PLANETARY NEBULAE: ADVANCES IN RADIO OBSERVATIONS

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I. INTRODUCTION

The most recent review on planetary nebulae at radio wavelengths appeared in 1974 by Thompson. Previous summaries were given by Terzian (1968) and Higgs (1973). Major advances in this subject include extensive continuum observations at 5 GHz of southern planetary nebulae; the highly successful aperture synthesis observations providing brightness temperature distributions with a resolution of a few arc seconds; the high sensitivity observations of radio recombination lines which have allowed the unambiguous detection of collisional broadening in NGC 7027; the very recent detection of molecular CO emission from NGC 7027, IC 418 and NGC 6543, and CO and OH emission from possible proto-planetary nebulae.

II. CONTINUUM RADIO OBSERVATIONS

A. Flux Density Measurements

The measurement of flux density, position, and angular size of planetary nebulae at radio frequencies has been pursued with higher sensitivities and better angular resolution. The most recent continuum survey by Milne and Aller (1975) reports the radio observations of 165 planetary nebulae at 5 GHz south of +27° declination. The half power beam width of this survey is 4'.5, and the limiting flux density is 0.01 Jy. These authors compare their results with Hβ fluxes and compute the extinction coefficients for each nebula. In this work the authors adopt Shklovsky's (1956) distance scale method and derive its radio frequency equivalent which gives the distance d (parsecs) of a nebula as

$$d \simeq 6.18 \times 10^{3}\ \theta^{-3/5}\ S^{-1/5}$$

where θ is the angular radius of the source in arc seconds, and S is its radio flux density (at 5 GHz, or at a frequency where the optical depth

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<< 1) in units of Jy.

Other recent continuum surveys include the interferometric observations of 69 mostly northern planetary nebulae at 2.7 and 8.1 GHz with a limiting flux density of 0.01 Jy (Cahn and Rubin 1974). Several other works have reported continuum observations at frequencies of 0.4, 1.4, and 7.8 GHz (Thomasson and Davies 1970); 3.2, 6.6, and 10.6 GHz (Higgs 1971a); 2.7 GHz (Aller and Milne 1972); 0.4 GHz (Terzian and Dickey 1973); and 31 and 85 GHz (Johnson 1973). A compilation of continuum radio observations of planetary nebulae up to 1971 has been given by Higgs (1971b).

The most essential information from the above work has been the determination of the continuum radio spectra of planetary nebulae, which in turn allow the determination of the nebular physical parameters. It has been well established that the radio spectra of planetary nebulae are due to thermal emission from free-free transitions in the ionized gas. No confirmed evidence of any non-thermal emission has been established.

