Molecules as Tracers of PN Structure

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Abstract. Molecular gas plays an important role in the structure of planetary nebulae: it is a major component of the equatorial tori of bipolar nebulae, it forms the cores of globules and related microstructures, and is the likely origin of multiple arcs. It is also a key component during the early stages of formation where interactions with outflows or jets provide an important shaping mechanism.

1. Introduction

The matter that evolves into a planetary nebula (PN) is initially ejected during the AGB and proto-PN phases, largely in the form of molecular gas. The structure in this gas and its response to ionizing radiation and fast winds or jets from the central star are important features of PN formation. In this paper we briefly describe and comment on some recent results which focus on this structural development.

2. Precursor Envelopes and Multiple Shells

We turn first to the structure of AGB envelopes which is basic for understanding PNe since it determines the environment in which the nebulae form. It is also crucial for understanding the mass-loss process and has been widely discussed (e.g., Olofsson 1999). A recent, valuable contribution on this issue is the atlas of circumstellar envelopes by Neri et al. (1998), which contains maps of 46 envelopes in the CO (1–0) and (2–1) lines, made using the IRAM telescopes. With respect to the structure of the envelopes, the authors conclude that within the sensitivity of their observations, AGB and post-AGB envelopes are for the most part spherical, with evidence for an inner shell and/or significant asymmetry in 30% of the sample. In fact, most of these cases are in the former category, so the truly asymmetrical envelopes are not very common. This is in marked contrast to the widespread asymmetries in the ionized gas of PNe, discussed throughout this volume.

One interesting question that arises in this context is: just how regular and symmetric is the mass loss of a typical AGB star? A good example with which one can address this question is the archetype of carbon-rich AGB stars, IRC+10216. The molecular envelope of IRC+10216 has been intensively observed for more than a decade using millimeter interferometry, in order to study the chemistry. Recent results are reviewed by Lucas & Guélin (1999). A key
point relevant to the structure of the envelope, is that some molecular species are observed to form more than one layer around the star, and the peaks of several species coincide, which suggests the presence of an underlying physical shell structure. About three distinct shells can be identified within $\sim 25''$ of the star (see Fig. 4 of Lucas & Guélin 1999).

This multiple shell picture of the envelope of IRC+10216 has recently been extended at optical wavelengths (Mauron & Huggins 1999). Deep images obtained with the CFHT reveal the envelope of IRC+10216 in dust-reflected, Galactic light. The left hand panel in Fig. 1 shows a $V$-band image, with a field of 223″, and the the right hand panel shows a close-up of the center, enhanced to show details.

The figures show that the envelope is not smooth, but consists of a series of nested, limb-brightened shells. The inner shells show a rough correspondence to those in the molecular gas. The shells are not complete in azimuth, and are separated by somewhat irregular intervals that correspond to time scales of $\sim 200$–800 yr. This structure appears to be a basic feature of the mass-loss process but is not yet understood: the time scale is much longer than the stellar pulsation period, but is much shorter than the interval between the thermal pulses.

The presence of these shells in the archetype AGB envelope is especially significant in the context of recent HST observations of multiple arcs (with similar spacings) in a half-dozen proto-PNe and young PNe (see Terzian, this volume). The number of cases found already suggests that they may be common, and may well be the norm for certain classes of objects. These arcs can almost certainly be identified with the shells seen in IRC+10216 – at a more advanced stage of evolution – so their origin can be traced back to the formation of the molecular/dust shells in the precursor AGB envelopes.
3. Molecular Gas in PNe

In spite of major changes in the mass loss and the onset of photo-ionization through the post-AGB phase, a significant component of molecular gas is found in many bone fide PNe, even in highly evolved cases. The most widely detected molecular signatures are the 1.3 and 2.6 mm lines of CO and the 2 µm vibrational lines of H₂. Recent survey work has been reported by Huggins et al. (1996) and Kastner et al. (1996) for CO and H₂, respectively, with more than 40 PNe detected in each species. Additional examples are continually being added to the lists (e.g., Josselin et al. 1999; Hora & Latter 1999). Other molecular species are also detected in the neutral gas, even in some evolved cases (Bachiller et al. 1997), and various aspects of the chemistry have recently been discussed by Natta & Hollenbach (1998), and Howe & Williams (1998).

The molecular gas is found predominantly in PNe at low Galactic latitude, and there is a strong correlation with morphology (e.g., see Fig. 2, right panel), which suggests that we detect the nebulae with higher mass progenitors. There is no doubt about the location of the gas. Except in the youngest PNe where the envelopes may still completely enshroud the nebula, the molecular gas is found around the waist of the ionized gas, in shapes variously described as rings, cylinders, or toroids.

