{\mathrm{s}}.9$	$+52°39'15''$	<0.5	...
M 1-15	07 29 37.1	-19 21 04	<2	<22
HBV 475 ...	20 49 02.6	$+35$ 23 37	<1	...

Three of the objects we observed at the VLA were not detected, and their upper limits are given in Table 3. The single dish measurement of M 1-15 was probably affected by confusion.

IV. INDIVIDUAL OBJECTS

a) M 3-10 (PK 358+3°1)

M 3-10 has been confirmed as a planetary nebula, based on the criteria of no observed continuum and strong HβN [O III] (Allen 1979). The spectrum is optically thin above 5 GHz. Figures 1*a* and 1*b* show the λ6 cm and λ2 cm maps of M 3-10 respectively. The nebula is clearly resolved with a measured angular diameter of $\sim 1''.2$.

b) SwSt-1 (HD 167362, PK 1−6°2)

SwSt-1 is a compact planetary nebula with a very low excitation spectrum and has a nucleus of a spectral type between Wolf-Rayet and Of (Smith and Aller 1969). Figures 2*a* and 2*b* show the VLA maps of SwSt-1 at λ6 cm and λ2 cm after self-calibration. The angular size obtained from model-fitting to the visibility data is $0''.8$, and the λ6 cm visibility curve, shown in Figure 3, confirms that the nebula is actually resolved. In Figure 4, we have plotted the spectrum of SwSt-1, combining data obtained at the VLA, the ARO, and the NRAO 3 element interferometer. The spectrum is optically thick up to $\nu = 8$ GHz, indicating an emission measure ($\langle E\rangle_{\mathrm{I}}$) of 2×10^{8} cm^{-6} pc, in agreement with the value estimated from the angular size ($\langle E\rangle_{\mathrm{II}}$). The spectral index in the optically thick regime is $\sim +1$. This adds one more planetary nebula to the very limited list of planetary nebulae where data exist for the optically thick part of the radio spectrum.

SwSt-1 is also one of the three compact planetary nebulae found to have 9.7 μm silicate dust emission (Aitken *et al.* 1979). This indicates that SwSt-1 has an oxygen envelope in spite of its carbon-rich nucleus. It has been suggested by Kwok (1980) that the 9.7 μm silicate feature, arising from the remnant circumstellar envelope of the red giant progenitor, should only be observable in young planetary nebulae. The small angular size and high emission measure of SwSt-1 are consistent with this suggestion.

c) Na 1 (PK 018+20°1)

Na 1 is classified by Kondrat'eva (1979) as a planetary nebula of moderate excitation. The nebula is easily resolved at the VLA and an angular size of $\sim 5''$ is found. The λ6 cm map of Na 1 is shown in Figure 5. The relatively large angular size and low flux density (~ 20 mJy) suggest that the thermal emission must be optically thin, and this is confirmed by our λ2.8 cm measurement at ARO.

d) M 3-38 (PK 356+4°2)

The λ6 cm and λ2 cm maps of M 3-38 are shown in Figures 6*a* and 6*b* respectively. We can see that, in both

