MOLECULES AND NEUTRAL HYDROGEN IN PLANETARY NEBULAE

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ABSTRACT. Molecules and/or neutral hydrogen have been detected in a modest number of planetary nebulae. However, when detected, these indicators of a significant neutral component can provide fundamental information on the total mass of the envelope, its chemistry and kinematics, and on the morphology and evolutionary status of the planetary nebula. A review of recent results is presented, giving emphasis to CO (carbon monoxide), H_2 (molecular hydrogen), OH (hydroxil), and HI (neutral hydrogen). A major development of the last few years has been the capability to map with considerable angular resolution these species in planetary nebulae. In the best studied cases, the neutral component appears to be located surrounding the "waist" of a bipolar planetary nebulae. These is evidence suggesting that molecules and neutral hydrogen are not as uncommon in planetary nebula as the present statistics suggest. Indeed, the outer parts of a considerable fraction of the known planetary nebulae could be neutral. It is possible that a combination of good selection criteria and long integrations with the best telescopes could increase largely the number of known cases.

1. INTRODUCTION

Until the early seventies the conception of a planetary nebula was that of an expanding, fully ionized envelope around a very hot star. There was no room in this picture for molecules or, in general, neutral gas. However, in 1975, Mufson *et al.* detected the $J = 1-0$ rotational transition of CO in NGC 7027. The angular extent of the CO emission is about 40" (Knapp *et al.* 1982), several times larger than the size of the optical object. At least in this case, we had a planetary nebula with an important molecular component. Furthermore, by then it was becoming clear that the progenitors of planetary nebula are stars at the tip of the asymptotic giant branch, of which the OH/IR stars and the carbon stars (Habing 1988) are well established examples. These stars have massive molecular winds and it was expected that remnants of these molecular winds could be found in young planetary nebulae. This expectation has been fulfilled in part; several planetary nebulae have shown associated molecules or neutral hydrogen. However, the numbers are still very small and from the present statistics, it would appear that significant neutral components

S. Torres-Peimbert (ed.), Planetary Nebulae, 129–137.

https://doi.org/10.1017/S0074180900137714 Published online by Cambridge University Press

are unusual in planetary nebulae. One possible explanation for these low numbers is that full ionization of the planetary nebula occurs rapidly. Assuming that the envelope was formed by a constant mass-loss-rate, constant velocity, spherically symmetric wind, one can show that the time for full ionization of the envelope since the wind stopped is given by:

$$\left[\frac{t}{\mathrm{yr}}\right] \simeq 100 \left[\frac{\dot{M}_*}{10^{-5} M_\odot \mathrm{yr}^{-1}}\right]^2 \left[\frac{v}{10\mathrm{kms}^{-1}}\right]^{-3} \left[\frac{N_i}{10^{48}\mathrm{s}^{-1}}\right]^{-1}, \tag{1}$$

where $\dot{M}_*$ is the mass loss rate, v the expansion velocity, and N_i the ionizing photon rate of the central star, assumed to have appeared and stayed constant since the wind stopped. For the values given in equation (1), one finds that full ionization of the envelope takes place in 10^2 years, two orders of magnitude less than the observable lifetime of a planetary nebula. However, one could also argue that other sets of parameters will give full-ionization times comparable to the observable lifetime of a planetary nebula and that in these cases, an outer molecular envelope could be present even in "evolved" planetary nebula.

