Imaging the cold molecular gas in pPNe

Javier Alcolea

Observatorio Astronómico Nacional (Spain) j.alcolea[at]oan.es

Summary. Although they were discovered in the late 80's, the importance of studying pPNe for the understanding of the formation of asymmetrical PNe has only be recognized in the last decade. This is one of the reasons why our knowledge of this type of envelopes is still evolving very fast. Since the central stellar component is not very hot (the post-AGB ages of these objects are always less than 1500–2000 yr) the mass of the circumstellar material is still largely dominated by the molecular gas component (plus 1% of dust grains), while only traces of ionized and atomic gas are found. The molecules usually remain in a cold gas phase, and they can be only observed by means of their rotational emission in the radio domain of the EM-spectrum, from the cm- to the sub-mm wavelength region. (In occasions, molecules do also emit lines in the IR, but this hot gas is much less massive, though their observation is crucial for studying the development of the AGB and post-AGB two-wind interaction). In this contribution I will review the new discoveries in the field of CO line radio-observations of pPNe, published since the previous APN meeting. I will focus on aspects such as the availability of interferometric maps of CO for a statistically significant number of pPNe, the discovery of Keplerian circumbinary disks around low-mass systems, and the discovery of a firework (fully self-similar) nebula.

Key words: stars: post-AGB; stars: mass-loss; circumstellar mater: pPNe

1 Introduction

The study of the pre-Planetary Nebula (pPN) phase is crucial for the understanding of the formation and evolution of Planetary Nebulae (PNe). Not only for (the large majority of) those that are highly axis-symmetric but also in the (few) cases in which the spherical symmetry is truly preserved; after all any PNe should undergo the pPN phase. By definition, primary central stars of pPNe can not photo-dissociate or ionize their circumstellar shells. In addition, this phase is so brief (1000 to 2000 yr) that even if the copious mass loss typical of the end AGB has stopped, the interstellar UV field cannot significantly modify the composition of the bulk of the nebula, which largely remains in the form of neutral molecular gas, (the next most abundant component being the dust grains, accounting for 1% or less of the total nebular mass). Other processes present in the pPNe phase such as shocks can also alter the chemical composition of these circumstellar envelopes, but observations have told us that the amount of circumstellar mass ionized by these means is also very small (0.1% or less). This molecular gas component dominates not only the mass content of the envelope, but it is also the major carrier of the linear momentum and kinetic and gravitational energies in these nebulae.

Except for the very inner and outer parts of these circumstellar envelopes, the gas phase is dominated by cold (10–50 K) neutral molecules, that can only be observed by means of their lowest rotational transitions, mainly in the mm- and sub-mm wavelength domains. These observations have advantage that mm-wave radio lines do not suffer from dust extinction (both circumstellar and interstellar), and therefore we can see through the nebula even in the least favorable conditions: e.g. using rare-isotopic substitutions rather than the main one when the latter becomes optically thick. At radio wavelengths, obtaining spectral resolutions much better than the velocity spread of the line emission presents no problem, and therefore we can map not only the structure of the envelope but also its velocity field. By far, the best tracer of this neutral molecular gas is CO. This simple compound is very abundant in all types of pPNe regardless of their chemical composition, and its rotational lines are fairly strong. CO also presents a low dipolar electric moment, which guarantees that the transitions are very close to the thermal equilibrium for the range of densities relevant to us (larger than $10^5\,\mathrm{cm}^{-3}$). This property eases the translation of the observed intensities into physical parameters of the nebulae using relatively simple models.

However, pPNe are nor very abundant, because of the short duration of this transition phase, and the typical distance to these objects is of the order of several kpc. At these distances, even huge shells 10^{17} in size are just few arc seconds across. Therefore the detailed observations of these post-AGB envelopes, and in particular their central parts, require arc and sub-arc second spatial resolutions. This can only be achieved by means of radio-interferometry. Using the present instrumentation we can obtain CO maps with spatial resolutions of $0\farcs25$ at best, but as we will see this is already enough to characterize the main structural properties of pPNe. This observational technique is very powerful but currently very time consuming (a good map would take about one full day of observing time at the top instruments), and typically sources are observed in dedicated projects one by one with few exceptions. Nevertheless the amount of published material is not scarce. In the following sections, I will review the latest CO maps that have come up in the literature, and summarize what we have learn from these observations and older ones.

