RADIO IMAGES OF PLANETARY NEBULAE

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ABSTRACT. The continuum radio spectra of planetary nebulae are discussed, and the structure of these objects is examined from the observed aperture synthesis brightness distributions determined with the Very Large Array. The use of radio observations in determining distances to planetary nebulae is examined. The detection of atomic neutral hydrogen at λ21 cm associated with planetary nebulae, as well as the associated CO and OH components are discussed. An upper limit, of the nebular magnetic field associated with the neutral material, of 1mG is reported for NGC 6302.

1. INTRODUCTION

Observations of planetary nebulae at radio wavelengths continue to make some of the most important discoveries about the nature and evolution of these objects. The aperture synthesis techniques using the Very Large Array (VLA) have made possible the detailed study of the brightness temperature distributions of many nebulae with angular resolutions ten times better than that obtained at optical wavelengths, and without suffering from any interstellar extinction. The λ3 mm CO observations, the λ18 cm OH observations, and the λ21 cm HI observations of planetary nebulae have made possible the study of the neutral envelopes of young nebulae and proto-planetary nebulae.

It appears that we are beginning to understand the relatively fast and interesting transition from red giant stars to proto-planetary nebulae and to the normal planetary nebulae. Such progress has been made possible by the identification and observations of several objects caught in the fast transition from red giant stars to normal planetary nebulae. The recent observations of the OH/IR stars promise to add more objects in these interesting and important phases of the late stellar evolution.

S. Torres-Peimbert (ed.), Planetary Nebulae, 17–28.

2. CONTINUUM RADIO EMISSION

2.1. Flux Density Measurements and Radio Spectra

Most of the flux density measurements of planetary nebulae at radio wavelengths during the last few years have been made as a by-product of the two dimensional aperture synthesis studies of these objects, or of the radio line observations of HI, OH and CO. Taylor et.al. (1987) have presented an analysis of the radio continuum spectra of 18 compact planetary nebulae based on published flux densities plus new observations at 327 MHz made with the Westerbork Synthesis Radio Telescope. They show that the radio spectra are well represented by a model in which the radio emission arises in a photon-limited, ionized shell of a stellar wind type envelope. Theoretical models seem to fit the observed spectra best when a radial density power law in the shell of the form r^{-2} is assumed.

When the central star of a planetary nebula is hot enough ($\gtrsim 2 \times 10^4$K) to ionize the neutral material surrounding it, then the free-free transitions in the ionized gas begin to produce observable radio emission. Such young nebulae have small radio angular sizes, and have relatively high electron densities approaching 10^6 cm^{-3}. The ionization front rapidly moves outwards, and as the central star evolves and reaches surface temperatures exceeding 5×10^4K, the surrounding nebula also undergoes rapid changes, and its radio emission increases. Recently Gathier (1986a) has computed theoretical radio continuum spectra as a function of time for a uniform density, spherical, and isothermal (electron temperature $T_e = 10^4$K) nebula with a total mass of 0.5 $M_\odot$. Figure 1 shows Gathier's results, which were computed for a central star of 0.6 $M_\odot$ and a surface temperature, at t = 0 yr, of 2.8×10^4K at a distance of 1 kpc. The initial electron density was 10^6 cm^{-3}, and the expansion velocity was 20 km/sec. It is clear from these results that the radio continuum spectrum should undergo significant changes as a function of the age of the nebula. Figure 2 shows the radio and infrared spectrum of the well observed planetary nebula NGC 7027 where the radio emission is due to free-free radiation from the ionized gas, and the infrared emission is due to thermal radiation from the warm dust.

Measurements of flux densities of compact nebulae have been made by Turner and Terzian (1984) at 2380 MHz with the Arecibo radio telescope, by Kwok (1985) at 5 GHz using the VLA, and by Schneider et.al. (1987) at 2380 MHz at Arecibo. The lower limit of the sensitivity of these observations is about 10 mJy. It should be possible to detect even weaker sources using the VLA or the Arecibo instruments with longer integration times. This might be useful in identifying the extremely young nebulae when the ionization is just beginning and the flux densities are still very low.

https://doi.org/10.1017/S0074180900137453 Published online by Cambridge University Press