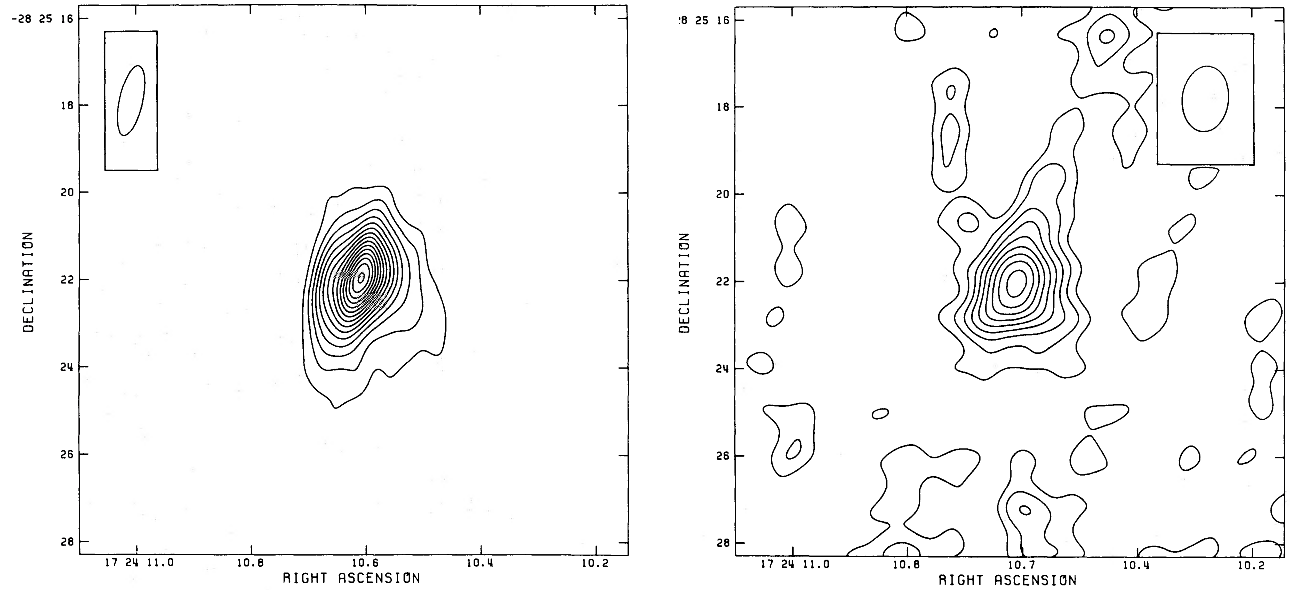

FIG. 1*a*

FIG. 1*b*

FIG. 1*a*.—λ6 cm map of M 3-10. The contour intervals are 1 mJy. The synthesized beam to the half-power is displayed at the corner of the map. 1*b*.—λ2 cm map of M 3-10. Contour intervals are 2 mJy.

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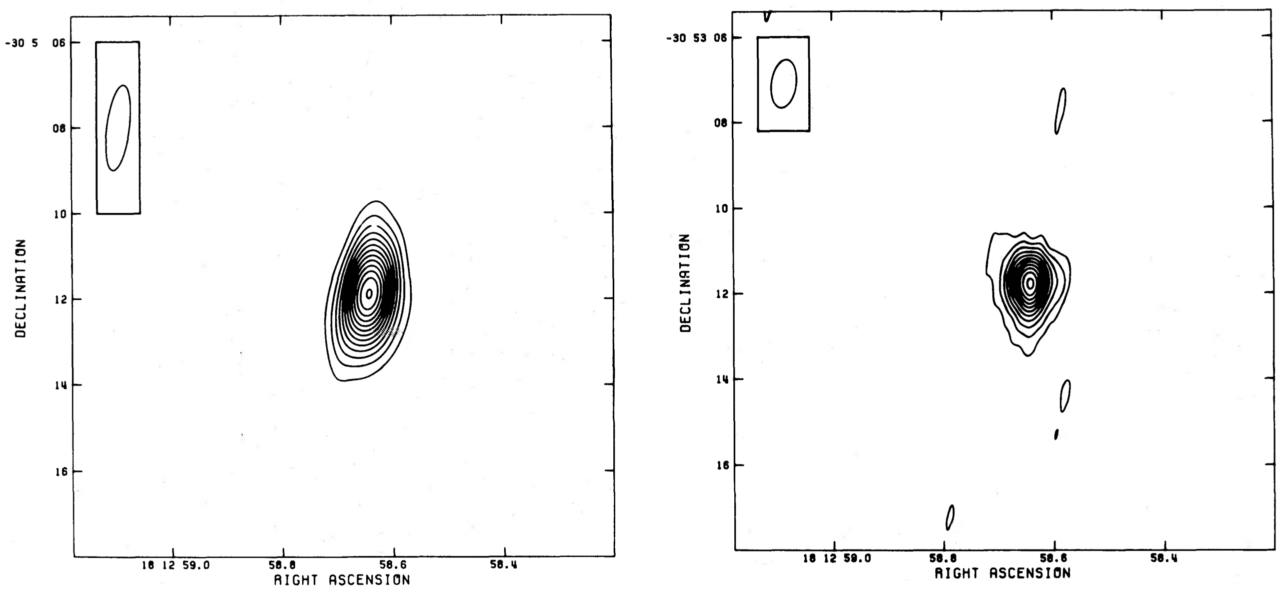