2 Data from the BIMA and OVRO interferometers

Although both BIMA and OVRO arrays stopped operations some time ago[1], new data have come along in the last few years. In 2004, Meixner et al. reported on the CO J=1–0 maps around HD 56126 [13]. This is a visible bright source surrounded by a faint optical reflection nebulae. CO data is consistent with a spherical shell of molecular gas, detached from the star. This is one of the examples of pPNe in which no fast molecular flow and no asymmetrical structure are found, just a simple

[1] The elements of these two arrays have been moved to Cedar Flat (USA), where now form part of the CARMA interferometer that shall be start producing data very soon.

spherical ball of gas, expanding and leaving behind a hole in the center as the mass loss ended about 1200 yr ago.

More recently, Fong et al. have published their results from a small mapping survey of CO on AGB shells (CW Leo and o Cet), pPNe (HD 161796, 89 Her, CRL 2343, CRL 2688, and IRAS 22272+5435) and one young PN (NGC 7027) [11]. In the case of the pPNe, the maps have moderate to poor resolution ($3''$–$7''$) and have been surpassed by other authors except for IRAS 22272+5435 (see [4], [8] and [10]). In this latter case the resolution does not show the structure of the shell. The spectral line does not present high velocity wings and consistently the maps are compatible with a spherical structure. However a central hole is detected in the NIR, and therefore this may be a case similar to HD 56126. In this paper the authors also present a compilation of the results from the mapping of CO in circumstellar envelopes in the AGB, pPN and PN phases. In their Fig. 14, they present a HR-diagram for the central stars with annotations on the observed circumstellar structures. From this diagram it is clear that deviations from sphericity start just beyond the AGB (though some AGB sources show disk structures). Other trends are not clear, maybe because the central star temperature is not a good parameter to track the post-AGB evolution of the envelope (see Sect. 5).

In APN III, Sánchez Contreras and Sahai reported on an OVRO CO J=1−0 snapshot survey of eight pPNe [21]: IRAS 18276−1431, 18560+0638, 19024+0044, 19255+2123 (K 3−35), 19292+1806, 19374+2359, 19520+2759, and 22036+5306. These maps have been only partially published in [16] and [20]; they are very crude and can only help in determining the size of the pPN. IRAS 19475+3119 (M 2−42) has been observed in CO J=2–1 in a dedicated mode, resulting in much better maps [19]. The structure of the nebula has been derived from the maps, consisting in a spherical detached shell that has been punctured by a fast bipolar flow running along the main axis of symmetry of the reflection nebula.

The same team has observed CRL 618 in CO J=2–1 with $1''$ resolution [18]. The observations reveal that the post-AGB ejection is confined to the central parts of the nebula, inside the spherical AGB shells. The fast molecular gas seems to be located at the interface between the bipolar lobes excavated by the jets seen in the optical and the slowly expanding AGB envelope. The highest expansion velocities in the gas are found at the base of the optical jets. Apparency, in this 400 yr old pPN the post-AGB ejections are still making its way through the massive AGB shell.

3 Data from the IRAM PdBI

Today, the IRAM Plateau de Bure Interferometer is the most productive one in providing maps of the molecular gas around evolved stars. Regarding pPNe, two surveys and about ten individual sources have been observed. The first survey (of which I am the PI) was carried out in the snapshot mode and was designed to test the prevalence of Hubble-law velocity fields in the fast flows of pPNe. The data acquisition is finished and is being analyzed right now. We observed eight targets pPNe, IRAS 04296+3429, 17436+5003, 19500−1709, 19548+3035, 23304+6147, (M 2−47), 23321+6545 (M 2−48), V Hya and R Sct. We find no high velocity CO in three cases: IRAS 04296+3429, IRAS 19548+3035, and R Sct; compact outflows inside the AGB shell (i.e. very much like CRL 618) in two cases: IRAS 17436+5003 and 19500−1709; and Hubble-laws in two other cases: M 2−47 and M 2−48. (For V Hya see next section.)