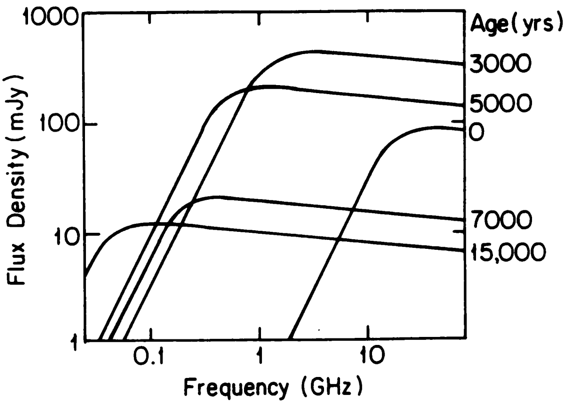

Figure 1. The evolution of the radio spectrum of a thermal spherical nebula with uniform density and temperature as described by Gathier (1986a).

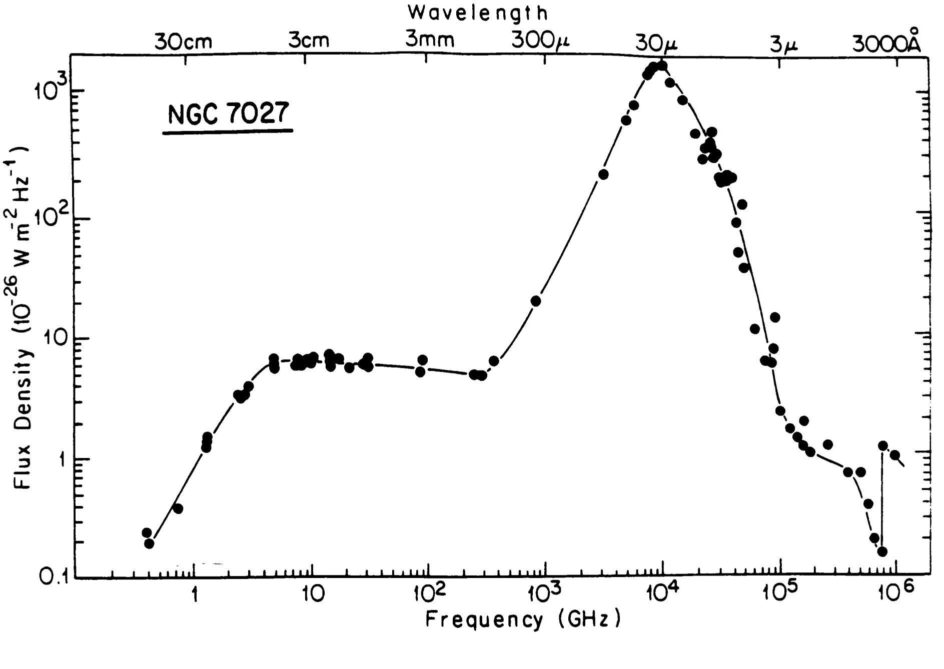

Figure 2. The radio, infrared and optical spectral regions of NGC 7027 adapted from Terzian (1977). The radio spectrum indicates a thermal origin of the emission with the nebula being optically thin at frequencies higher than ~ 5 GHz, and optically thick at lower frequencies. The infrared spectrum indicates the presence of a warm dust envelope. The submillimeter fluxes at 370, 780 and 1090 μm are from Gee et.al. (1984).

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2.2. Aperture Synthesis Brightness Distributions

One of the most important contributions of the radio observations of planetary nebulae has been the high angular resolution mapping of these objects, and unaffected by interstellar extinction. Aperture synthesis results of planetary nebulae were first reported by Balick et.al. (1973) and Scott (1973) for NGC 7027, and by Terzian et.al. (1974) for 14 nebulae. These early observations achieved resolutions of 2 arc seconds and were performed with the use of the Green Bank 3-element interferometer, and the Cambridge 5-km radio telescope. The Very Large Array during the last several years has made possible such high resolution mapping with much higher efficiency and accuracy. A review of the early VLA work has been given by Bignell (1983). Gathier et.al. (1983) used the VLA to observe many nebulae in the direction of the galactic center, and Kwok (1985) has reported VLA observations of ten compact nebulae with angular resolutions of ~ 0.4 arc second. Similar additional measurements have been reported by Balick et.al. (1987), and Terzian (1987). It is now possible to achieve a resolution of up to 0.06 arc second with the VLA at a frequency of 22 GHz. Kwok (1987) states that approximately 100 nebulae have been observed to date with the VLA and that most of them are resolved with an angular resolution of 0.4 arc second at a frequency of 5 GHz. Figure 3 shows examples of radio maps of compact nebulae observed by Kwok (1985). These results show a clear shell structure with abrupt boundaries expected from ionization fronts. It can be seen that the nebula II 5117, which has a very high electron density of $\sim 10^5$ cm^{-3}, is resolved into a bipolar structure with an overall angular size of 1.6 arc seconds. Such nebulae represent the very young stages of planetary nebulae and may be only slightly more evolved than the extremely young and compact objects like Vy 2-2 and CRL 618.

