Molecular line mapping of (young) planetary nebulae

Valentín Bujarrabal

1Observatorio Astronómico Nacional (OAN, IGN), Ap. 112, 28803 Alcalá de Henares, Spain
E-mail: v.bujarrabal@oan.es

Abstract. In this contribution, I will review recent results obtained from high-resolution observations of molecular emission of planetary nebulae in the millimeter and submillimeter waves, stressing the easy interpretation of the data and the great amount of quantitative results obtained from them. Radio interferometers have been shown to be very efficient in the observation of our objects and, particularly since the arrival of ALMA, the amount of results is becoming impressive. We will deal mainly with young planetary nebulae or protoplanetary nebulae, since, as we will see, molecular lines tend to be weak in evolved objects because of photodissociation. In relatively young nebulae, the molecular gas represents most of the nebular material and can be well observed in line emission in mm- and submm-waves. Those observations have yielded many quantitative and accurate results on the structure, dynamics, and physical conditions of this largely dominant nebular component. In more evolved sources, we can follow the evolution of the chemical composition, although the data become rare.

1. Introduction

This is a review talk intended, following suggestions of the organizers, to present the general properties of molecular line emission in planetary nebulae and to summarize recent results obtained from imaging of molecular lines in these objects.

Molecular lines in the mm- and submm-wave regimes are very useful tools to study planetary nebulae (PNe). In these objects, in which the central star is often hot, photodissociation by the stellar UV field becomes a key process. Molecules are very abundant in young PNe and protoplanetary nebulae (PPNe), and, as we will see, molecular gas is the dominant component, representing the bulk of the nebular material. However, in more evolved nebulae molecules are mostly destroyed because of the increasingly strong UV field and diffuse nebular shells (which allows photon penetration across the nebula), see e.g. [1]. At some intermediate point, when photodissociation is already efficient, radicals appear and can be relatively abundant, due to photon-induced chemistry [2], but with a trend to molecular destruction and weak molecular lines. Photodissociation from interstellar UV [3] is also important in PNe, limiting the outer extent of the molecule-rich shells, as already occurs in the AGB circumstellar envelopes. As a result, very extended outer halos are not detected in molecular line emission. However, due to presence of a very important increase of the mass-loss rate in the very late AGB phases (or very early post-AGB phases), the amount of material in the inner shells that are not affected by the interstellar UV field is much larger than that in the outer halos. The actual outer limit of the molecular shells is in fact given by a significant increase of density in those inner layers [4, 5].

Carbon monoxide is by far the most abundant molecule emitting at these frequencies and, in spite of its low dipole moment, that showing the strongest lines. CO is also known to...
be the molecule that better survives photodissociation, because its high abundance leads to a very important self-shielding [3]. As a result, most molecular observations of PNe and PPNe have been performed in CO lines, mostly in CO rotational lines, because of the low excitation requirements of these transitions. Other molecules have been rarely mapped with high resolution, because of their lower intensities (they are significantly less abundant) and small and irregular extent (they tend to occupy only regions with a peculiar chemistry). Most of the results I will show here come from observations of CO rotational lines.

1.1. Excitation of molecular lines: CO rotational transitions

CO rotational lines are characterized by their low excitation energy and Einstein coefficients. As for most observed molecules, the rotational levels of CO (in the ground vibrational and electronic states) are placed at a low energy over the ground. The excitation energy of the first excited level, \( J=1 \), is only of about 5 K; the energy of other levels is proportional to \( J(J+1) \). The low-\( J \) transitions of CO (allowed only if \( \Delta J \) is equal to 1, i.e. \( J=1-0, J=2-1, \ldots, J=6-5 \), etc) therefore require very low excitation conditions, present even in the cool molecule-rich gas. These low level energies lead of course to low emitting frequencies, which can be efficiently observed with radio interferometers: for the abundant isotope \(^{12}\text{CO} \), \( \lambda(1-0) = 2.7 \text{ mm}, \nu(1-0) = 115 \text{ GHz} \), and \( \nu(J-J-1) \) is proportional to \( J \).

