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ON THE ABUNDANCE OF ATOMIC AND MOLECULAR HYDROGEN IN THE OUTER PARTS OF YOUNG PLANETARY NEBULAE

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RESUMEN

Usando el conjunto muy grande de radio telescopios, *VLA*, buscamos H I en absorción contra el continuo de siete nebulosas planetarias compactas. Con la excepción de la componente en NGC 6302 previamente reportada, todas las líneas de absorción observadas pueden atribuirse a nubes en la línea de visión sin relación con las nebulosas planetarias. Los límites superiores típicos para el hidrógeno asociado son $\leqslant 0.01\ M_\odot$.

Consideraciones teóricas (Glassgold y Huggins 1983) sugieren que solo puede existir H I detectable en nebulosas planetarias con progenitoras relativamente calientes ($T_* \geqslant 2500$ K). También se espera teóricamente que estas estrellas produzcan enriquecimiento considerable de nitrógeno. En concordancia con estas ideas, NGC 6302 tiene uno de los cocientes N/O más grandes observados en nebulosas planetarias.

ABSTRACT

Using the *VLA* we searched for H I in absorption against the continuum of seven compact planetary nebulae. With the exception of the previously reported feature in NGC 6302, all observed absorption lines can be attributed to line of sight clouds unrelated to the planetary nebulae. Typical upper limits for associated H I are $\leqslant 0.01\ M_\odot$.

Theoretical considerations (Glassgold and Huggins 1983) suggest that detectable H I may exist only for planetary nebulae with relatively hot ($T_* \geqslant 2500$ K) progenitors. It is also expected theoretically that these stars will produce considerable nitrogen enrichment. In agreement with these notions, NGC 6302 has one of the largest N/O ratios observed in planetary nebulae.

Key words: NEBULAE-PLANETARY – RADIO SOURCES-21-cm RADIATION – STARS-LATE-TYPE

I. INTRODUCTION

Recently formed planetary nebulae are expected to be radiation bounded, that is, to have their inner regions ionized, while retaining their outer parts neutral. In objects like NGC 7027 (Mufson, Lyon and Marionni 1975) and CRL 618 (Zuckerman *et al.* 1976) the outer gas is predominantly molecular, while in NGC 6302 (Rodríguez and Moran 1982) it is mainly atomic. The present chemical conditions of the outer neutral regions must be a consequence of the nature of the progenitor and of the evolution of the planetary nebula.

Spergel, Giuliani and Knapp (1983) have estimated that the ionization bound stage should last $\sim 2 \times 10^4$ years for planetary nebulae formed from stars with high mass loss rates, $\dot{M} > 10^{-4}\ M_\odot\ yr^{-1}$. Correspondingly, if we assume a typical expansion velocity of 20 km s^{-1}, at least some planetary nebulae with radii smaller than a few tenths of pc should have an outer, neutral envelope. In this paper we present observations of H I in absorption against the radio continuum emission of seven compact bipolar planetary nebulae searching for atomic hydrogen around them. The observations are presented in §II, while an interpretation of the data is given in §III. We summarize the paper in §IV.

II. OBSERVATIONS

We selected a sample of six planetary nebulae according to the following criteria:

1) Compact size, that is, a characteristic dimension smaller than ~ 0.1 pc.

2) Bipolar morphology. This criterion was introduced because the only known planetary nebula with associated H I, NGC 6302, is bipolar. Although it is not known if a bipolar shape is related to the presence of atomic hydrogen, the arguments of Calvet and Peimbert (1983) favor relatively massive envelopes for bipolar planetary nebulae.