Another argument that can be used to account for the small number of detections of molecules in planetary nebulae is that, even in the favorable case that, let us say, one half of the envelope is still molecular, detection is not easy. Assuming that the CO emission of the envelope is optically thin, thermalized at about 50K, and that CO/H_2 has a ratio similar to that found in molecular clouds, one expects peak line temperatures for the $J = 1 - 0$ rotational transition of

$$\left[\frac{T_L}{\mathrm{K}}\right] \simeq 0.1 \left[\frac{D}{\mathrm{kpc}}\right]^{-2} \left[\frac{M_{H_2}}{0.1 M_\odot}\right] \left[\frac{\Delta v}{20\mathrm{kms}^{-1}}\right]^{-1} \left[\frac{\theta_B}{\mathrm{arcmin}}\right]^{-2}, \tag{2}$$

where D is the distance of the planetary nebula, M_{H_2} its mass in molecular hydrogen, Δv is the line width (about twice the expansion velocity), and θ_B is the half-power beam width of the radio telescope. For the values in equation (2) we expect line temperature of about 0.1K. These line temperature values are still hard to detect (see Knapp 1985 for typical upper limits in CO searches toward planetary nebulae).

In this review we emphasize recent observational results regarding CO, H_2, OH, and HI. Our discussion will be restricted to objects where a significant part of the envelope is ionized and can be called planetary nebulae. Transition objects have been reviewed in Kwok (1987) and Rodríguez (1987). An excellent review of results prior to 1983 was given by Black (1983).

2. RECENT RESULTS

2.1 Carbon Monoxide

The millimeter rotational transitions of CO are expected to emit close to thermal conditions. Therefore, their measurement allows (especially when combined with observations of the optically thin ^{13}CO isotopic species) estimates of masses. CO has been detected in NGC 7027 (Mufson *et al.* 1975), NGC 2346 (Knapp 1986; Huggins and Healy 1986*b*), NGC 7293 (Huggins and Healy 1986*a*); NGC 6720 (Huggins and Healy 1986*b*), NGC 6302 (Zuckerman and Dyck 1986), and Vy 2-2 (Knapp and Morris 1985).

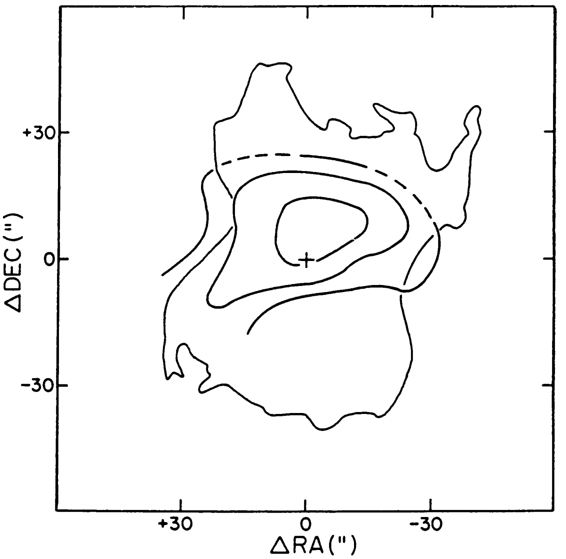

Figure 1. The integrated CO emission (thick line) down to the half-power contour is shown superposed on a sketch of NGC 2346 (thin line). The cross marks the position of the central star (actually a binary). Data from Healy and Huggins (1987) and Walsh (1983).

In these planetary nebulae it is estimated that the envelope is in good part ($>$ 10%) molecular. A surprising result, not yet fully understood, is that evolved planetary nebulae like NGC 7293 and NGC 6720 (Huggins and Healy 1986*a*; 1986*b*) still retain a molecular component.

The CO distribution has been mapped in a few cases. The best studied examples are NGC 7027 (Masson *et al.* 1985) and NGC 2346 (Healy and Huggins 1987). In both cases the molecular gas seems to be in an oblate structure perpendicular to the major axis of the ionized gas. In Figure 1 we show the integrated CO emission associated with NGC 2346 superposed on a sketch of the optical nebula (Healy and Huggins 1987). These data can be interpreted as indicating that the neutral gas surrounds the waist of the optical nebula. A natural explanation of the bipolar structure is then provided.

