THE ORIGIN OF THE BIPOLARITY IN THE POST-AGB EVOLUTION: THE CASE OF OH 238.1+4.2

J. Alcolea[1,2], V. Bujarrabal[1], and C. Sánchez Contreras[1,3]

[1]Observatorio Astronómico Nacional, Apartado 1143, E-28800 Alcalá de Henares, Spain
[2]Observatorio Astronómico Nacional, Alfonso XII N°3, E-28014 Madrid, Spain
[3]Jet Propulsion Laboratory, MS 183-900, 4800 Oak Grove, Pasadena CA 91109, USA

Abstract

One of the most debated issues on the post-AGB evolution of mid-mass sources is the question of the origin of the bipolarity often observed in PNe and PPNe. Today, it is firmly established that PNe are the result of the post-AGB evolution of the CEs around AGB sources. However CEs in the AGB are spherically symmetric, as the result of an isotropic mass loss due to photon pressure on the dust grains. It is though that the origin of this symmetry breakup at the end of the AGB, is due to the interaction a fast and highly collimated post-AGB wind of the old spherical CE.

To study the details of this interaction, and the nature and origin of the post-AGB ejections, we have undertaken a series of multi-wavelength imaging of selected post-AGB sources. Here we present the results of our studies on OH 231.8+4.2, a beautiful bipolar nebula surrounding a late AGB star. We have carried out high resolution observations of the molecular component (interferometric maps of CO and some tracers of shock chemistry), the circumstellar dust (broad band NIR imaging), and of the shocked excited hot phase (atomic line long-slit and imaging). These works have been very revealing but we still lack of information on the mid-excitation gas in this source (OH 231.8+4.2 could not be observed with ISO). The study of this component is of fundamental importance for better understanding how the shocks responsible for the nebular bipolarity operated, and what is their energy source. The observations of sub-mm molecular lines are crucial in this respect. On the other hand, due to its large extent, kinematics and molecular richness, this extremely interesting PPNe constitutes an ideal target for the HIFI instrument on-board the FIRST mission.

Key words: Stars: AGB and post-AGB – Stars: circumstellar matter – Radio lines: stars

1. Introduction

Long period variables in the asymptotic giant branch lose material at rates between 10^{-8} to 10^{-5} $M_{\odot}\,\mathrm{yr}^{-1}$, forming spherical shells known as circumstellar envelopes (CEs), mostly consisting of molecular gas and dust grains. This mass loss is driven by the stellar photon pressure onto dust grains, which transfer their momentum to the gas via drag forces, resulting in a gently expansion of both phases of the CE, which flows radially outward at velocities of the order of 10 $\mathrm{km\,s^{-1}}$.

Today it is firmly established that planetary nebulae (PNe) originate from the post-AGB evolution of the CEs around AGB stars of low/intermediate mass. At the end of the AGB evolution, the red giant AGB star becomes a white/blue dwarf, i.e., the planetary nebula nucleus. The copious mass loss characteristic of the AGB phase stops and is replaced by a tenuous but much faster wind, that would compress and accelerate the old AGB shell. At the same time, the intense UV flux from the very hot central star dissociates the molecules of the circumstellar shell and ionizes the atoms, resulting in the formation of the planetary nebulae. All these dramatic changes, from a cold molecular-rich environment to a photon-dominated heavily-ionized region occur in a very brief period of the stellar evolution, probably lasting less than 10 000 yr.

Due to the superb image quality of the present optical instrumentation (better CCD performances, new and bigger telescopes, the fixing of the optics of the HST), the world of PNe has been recently shocked by a unexpected new discovery: most PNe are not spherically symmetric. This post-AGB symmetry breakup is not understood: it has been postulated that the post-AGB wind could be bipolar. However, how this collimation would occur and how this new dynamics affects the general PN shaping is not known at all. To better understand and the problem of PNe shaping and kinematics, and of the origin of the bipolarity in the post-AGB evolution, we have undertaken a series of very detailed studies on sources chosen to be at this short evolutionary phase between the AGB and PN stages: these sources are usually known as proto-planetary nebulae (PPNe). These studies include CO mapping using the Plateu de Bure interferometer, ground and space based optical and NIR imaging, and optical long-slit spectroscopy. So far we have studied 4 targets: M 1–92, M 2–56, Frosty Leo, and OH 231.8+4.2. Here we summarize our results on this latter source.

