EVOLUTION OF CARBON-RICH PROTO-PLANETARY OBJECTS

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Abstract

We compare *ISO LWS* observations of three C-rich objects typical of each step of the fast transition of an AGB star to the Planetay Nebula stage: CRL 2688, a very young Proto-Planetary Nebula, CRL 618, a Proto-Planetary Nebula, and NGC 7027, a young Planetary Nebula. Furthermore, we study the mm, submm, and IR CO emission from CRL 2688. We underline the violent changes that occur in the chemical composition of these objects during their evolution due to the increasing UV radiation field and the strong shocks generated by fast stellar winds. The importance of these mechanisms depends on the degree of evolution of the star.

The circumstellar envelopes of evolved stars are important objects for the stellar evolution. As proved by ISO, these objects are very good targets for the Herschel Space Observatory (HSO, ex-FIRST). We present here what the HSO will teach us about these objects.

Key words: infrared: stars — line: identifications — planetary nebulae: individual (CRL2688, CRL618, NGC7027) — stars: abundances — stars: carbon — stars: evolution

1. Introduction

During the evolution of an Asymptotic Giant Branch (hereafter *AGB*) star to the Planetary Nebula (hereafter *PN*) stage, extreme physical conditions take place. The circumstellar gas is exposed to very strong UV radiation fields from the evolving central objects, and also undergoes violent shocks generated by fast stellar winds colliding into the slower expanding AGB envelope. The importance of these mechanisms depends on the degree of evolution of the object, as the strength of the UV field is related to the temperature of the central star and large shocks are thought to disappear towards the end of this transition leading to the final PN stage. These fast and extreme changes of the physical conditions considerably modify the chemical composition of these objects: O-bearing molecules can be formed in C-rich objects (Herpin & Cernicharo 2000), as complex organic molecules (Cernicharo et al.2001 a and b). Moreover their morphology changes drastically during this evolution. In order to better understand this evolution from an AGB star to the PN stage, we perform here a comparative study of the far-IR (80-195 μm) emission from 3 objects that represent different stages of this fast transition ($\sim 10^3$ yr): CRL 2688, a very young Proto-Planetary Nebula (hereafter *PPN*), CRL 618 a PPN and NGC 7027 a young PN. We also perform a study of the CO emission from the 3 objects that provides the necessary kinematic information to precise their wind morphology.

CRL 2688 (the *Egg Nebula*) has an effective temperature around 6600 K (Justtanont et al.1997). This object is evolving very fast towards the PN stage, and was still probably in the AGB phase about 100 years ago (Jura & Kroto 1990). The central star is still relatively cool and thus has not yet photodissociated the molecular gas ejected during the AGB phase; no Photo-Dissociation Region (hereafter *PDR*) has yet been formed. The molecular gas is found to be in expanding, fragmented, shell structures, and shocks are thought to heat it.

CRL 618 must be a $\sim$ 200 years old PPN, i.e. the superwind phase terminated about 200 years ago. It has a compact HII region created by a hot central star (30 000 K, Justtanont et al.1997). CRL 618 is seen as a bipolar nebula at all wavelengths. The expansion velocity of the outer envelope is around 20 $\mathrm{km\,s^{-1}}$. However, CO observations show the presence of a high-velocity outflow with velocities as high as 300 $\mathrm{km\,s^{-1}}$(Cernicharo et al. 1989). The high velocity wind and the UV photons from the star perturb the circumstellar envelope (CSE) producing shocks and a PDR (Herpin & Cernicharo 2000).

The temperature of the central star of NGC 7027 is estimated to be more than 140 000 K (Liu et al.1996). This PN is very young though, having left the AGB only 10^3 years ago (Volk & Kwok 1997). Emission from the inner envelope is dominated by continuum and line emission from the ionized nebula. A ionized region is revealed by [OIII] fine-structure lines. The UV photons from the central star produce a PDR and the gas cools mainly via ionic and fine-structure atomic lines.