FIG. 2*a*

FIG. 2*b*

FIG. 2*a*.—λ6 cm map of SwSt-1. The map has been subjected to the self-calibration procedure. The contour intervals are 5 mJy. 2*b*.—λ2 cm map of SwSt-1 after self-calibration. Contour intervals are 10 mJy.

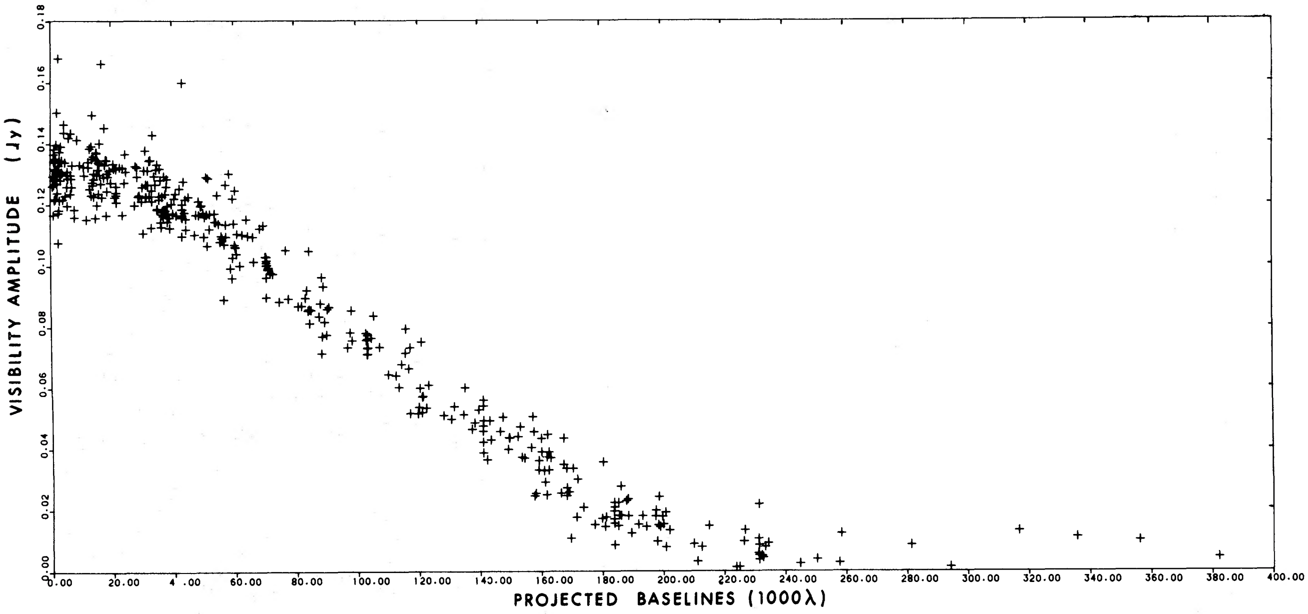

FIG. 3.—λ6 cm visibility data of SwSt-1, showing fringe amplitude as a function of projected spacings within the array in units of 1000 wavelengths. The uncertainty to be associated with each datum point is indicated by the results at large spacings for which the source appears to be completely resolved.