Figure 1 shows the composite continuum spectrum of NGC 7027 from

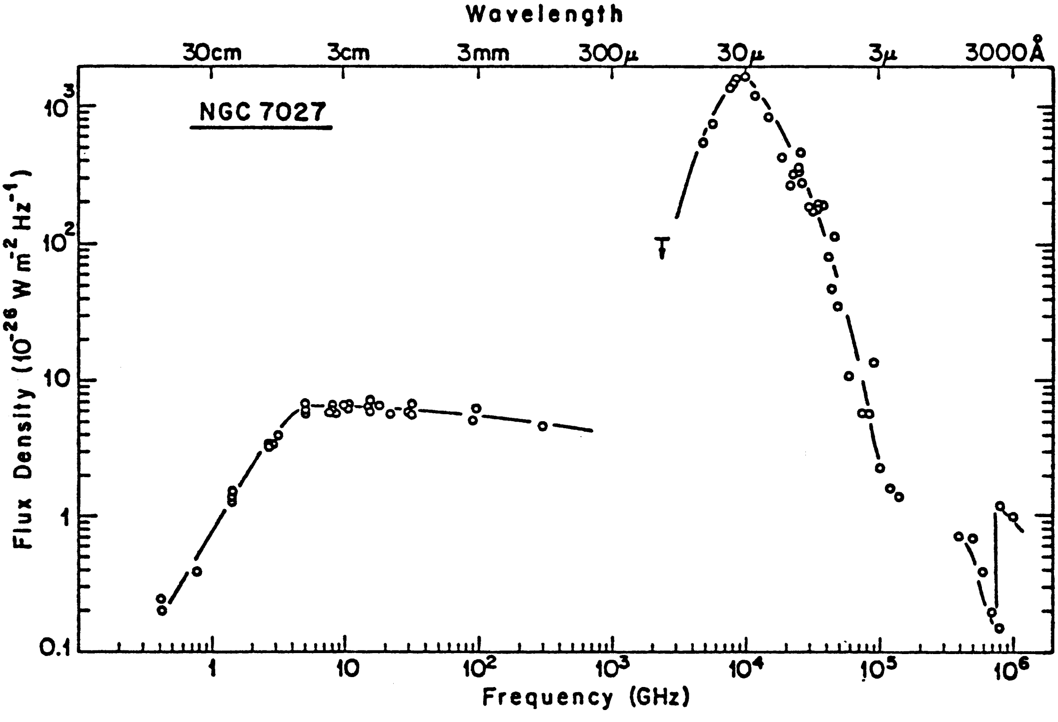

Figure 1. The continuum spectrum for NGC 7027. (The author is indebted to W. Forrest for most of the information on the infrared fluxes, to J. Houck for the λ1 mm flux and to B.L. Ulich for the λ3.3 mm flux.)

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optical to radio wavelengths. With the recent infrared observations this spectral range has almost entirely been observed. An analysis of the continuum radio spectra of twelve well observed nebulae has allowed the determination of the critical frequency (i.e., low frequency turn-over), and the evaluation of the nebular emission measures.

The knowledge of the critical frequency ν_c gives the emission measure E as:

$$<E>_I \equiv \frac{\int E(\theta,\phi)\,d\Omega}{\int d\Omega} = \frac{\nu_c^2 \; T_e^{3/2}}{\zeta_c}$$

where ν_c is in MHz, E in cm^{-5} and $\zeta_c = 9.8 \times 10^{-15}\, \ell n\,(49.5\; T_e^{3/2}/\nu_c)$. When the source is known to be optically thin at a high radio frequency the emission measure can be derived by using:

$$<E>_{II} \equiv \frac{\int E(\theta,\phi)\,d\Omega}{\Omega_{opt}} = \frac{36.3\; S_\nu\; T_e^{1/2}}{\zeta\; \Omega_{opt}}$$

where S_ν is the flux density in units of Jy. For a homogeneous density distribution of ionized gas $<E>_I = <E>_{II}$; however there always exist clumpiness and fine structure in the ionized gas. The degree of clumpiness is defined as:

$$f \equiv \frac{<E>_{II}}{<E>_I}$$

and ranges from 0.06 to 0.69 for the nebulae listed in Table 1.

Table 1. Critical Frequencies and Emission Measures

Nebula	ν_c (GHz)	$<E>_I$ (10^6 cm^{-6} pc)
NGC 6790	4.5±0.5	92.5±21.3
NGC 7027	3.5±0.5	70.5±20.7
NGC 6572	2.9±0.4	30.0± 7.6
BD30-3639	2.3±0.3	26.9± 6.2
IC 418	2.2±0.4	17.9± 5.9
NGC 6543	1.8±0.8	9.2± 6.9
NGC 6369	1.3±0.5	8.4± 5.8
NGC 3242	0.9±0.3	2.7± 1.5
NGC 7662	0.9±0.1	3.6± 0.8
NGC 7009	0.8±0.3	2.1± 1.3
NGC 6818	0.8±0.3	3.9± 2.4
NGC 6210	0.7±0.2	1.6± 0.9

This table indicates the critical frequencies and emission measures for twelve planetary nebulae (from Terzian and Dickey, 1973).

B. Brightness Temperature Distributions

One of the most successful experimental techniques in radio astronomy in recent years has been the aperture synthesis observations of radio sources. Such observations of planetary nebulae with angular resolution of the order of 2 arc seconds were performed with the U.S. National Radio Astronomy Observatory 3-element interferometer at 8.1 GHz (Balick et al. 1973, Terzian et al. 1974a), and with the U.K. Cambridge 5 km telescope at 5 GHz (Scott 1975). Lower resolution observations at 5 GHz were also performed with the Westerbork array (George et al. 1974), and the NRAO 3-element interferometer at 2.7 GHz (Terzian et al. 1974a). It has been very encouraging to find that the general radio structure of the nebulae observed with the above different systems are in excellent agreement. The radio brightness temperature distribution of more than a dozen nebulae can now be compared with optical intensity maps from which the two dimensional distribution of the extinction can be derived. In this regard the classical example is NGC 7027 where the radio synthesis maps clearly show a two-component radio source with a central intensity depression, and the optical source coincides only with one of the two radio components. We can conclude that the extinction is too severe to allow any optical emission to be visible for almost half of the ionized cloud.

The radio maps of NGC 7027 are in excellent agreement with the 10μ maps (Becklin et al. 1973) indicating the presence of dust which immediately surrounds the ionized nebula, or which is partially mixed with it.