The second survey is part of a much larger atlas of CO maps around evolved stars of all kinds [7] (see also the contribution by Castro-Carrizo in this volume). The list of observed targets include IRAS 10491−2059 (V Hya), 18276−1431, 19475+3119 (M 2−42), 19500−1709, 19548+3035, 20028+3910 (M 2−43), 21282+5050, 22223+4327, and 2331+6545 (M 2−48). The data is still in the calibration phase and only preliminary results can be given. The maps of M 2−42 confirm the results by [19] and reveal the existence of the Hubble-law in the molecular fast jet. On the contrary, for M 2−43 we may be in a case of a jet still carving its way through the AGB envelope.

Two low-mass pPNe have been observed in detail with this instrument, the Red Rectangle [3] and 89 Her [4], two sources that are well known binary systems. In the Red Rectangle the molecular gas is confined to a thin equatorial disk perpendicular to the axis of symmetry of the optical nebula. This disk is found (for the first time) in Keplerian motion around the binary. In 89 Her, the CO envelope consist of self-similar expanding hour-glass structure and a relatively massive compact a core. The observations could not resolve this central part but the observed line profile supports the existence of a gravitationally-bounded rotating disk is this system too.

At the opposite end of the mass range, two yellow hyper-giants have also been observed in CO [8] (and other molecules too, see contribution by Quintana-Lacaci). CRL 2343 and IRC +10420 are in fact the only two hyper-giants with massive circumstellar envelopes. In the two cases the gas is located in a series of concentric spherical cocoons, resulting from episodes of enhanced mass loss. Irregularities are also found, but we can say that in general both objects have circumstellar envelopes fairly spherically symmetric.

The detailed observations of M 2−56 [5] and Frosty Leo [6] showed two cases of highly bipolar envelopes with self-similar expanding (i.e. with Hubble-low velocity field) flows. In M 2−56 the envelope presents a clear hour-glass structure, while Frosty Leo if bilobed. Also in these two objects a dense slowly expanding component is found at the equatorial plane.

The structure and kinematics of these equatorial component can hardly be resolved by the current instrumentation. Just in certain cases like the relatively close by Red Rectangle. However by using the most extended configurations now available at PdBI we can easily reach resolutions of $0\farcs25$ (and very soon less than $0\farcs2$). The use of these new capabilities have resulted in another turn of the screw. The new observations of M 1–92 [2] (see also the contribution by Alcolea et al.) have revealed that in this case the equatorial disk is in expansion but sharing the same Hubble-like velocity law that the bipolar outflow. This is expected only if the whole nebula is formed from a single short acceleration event, after which the gas keeps expanding freely, very much like fire particles after the explosion of a pyrotechnic case. This could be explained as result of the sudden ejection of a common envelope.

4 Data from the SMA

The SMA interferometer is also providing new and exciting data of pPNe and circumstellar envelopes in general. Designed to work at frequencies higher than the other present instruments, can probe the contents of relatively warm gas. However, interferometry at sub-mm wavelengths is not an easy task and up to now the efforts have been concentrated in the observations of the J=3–2 and 2–1 line of CO. So far there are published data on two peculiar AGB stars, V Hya [12] and π^1 Gru [9], the red super-giant VY CMa [14], and the pPNe CRL 618 [15] and IRAS 22036+5306

[17]. V Hya and π^1 Gru show very similar results. The molecular envelope consist in an equatorial expanding disk and a bipolar fast flow running along the perpendicular direction. For the case of red super-giant VY CMa (a very massive object) the authors conclude that the envelope consist of a slowly expanding spherical shell plus a fast bipolar outflow along the polar directions. IRAS 22036+5306 is a water-fountain source (see contributions by M. Claussen and B. Creel in this volume) where the CO data shows a bipolar fast flow along the symmetry axis of the nebula, but apparently not showing the Hubble-law characteristic of this type of sources. Finally, the observations of CRL 618 by [15] have been performed in CO J=6–5. The combination of these results with those by [18] allows a much better study of the stratification of the molecular gas excitation in this pPN. In particular it seems that the warm gas is only present in the central parts of the molecular flow, where the interactions with the ionized jet are expected to be stronger.

5 Some considerations and concluding remarks

Including a couple of objects for which no recent CO observations exist, namely CRL 2688 [10] and OH 231.8+4.2 [1], the total number pPNe (and related objects) for which interferometric CO maps are available is 33. These objects are listed in Table 1. As we can see, this database is already somewhat extensive. Certainly, we still have to sort out biases and other selection effects in the sample, but the results we can derive from this data set must be statistically significant. The situation will clearly improve when ALMA and CARMA come in fully operation, but we cant star doing some analysis that will guide us to prepare the forthcoming observations with these two new instruments.