2. The case of OH 231.8+4.2

OH 231.8+4.2 is a well known bipolar reflecting nebula illuminated by the M9III long period variable QX Pup, that lies hidden at its center. This nebula belongs to the

Proc. Symposium *'The Promise of the Herschel Space Observatory'* 12–15 December 2000, Toledo, Spain
ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

open cluster NGC 2437, which allows a precise determination of the distance (1.5 kpc), luminosity ($10^4\,L_\odot$), age (300 Myr), and initial mass of the central source ($3\,M_\odot$). The nebula is very large (50″) along its conspicuous axis of symmetry, which makes it an ideal target for FIRST (it is probably the only PPNe in which real maps can be performed). The two lobes are not symmetric, the south one being twice larger and more extended. In the optical the south lobe resembles an inflated bubble, while the one in the North is much narrower (see Figure 1). The nebula in an intense molecular line emitter; it shows strong CO lines, as well as from other molecules. Both the star and the nebula are O-rich (it shows SiO, H_2O, and OH masers), the nebula also presenting a peculiar chemistry very rich in N– and S–bearing molecules. The work performed by us in this source includes:

- Optical imaging in bands B & R, and in Hα, and long-slit optical spectroscopy in Hα, Hβ, [OI], [OII], [OIII], [NII], and [SII] (Sánchez Contreras et al. 2000a).
- NIR imaging in bands J, H, and K′ (Alcolea et al. 2001).
- mm-wave interferometric observations of ^{12}CO J=1−0 and J=2−1, HCO^+ J=1−0, SO $J=2_2$–1_1, SiO v=1 J=2−1, H^{13}CN J=1−0, and NS J=5/2–3/2, (Alcolea et al. 2001, Sánchez Contreras et al. 2000b).
- mm-wave single-dish observations of ^{12}CO, ^{13}CO and other molecules (Sánchez Contreras et al. 1997).

3. The molecular envelope

We have performed high-sensitivity observations of the J=1−0 and J=2−1 lines of ^{12}CO using the IRAM Plateau de Bure interferometer, reaching resolutions of $\sim 2''$ and $1''$ respectively, which have revealed both the structure and kinematics of the molecular gas in OH 231.8+4.2. As it can be seen in Figure 1, in contrast with the optical appearance, the location of the molecular material in OH 231.8+4.2 is restricted to a very narrow strip (2″–6″ wide) along the nebular axis; in this direction, the nebula is 55″ long. Also in CO, the two lobes of the nebula are clearly not symmetric, the south lobe being twice extended than the north one. Is is noticeable the large expansion velocities found in the lobes, that after correcting for the orientation of the axis of the nebula with respect to the plane of the sky, reach values of $\sim$ 210 km s^{-1} in the north and, 375 km s^{-1} in the south. This is the fastest molecular material ever detected in AGB or post-AGB sources. Since these velocities are much larger than the typical AGB expansion velocities, we believe that the fast moving gas represents the old AGB shell after been accelerated and re-shaped due to the post-AGB "two-wind interaction".

Another remarkable result is that the kinematics of the molecular gas is dominated by a constant velocity gradient, of 6 km s^{-1} per ″, along the full extent of the nebula. From this value we derive a kinematic age for the fast moving gas of only 775 yr. The easiest explanation for this Hubble-like velocity field, is that the present kinematics is the result of an interaction which lasted much less than the kinematic age, after which free movement dominated the expansion of the nebula. We derive an upper limit to the duration of the post-AGB interaction of $\sim$ 125 yr.

From our interferometric data, and ^{13}CO J=1−0 and J=2−1 data obtained with the IRAM/PdV 30 m telescope, we have computed some physical parameters for the different regions of the envelope. These regions, for simplicity, have been set by dividing the envelope in several velocity intervals. Note that thanks to the high velocity gradient, dividing the molecular emission in velocity intervals is equivalent to divide the envelope in different regions; in this way we can also improve the effective resolution of the single-dish observations. We have chosen the velocity intervals to separate the strong line core from the central part (velocity interval +10:+55), from the weaker wings due to the accelerated lobes. We have also divided the two lobes in several parts, to study the variations of the physical conditions along them. In this computation we have adopted fractional abundances (with respect to H_2) for ^{12}CO and ^{13}CO of $2\,10^{-4}$ and $2\,10^{-5}$, respectively (these abundances are typical of other O-rich AGB and early post-AGB sources). For each region/velocity-interval we have estimated the mean rotational temperature (T_r, assuming that CO is thermalized), the total molecular mass (M_i), the mean density (ρ_i), the linear momentum in the direction of the axis of symmetry (P_i), and the kinetic energy (E_i). We have also estimated for the same regions/velocity-intervals the fractional abundances of the other molecules observed.