2.2 Molecular Hydrogen

The search for the infrared ($2\mu m$) vibration-rotation transitions of H_2 in planetary nebulae has been the most successful in the number of objects detected. Zuckerman and Gatley (1988) list 16 cases. The H_2 lines require excitation temperatures above 1000K and it is generally believed that they are shock-excited. Probably the shock is driven by the pressure of the expansion of the ionized gas. Under this interpretation, the $2\mu m$ lines trace, at a given moment, only a small, highly excited (that recently shocked) fraction of the molecular gas. Then, they can not be used as mass indicators. However, Black and van Dishoeck (1987) have analyzed the possibility of excitation by ultraviolet fluorescence. In this case, one would be detecting emission from a much larger fraction of the molecular component. Observations of higher transitions are required to assess the importance of

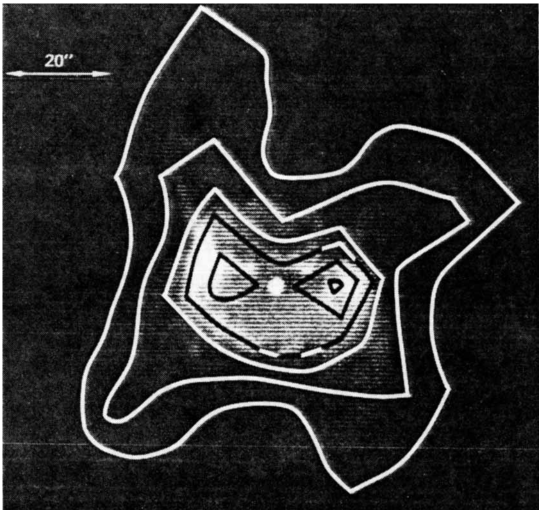

Figure 2. Contour map of the $S(1)$ $v = 1 \rightarrow 0$ molecular hydrogen emission superposed on an $[NII]$ $\lambda6584$ image of NGC 2346. Data from Zuckerman and Gatley (1988) and Balick (1987).

fluorescent excitation.

In this meeting we have seen striking examples of images of H_2 emission associated with planetary nebulae (Greenhouse, Hayward and Thronson 1988; Smith *et al.* 1988; Payne *et al.* 1988; Dinerstein *et al.* 1988). Payne *et al.* (1988) have proposed that there is a correlation between Type I planetary nebulae (Peimbert and Torres- Peimbert 1983) and strong molecular hydrogen emission. In general, the H_2 emission lies outside and closely traces the distribution of ionized gas.

As in the case of CO, there is evidence from the H_2 that in bipolar planetary nebulae the neutral gas is located around the waist of the object. In Figure 2 we show the $S(1)$ $v = 1 \rightarrow 0$ contour map of Zuckerman and Gatley (1988) superposed on an $[NII]$ $\lambda6584$ photograph (Balick 1987) of NGC 2346. As the CO, the H_2 can be interpreted to be in a torus around the waist of the nebula.

2.3 Hydroxil

The OH/IR stars, one of the most likely precursors of planetary nebulae, are characterized by the double peaked 1612 MHz maser line emission of OH. As the stellar nucleus evolved, it was expected that these objects could go through a stage where the central parts of the envelope are ionized (and could be detected via its radio continuum), while the outer parts of the envelope keep their OH maser emission. In this phase, the ionized core is optically thick at 1612 MHz and does not allow the detection of the redshifted peak of the characteristic double-peaked profile of OH/IR stars. Despite sensitive searches for radio continuum toward OH/IR-like objects (Herman, Baud and Habing 1985; Rodríguez, Gómez and García-Barreto 1985), only Vy 2-2 appeared to have blueshifted OH maser emission and radio continuum (Seaquist and Davis 1983). However, very recently, sev-

https://doi.org/10.1017/S0074180900137714 Published online by Cambridge University Press

eral other objects have been reported. Payne, Phillips and Terzian (1987) detected the 1612 MHz line and rotationally excited lines of OH at 5cm in NGC 6302. Using better defined selection criteria than in earlier surveys, Pottasch, Bignell, and Zijlstra (1987) found radio continuum in two OH/IR objects, G349.2-0.2 and G0.9+1.3. Two additional sources have been reported by Zijlstra *et al.* (1988). Obviously, OH maser emission in planetary nebulae is much more common than thought just a couple of years ago.