3) With the exception of NGC 2452, all observed planetary nebulae have detectable [O I] λ6300 A emission (Kaler 1976). Although the presence of neutral

TABLE 1

OBSERVED PLANETARY NEBULAE

Source	Coordinates (1950) α	δ	V^a_{LSR} (km s^{-1})	V^b_{esp} (km s^{-1})	Distance[c] (kpc)
NGC 2440	$07^h39^m41.4^s$	– 18°05′24″	+ 45	22	1.0
NGC 2452	07 45 23.3	– 27 12 36	+ 50	22	2.6
NGC 6302	17 10 21.3	– 37 02 43	– 31	10	2.4
Hb5	17 44 43.9	– 29 58 39	– 18	22	0.8
NGC 6537	18 02 15.2	– 19 50 51	– 5	22	0.7
NGC 7026	21 04 35.5	+ 47 39 02	– 26	42	1.3
NGC 7027	21 05 09.6	+ 42 02 02	+ 26	18	1.0

a. V_{LSR} is taken to be the systemic radial velocity of the planetary nebula. Data are from the catalog of Schneider *et al.* (1983).

b. Data from Robinson, Reay, and Atherton (1982). For NGC 2452, Hb5, and NGC 6537 there were no available measurements, so we adopted 22 km s^{-1}, the mean value of 85 planetary nebulae catalogued by Robinson *et al.* (1982).

c. Distances are from Daub (1982), except for NGC 6302 and NGC 7027, where we used the determinations of Rodríguez and Moran (1982) and Pottasch *et al.* (1982), respectively.

oxygen does not necessarily imply the presence of neutral oxygen, it can be taken as suggestive of the presence of transition regions (ionized to neutral) within the nebula.

4) The expected v_{LSR} of any H I associated with the planetary nebula should preferentially be at radial velocities as different as possible from those of interstellar gas in the line of sight. Otherwise, it is very difficult to discriminate between nebular and interstellar H I.

We have assumed the H I expansion velocity to be equal to the expansion velocity of the ionized gas (available from optical data), an assumption known to be valid for NGC 6302.

5) The planetary nebula should be a relatively strong radio continuum source, that is, to have a flux in excess of $\sim$ 0.1 Jy. A strong background flux increases the signal to noise ratio of absorption lines.

6) Observability from the northern hemisphere.

The selected sources and some of its parameters are listed in Table 1. We also included NGC 6302 as a check source.

The observations were made during 1983 January 28 and 29 using the *Very Large Array** in the C configuration. We used the system in the spectral line mode with a total bandwidth of 6.25 MHz. Limitations in the number of correlators then available permitted us to use only the central 31 channels with an individual width of 48.8 kHz or 10.3 km s^{-1} at the frequency of neutral hydrogen, ν = 1420.406 MHz. The continuum from the central 75% of the total bandwidth is registered in channel zero. With this number of channels, the number of antennas allowed was 21. The single antenna HPBW at the observing frequency was approximately 30′, the system temperature was $\sim$ 60 K, and the synthesized beamwidths had angular dimensions in the 10″ – 20″ range. This angular resolution was selected to match approximately the angular diameter of the sources. We chose phase calibrators relatively close to the sources. In Table 2 we list these calibrators with their boot-strapped fluxes. We used 3C 286 as the primary amplitude calibrator, adopting for it a flux of 14.51 Jy at 21-cm.

TABLE 2

PHASE CALIBRATORS

Sources	Calibrator	Bootstrapped Flux (Jy)
NGC 2440,NGC 2452	0733 – 174	2.84 ± 0.04
NGC 6302,Hb5,NGC 6537	1748 – 253	0.95 ± 0.02
NGC 7026,NGC 7027	2200 + 420	2.00 ± 0.02

We calibrated the data using the standard *VLA* procedures (Hjellming 1982) and we obtained the spectrum of each source using the program PASSUM. This program produces the spectrum observed by the synthetized beam in a given position of the field. The spectra of each source (with uniform weighting) are given in Figure 1. In this figure we show with an arrow the expected velocity for H I associated with the planetary nebula. This velocity was estimated subtracting the expansion velocity of planetary nebula from its systemic V_{LSR}. We also show with a horizontal bar the range of radial velocities for clouds along the line of sight to the planetary nebula. This range of velocities was obtained using the Schmidt (1965) model for galactic rotation and adding 10 km s^{-1} to each end of the range given by the model in order to account for clouds with peculiar velocities.