The total mass detected by CO amounts to nearly $1\,M_\odot$. Taking into account the extent of the central core (the nebular material less affected by the post-AGB interaction) and a former AGB expansion velocity of 6 km s^{-1}, we derive a huge mass loss rate of $\sim 1.6\,10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$ during the last 4 500 yr. We measure a very low kinetic temperature in the lobes, 10–20 K. Since this gas has been accelerated via strong shocks, we interpret this result as due a very efficient cooling after the shock passage, i.e. we are dealing with a quasi-isothermal shock, in agreement with the very elongated shape of the nebula (little energy was transformed into transversal motion).

The total linear momentum gained by the CE after the "two-wind interaction" is huge: $3.0\,10^{39}$ and $2.5\,10^{39}$ g cm s^{-1} in the north and south lobe respectively; $5.5\,10^{39}$ g cm s^{-1} in total. Note that the luminosity of the central star can only account for $4\,10^{34}$ g cm s^{-1} per year. Therefore, since the interaction lasted for only 125 yr, the stellar photon pressure (the mechanism responsible for the mass loss during the AGB) is unable to produce the observed gained momentum by a factor 1000. Even if we consider multiple scattering and we relax the interaction time to the whole kinematic age of the outflow (775 yr), photon pressure onto dust grains still fails to provide enough momentum by a factor 50 to 20. This robust result (it is independent on the distance and all assumptions we have made, if wrong, would lead to an under-estimation of the mass, momentum and energy of the nebula) clearly rules out photon pressure as a candidate for powering the post-AGB bipolar ejecta responsible for the present shape and kinematics of the nebula. Since this large momentum is a general result among PPNe (see the contribution by V. Bujarrabal et al. in these proceedings), we conclude that at the AGB/post-AGB transition not only the characteristics of the mass loss changes (from slow, massive and isotropic into fast, diffuse and bipolar), but also the source of energy powering these mass loss processes.

SO is only detected in the thick disk of circumstellar material dividing the two reflecting lobes. This disk is not seen in rotation, but in radial expansion with a velocity of 6 $\mathrm{km\,s^{-1}}$. Since we believe that this disk represents those parts of the dense AGB-shell not accelerated by the post-AGB interaction, we conclude that the previous AGB-expansion velocity was of 6 $\mathrm{km\,s^{-1}}$. On the contrary HCO^+ presents a local minimum near the star position, while relative maxima are found in the accelerated lobes. This supports the hypothesis that HCO^+ is due to a shock-activated chemistry taken place in the lobes of OH 231.8+4.2. This scenario would also explain the high abundance of SiO found at large distances from the central core. This is completely unusual in AGB envelopes, since SiO is almost exhausted in the formation of grains. One possible explanation for the presence of SiO in the outer lobes could be that thanks to the shocks, some gaseous SiO has been released from the grains. We have also detected for the first time circumstellar NS ($^2\Pi_{1/2}$ J=5/2–3/2 parity-e quintuplet), for which we derive a relative abundance $[NS]/[H_2] \sim 2\,10^{-8}$.

4. The dust component

We have performed near-IR observations in the J, H, and K′ bands of OH 231.8+4.2 using the IRAC-2b camera on the ESO/MPI 2.2 m telescope at la Silla. The NIR emission in OH 231.8+4.2 is due to first and second order scattering of the light emitted by the central star QX Pup. The low level noise and large size of our images have lead to the discovery of two new components, in addition to the well know image of the two bright reflecting bipolar nebula:

The long curled tail at the end of the south lobe, which is the counterpart of the end of the south lobe detected in CO. As it is shown in Figure 1, there is one to one correspondence between the clumps detected in CO and in the NIR. This perfect coincidence between the molecular gas and dust particles also reveals that photon pressure, acting in the traditional way, can not account for the present kinematics. As we have stated before, for photon pressure to push also the gas, there must be a drag force between the gaseous and solid phases of the envelope. It can be shown that in our case, the dust should move about $100\,\mathrm{km\,s^{-1}}$ faster than the gas to push the gas at the observed velocities. The high similitude between the maps of the gas (CO maps) and dust (NIR images) also contradicts the previous hiphothesys.