2. CO millimeter and submillimeter observations

The main goal of our millimeter and submillimeter CO analysis is to get some insight into the onset and properties of fast–winds in PPN objects. This bad-known process is decisive for a well understanding of the post–AGB evolution. PPN envelopes becoming highly asymmetric suggest that shaping occurs before reaching the PN phase. This

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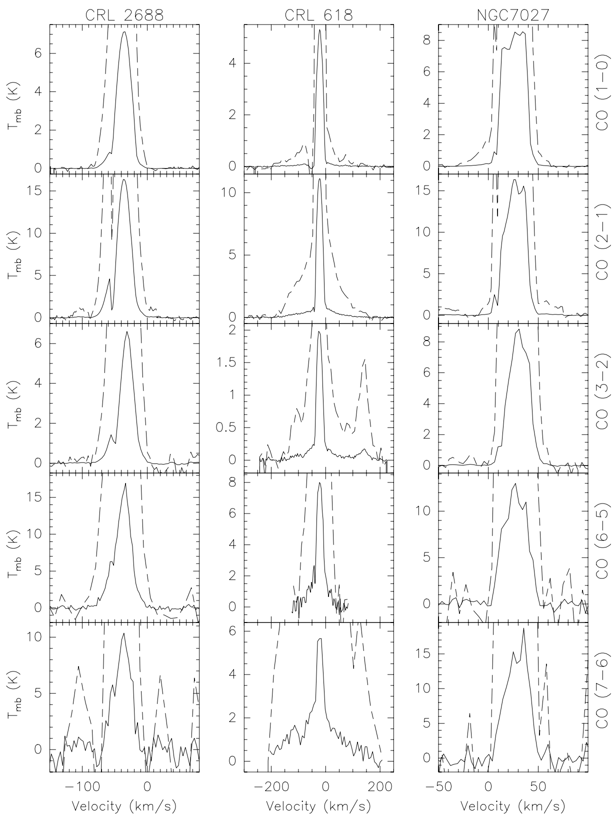

Figure 1. Spectra for the ^{12}CO J=1-0, 2-1, 3-2, 6-5 and 7-6 transitions for CRL 2688, CRL 618 and NGC 7027. The main beam temperatures are in K and the velocity in km s^{-1}. Baselines were applied. The 1-0 and 2-1 lines are IRAM 30m observations; the others were made with the CSO and are smoothed. For each line, in the same caption, is shown in dashed line the high velocity emission with an expanded verticale scale ($\times$10).

may be due to the appearance of super–winds interactions associated with final events of mass loss at the end of the asymptotic branch. Carbon monoxide emission in different low-excitation lines traces the circumstellar winds. We have complete observations of the CO low-excitation lines J=1-0, 2-1 (IRAM 30-m) , 3-2, 6-5 and 7-6 (CSO, Hawaii) for the 3 objects (see Fig. 1). From these observations we have derived useful informations like the flow velocity for each of the detected winds (see Herpin et al.2001).

For CRL 2688 we can distinguish two main flows. The main outflow velocity is around 20 km s^{-1}, a value typical of AGB stars. The second flow is a moderate velocity wind at a velocity of approximately 50 km s^{-1}. Wing contribution is expected to be larger as J increases because emission will be thicker (line emission is proportional to the opacity in the thin case). Several high-J CO lines were observed in Fabry-Perot mode with the LWS (see Herpin et al.2001), and these winds are also seen in these observations.

Two outflows can be seen in the CO line profiles from CRL 618. A main outflow has expansion velocity of roughly 20 km s^{-1}. The *High Velocity Wind* is observed here with a velocity of $\sim$ 200 km s^{-1}(280 km s^{-1}for the deprojected velocity). This *HVW* is associated with a biconical outflow. According to Cernicharo et al.(1989), the CO flow could be decelerated.