The general results of the synthesis observations show that the nebulae have a characteristic projected general "double structure", with central intensity depressions. In addition elliptical shells are evident, and fine structure is seen with a resolution of ∿2 arc seconds. Figure 2 shows the synthesized radio maps of NGC 7027 and NGC 6543. Scott (1973) and George et al. (1974) have tried to fit the observed brightness temperature distributions with cylindrical shells; however no physical understanding for such a model exists at present.

In 1976 Balick and Terzian attempted sub-arc second long baseline interferometric observations of 11 planetary nebulae at 2.7 and 8.1 GHz. Resolutions up to 0.2 arc seconds were achieved in this survey. The results did not show any very bright structure smaller than 1 to 2 arc seconds. In particular the 'hot spot' with brightness temperature as high as $10^{5.8}$ °K reported by Miley et al. (1970) was not confirmed even though the system was an order of magnitude more sensitive than the one used in 1970. In this survey we detected for the first time radio emission from the suspected proto-planetary nebula FG Sge (flux lower limit of 20 mJy at 2.7 GHz; more recent results show a flux of 36±6 mJy by Balonek and Terzian 1977).

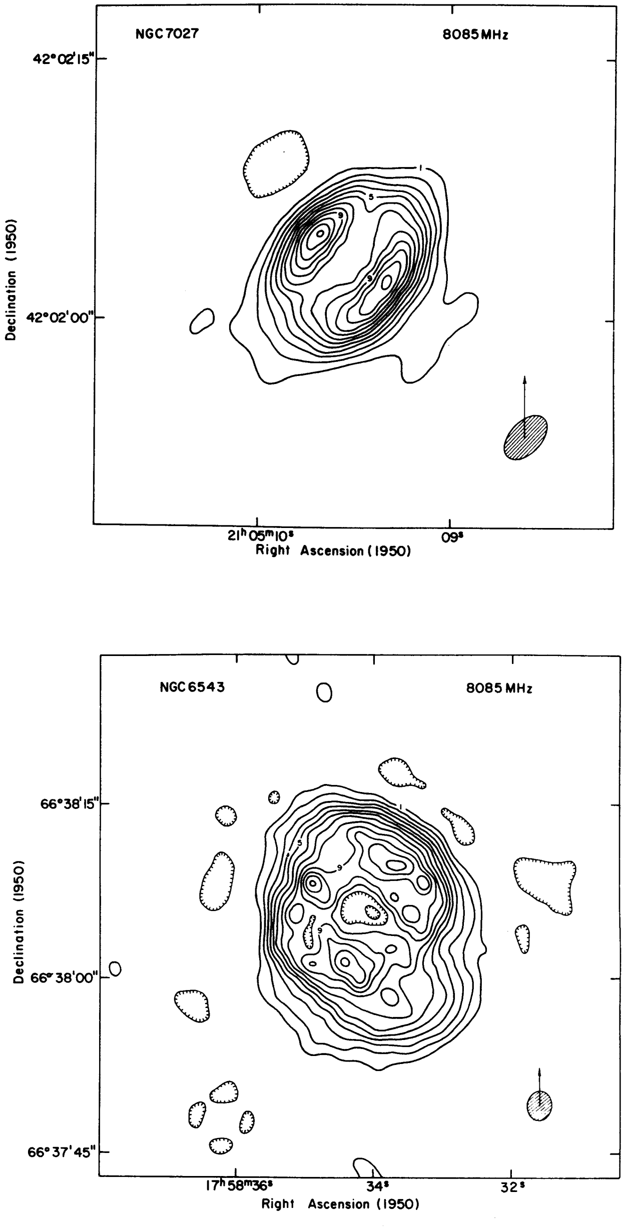

Figure 2. Brightness temperature distributions of NGC 7027 and NGC 6543 at 8.1 GHz with resolutions of the order of 2".

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III. RADIO RECOMBINATION LINES

Due to the low microwave flux densities of planetary nebulae it has been very difficult to detect radio recombination lines from these objects. At present Hnα lines have been detected from only five planetary nebulae, and H113β, and He^{+} 121α lines have been detected from NGC 7027. Table 2 gives the relevant observations where it is evident from the line-to-continuum temperature ratios (T_ℓ/T_c) that the line intensities are only a few percent of that of the continuum. Figure 3 shows examples of Hnα line observations. Such results have been employed to determine the physical conditions within the nebulae after assuming a geometrical model.