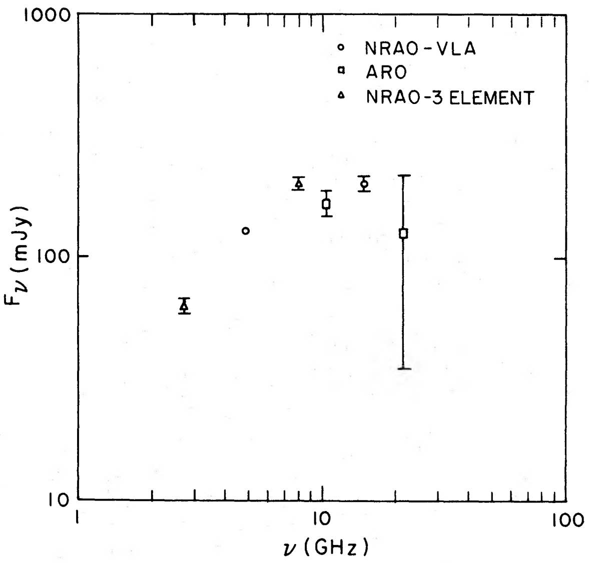

FIG. 4.—The radio spectrum of SwSt-1. The NRAO 3-element data are taken from Marsh, Purton, and Feldman (1976).

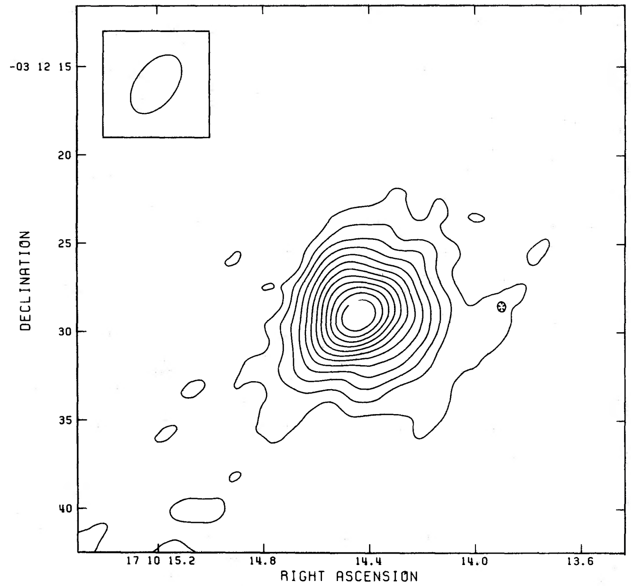

FIG. 5.—λ6 cm map of Na 1. The contour intervals are 0.5 mJy

maps, there exists a point source surrounded by a "halo." The point source has an angular size less than 0″.3 and is optically thick between λ6 and λ2 cm. Subtraction of point sources of 15 and 25 mJy respectively from the λ6 and λ2 cm maps results in flux densities of ~ 10 mJy from the remnant halo. This is confirmed by measuring the peak flux densities from low resolution maps.

If the nebula is to be identified with the core, then it has a very small angular size and correspondingly high emission measure. Unfortunately, it is impossible to determine the spectral index from the data we have.

Extended faint optical halos are known to exist around planetary nebulae (Kaler 1974; Millikan 1974), but such halos have never been detected in the radio. However, M 3-38 is located on the galactic plane, and it is difficult to establish whether the core and halo components are in fact associated with each other. We can see from Figure 6 that there are low-level emissions in the vicinity of the nebula, and positional coincidence of the nebula with a confusing source is a real possibility.