The quasi-spherical low level emission surrounding the central parts of the nebula, which extends farther than 12″ (2.7^{17} cm) from the central star, and that has no molecular counterpart. Along the equatorial plane of the nebula, the flux of this component follows a $1/r^{2.5}$ dependence that is compatible with the emission from a spherical shell with a constant mass loss. This $1/r^{2.5}$ dependence is lost at distances shorter than 5″ from the center, in coincidence with the detection of CO. We interpret these two results as due to the photo-dissociation of CO in the outer regions of the envelope. Following standard procedures, from the non detection of CO at radii larger than 5″, we can derive an upper limit to the mass loss in that epoch. We found that both NIR and CO images are compatible with a constant mass loss $\leq 2\,10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$, which lasted from at least 10 000 yr ago to 5 000 yr ago. At that moment, a large increase of the mass loss took place, since we have derived a mass loss of $\sim 1.6\,10^{-4}\,M_\odot$ during for the last 4 500 yr. This increase of the mass loss derived in this way is also compatible with the steeper dependence of the NIR flux found at distances closer than 5″.

5. The atomic gas

Our optical broad band and Hα images show that the shape of the nebula at these wavelengths is very different from that in the NIR or in molecular lines. In particular, it is very noticeable the different shape of the south lobe, that in the optical shows a bubble-like structure much wider than at longer wavelengths. In the optical, this lobe ends in a arc-like structure suggesting the passage of a spherical shock. This result stress the importance of studying this type of sources using different instruments, which probe gas with very different physical conditions. Our optical spectroscopic observations have revealed that OH 231.8+4.2 shows strong emission from forbidden lines of low excitation atoms; we conclude that they arise from hot gas excited via a shock passage. The lines are much stronger in the north lobe than in the south one, due to the higher density of the region that is being presently shocked in the north. We have also estimated the total mass of the ionized material in the nebula, deriving a value of only $5\,10^{-4}\,M_\odot$, i.e., $\sim 1/1\,000$ times the mass of the molecular component, even if we exclude the central dense clump. Therefore, all mass, momentum and kinetic energy in the envelope are dominated by the neutral molecular gas, as it is expected for a PPN at its earliest stages of the post-AGB evolution.

The shape and velocity in the south lobe can be explained with a model in which, superimposed to the velocity gradient found in molecular lines, there is a radial expansion from a point located near the center of the lobe.