We detected absorption features in all sources, except NGC 2452. The single features detected in Hb5 and NGC 7026 are clearly due to line-of-sight clouds, with

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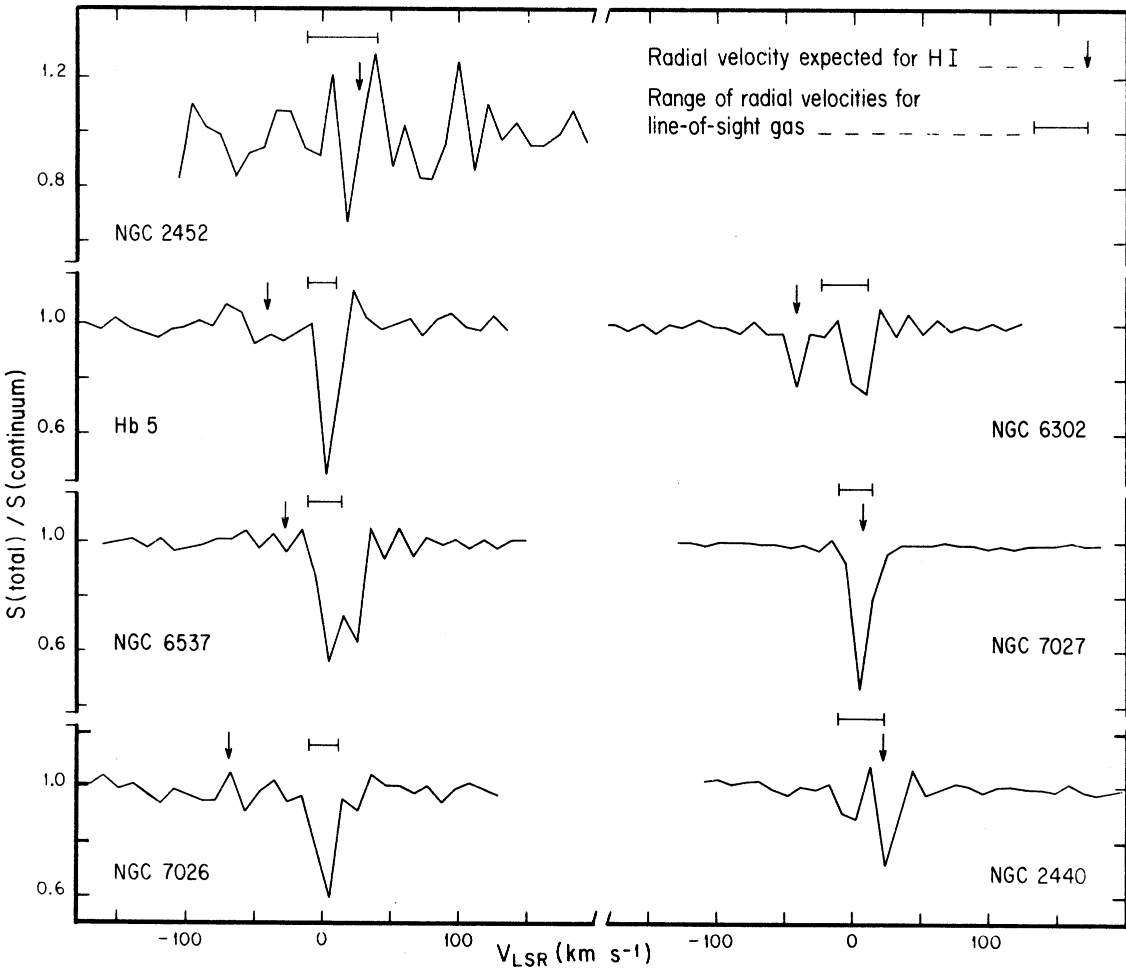