Many planetary nebulae also show outer extended faint envelopes at optical wavelengths (see for example Terzian 1983). If these represent low density ionized gases then these envelopes should also be detectable at radio waves with full-synthesis VLA observations. The current work by Aaquist and Kwok (reported by Kwok 1987) shows that such extended haloes are indeed detectable with the VLA in some cases.

Very recently Basart and Daub (1987) have also presented VLA observations of BD30°3639, NGC 6572, NGC 6590 and NGC 7027 at 1.4 and 5.0 GHz. In addition to presenting brightness temperature distributions for these objects they also construct models and show the two dimensional optical depth, emission measure, and electron temperature distributions. Three of these nebulae, BD30°3639, NGC 6572 and NGC 7027 have also been observed with the VLA by Terzian et.al. (as reported by Terzian 1987), together with the nebulae NGC 3242, NGC 2392 and NGC 6210 in a continuing program to measure the angular expansions of these objects. In order to test the response of the different observing instruments and techniques, Figure 4 shows three

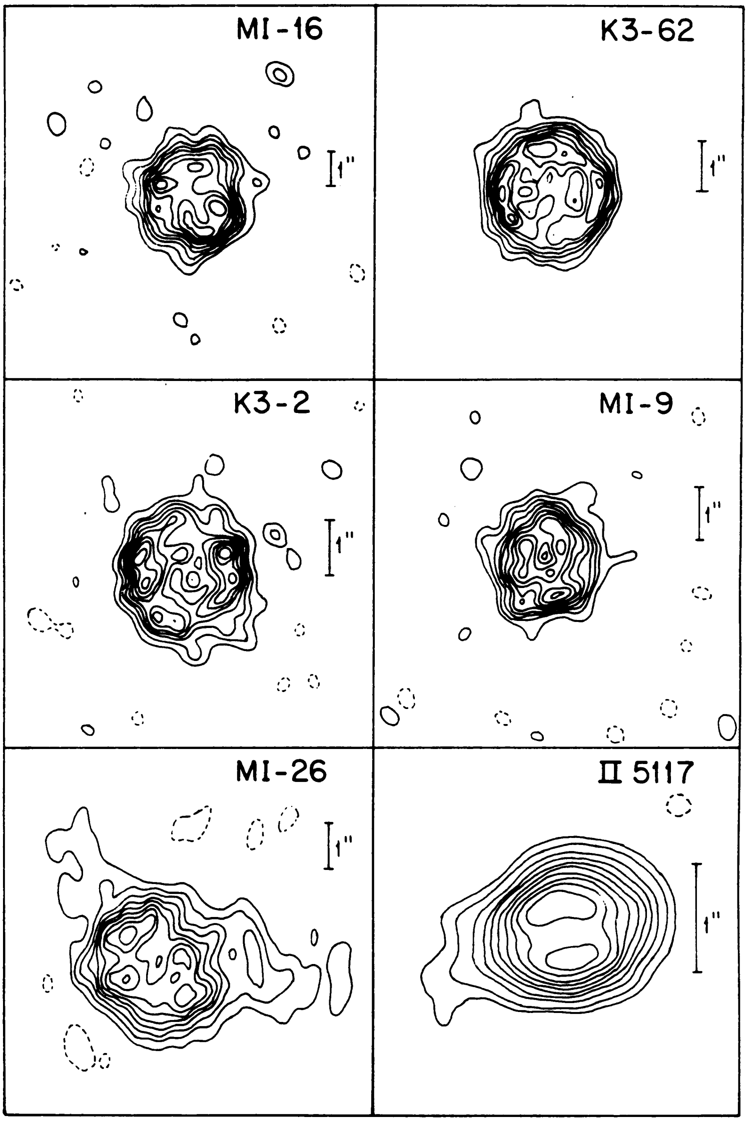

Figure 3. Six representative radio images of planetary nebulae made with the VLA at a frequency of 5 GHz, and a resolution of ~ 0.4 arc sec., selected from the work by Kwok (1985).