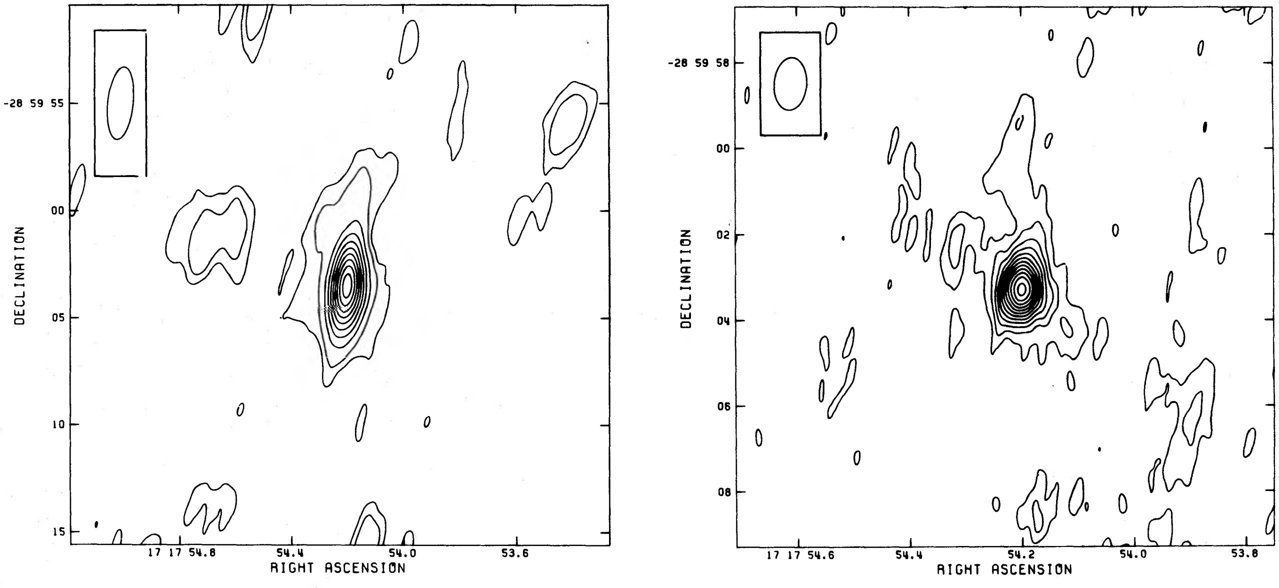

FIG. 6a

FIG. 6b

FIG. 6a.—λ6 cm map of M 3-38. The contour intervals are 2 mJy except that the 1 mJy contour is also added. 6b.—λ2 cm map of M 3-38. The contour intervals are 2 mJy.

e) *VV 8* (*M 1-2, PK 133−8°1*)

VV 8 is a planetary nebula which is often suggested to be young. It shows Balmer-line self-absorption, implying an extremely dense nebula (Barker 1978). An upper limit of 0.5 mJy at 5 GHz was obtained by us using the VLA (see Table 3). If the density (10^6–10^7 cm^{-3}) measured by optical methods is representative of the whole nebula, then it will certainly be optically thick at 5 GHz. Our upper limit implies a backbody size of $< 0''.06$, or, at a distance of 700 pc (Zipoy 1975), a size limit of 6×10^{14} cm. This leads to a total ionized mass of $< 10^{-5}\ M_{\odot}$, small compared to the typical mass of planetary nebula. However, the possibility exists that the nebula is ionization bounded and that most of the object is in fact neutral. Further monitoring at 5 GHz is desirable to decide this issue.

f) *M 3-27* (*PK 43+11°1*)

M 3-27 is spectroscopically similar to VV 8 and has also been suggested to be a young planetary nebula (Barker 1978). An upper limit of 15 mJy at λ2.8 cm was obtained at ARO.

g) *NGC 6833* (*PK 082+11°1*)

NGC 6833 is a stellar planetary nebula with an electron density as high as 10^5 cm^{-3} (Barker 1978), and, yet, it is optically thin above 5 GHz, implying an emission measure of $< 10^8$ cm^{-6} pc. The optical and radio results are consistent only if the linear size of the nebula is $< 3 \times 10^{16}$ cm, i.e., at a distance of 500 pc having an angular size of $< 4''$. However, optical measurements are known to weigh more to high-density regions, and the average density of the nebula may in fact be lower.

h) *II 5117* (*PK 89−5°1*)

II 5117 has been found by Johnson, Balick, and Thompson (1979) to have angular size of $\sim 1''$ and a corresponding emission measure ($\langle E \rangle_{\rm II}$) of $\sim 1.4 \times 10^8$ cm^{-6} pc. Our measurement at 10.6 GHz shows that the radio spectrum of II 5117 is optically thin above 5 GHz. This implies that $\langle E \rangle_{\rm I} < 10^8$ cm^{-6} pc. Since the electron temperature is uncertain, the discrepancy between $\langle E \rangle_{\rm I}$ and $\langle E \rangle_{\rm II}$ is within the error of our present calculation. Measurement at a frequency below 5 GHz would be useful in determining the critical frequency.