Fig. 1. H I absorption spectra for the observed planetary nebulae. The arrow marks the expected radial velocity with respect to the local standard of rest for associated H I. The horizontal bar gives the expected range of radial velocities for line-of-sight gas.

no detectable absorption at the expected radial velocity for H I associated with the planetary nebula. In NGC 2440, NGC 6302, and NGC 6537 there are double absorption features. The double feature in NGC 6537 is marginally observed in our low velocity resolution spectrum, but appears clearly in the spectrum of Pottasch (1983). If the + 26 km s^{-1} feature is interstellar, it would imply a lower limit of $\sim$ 4.0 kpc for the distance of NGC 6537. The components near 0 km s^{-1} are most probably caused by nearby, line-of-sight clouds. The feature at $\sim$ 25 km s^{-1} in NGC 2440 is interesting since it could be caused either by gas associated with the planetary nebula or by an interstellar cloud if the planetary nebula were located beyond $\sim$ 2 kpc, as proposed by Pottasch, Gathier, and Goss (1983). Single dish observations in the direction of NGC 2440 (Weaver and Williams 1973) show emission components at $\sim$ 0, 25, and 50 km s^{-1}. More detailed observations with high angular resolution are required to determine unambiguously the origin of this absorption component. The -40 km s^{-1} component in NGC 6302 has been discussed by Rodríguez and Moran (1982), who conclude that it is associated with the planetary nebula. This result was corroborated by the high angular resolution map of Rodríguez *et al.* (1984) that shows that the absorption originates in the dark lane evident in short exposure photographs. Furthermore, Lester and Dinerstein (1984) have detected an IR disk coincident with the H I absorption and optical dark lane. The component at +30 km s^{-1} in NGC 6537 is most probably due to the Sagittarius arm, as proposed by Pottasch (1983). This would imply that NGC 6537 is more distant than 1.5 kpc.

Finally, the absorption feature in NGC 7027 has a radial velocity compatible with both an interstellar or nebular origin. The detailed study of Pottasch *et al.* (1982) indicates an interstellar origin.

By analysing the correlated flux in channel zero against the distance to the center of the (u,v) plane, we obtained the total flux and angular diameter of the sources. These parameters are given in Table 3. The total

TABLE 3

DERIVED PARAMETERS

Source	Continuum Flux (Jy)	Angular Diameter (arcsec)	Radius (pc)	N_{HI} (10^{20} cm^{-2})	M_{HI} ($M_\odot$)
NGC 2440	0.34	19	0.05	9[a]	0.11[a]
NGC 2452	∿0.06	21	0.13	< 6	< 0.5
NGC 6302	1.60	15	0.09	4	0.16
Hb5	0.28	11	0.02	< 1	< 0.002
NGC 6537	0.50	11	0.02	< 1	< 0.002
NGC 7026	0.26	16	0.05	< 1	< 0.01
NGC 7027	1.30	10	0.02	< 1[b]	< 0.002[b]

a. Assuming the 25 km s^{-1} absorption component is associated with the planetary nebulae.
b. Estimate of Pottasch *et al.* (1982).

flux was obtained extrapolating to zero spacing. The angular diameter was derived assuming that the source has a circular distribution of uniform brightness. The physical radius (Table 3) was derived adopting the distance given in Table 1. We also obtained a determination or an upper limit for any H I associated with the planetary nebula. For this, we assumed the H I to be optically thin and distributed uniformly in a plane-parallel layer in front of the nebula. The column density of H I is given by

$$\left[\frac{N_{HI}}{cm^{-2}}\right] \sim 1.9 \times 10^{18}\, \tau_0 \left[\frac{\Delta v}{km\ s^{-1}}\right] \left[\frac{T_{ex}}{K}\right] ,$$

where τ_0 is the optical depth in the center of the absorption line, Δv is the HPFW of the line, and T_{ex} is the excitation temperature of the transition. We assumed $T_{ex} = 100$ K. The upper limits were estimated for $\Delta v = 10$ km s^{-1}. The values or upper limits for the column density and mass of H I are given in Table 3. The values for the masses are multiplied by a correction factor of 2 to crudely account for gas in the back of the planetary nebula, which cannot be observed in absorption. This correction factor can be considerably larger, depending on the nebular geometry, and the mass upper limits should be taken as rough estimates.