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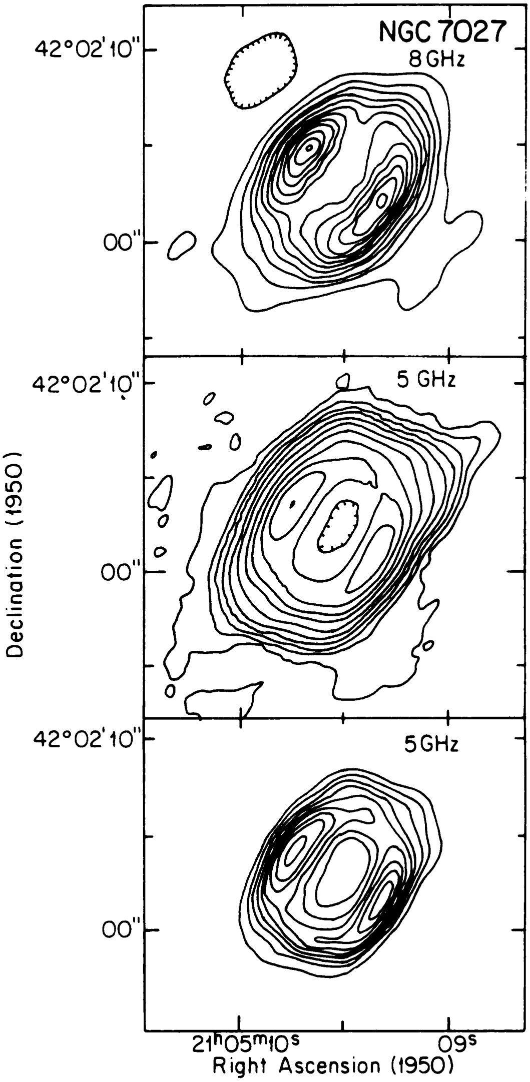

Figure 4. A comparison of the observations of the radio brightness temperature distribution of NGC 7027. The top figure shows the results obtained by Terzian, Balick and Bignell in 1974 using the NRAO Green Bank 3-element interferometer. The middle figure is from Basart and Daub (1987), and the lower figure is from Masson (1986), both of which were made with the VLA.

independent aperture synthesis radio maps produced by different authors. The first image is from Terzian et.al. (1974) and was made with the Green Bank 3-element interferometer at a frequency of 8 GHz, the second image is from Basart and Daub (1987), and the third image is from Masson (1986), the last two were made with the VLA at a frequency of 5 GHz. In general there is very good agreement between these radio maps, and the minor differences are probably due to somewhat different criteria in cleaning the data from the noise.

3. DISTANCES FROM RADIO MEASUREMENTS

The problem of distance determinations of planetary nebulae has remained very difficult, inspite of several studies that have examined this issue very carefully. It is now clear that the assumption of a constant nebular mass in deriving distances is not adequate even in a statistical manner, as discussed by Gathier et.al. (1983) in their study of planetary nebulae at the Galactic Center. Schneider et.al. (1987) have also examined the distance scale problem of planetary nebulae. They use the results of Schneider and Terzian (1983), who showed that for a large sample of nebulae in order for them to be consistent with Galactic rotation they must have a distance scale of 1.4 times Acker's (1978) statistical value. Schneider et.al. (1987) then use the results by Milne (1982) who had scaled his radio distances by a factor of 1.45 times Acker's, and by applying a small correction (to be consistent with the above factor of 1.40) derive a radio distance relation for young, optically thick nebulae as follows:

$$D = 27(S_{6cm})^{-1/2} ,$$

and for optically thin nebulae

$$D = 24(S_{6cm})^{-1/5}(\theta)^{-3/5} ,$$

where the distance D is in kpc; the flux density at the wavelength of 6 cm, S_{6cm}, is in mJy; and θ, the angular radius is in arc seconds. The last expression, for example, gives a distance of 1.4 kpc for NGC 7027 assuming that this object is optically thin. This value agrees well with that of Pottasch et.al. (1982) who derived a distance between 1.0 and 1.5 kpc for this object using various methods. However, assuming the nebula to be optically thick, which is likely given the molecular envelope surrounding NGC 7027, one obtains a distance of only 330 pc. Clearly significant uncertainties exist in the method used by Milne (1982) and Schneider et.al. (1987) since the method assumes a constant luminosity for the nebula, which is not realistic (Gathier 1986b).