While the single/primary star is not releasing the hot wind, the evolution of the envelope is detached from the stellar evolution undergoing at the center. At large scale, this evolution is only controlled by the interaction of the slow regular AGB wind and the fast (and mainly bipolar) post-AGB wind. The result of this interaction must largely depend on the kinetic momentum ratio between these two flows, i.e. on the ratio between the mass loss rate in the last 10 000 yr of the AGB phase and at the onset of the post-AGB phase, $\Omega = \dot{M}_{\rm late-AGB}/\dot{M}_{\rm post-AGB}$. Self-similar nebular structures like in M 1–92 and OH 231.8+4.2 would speak in favor of very low values of Ω, while bounded carving jets like in CRL 618 and IRAS 17436+5003 would point out to relatively large values of Ω. Understanding the origin of the apparently wide range of Ω values is probably the heart of the mystery. In particular we should find what can produce huge values of $\dot{M}_{\rm post-AGB}$ in stars with thin envelopes AGB around. Common envelope ejection is an option we must explore, but at the same time we need to understand why other well known (low-mass) binary systems, like the Red Rectangle and 89 Her, only produce faint envelopes that may will never result in real PNe.

References

1. Alcolea, J., Bujarrabal, V., Sánchez Contreras, C., Neri, R., Zweigle, J.: The highly collimated bipolar outflow of OH 231.8+4.2. A&A **373**, 932–949 (2001)
2. Alcolea, J., Neri, R., Bujarrabal, V.: Minkowski's footprint revisited. Planetary nebula formation from a single sudden event? A&A **468**, L41–L44 (2007)

Table 1. IRAS and other designations of pPNe and related objects mapped in CO

IRAS	CRL	SAO/HD	GCVS	Nebula name	Nickname
04296+3429					
04395+3601	CRL 618		V353 Aur		Westbrook Nebula
06176−1036	CRL 915	HD 44179	V777 Mon		Red Rectangle
07209−2540	CRL 1111	HD 28061	VY CMa		
07399−1435	CRL 5237		QX Pup	OH 231.8+4.2	The Rotten Egg
09371+1212					Frosty Leo
10491−2059	CRL 1439	SAO 179278	V Hya		
17436+5003	CRL 5384	HD 161796	V814 Her		
17534+2603			89 Her		
	CRL 2688		V1610 Cyg		The Egg Nebula
18276−1431	CRL 5497		V445 Sct	OH 17.68−2.03	
18448−0545	CRL 5296S	HD 173819	R Sct		
18560+0638	CRL 2290		V1366 Aql	OH 39.7+1.5	
19024+0044				M 2−39	Starfish Nebula
19114+0002	CRL 2343				
19244+1115	CRL 2340		V1302 Aql	IRC +10420	
19255+2123				K 3−35	
19292+1806					
19343+2926				M 1−92	Minkowski's Foot.
19374+2359					
19475+3119		HD 331319		M 2−42	
19500−1709	CRL 5568	HD 187885	V5112 Sgr		
19520+2759					
19548+3035	CRL 2477				
20028+3910				M 2−43	
21282+5050					
22196−4612	CRL 4289	HD 212087	π^1 Gru	Hen 4−202	
22223+4327			V448 Lac		
22036+5306					
22272+5435		HD 235858			
23304+6147				M 2−47	
23321+6545				M 2−48	
23541+7031	CRL 3181			M 2−56	

3. Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., Neri, R.: The orbiting gas disk in the Red Rectangle. A&A**441**, 1031–1038 (2005)
4. Bujarrabal, V., van Winckel, H., Neri, R., Alcolea, J., Castro-Carrizo, A., Deroo, P.: The nebula around the post-AGB star 89 Herculis. A&A**468**, L45-L48 (2007)
5. Castro-Carrizo, A., Bujarrabal, V., Sánchez Contreras, C., Alcolea, J., Neri, R.: The structure and dynamics of the molecular envelope of M 2−56. A&A**386**, 633–645 (2002)
6. Castro-Carrizo, A., Bujarrabal, V., Sánchez Contreras, C., Sahai, R., Alcolea, J.: The disrupted molecular envelope of Frosty Leo. A&A**431**, 979–991 (2005)