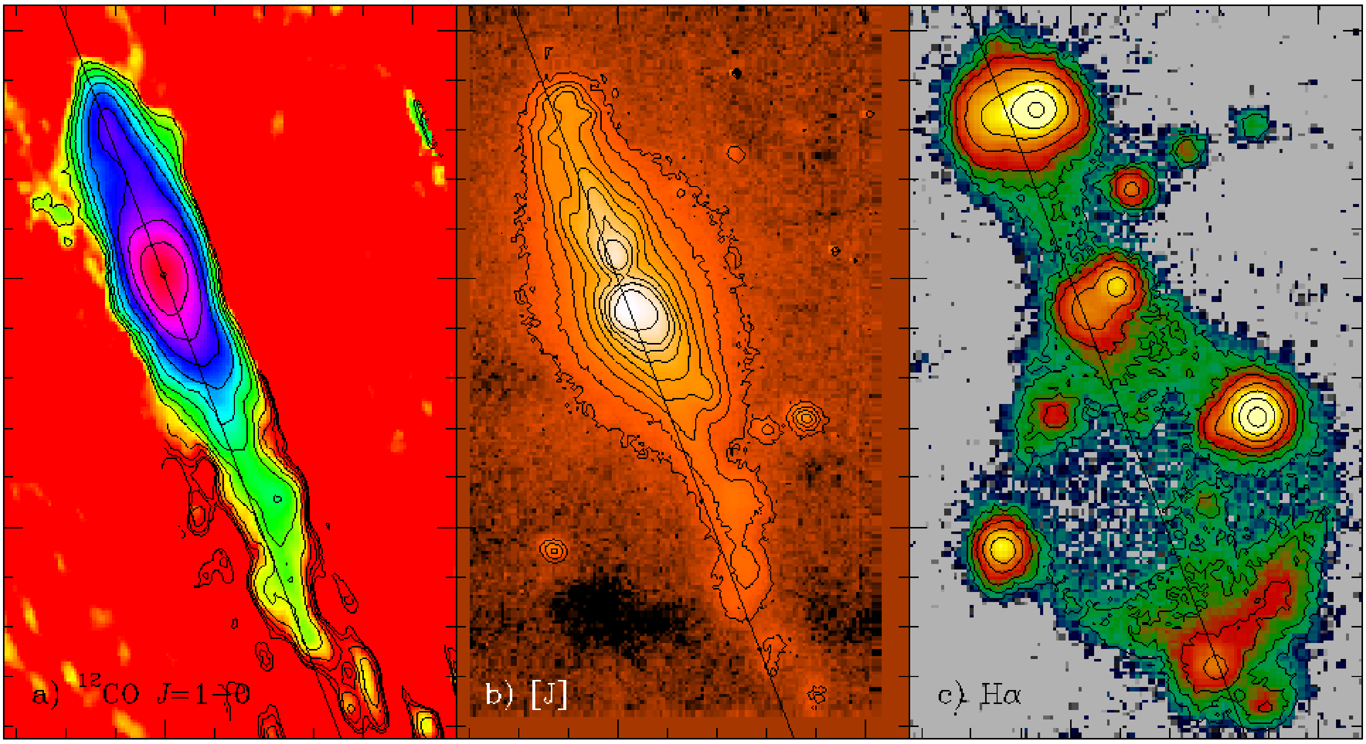

Figure 1. Images of OH 231.8+4.2 tracing different envelope components. a) The cool molecular gas (total emission of the ^{12}CO J=1−0 line. b) dust scattered light as seen in the J-band. c) Hα image showing the location of the hot shock-excited atomic gas. North is up and East is left; each tick corresponds to 4 arc seconds. We also show the nebular symmetry axis.

We interpret this peculiar kinematics of the as a result of a change in the type of shock. About 500 yr ago a transition from quasi-isothermal to adiabatic shock took place (due to a decrease of the cooling rate as the shock moved outward into less dense regions of the former AGB shell); once the adiabatic regime started, a significant fraction of the energy was converted into transversal motion via thermal pressure, producing the bubble-like shape of the south lobe.

6. Concluding remarks and the role of FIRST

In spite of all the work devoted to this and other PPNe, we are still far from having definitive answers to the problem of the shaping of PNe: in particular we have just started to constrain the possible engine responsible for the origin of the bipolarity in the post-AGB evolution. We already know many details on the resulting envelope after the post-AGB "two-wind interaction", but a fundamental piece of information is still missing: data on mildly excited gas, from several tenths to several hundreds K. In this respect the contribution from FIRST, and in particular by the HIFI instrument, would be crucial since at the operating wavelength it will probe the mildly excited gas with unprecedent spectral resolution and sensitivity. OH 231.8+4.2 will we a crucial target in these types of studies since it is a very strong molecular emitter and the only PPNe extended enough to be mapped by FIRST.

Moreover, OH 231.8+4.2 shows a very rich chemistry probably triggered by the presence of a strong shock activity in the envelope. This makes OH 231.8+4.2 an ideal source for studies on molecular spectroscopy in O-rich circumstellar environments. The strong velocity segregation of the the two dynamical components of its envelope (the parts of the former AGB shell affected and not yet affect by the shocks), would allow to disentangle the influence of the shocks in the chemistry, even at those wavelengths at which the spatial resolution of FIRST is poor. In view of the importance of the source, and considering that it could not be observed by ISO, we believe that to perform a high-resolution full frequency scan with HIFI would be very desirable.

Acknowledgements

This work has been financially supported by the Spanish DGES (project PB96-104), and by the Spanish CICYT and the European Commission (grants ESP-1291-E and 1FD1997-1442).

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