The best studied cases of planetary nebulae with OH are Vy 2-2 (Seaquist and Davis 1983) and NGC 6302 (Payne, Phillips and Terzian 1987). Using the VLA, these last authors have mapped the 1612 MHz emission associated with NGC 6302. The molecular gas has a considerable velocity gradient (Figure 3) and lies along the dark dust lane visible in optical photographs (Rodríguez *et al.* 1985). Once again, this dust lane is aligned approximately perpendicular to the axis of the ionized nebula.

Given the maser nature of the OH emission, this molecule can not be used for mass estimates.

2.4 Neutral Hydrogen

The 21 − cm hyperfine transition of HI appears as a good possibility to search for neutral components in planetary nebulae. However, confusion from line of sight interstellar gas makes the identification difficult and the measurement can be made reliably only with an interferometer. HI absorption against the radio continuum of the ionized core of NGC 6302 was observed by Rodríguez and Moran (1982) using the VLA. Other planetary nebulae with associated HI in absorption are NGC 6790 (Gathier, Pottasch and Goss 1986), IC 4997 (Altschuler *et al.* 1986), and IC 418 (Taylor and Pottasch 1987). Even when the amount of HI in the envelopes is subject to uncertainties as a result of the unknown excitation temperature, it seems that roughly comparable amounts of neutral and ionized hydrogen are present.

HI is, as CO and the other molecules, expected to be present as long as the envelope is not fully ionized. There is, however, an additional restriction in the case of HI; the neutral hydrogen present could well be in molecular, as opposed to atomic, form. Following the theoretical considerations of Glassgold and Huggins (1983), Rodríguez and García-Barreto (1984) have argued that detectable HI may exist only for planetary nebulae with relatively hot ($T_* > 2500$K) progenitors. For stellar temperatures above this value hydrogen is mainly atomic in the wind, while for values below, it is mainly molecular.

The HI in absorption associated with NGC 6302 has been mapped by Rodríguez, García-Barreto and Gómez (1985). The location of the HI (Figure 4) coincides with the dark dust lane and with the OH emission (Payne, Phillips and Terzian 1987; see Figure 3). Once more, the interpretation implies a neutral torus around the waist of the optical nebula.

2.5 Other Observational Results

CN has been detected in NGC 7027 (Thronson and Bally 1986), while HCN has been detected in the same object (Sopka *et al.* 1988) and in NGC 2346 (Walsh, Clegg and Ukita 1988). These results confirm the carbon- rich chemistry of both planetary nebulae.

An optical astronomer may wonder why lines as [O I] λ6300 or [N I] λ5200 are not included in this discussion of neutral gas in planetary nebulae. The usual argument is that