In NGC 7027, the main emission has an expansion velocity of 15-20 km s^{-1}. The line profiles show also some wings that could be the signature of a faster outflow, whose velocity is decreasing with increasing J (47 to 24 km s^{-1}). We then think that the velocity of this *Medium Velocity Wind* may be around 45 km s^{-1}. This flow may be the relic of a *High Velocity Wind* ejected during the PPN phase and not yet completely ionized or decelerated by contact with the low velocity envelope.

3. ISO LWS spectrum from the 3 objects

We tried to model the ISO/LWS spectrum, using the kinematic information derived from the individual CO lines presented before and also information available from other works. We used a simple LVG-model and obtained satisfactory fits (see Fig. 2). See Herpin et al.(2001) for details about the models. The abundances are given in Table 1.

4. Discussion

The only far-IR line emissions present in the far-IR (^{12}CO , ^{13}CO , HCN) of CRL 2688 are well reproduced by our shock model. The PPN exhibits a very fast wind (characteristic of an object at the beggining of its transition to the PN stage) which runs into the AGB remnant envelope. The gas then cools then via molecular lines. Concerning the ^{13}CO emission, we must stress that at the resolution of the grating spectrometra this emission is not detectable, and we can only derive a maximum value of abundance ($<$ 2.5 $10^{-5}/H_2$, with [CO/H_2]=6 10^{-4}). The ^{12}CO material is not yet reprocessed. We find that the HCN/CO abundance ratio may be lower in the fast wind than in the slow wind ($\leq$ 6 10^{-6} and $\leq$ 2 10^{-5} respectively. Note that in the innermost regions of the C-rich AGB circumstellar envelopes (e.g., IRC +10216) HCN is the main coolant, while in the external parts CO and HCN play this role. Furthermore, HNC is not detected here.

In CRL 618, Herpin & Cernicharo (2000) have shown that O-bearing species, H_2O and OH, are produced in the innermost region of the circumstellar envelope. Also Cernicharo et al.(2001a and b) have detected in this object the poli-acetylenic chains C_4H_2 and C_6H_2, methyl-polyynes, and benzene. The gas cools via CO, C^+ and [OI] lines. The UV photons from the central star photodissociate most of the molecular species produced in the AGB phase and allow a chemistry dominated by standard ion-neutral reactions. Not only allow these reactions the formation of O-bearing species, but they also modify the abundances of C-rich molecules like HCN and HNC for which we found an abundance ratio of $\simeq$ 1, much lower than in AGB stars.