The Einstein A-coefficients of those lines, which give the spontaneous radiative deexcitation probability, are also particularly low, due to the anomalously low permanent dipole moment of CO. For instance, the value of the A-coefficient of \( J=2-1 \) is just \( 6.9 \times 10^{-7} \text{ s}^{-1} \); for other transitions \( J \rightarrow J-1 \), \( A \) roughly varies with \( J^3 \). As a result the collisional transitions between the CO low-\( J \) levels easily dominate over radiative ones and the low-\( J \) lines are easily thermalized to the kinetic temperature; note that the probability in \( \text{s}^{-1} \) of the inelastic collisional transitions is typically \( \sim 10^{-10} n \), where \( n \) is the total density in \( \text{cm}^{-3} \). Therefore, the excitation temperature of these transitions is often very similar to the kinetic temperature, \( T_{\text{exc}} \sim T_k \), allowing the definition of a rotational temperature \( T_{\text{rot}} = T_{\text{exc}}(\text{low}-J) \). Detailed excitation calculations for our sources confirm this result [6], the mm-wave transitions of CO, \( J=1-0 \) and \( J=2-1 \), are thermalized for \( n \gtrsim 10^4 \text{ cm}^{-3} \). Higher-\( J \) transitions, in the submm or FIR, require higher, but in any case moderate, excitation conditions [7]. In any case, because of the simple level structure and efficient collisional excitation of the carbon monoxide rotational ladder, detailed calculations of the level populations and line intensities are in our case simple and reliable.

The same conclusions apply for rare isotopic substitutions of CO, like \(^{13}\text{CO} \). Their observations, in combination with those of \(^{12}\text{CO} \), are particularly useful, because the \(^{13}\text{CO} \) lines also present favorable excitation conditions but show a much lower optical depth, with often optically thin emission, allowing the analysis of the opacity effects.

Because of the low temperatures of molecule-rich gas in PNe and PPNe, only rotational lines in the ground vibrational state are observed for almost all molecules (only a few vibrationally excited lines are detected, including notably some lines of HC3N and, of course, H2 emission, which is not discussed in this contribution). For other molecules, the line excitation tends to be more difficult to describe, but calculations can be performed, using for instance the well known LVG approximation, which is very efficient and justified in our case (large macroscopic velocities are almost always present in PNe, but we will see some exceptions later). The line emission of rarer molecules depends more critically on the density and temperature, and observations often select condensations (in which, moreover, it is easier for those species to survive UV effects).

2. Molecular lines in protoplanetary nebulae

Very young PNe or PPNe represent a particularly important phase in the late stellar evolution, because in them the spectacular post-AGB dynamics is still active and the typical PN axisymmetric shapes incipiently appear. For the definition and identification of PPNe, the
pioneering work by Kwok and colleagues [8, 9] is often followed. As expected, the SEDs of PPNe show already that the star is not loosing material at present, with two-component shapes due to the stellar and the nebular emissions, but does not show yet the high-excitation characteristics of PNe. Many of the PPNe studied in molecular lines (and by other means) have been identified from those properties.

2.1. M 1–92: an example of the power of molecular line mapping

M 1–92 is a protoplanetary nebula that can be very well studied using molecular lines. A lot of quantitative and accurate information on the nebula structure, velocity, and physical conditions has been derived. It was first mapped in CO lines in the 90’s, using the Plateau de Bure interferometer (PdBI) [10]. The maps reveal a double bubble with a radial expansion velocity characterized by a clear linear gradient (a Hubble-like field). The velocities are high, \( \sim 70 \text{ km s}^{-1} \) at the tips of the nebula. The total mass derived from CO emission is \( \sim 1 \text{ M}_\odot \), and about 0.5 \( \text{ M}_\odot \) are found to be in expansion at \( \sim 30 \text{ km s}^{-1} \). This implies a very high linear momentum, much higher than what radiation pressure can provide, showing that other engine was necessary to power the nebular dynamics. Densities of about \( 10^5 \text{ cm}^{-3} \) were found and the molecule-rich gas was shown to be cold, \( T_k \lesssim 30 \text{ K} \). Molecular gas represents by far the dominant nebular component and probably includes most initial stellar mass, now ejected to form the nebula. These properties are found to be characteristic of PPNe and young PNe and similar results are found in M 2–56, CRL 618, HD 101584, OH 231.8+4.2, the Boomerang Nebula, NGC 7027, etc.