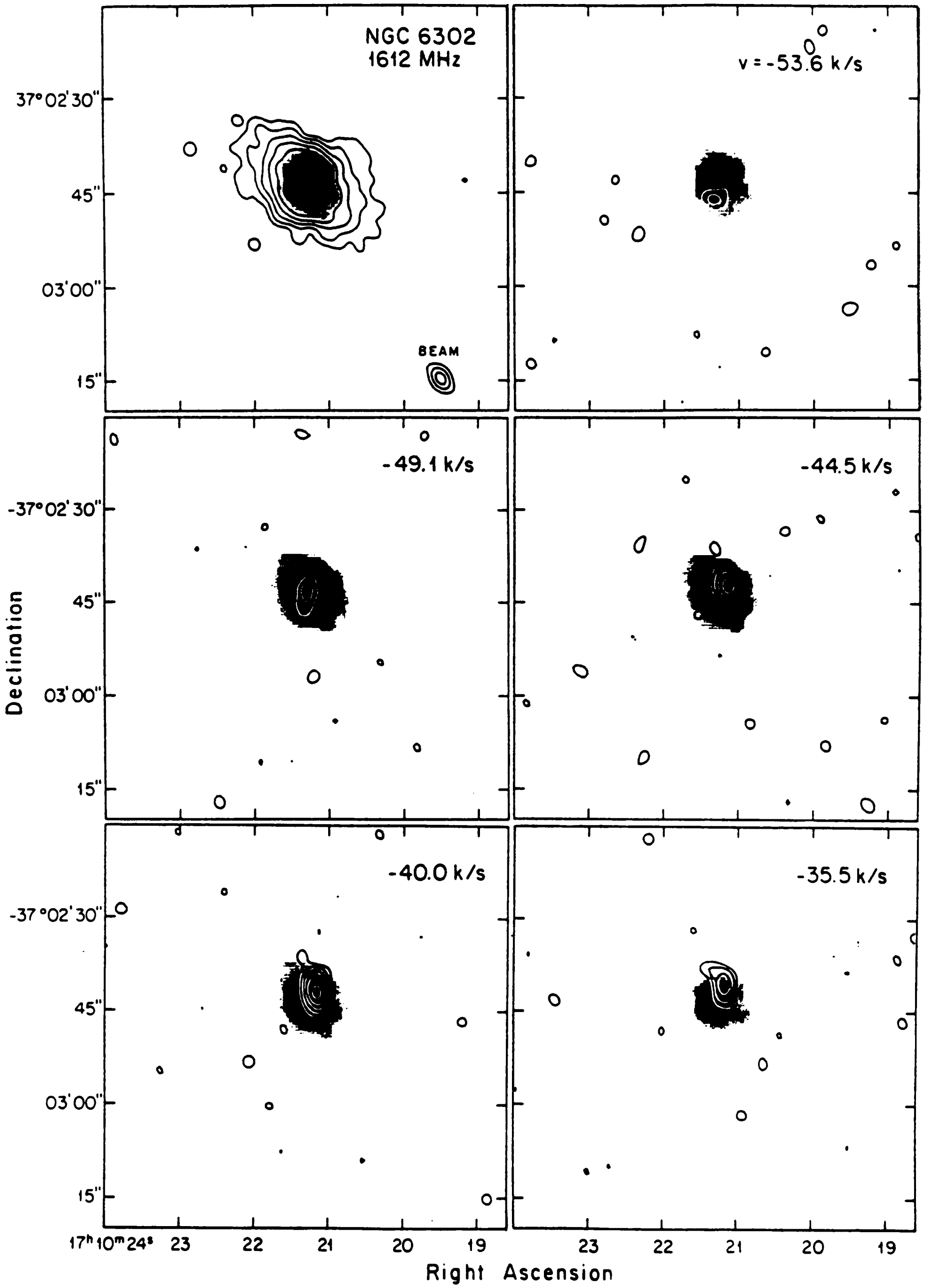

Figure 3. VLA 1612 MHz and continuum maps from Payne, Phillips and Terzian (1987). The continuum map is shown in the upper left panel. The 1612 MHz emission at different radial velocities is shown in the other panels. All panels include contour and grey scale representations.

https://doi.org/10.1017/S0074180900137714 Published online by Cambridge University Press