One example which illustrates the relation of the molecular gas to the nebula is M2-9. This young ($\tau_{\text{exp}} \sim 1,500$ yr), bipolar PN is well known from imaging with HST. It is seen nearly sideways-on, and is dominated by elongated, twin outflows or jets. The H₂ emission in M2-9 lies along the edges of the cylindrical structure formed by the jets (Hora & Latter 1994). The CO emission, which traces the densest gas, is found only in a slowly expanding ($V_{\text{exp}} = 7$ km s⁻¹) torus which fits tightly around the waist of the nebula (Zweigle et al. 1997).
A second example is the Helix nebula (NGC 7293) which is a much older system ($\tau_{\text{exp}} \sim 10,000$ yr), seen nearly end-on. The 2 µm H$_2$ emission has been imaged by Kastner et al. (1996) and the whole nebula has recently been mapped in the CO(2–1) line by Young et al. (1999). The left panel of Fig. 3 shows an $R$-band image of the Helix (mainly H$\alpha$ and [N II]), and the next panel shows the CO map. These two views are quite similar: it is evident that the ionized nebula abuts the envelope and has formed through photo-ionization of the neutral gas. Thus, in both the Helix and M2-9, and in many other PNe as well, the molecular gas is a main structural feature of the nebula and an important key to its morphology.

The mass of molecular gas in the PN envelopes is not easy to determine, even though the major constituent (H$_2$) is directly observed. This is because the 2 µm emission arises from high lying levels (> 6000 K) and typically samples only a small fraction of the gas. (For recent work on whether shocks or ultraviolet radiation excite the lines, see Hora & Latter 1999). More useful mass estimates come from the low lying lines of CO, which are thermalized under a wide range of conditions. The CO fluxes can be used to estimate the total number of CO molecules, and with reasonable assumptions on the CO abundance lead to an estimate of the mass. Masses estimated in this way range up to a few $M_\odot$.

To illustrate the evolution of the envelopes, the mass ratio of molecular to ionized gas in a large number of PNe is shown in Fig. 2 (left panel) vs. PN size – which is a rough measure of the age. The upper envelope of this plot defines a striking evolutionary trajectory for PNe with a significant molecular component (statistically the bipolar PNe): the young PNe are dominated by the envelope, which remains a significant component of the circumstellar gas until they reach a size of $\sim 0.1$ pc. In other PNe, the molecular gas is photo-dissociated more rapidly.

In addition to the molecular gas, there is, not surprisingly, ample evidence for neutral atomic gas in PNe, e.g., from observations of the 21 cm line and infrared fine structure lines. This gas is in interface regions between the molec-
ular and ionized gas, and in envelopes that are essentially completely atomic. The masses in these components are substantial (e.g., Taylor et al. 1990; Dinerstein et al. 1995; Young et al. 1997), but they have not yet been studied in large numbers of PNe or at high angular resolution, so they do not yet provide a systematic or detailed picture.

4. Large and Small Scale Structure in the Molecular Gas

The detailed structure of the molecular gas in PNe is of considerable interest since it contains information on the physical processes that produce the nebulae. For space considerations, we focus here on one example, the Helix nebula, which is among the nearest PNe and can be examined with high spatial resolution.

One aspect of the structure in the gas is the high degree of fragmentation. The cometary globules located within the inner, ionized gas are well known from optical imaging with HST, and have been discussed by O’Dell & Burkert (1997). Millimeter CO observations have shown that the globules have dense cores of molecular gas (Huggins et al. 1992); in fact without this structure it would be hard to account for their presence in large numbers, because they would be rapidly photo-ionized and disperse on short timescales, compared to the age of the nebula. Recent work by Meaburn et al. (1998) shows that the globules have kinematic similarities to the inner CO ring seen in Fig. 3, and it seems likely that they share a common origin with the more extended molecular envelope.

This envelope itself is also highly fragmented. The clumpy structure in the CO map in Fig. 3 (resolution 30″) is seen to consist of many smaller clumps at higher resolution (see Huggins 1999). The masses of the clumps cannot be more than an order of magnitude more than the cometary globules in the ionized gas, and they share remarkably narrow line widths of \( \sim 1 \text{ km s}^{-1} \). These fragments appear to be close cousins of the cometary globules, and probably represent a slightly earlier stage in the development of these structures.