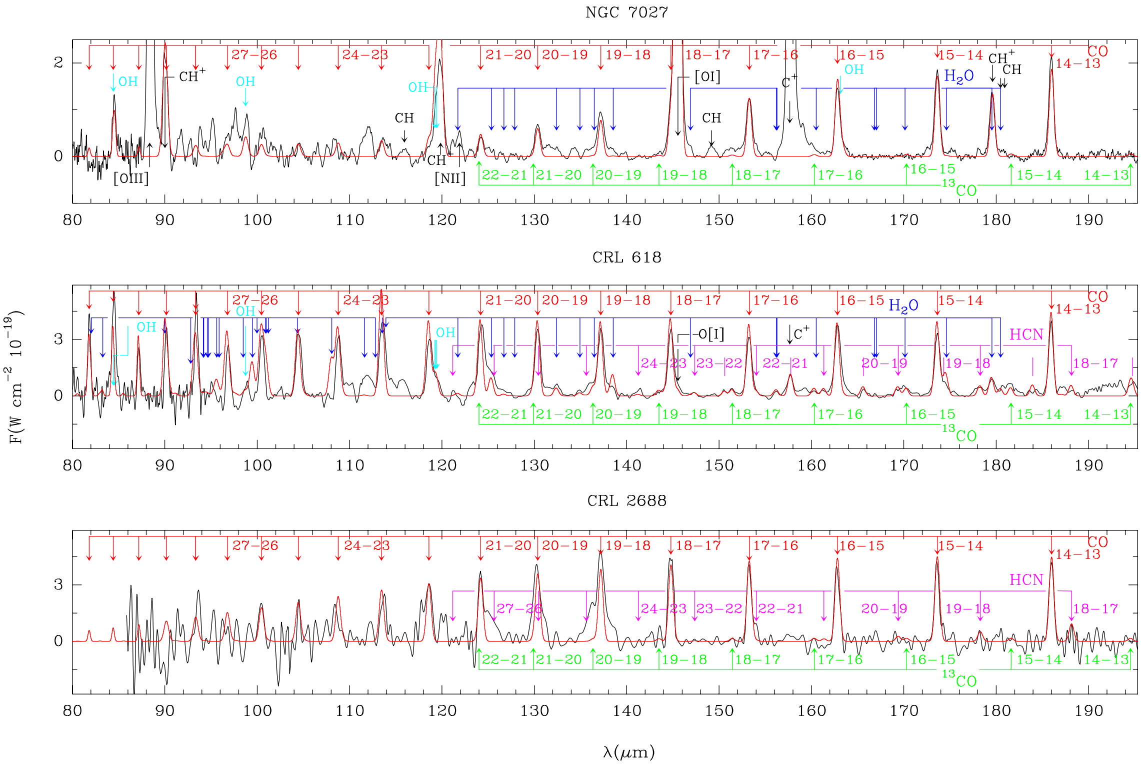

Figure 2. *Continuum subtracted ISO LWS spectra of CRL 2688 (bottom caption), CRL 618 (middle caption) and NGC 7027 (top caption). The result of our models is shown by the continuous red line. The lines of ^{12}CO, ^{13}CO, HCN, H_2O, CH^+ and OH are indicated by arrows while those of HNC in CRL 618 are indicated by vertical lines (from J=22-21 at 150.627 μm to J=17-16 at 194.759 μm). The C^+ and [OIII] transitions are not included in our models; the plots indicate gaussian fits to these features.*

We derived a [^{12}CO /^{13}CO] ratio of 20. The HCN abundance goes from 10^{-3} close to the torus to 10^{-1} in the lobes due to the efficient dissociation in the second region. The abundances of H_2O and OH relative to ^{12}CO are 4 10^{-2} and 8 10^{-4} respectively.

NGC 7027 has a very hot central star. Because of the resulting important UV flux, there is a strong presence of atomic lines. UV photons from the central star produce a PDR and the gas cools mainly via fine-structure atomic lines. Species like CH^+, CH, [OIII], [NII], OH are detected, but no H_2O . In the PDR, most of the CO molecules having been photodissociated (Liu et al.1996). Due to the high temperatures, densities and UV radiation field in the PDR, the formation of CH^+ leads to the creation of CH_2^+ and CH_3^+, whose dissociative recombination will form CH very efficiently at high temperature (Sternberg & Dalgarno 1995). Moreover, the only presence of [OI] and CH^+ in the hottest shells of the atomic region, and the low abundance of CO in the adjacent shells indicate that the CO molecules have been largely reprocessed there through UV photons. The non detection of H_2O and the detection of OH indicate that the H_2O molecules formed in the previous stage may have been also reprocessed due to the strong UV field. UV radiation can transform H_2O into OH and H, and so increase the amount of OH. Concerning HCN, Deguchi et al.(1990) derived a HCN to CO ratio of 9 10^{-5} that explains why we do not detect line emission from this molecule. As a consequence, observed CO in these objects are newly formed molecules rather than remnants from the AGB circumstellar enveloppe. The detected molecules are constantly formed as well as destroyed in NGC 7027 (Hasegawa et al.2000).