![Figure 1. CO-line maps of M 1–92, adapted from [11]. Left: position-velocity diagram along the nebula axis. Center: the same for the central region of the nebula. Right: maps of the center of the nebula for selected velocities. The radial velocity gradient is remarkably constant and holds even very close to the star and for very low velocities.](image)

Some years later, M 1–92 was mapped again with the PdBI [11], reaching a resolution higher than 0′′5. A very accurate description of the nebula was obtained, see Fig. 1. In particular, the linear velocity was found to apply down to distances \( \lesssim 0′′3 \) (around \( 10^{16} \text{ cm} \)) and expansion velocities of about 1 \( \text{ km s}^{-1} \). Surprisingly, in equatorial regions close to the central star, the expansion velocity of this source is significantly smaller than the expansion velocity in AGB circumstellar envelopes (in general \( \sim 10 \text{ km s}^{-1} \)). It is not yet understood if this persistent velocity gradient, also found as we will see in other objects, is due to ejection of material starting not from the star but from a stable disk (probably in rotation, but not yet detected in this source) or to a peculiar ejection process that takes place in the very late AGB and could involve binary interaction [11].
2.2. Data of other PPNes and young PNe

Among other recent observations, we can mention those of IRAS 19475+3119 [12], a PPN identified from the properties of its SED. These data are part of COSAS, a big survey of observations of evolved nebulae performed with the PdBI. CO data confirmed its classification as PPN. IRAS 19475+3119 shows a central empty region and a bipolar outflow sharing the main results found in M 1–92, including the linear velocity gradient and high mass and momentum.

A particularly well studied object is CRL 618. It was first observed with OVRO [13]. The general properties of the complex nebula where derived, CRL 618 was found to be composed of a dense halo extending more than $10^{17}$ cm and expanding at moderate velocity, a central equatorial region very dense and expanding a low velocity (which decreases towards the center down to less than 5 km s$^{-1}$), a double bubble, and a very fast outflow inside the bubbles with velocities that increase to more than 300 km s$^{-1}$. CRL 618 was later observed in CO $J=3–2$ with the SMA [14], with a resolution as high as 0.′′3. The very fast jet was resolved and found to be composed of multiple outflows and to show a bow-like tip apparently due to shock acceleration. These authors [15] also mapped the source in lines of other molecules, namely HCN and HC$_3$N, which were found to be mainly confined to the dense central region of the slow condensation. For more details, see contribution by Lee et al. to this symposium.

Data of similar sources have been recently obtained with ALMA. HD 101584 was found to show a high-mass double bubble with a clear linear velocity gradient [16]. Velocities are very high in this source, higher than 100 km s$^{-1}$ in the prominent condensations placed at the tips of the bubbles. These results, together with maps of other molecules that show the presence of rich chemical processes, are discussed in the contribution by Olofsson et al. The Boomerang Nebula, a source that seems to show a very cold and fast outer halo, was also observed with ALMA [17]. The data mainly give information on the central part of the nebulae, again a double bubble expanding at high velocity. ALMA observations of other young PNe (NGC 6302, Mz–3, OH 231.8+4.2, ...) have also yielded impressive data, but they are still under analysis.

A source that presents a completely different distribution of molecule-rich gas is M 2–9. M 2–9 is thought to harbor in its center a binary star and shows a beautiful butterfly-like nebula in the optical that extend almost 1'. However, high-quality observations performed with the PdBI [18] have shown that molecules are only abundant in two equatorial rings. As the rest of the data we are presenting until now, the rings are expanding, in this case with quite low velocities, respectively at 4 and 8 km s$^{-1}$. They correspond apparently to two ejection events separated by about 500 yr. The mass of the rings is low, 0.05 $M_\odot$, about a 20% of this nebula, most of whose (relatively low) mass is placed in a PDR. A careful analysis of the M 2–9 maps has shown that the centroids of the rings both in position and velocity are slightly but noticeably different. The easiest explanation is to assume that the ejections of the rings took place in two different phases in the orbit of the post-AGB star, such that the systemic velocities of the rings are different, which also yields a detectable difference in the position of the center of the rings after several hundred years; the process is similar to that thought to yield the spiral-like structures found in many AGB and post-AGB sources (see contributions by Maercker, Quintana-Lacaci, and colleagues). Assuming this scenario, it is possible to derive the orbital parameters, it was in particular found that the mass of the secondary is very low, $<0.2$ $M_\odot$.