This picture of a fragmented torus is confirmed by observations with ISO (Cox et al. 1998). Spectroscopy at 5–17 \( \mu \text{m} \) with ISOCAM reveals a strong, pure \((v = 0 - 0)\) rotational spectrum of H\(_2\) in the Helix, from the S(2) to the S(7) lines. As one moves from the ionized cavity to the limb, the spectrum changes from nearly featureless, to being dominated by the H\(_2\) emission. The line intensities indicate an excitation temperature of \( \sim 900 \text{ K} \), thus the H\(_2\) is warmer than the CO, and probably forms a skin on the cooler gas. The S(5) line emission dominates the ISO LW2 filter so it has also been possible to image the large scale distribution of H\(_2\) over the whole nebula. The image, at 6″ resolution, is shown in Fig. 3, right panel. It shows finer details than the CO map, including flocculent radial rays and clumps of globules around the inner periphery, and generally underscores the completely fragmented picture of the molecular gas.

A second aspect of the distribution of the molecular gas is its global structure. Fig. 3 shows that it is not simply a regular torus, and the apparent “double ring” seen in optical images has long been a target for speculation. The large scale geometry has recently been discussed by Young et al. (1999) using their CO observations. The CO map in Fig. 3 actually consists of 3425 spectra which record the velocity of the gas along the line of sight as well as the intensity.
Since the system is expanding, these can be used to study the 3-dimensional structure.

When examined in this way, the data indicate that the inner ring in Fig 3, is a true ring, tilted $\sim 37^\circ$ to the line of sight. The outer arcs to the east and west peel away from the ring (from the north and south, respectively), with a remarkable degree of point symmetry in their geometry (see Fig. 7 in Young et al. 1999). For each point in the structure, there is a similar one on the opposite side of the central star. There seems little doubt that this structure, which dominates the nebula, was formed at an early stage by the interaction of the envelope with collimated, bipolar outflows or jets.

5. Shaping the Envelopes

The actual shaping of envelopes by collimated outflows or jets from the central star system is well documented in a number of proto-PNe and young PNe by high resolution observations of the molecular gas. These observations are especially interesting in light of the growing number of PNe that are seen to exhibit point symmetries (especially young PNe observed with HST, see Sahai this volume). These symmetries indicate that collimated outflows – and their interactions – are common in young PNe, and can provide a general shaping mechanism.

The presence of a molecular (or atomic) envelope is an interesting part of this scenario: it not only affects the dynamics of the interaction, but the high densities and low temperatures of the neutral gas preserves the results of the interactions for much longer than the ionized gas. Thus at later stages, this structure can dominate the appearance of the PNe, as is the case in the Helix nebula described above.
Examples of outflow-envelope interactions in the proto-PN phase are described elsewhere in this volume (e.g., by Lucas, and Alcolea), and we focus here on young PNe. The most spectacular outflows are those in KjPn 8. These consist of pairs of bipolar jets, the most recent of which have expansion velocities $\sim 200 \text{ km s}^{-1}$ and extend over $\sim 4\arcmin$, even though the ionized nebula is only $\sim 4\arcsec$ in size (see López, this volume, for details). Using the IRAM interferometer, Forveille et al. (1998) have recently mapped the molecular emission from the KjPn 8 system (Fig. 4, left panel). The molecular gas forms a disk that surrounds the ionized nebula (which corresponds to the hole in the center of the figure), and exceeds it in mass by a factor of $\sim 60$, so it dominates the circumstellar environment.

The disk axis and the jets are aligned in KjPn 8, and their expansion time scales are similar (a few thousand yr). A likely scenario is that common (or related) mechanisms ejected the molecular gas and formed the jets close to the central star. The jets and the gas clearly interact. In the right panel of Fig. 4, the CO channel map at the systemic velocity shows a wind swept disk, with gas extending along the edges of the jet cavities; other channels show that this gas has the highest velocities, and is entrained in the flows. In this case, a primary result of the interaction is the shaping of the disk or torus.

A second example of outflow-envelope interactions occurs in He3-1475. In this young PN, high resolution optical imaging with HST (Borkowski et al. 1997) shows high velocity, bipolar outflows with large opening angles that are apparently focussed into narrow jets by interactions with their surroundings. Recent CO observations with the IRAM interferometer (Forveille, private communication) reveal a torus of molecular gas around the outflows. The torus extends a few arc seconds along the flows, roughly corresponding the region in which the flows are collimated; much of the molecular gas is also at high velocities and is entrained. The interesting perspective here is that the outflow-envelope interactions are complex: the molecular torus is probably the focusing agent of the jets, while at the same time the flows are acting to shape and disrupt the envelope. Further studies of these types of shaping interactions are currently in progress.

6. Concluding Remarks

The examples described here illustrate and underscore the important role of molecular gas in the structure of PNe.

- In the equatorial tori that dominate the evolution of bipolar and related PNe for much of their lives.
- As the dense cores of globules and other microstructures,
- As the origin of multiple arcs.

High resolution observations of the molecular gas are also beginning to reveal details of the shaping of PNe by envelope interactions with collimated outflows or jets at an early phase.
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