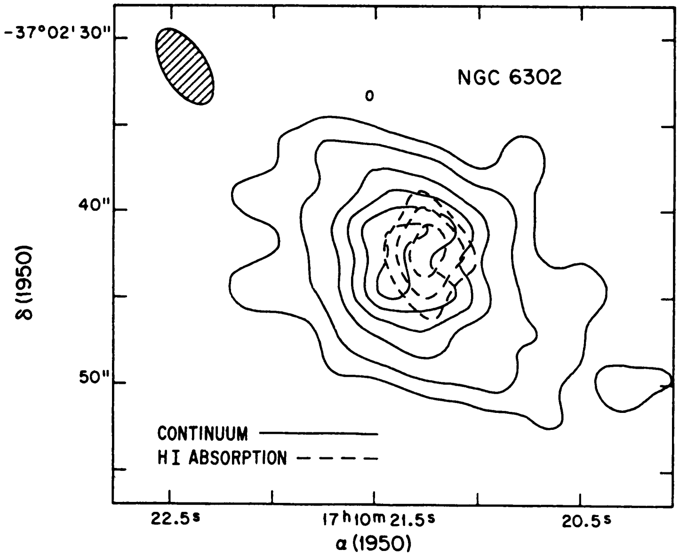

Figure 4. *HI* absorption (dashed lines) superposed on the continuum (solid lines) of NGC 6302, taken from Rodríguez, García- Barreto and Gómez (1985). The *HI* absorption coincides spatially with the optical dark dust lane and the *OH* emission (Payne, Phillips and Terzian 1987).

these lines originate in the transition zone where hydrogen goes from ionized to neutral and, consequently, only small amounts of gas are being traced. However, several of the planetary nebulae discussed here also have these optical lines and it is obvious that some kind of correlation could exist. Unfortunately, very little has been made to explore it in detail.

3. DISCUSSION

The field of neutral gas in planetary nebulae has had important advances in the last few years. Nevertheless, the number of objects detected in the tracers discussed here is very small. Does this mean that most planetary nebulae are density bounded (that is, fully ionized)? This conclusion is hard to accept because other results suggest the opposite. The well known mass-radius correlation (Maciel and Pottasch 1980) can be taken to imply that most planetary nebulae are ionization bounded (see Gathier 1987 for a recent discussion). In brief, it is found that $M \propto R^{1.5}$, as expected for massive envelopes that remain ionization bounded over most of the planetary nebula lifetime.

To complicate matters further, in this meeting we have seen that ionized halos are common around planetary nebulae (Chu 1988). This result is consistent with the rarity of molecules, since apparently a density bounded planetary nebula is needed to ionize a halo. However, the mass-radius correlation also seems well established and we have a controversy over such a seemingly simple issue as whether most planetary nebulae are density or ionization bounded.

Some of the results discussed here may offer an explanation. It is known that about 50% of the planetary nebulae are bipolar (Zuckerman and Aller 1986). At least for the bipolar nebulae discussed here it makes no sense to try to classify them as either ionization bounded or density bounded. They are both, ionization bounded in the waist, and density bounded in the poles. Is this situation common and thus all our classification of planetary nebulae as either ionization or density bounded dubious? I do not think the answer is known.

Given the present state of uncertainty, one could argue that most planetary nebulae have sizable neutral components yet undetected. In what refers to CO, a major search program with the new millimeter and submillimeter radio telescopes in Nobeyama, Pico Veleta and Mauna Kea appears worthwhile. Along the same lines the VLA and Arecibo could possibly yield additional OH and HI detections if the selection criteria were improved. Finally, the fast mapping that the new infrared arrays are capable of achieving should reveal H_2 in a considerable number of planetary nebulae.

4. CONCLUSIONS

I reviewed the recent observational developments regarding molecules and neutral hydrogen in planetary nebulae. When the neutral mass can be determined it turns out to be comparable with that of the ionized gas. In the best studied cases the neutral gas is located in a torus around the waist of a bipolar planetary nebulae.The number of planetary nebulae with a sizable neutral component remains small. At present it is unclear if this implies that most nebulae are density bounded or if we are still sensitivity limited. A major observational effort with the new millimeter and submillimeter radio telescopes could solve the issue.

The theoretical aspect is, in general, poorly developed. There could be more objects like NGC 6302 where hydrogen is present in ionized, atomic, and molecular form. Detailed models for the structure of these nebulae are not available.

Another important result that emerges from the study of planetary nebulae with molecules or neutral hydrogen is that, at least for the bipolars, one can not classify them as either ionization or density bounded, since they are both: ionization bounded in the waist and density bounded in the poles. Since about half of the planetary nebulae are bipolar, this ambiguity could be a major problem for methods (*i.e.* distance scales) that segregate nebulae into ionization bounded and density bounded.

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