I will finally mention the SMA maps of NGC 7027 [19], a nebula surrounding a very hot blue dwarf that is often catalogued as a young PN. The maps show a double elongated shell that surrounds the optical image of the nebula. Those maps were analyzed in combination with single-dish (i.e. low-resolution) observations of low- and high-$J$ CO lines [20], including FIR lines up to $J=16–15$ observed with Herschel/HIFI. For the analysis, the code SHAPEMOL was used, which allows predicting brightness distributions and angle-integrated profiles of molecular lines from PNe and PPNes. The use of low- and high-excitation lines allowed the identification and study of warm layers, which in this source are particularly important. The molecular shell
was divided for modelling purposes in 4 adjacent subshells (I, M1, M2, and O), in the center of
which a PDR, an HII region, and even X-ray emitting gas are placed (Figs. 2, 3). In addition,
two fast axial clumps are found to remain molecule-rich within the hot gas. The properties of
the inner molecular subshell (labeled I) are remarkable: it is found to be faster and denser than
outer regions. It is probably a thin layer compressed by the expansion of the HII region, an
example of the interacting wing paradigm, expected to affect the evolution of many PNe [21].

![Figure 2. Sketch of the model deduced for NGC 7027 from maps and single-dish observations of molecular lines, adapted from [20]. The description of the nebula structure is particularly detailed for this source.](image)

3. More evolved nebulae: rings, bullets and globules
As mentioned, the effects of photodissociation are very relevant to understand the properties
of molecule-rich components in evolved planetary nebulae. Often, molecules only survive the
stellar UV effects in dense regions in which shielding is particularly important.

In many PNe, the densest regions are equatorial rings or tori and molecules are often abundant
only in such regions. This is the case of NGC 6720, the Ring Nebula [22]. The line emitting
region is a ring similar to the optical image but slightly more extended. The probed mass is
relatively low, 0.1 $M_\odot$, confirming the effects of photodissociation, but still larger than the mass
detected by other means, particularly from ionized gas emission. The characteristic temperature
of the molecule-rich gas is low, $\sim 30$ K, and the (expansion) velocity is moderately high, $\sim 20$
$km\,s^{-1}$, somewhat higher than in most AGB stars. Similar properties have been found in other
PNe, in which molecular emission only comes from equatorial regions. This is the case of, for
instance, M1–16, which shows a ring like emitting region, in spite of the very extended axial
extent [23], and of NGC 2346, KjPn 8, the Helix Nebula, etc.

A completely different case is that of BD +30 3639. This source show molecular line emission
coming from two clumps flowing very fast along the nebula axis [24], at $\sim 50$ km\,$s^{-1}$. In this

![Figure 3. Details of the physical conditions deduced for the molecular shells of NGC7027, adapted from [20].](image)
source, the high density of the axial condensations, probably similar to the fliers (fast low-ionization emission regions) detected in other wavelengths, preventing photodissociation, while a ring-like equatorial feature is found to be ionized.

Another interesting case is the Helix, whose large angular size ($\sim 15'$) allowed high-quality maps years ago [25]. Complex structure and dynamics are found, the nebula apparently shows several superposed components with quite different velocities. As for the Ring Nebula, CO is mostly placed in a ring, similarly but slightly more extended than the well-known optical image. The high expansion velocities found are remarkable. Although the ring is placed almost in the plane of the sky, velocities projected in the line of sight as high as 25 km s$^{-1}$ were measured. It was also possible to map one of the cometary globules detected in the optical [26]. The molecule-rich gas is placed behind the optically bright head, which is able to shield molecular gas from the stellar UV. Again, it was possible to derive physical conditions of the molecule-rich clump, which was found to be massive, $\gtrsim 10^{-5}$ M$_{\odot}$ (a lot for such small features), and cold, $\sim 25$ K.

Figure 4. Observations of one of the globules detected in the Helix Nebula [26]. The integrated emission and several velocities are shown, together with images at other wavelengths. The head of the globule seem to be shielding the molecule-rich gas from the stellar UV (which comes from the south in this case).