In summary, only NGC 6302 is unambiguously associated with H I. The 25 km s^{-1} absorption component in NGC 2440 should be studied further. H I does not appear to be present in the remaining planetary nebulae, at least in an amount comparable to that of H II, $M_{HII} \sim 0.01$-$0.2\ M_\odot$. For Hb5, NGC 6537 and NGC 7026 we conservatively estimate $M_{H\,I} < 0.01\ M_\odot$.

III. INTERPRETATION OF THE DATA

There are two possible explanations for the lack of significant amounts of H I in Hb5, NGC 6537, NGC 7026, and NGC 7027:

1) All or most of the hydrogen is in the form of H II (density bounded case), or 2) there is neutral gas (radiation bounded case), but it exists predominantly as H_2.

The [O I] emission from all four nebulae (Kaler 1976), and the classification of NGC 6537, NGC 7026, and NGC 7027 as optically thick in the Lyman continuum according to the criterion of Daub (1982) favors the second possibility. For NGC 7027 the presence of considerable amounts of molecular gas is further supported by the detection of carbon monoxide (Mufson, Lyon, and Marionni 1975; Thronson 1983) and molecular hydrogen (Treffers *et al.* 1974; Beckwith *et al.* 1980). We tentatively propose that the neutral hydrogen in these nebulae is in molecular form.

Glassgold and Huggins (1983) have discussed the abundance of atomic and of molecular hydrogen in the circumstellar envelopes of late-type stars. They conclude that for stars with photospheric temperatures $T_* \geqslant 2500$ K, the outflowing hydrogen is mainly atomic, whereas in cooler stars it should be substantially molecular. From our observational results and those of Pottasch *et al.* (1983) we suggest that the progenitors of Hb5, NGC 6537, NGC 7026 and NGC 7027 were cooler and less massive than that of NGC 6302 (and perhaps also than that of NGC 2440). It is interesting to point out that NGC 6302 and NGC 2440 are the sources with highest N/O ratios among the 27 Type I planetary nebulae compiled by Peimbert and Torres-Peimbert (1983). The degree of nitrogen enrichment is believed to be correlated with the mass of the progenitor.

In summary, based on the results of Glassgold and Huggins (1983), we suggest that H I may be detected only in planetary nebulae with massive, relatively hot ($T_* \geqslant 2500$ K) progenitors. Since these stars will also produce large nitrogen enhancements, H I should be searched systematically in planetary nebulae with large N/O ratios.

IV. CONCLUSIONS

Our main results can be summarized as follows: 1) We observed H I in absorption against the continuum of 7 compact planetary nebulae. With the exception of the absorption feature in NGC 6302 reported by Rodríguez and Moran (1982) and of a possible feature in NGC 2440 (that should be studied in more detail), all other absorption components are due to line-of-sight clouds and are unrelated to the planetary nebulae. 2) Upper limits for H I of $\sim 0.01\ M_{\odot}$ were derived for Hb5, NGC 6537 and NGC 7026. Neutral hydrogen in these nebulae and in NGC 7027 (Pottasch *et al.* 1982) must be predominantly molecular, which implies a relatively cool ($T_* \leqslant 2500$ K) progenitor (Glassgold and Huggins 1983). 3) Neutral hydrogen may be detectable only in planetary nebulae with relatively hot ($T > 2500$ K) progenitors. These stars will also produce considerable nitrogen enrichment. Consequently, large N/O ratios and detectable H I may be correlated.

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