Table 2. Summary of Radio Recombination Lines

Source	Line	Frequency GHz	T_ℓ/T_c	Line Width KHz	Rad.Veloc. (LSR) km s^{-1}	Reference
IC 418	H 76α	14.7	0.075	1264±416	41±4	1
	H 85α	10.5	0.096	1370±110	46±3	5
NGC 6543	H 76α	14.7	0.122	2027±578	-45±5	1
	H 85α	10.5	0.057	2000±380	-55±3	2
	H 94α	7.8	0.078	895±250	-50±4	3
	H 109α	5.0	0.036	774±150	-57±2	4
M 1-78	H 85α	10.5	0.030	1890±410	-77±3	2
	H 109α	5.0	0.018	1080±200	-76±4	4
NGC 7027	H 76α	14.7	0.030	2008±234	24±3	1
	H 85α	10.5	0.023	1496±40	23±3	5
	H 90α	8.9	0.017	1464±150	25±2	4
	H 94α	7.8	0.010	1140±300	17±4	3
	H 109α	5.0	0.0035	1090±200	24±2	4
	H 113β	8.9	0.0035	2279±400	29±6	4
NGC 7662	H 85α	10.5	0.039	1720±720	- 4±4	2

References: 1. Bignell (1974); 2. Terzian et al. (1974b); 3. Goad and Chaisson (1973); 4. Churchwell, Terzian and Walmsley (1976); 5. Terzian and Balick (1972); Terzian and Balick (1969).

In the case of NGC 7027 the line widths increase with principal quantum level, and T_ℓ/T_c decreases faster than $\nu^{-1.1}$ indicating departures from local thermodynamic equilibrium. Churchwell et al. (1976) have explained these observations by the combined effects of expansion, electron impact (collision) broadening and a high electron temperature of 19000 °K in a non-LTE analysis of all the observations. These authors also suggest that the core of NGC 7027 may contain clumps with densities of the order of 2 x 10^5 cm^{-3}. In another study of NGC 7027 Chaisson and Malkan (1976) report $T_\ell/T_c \simeq 0.01$ for the H110α line, a

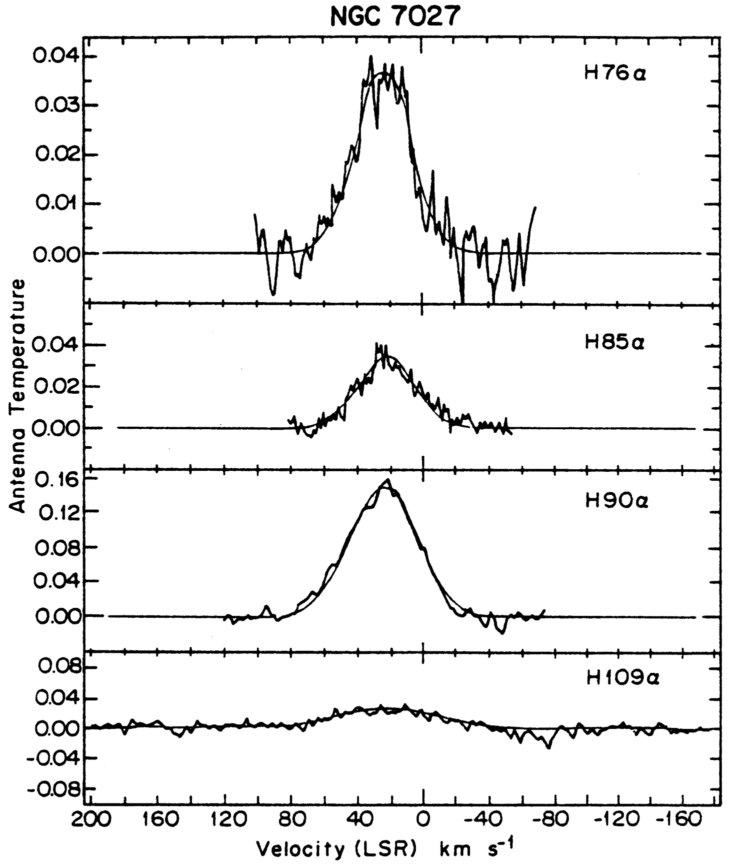

Figure 3. The Hnα observations for NGC 7027, adapted from various works in the literature (see References in Table 2).

value which is about three times higher than the observations by Churchwell et al (1976). This high value is also inconsistent with the work reported by Terzian and Balick (1969) who had reported an upper limit of $T_\ell/T_c \lesssim 0.0058$ for the H109α line.

New attempts should be made to detect a larger number of Hnα lines from planetary nebulae; special emphasis should be put on observations at the lower frequencies ($n \gtrsim 100$) in order to examine the line broadening due to electron collisions.