The high angular resolution provided by the VLA presents new possibilities in deriving accurate distances by measuring the angular expansion of the planetary nebulae as a function of time. Masson (1986) has used this method and has derived a distance of 940 ± 200 pc for NGC 7027. Terzian et.al. (as reported by Terzian 1987) have also begun such a program at the VLA and the first epoch observations, performed during 1983-84, include the objects BD30°3639, NGC 7027, NGC 3242, NGC 2392, NGC 6572 and NGC 6210. The second epoch observations will be made in 1988-89.

Neutral hydrogen λ21 cm absorption observations have been used for 24 nebulae by Gathier et.al. (1986), using the Westerbork Synthesis Radio Telescope to determine kinematic distances to these nebulae. For 12 nebulae the derived distances have an uncertainty of ~ 50%, and such methods provide only lower limits to the distances of the nebulae.

The problem of determining accurate distances of planetary nebulae has remained very difficult, but significant new efforts and some progress have been made.

4. ATOMIC NEUTRAL HYDROGEN IN PLANETARY NEBULAE

We are beginning to understand that only a few thousand years separate the end of the Asymptotic-Giant-Branch evolution and the onset of the ionization of planetary nebulae. During this transition period the surface temperature of the central star increases to the point where the neutral gas surrounding it begins to get ionized. Such proto-planetary nebulae are composed of a compact very dense ionized core surrounded by neutral material. Since part of this neutral gas is in the form of atomic hydrogen radio astronomers have tried to detect the λ21 cm line emission from it. Only recently such attempts have given positive results when Rodriguez and Moran (1982) detected an HI absorption feature in the direction of the young planetary nebula NGC 6302. Rodriguez et.al. (1985) showed that the HI arises from the dark lane perpendicular to the bipolar ionized nebular components.

More recently Altschuler et.al. (1986) have reported HI absorption towards the young nebula IC 4997, and Taylor and Pottasch (1987) have detected absorption and emission components associated with the compact nebula IC 418. Figure 5 shows the neutral hydrogen spectra of NGC 6302, IC 4997 and IC 418. In all three cases the HI gas is blue-shifted with respect to the radial velocity of the ionized nebula as indicated in Table 1. In addition to the above observations Gathier et.al. (1986) have reported the marginal detection of HI absorption in the direction of NGC 6790. The HI mass detected in these objects ranges from 0.002 to 0.07 $M_\odot$ and represents only a very small percentage of the total nebular mass.

A few dozen other nebulae have been searched for associated neutral hydrogen with negative results, and it appears that in most