i) *HBV 475* (*V 1329 Cygni*)

HBV 475 is a peculiar emission-line star which has undergone irregular outbursts (Stienon, Chartrand, and Shao 1974) and has been suggested to be a protoplanetary nebula (Crampton *et al.* 1970) and a symbiotic star (Stienon, Chartrand, and Shao). In contrast to SwSt-1, it is a high-excitation object. Radio emission of 12 ± 4 mJy at 10.7 GHz was reported by Altenhoff and Wendker (1973). In 1978 Hjellming (private communication) measured a flux density of 5 mJy at λ6 cm. Our 1980 upper limit of 1 mJy at λ6 cm suggests that radio emission from this object may be time variable.

V. GENERAL DISCUSSION AND CONCLUSIONS

We have observed approximately 40 compact planetary nebulae and have successfully resolved four which were previously designated as "stellar." Two nebulae, M 3-38 and SwSt-1, are found to have a high turnover frequency (> 5 GHz), small angular size ($< 1''$), and high emission measure ($> 10^8$ cm^{-6} pc), and, therefore, are good candidates for very young planetary nebulae. In Table 4, we have listed all the planetary nebulae which are known to have emission measures $> 10^8$ cm^{-6} pc. In all cases (except M 3-38), the optically thick parts of the spectra have been measured at several frequencies, and the spectral indices are well determined. The emission measures are calculated using both methods given in § III, and the spectral index optically thick regime is given in the last column of Table 4. NGC 7027 is also listed for comparison. It is interesting to note that all the high-emission-measure nebulae are compact in size and have spectral indices over a significant frequency range which are smaller than the value of +2 that one expects from a uniform gas shell. The radio spectra of Hb 12 and Vy 2-2 are found to be best fitted by density models of the form $n^{-\alpha}$, where $\alpha = 2$ (Marsh 1975). It is also clear that the spectra of H 1-36 and SwSt-1 cannot be fitted satisfactorily by a uniform-density model. It should be noted that

TABLE 4

PLANETARY NEBULAE WITH HIGH EMISSION MEASURE

Nebula	ν_c (GHz)	Angular Diameter (arcsec)	$\langle E \rangle_{\rm I}$ (cm^{-6} pc)	$\langle E \rangle_{\rm II}$ (cm^{-6} pc)	Radio Spectral Index at $\nu < \nu_c$
Hb 12 …………	30[a]	0.18[b] (15 GHz)	4×10^9	7×10^9	0.90 ± 0.11
Vy 2-2 ………..	16[a]	…	9×10^8	…	1.49 ± 0.30
H1-36 ………..	9.5[a]	<1[d]	3.5×10^8	$>7 \times 10^7$	0.90 ± 0.18
M 3-38 ……….	>5	<0.3	$>9 \times 10^7$	$>2 \times 10^8$	>0.5
SwSt-1 ………..	7	0.8	2×10^8	2×10^8	1.22 ± 0.12
NGC 7027 ……	3.5[c]	~10	4×10^7	4×10^7	1.17 ± 0.10[e]

[a] Purton *et al.* 1981.

[b] Newell and Hjellming 1980.

[c] Terzian and Dickey 1973.

[d] Purton *et al.* 1977.

[e] Spectral index ~1.2 between 1.4–5 GHz. Below 1.4 GHz, the spectral index ~2 (Higgs 1971).

the optically thick part of the radio spectrum of planetary nebulae in general is very poorly determined. In the best-studied case of NGC 7027, there is also doubt that it can be explained by a uniform-density model (Viner, Vallée, and Hughes 1979).

Among the planetaries in Table 4, Hb 12 and SwSt-1 are two of the three planetary nebulae detected to have silicate dust emission. If the silicate feature is indeed an indication of young age, then these planetaries are ideal candidates for a study of the early evolution of planetary nebulae.

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