7. Castro-Carrizo, A., Quintana-Lacaci, G., Alcolea, J., Bujarrabal V. Grewing, M., Lucas, R., Neri, R., Olofsson, H., Schoier, F.L., J.M., W.: Study of the circumstellar envelopes of AGB and early post-AGB stars. In: F. Kerschbaum, C. Charbonnel, R. Wing (eds.) Why galaxies care about AGB stars?, *Astronomical Society of the Pacific Conference Series*, vol. 378 (2007)
8. Castro-Carrizo, A., Quintana-Lacaci, G., Bujarrabal, V., Neri, R., Alcolea, J.: Arcsecond-resolution ^{12}CO mapping of the yellow hypergiants IRC +10420 and AFGL 2343. A&A**465**, 457–467 (2007)
9. Chiu, P.J., Hoang, C.T., Dinh-V-Trung, Lim, J., Kwok, S., Hirano, N., Muthu, C.: A Slowly Expanding Disk and Fast Bipolar Outflow from the S Star π^1 Gruis. ApJ**645**, 605–612 (2006)
10. Cox, P., Lucas, R., Huggins, P.J., Forveille, T., Bachiller, R., Guilloteau, S., Maillard, J.P., Omont, A.: Multiple molecular outflows in AFGL 2688. A&A**353**, L25–L28 (2000)
11. Fong, D., Meixner, M., Sutton, E.C., Zalucha, A., Welch, W.J.: Evolution of the Circumstellar Molecular Envelope. I. A BIMA CO Survey of Evolved Stars. ApJ**652**, 1626–1653 (2006)
12. Hirano, N., Shinnaga, H., Dinh-V-Trung, Fong, D., Keto, E., Patel, N., Qi, C., Young, K., Zhang, Q., Zhao, J.: High-Velocity Bipolar Outflow and Disklike Envelope in the Carbon Star V Hydrae. ApJ**616**, L43–L46 (2004)
13. Meixner, M., Zalucha, A., Ueta, T., Fong, D., Justtanont, K.: The Molecular and Dust Envelope of HD 56126. ApJ**614**, 371–379 (2004)
14. Muller, S., Dinh-V-Trung, Lim, J., Hirano, N., Muthu, C., Kwok, S.: The Molecular Envelope around the Red Supergiant VY CMa. ApJ**656**, 1109–1120 (2007)
15. Nakashima, J.i., Fong, D., Hasegawa, T., Hirano, N., Koning, N., Kwok, S., Lim, J., Dinh-Van-Trung, Young, K.: Submillimeter Array Observation of the Proto-Planetary Nebula CRL 618 in the CO J=6−5 Line. ArXiv e-prints **707** (2007)
16. Sahai, R., Sánchez Contreras, C., Morris, M.: A Starfish Preplanetary Nebula: IRAS 19024+0044. ApJ**620**, 948–960 (2005)
17. Sahai, R., Young, K., Patel, N.A., Sánchez Contreras, C., Morris, M.: A Massive Bipolar Outflow and a Dusty Torus with Large Grains in the Preplanetary Nebula IRAS 22036+5306. ApJ**653**, 1241–1252 (2006)
18. Sánchez Contreras, C., Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., Sargent, A.: 1″ Resolution Mapping of the Molecular Envelope of the Protoplanetary Nebula CRL 618. ApJ**617**, 1142–1156 (2004)
19. Sánchez Contreras, C., Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., Sargent, A.: Interferometric CO J=2−1 Emission Mapping of the Protoplanetary Nebula IRAS 19475+3119. ApJ**643**, 945–955 (2006)
20. Sánchez Contreras, C., Le Mignant, D., Sahai, R., Gil de Paz, A., Morris, M.: Adaptive Optics Imaging of IRAS 18276-1431: A Bipolar Preplanetary Nebula with Circumstellar “Searchlight Beams” and “Arcs”. ApJ**656**, 1150–1166 (2007)
21. Sánchez Contreras, C., Sahai, R.: Very Young PPNe: OVRO Snap-Shot CO (1−0) Emission Survey. In: M. Meixner, J.H. Kastner, B. Balick, N. Soker (eds.) Asymmetrical Planetary Nebulae III: Winds, Structure and the Thunderbird, *Astronomical Society of the Pacific Conference Series*, vol. 313, pp. 377-380 (2004)