5. Evolution scheme

The study of our 3 objects sample shows well the importance of the winds and the increasing importance of the UV flux during the evolution of an AGB star to the PN stage. This is clearly indicated by the atomic and ionic lines appearing in CRL 618 and present in the spectra of NGC 7027. On the other hand, the shocks are less important as the evolution goes on, as the wind velocity is decreasing. The strongest shocks occur just after leaving the AGB when the central star is ejecting large amounts of material in a very fast wind (the case of CRL 2688). The AGB remnant envelope is progressively ejected to the very outer parts of the object, being shocked by the strong wind from the star. As the object is C-rich, these shock-conditions further the ^{12}CO , ^{13}CO and HCN emissions. The ^{13}CO abundance remains quite stable according to the AGB phase. The fast increase of the stellar temperature, when the object evolves, will produce a new chemistry, a UV-based chemistry in fact. These new conditions (UV associated with shocks) will deeply modify the constitution of the inner parts of the envelope. Indeed, in CRL 618 O-bearing molecules appear (H_2O and OH), as complex organic molecules. Furthermore, CO will be reprocessed. HCN molecules will also be reprocessed, leading to strong HNC emission close to the PDR (same abundance of HCN and HNC). At this point, CO lines and [OI] atomic lines are the dominant coolants. As the star reaches the PN stage, the mass ejection is quite finished, the strong fast winds have disappeared, and slow expanding shells constitute the PN envelope around a large and hot atomic region. All the *old* AGB material has been reprocessed: the CO and other molecules are constantly produced and destroyed. The spectra is now dominated by atomic and ionic lines. New species such as CH^+ and CH appear. There is only weak HCN, or HNC emission. H_2O has probably also been reprocessed and is only an intermediate molecule of the PPN stage.

Table 1. Table of the molecular, atomic and ionic abundances (relative to ^{12}CO) in CRL 2688, CRL 618 and NGC 7027 as seen by the model.

Species	**CRL 2688**	**CRL 618**	**NGC7027**
^{13}CO	$< 1/25$	1/20	$< 1/30$
HCN	$< 1/30 - 1/100$	$1/10 - 1/1000$	
HNC		$1/10 - 1/1000$	
H_2O		1/25	$< 1/650$
OH		1/1250	1/20
[OI]		4.5	875
CH^+			1/80

6. Herschel Space Observatory

As these evolved objects are very important for the interstellar medium, due to their interaction (mass loss...), as they are unique laboratories, the AGB, PPNs and PNs are very interesting targets for the HSO.

The HSO (mainly HIFI) will allow the study of the inner layers where dust and wind formation occur, to trace shocks, to study the intern photodissociation (PDR, physical and chemical conditions), and more especially the mass loss history (via imaging of the continuum emission to detect compact detached shells and the changes in the mass loss rate, the morphological changes). HIFI will provide informations about the velocity structure of the envelopes. Black-bodies with temperatures between 10 K and 50 K peak in this wavelength range. Gases with temperatures between 10 K and a few hundred K emit their brightest molecular and atomic emission lines here. The observation of new transitions of H_2O (a complete study of H_2O and its isotopes will be possible) and CO with a high velocity resolution will allow the study of the circumstellar envelopes at intermediate temperatures (the ^{12}CO J=6-5 to J=17-16 lines will be observable, filling the gap between mm and ISO observations, thus providing informations about intermediate regions). New molecular emissions will be discovered, and fine-structure lines will be observed, as low-lying ro-vibrational transitions of complex species such as PAHs, or long carbon chains (more than 15 atoms, bending modes). We can expect with these new observations to distinguish between chemical models.

HIFI will allow very high resolution spectroscopy observations between 157-212 μm and 240-625 μm. A sensitivity 100 to 1000 times better than ISO will be reachable (10^{-18} Wm^{-2} in line observations with 5 σ in 1 hour). Thus thousands of molecular, atomic and ionic lines will be observable with this high resolution, providing more accurate abundances. With a complete line survey, more accurate constraints on the physical parameters, the dynamical processes will be derived.

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