IV. MOLECULAR OBSERVATIONS

Late in 1975 Mufson et al. reported the detection of carbon monoxide (^{12}CO, ν = 115.2712 GHz) in emission from the planetary nebulae NGC 7027, IC 418, and NGC 6543. In particular it is found that the CO emission from the direction of NGC 7027 is extended ($\sim$ 3 arc minutes) compared to the size of the ionized nebula ($\sim$ 15 arc seconds from radio maps). The derived lower limit to the CO mass around NGC 7027 is 1.4 $M_{\odot}$, which is somewhat high given our current notions of the total mass ejected from stars assumed of being proto-planetary nebulae. However it is stil possible to attribute some (or all) this mass to a chance superposition of a molecular cloud in the line of sight to NGC 7027.

Earlier suggestions that NGC 2438 is associated with OH emission is incorrect since it has been shown that the molecular source is displaced from the planetary nebula by 6'.5.

More recent molecular observations of CO and HCN from infrared objects like CRL 2688, CRL 618, IRC + 10216, have been successful and such objects have been proposed as representing expanding envelopes of evolved stars which may be proto-planetary nebulae. (Zuckerman et al. 1976, Lo and Bechis 1976, Zuckerman et al. 1977).

V. CONCLUSIONS

The observational advances of planetary nebulae at radio wavelength in recent years give great promise in understanding several phases of the nebular evolution. In the near future it should be possible to map the radio brightness distributions of many planetary nebulae with a resolution of $\sim$ 1 arc second. It should also be possible to survey the region of the galactic center for planetary nebulae at radio wavelengths Hnα radio recombination line maps of the nebulae should also be possible to synthesize. And the study of molecular envelopes around proto-planetary and young nebulae should be vigorously continued.

Very recently radio sources in the direction of globular clusters have been detected (Johnson 1976, Terzian and Conklin 1977). Some of these sources may be associated with planetary nebulae in the globular clusters. A careful examination of this problem also seems very essential.

These are a few of the promising research areas which I foresee, undoubtedly many other interesting problems will emerge to enrich our understanding and curiosity of the planetary nebulae.

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DISCUSSION

Bignell: The VLA has been operating for scientific use for about a year. The first detailed radiosynthesis map involving 7 antennas was made two weeks ago by Bruce Balick, Carl Bignell, and Bob Hjellming. This synthesized map is of the planetary nebula NGC 40. The wavelength is 6 cm and the half power beam width is roughly 2" x 3". Comparison with optical photographs and an earlier Westerbork map with 6" resolution shows excellent correspondence.

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Peimbert, M.: The mass of the gas in atomic and molecular form in NGC 7027 depends critically on the adopted distance. I think that the distance of 0.5 kpc based on the Cudworth and Minkowski distance scales for optically thick objects is more appropriate than the value based on the optically thin distance scale.

Terzian: This point must be strongly emphasized - depending upon what distance we adopt for NGC 7027 we get different masses. Estimates of the distance to NGC 7027 range from 500 pc up to more than 2000 pc.

Zuckerman: I would like to make some remarks concerning the mass of NGC 7027, its distance from earth, and possible evidence for a large decrease in the luminosity of the central star in the past $\lesssim 10^3$ years. The mass of the molecular envelope surrounding NGC 7027 has been estimated from observations of CO and also H_2 to be $\gtrsim 1\ M_\odot$ for an assumed distance of $\sim$2 kpc. There is an additional problem: the CO luminosity to integrated infrared luminosity for NGC 7027 is ten or more times larger than similar ratios for other evolved stars with large mass loss rates (mostly red giants). There are good reasons to believe that the observed CO has been ejected from NGC 7027 and is not due to chance interstellar material along the line of sight. A way to get around the large mass for the CO cloud is to accept the Cudworth distance of 500 pc to NGC 7027. This still leaves the problem of how a star of only $\sim 10^3\ L_\odot$ (based on a 500 pc distance and the observed infrared flux) could eject a few tenths $M_\odot$ in gas and dust since the critical luminosities for ejection of planetary nebulae shells are believed to be $\sim$10 times larger. Therefore, I suggest that the central star of NGC 7027 has decreased in luminosity by a factor of 10 or so since it ejected the observed CO and H_2 about 10^3 years ago. I wonder if this is compatible with other observations of NGC 7027. Recall that the (underluminous) central star is not visible.

Johnson: How much effort has been put into λ21-cm observations toward planetary nebulae?

Terzian: Not very much. Sometime ago some interferometric observations at 21 cm were made with no positive results. Recently, Zuckerman, Silverglate and I have tried some more at Arecibo which, in my opinion, have not yet yielded positive results.