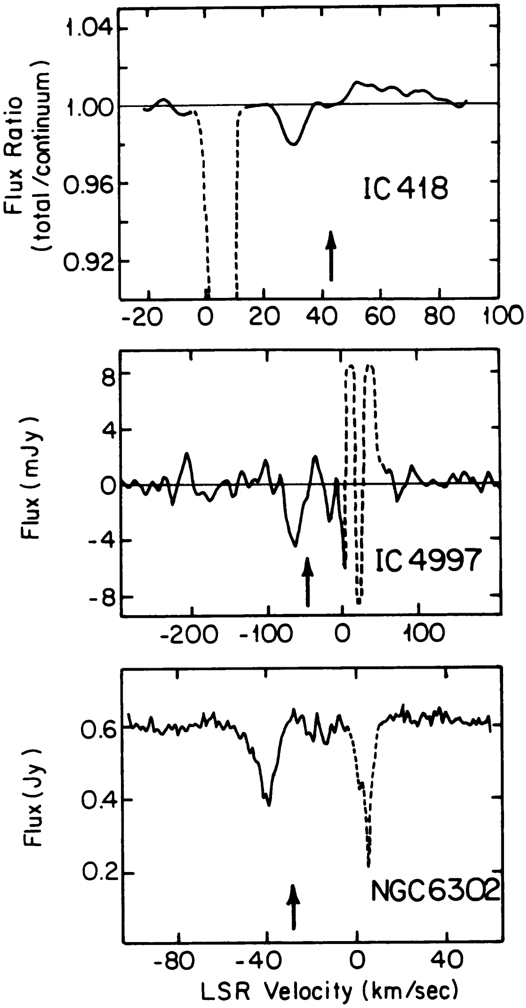

Figure 5. The radio spectra of the three planetary nebulae showing the HI λ21 cm absorption lines due to the neutral nebular envelopes surrounding the ionized clouds. The arrows indicate the radial velocities of the ionized hot nebulae. The dashed profiles indicate HI due to galactic absorption and emission not associated with the nebulae. Note that in all cases the nebular HI absorption is blue-shifted from the radial velocities of the ionized clouds. (Spectra adapted from Taylor and Pottasch 1987, Altschuler et.al. 1986, and Rodriguez et.al. 1985).

cases the ionization of a circumstellar envelope takes place during a relatively short period of time.

TABLE 1. HI MEASUREMENTS

Nebula	Radial Velocity* km/sec	HI Absorption Velocity* km/sec	HI Mass** $M_\odot$
IC 418	+ 43.4	+ 30	0.07
IC 4997	- 49.8	- 64	0.002
NGC 6302	- 31.4	- 40	0.06
NGC 6790	+ 56.8	+ 40	0.01

*Velocities are with respect to the Local Standard of Rest.

**Masses are uncertain since they depend on parameters like nebular distances, geometry and HI excitation temperature, all of which are not well known.

5. MOLECULES IN PLANETARY NEBULAE

A significant fraction of the information on proto-planetary nebulae and the early stages of their evolution has come from infrared and molecular observations. Both of these subjects are treated in detail by other authors in these proceedings. At radio waves CO, CN, and OH have been detected from young and compact nebulae indicating mass loss rates in the range of 10^{-6} to 10^{-4} $M_\odot$/yr. Knapp (1986) has listed ten nebulae with detected molecular envelopes of CO, OH, and H_2. Some of these nebulae, like NGC 7293 and NGC 6720, are well established planetary nebulae, yet molecular emission is still detectable and it must come largely from the outer regions of the nebular envelopes. It is also possible that the molecules survive because they may be shielded from the stellar radiation by dust particles.

Until recently mostly CO and H_2 were observed in association with planetary nebulae. OH was only seen in Vy 2-2, and CN only in NGC 7027. However, Payne et.al. (1987) have now detected OH from NGC 6302, and Pottasch et.al. (1987) have detected continuum radio emission from two OH/IR stars which make them probable objects in transition from OH/IR stars to planetary nebulae.

6. NEBULAR MAGNETIC FIELDS

Very little is known about magnetic fields in planetary nebulae. Gurzadyan (1962) and very recently Pascoli (1987) have discussed the possible influence of a dipole magnetic field as the origin of the bipolarity in the observed morphology of planetary nebulae. Rodriguez et.al. (1985) have tried to measure the intensity of the magnetic field in the HI gas near NGC 6302 by the Zeeman effect in the λ21 cm line. They used the VLA and recorded the right and left circular polarizations of the λ21 cm line. The difference in the right and left circular polarization spectra produce the characteristic "S" shaped Zeeman pattern which results from a substantial magnetic field. No significant magnetic field signature was detected and a 3σ upper limit of ~ 1 mG was derived for the magnetic field strength in the neutral gas of NGC 6302. However, it should be possible to extend these observations with longer integration times and even with better frequency resolutions, to examine this important issue further.

7. CONCLUSIONS

Significant advances in our knowledge of planetary nebulae have taken place during the last few years through observations of these objects at radio wavelengths. High angular resolution radio images of many nebulae have revealed their structure, neutral hydrogen λ21 cm and OH λ18 cm measurements have indicated the presence of neutral envelopes around these objects, and CO λ3 mm observations have given us realistic estimates to the mass loss from the progenitors of planetary nebulae.

Future work will certainly include the examination of the neutral envelopes, the derivation of accurate physical parameters from radio synthesis observations and the possibility of establishing a more accurate distance scale for the planetary nebulae population by the nebular expansion method using high resolution radio images.

The author wishes to thank R. Gathier for providing information in advance of publication. This work was supported in part by the National Astronomy and Ionosphere Center, which is operated by Cornell University under a management agreement with the National Science Foundation.

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