4. Keplerian disks around post-AGB stars

To finish, I would like to present studies of a kind of objects in which I have been working in the last years: Keplerian disks orbiting post-AGB stars. Practically all the gas we detect in post-AGB nebulae, PPNe or PNe, is found to be in expansion. In particular, all the observations I have mentioned before reveal only the presence of expanding gas. However, rotating disks are particularly important to understand the reaccretion of circumstellar material by the post-AGB star (or a companion) and the launching of the very fast post-AGB jets. These post-AGB jets are thought to generate shocks when impinging the previously ejected gas, which contains most of the nebular material, accelerating it and so explaining the high axial velocities and bipolar shapes found in most PPNe and PNe, see e.g. [27] and the contribution by B. Balick to this symposium. Such rotating disks have been very elusive for our telescopes, particularly due to the need of very accurate spectroscopic mapping. Until two years ago, equatorial gas in rotation
had been well detected only in one post-AGB object, the Red Rectangle, by means of PdBI maps of CO lines [28]. The Red Rectangle belongs to a relatively wide class of binary post-AGB stars which were suspected to be surrounded by rotating disks, see [29], [30], etc. These sources show some characteristics that suggests the presence of disks. In particular, their SEDs show, together with the usual two-maxima structure, a remarkable NIR excess that can be explained by the presence of hot dust kept in some way close to the star. This stable component should in principle be in rotation. A new argument supporting the presence of rotating disks in these sources was recently published [31]. Single-dish observations of CO emission systematically show peculiar line profiles, narrow and with a prominent central peak. Such profiles, found also in the Red Rectangle, are expected in Keplerian disks, both from previous observational data and theoretical predictions [31]. These disks detected in molecular line emission must be extended, around $10^{16}$ cm, much more than the tiny disks invoked to explain the NIR excess, which would just occupy $\lesssim 10^{15}$ cm. The CO profiles in these sources also show relatively intense wings, which were suggested to be due to the presence of low-velocity outflows (together with the disks).

![Figure 5](image)

**Figure 5.** ALMA observations of the Red Rectangle in $^{12}$CO $J=3-2$ emission, superposed on an HST image. Note the emissions of the equatorial rotating disk, in the central velocities, and of the outflowing gas, the X-shaped feature at more extreme velocities. Adapted from [32].

Recent ALMA observations of the Red Rectangle have spectacularly confirmed the presence of the rotating disk as well as of a faint outflow, probably composed of gas escaping the disk [32]. These data included high-quality maps of the $J=3-2$ and $J=6-5$ lines of $^{12}$CO and rare isotopes; a resolution as high a $0'025$ and a S/N ratio of several hundred were obtained, allowing the identification of the different components. The maps of different lines, with different excitation requirements and opacities, also help in the analysis, allowing a good study of the physical conditions, although sophisticated numerical treatments are necessary, since LTE is not satisfied by high-$J$ lines and the LVG approximation does not apply in the presence of rotation.

Two other NIR-excess post-AGB stars, 89 Her and IRAS 19125+0343, have been mapped with high resolution, but in them only outflowing gas was found. The disks may be hidden in a central unresolved condensation. Only very recently, a new rotating disk has been well detected around one of these NIR-excess post-AGB stars, AC Her [33]. The Keplerian disk is very well identified from the position-velocity diagram, but no trace of expanding gas is found. New ALMA data of IW Car, which remain to be well analyzed and are not yet published, have found a third Keplerian disk. In this case, outflowing gas is also detected. With all these (more or less new) data, we can conclude that extended Keplerian disks are systematically present in
this class of post-AGB objects with NIR excess. Their mass is relatively small, $\lesssim 10^{-2} \, M_\odot$, but, in most cases, it represents most of the detected nebular material. The temperature of the disk gas is high, compared with molecule-rich gas in most PNe, reaching in most cases, it represents most of the detected nebular material. The temperature of the disk is high, in general over 100 K in central regions.

Molecule-rich outflows with moderate velocity, $\sim 5 \, \text{km} \, \text{s}^{-1}$, also seem to be systematically present in these NIR-excess post-AGB stars. Their mass is also small, in general smaller than that of the disk, and their temperature is also high, in general over 100 K. Comparing the mass and velocities of the outflow with that of the disk, we can deduce the lifetime of the rotating structures, provided that the mass ejection rate is kept roughly constant. The estimates are uncertain, but we get from the different observations quite coherent lifetimes of $\sim 10000$ yr. This time is short but not much shorter than the total life of detectable PNe, around 20000 yr. Therefore, it seems that the disk-phase is not a minor stage in the post-AGB evolution of these binary stars and that disks could survive around a significant fraction of PN central stars.

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