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Characterisation of circumstellar envelopes in AGB stars with UV/X-ray emission

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Abstract

In this talk, I present the main results from our recent works, which are focused on the characterisation of the circumstellar envelopes around a special class of AGB stars with ultraviolet and X-ray emission, which are binary candidates. We have studied the physical and chemical properties of their gas and dust envelopes. We found that this high energy radiation produces a lower gas-to-dust ratio and, in sources with internal X-ray radiation, an abundance enhancement of certain molecular species like HCO^+.

1 Introduction

Low and intermediate mass stars (i.e. with masses in the $1 - 8\,M_\odot$ range) evolve from the main sequence to the Asymptotic Giant Branch (AGB) phase increasing their luminosity and reducing their effective temperatures. At this stage, they exhibit dense, roughly spherical, circumstellar envelopes (CSEs) expanding at low velocities ($V_{\rm exp} \simeq 5 - 30\,{\rm km\,s^{-1}}$), which are composed of molecular gas and dust, showing a very rich chemistry, see[7].

At later stages of their evolution, they become pre-Planetary Nebulae (PNe), developing high-velocity winds ($V_{\rm exp} \simeq 100\,{\rm km\,s^{-1}}$) and shaping their CSEs into complex structures [13], and afterwards ending as Planetary Nebulae (PNe), when they exhibit a wide variety of shapes that deviate from simple spherical shell [16]. Despite the progress made in the last decades, the pre-PNe-shaping process is still not well understood, see [5].

Binarity is widely accepted as a promising mechanism to explain these morphological and dynamic changes during the post-AGB phase, see e.g. [5]. However, the high luminosity and pulsation variability of the AGB stars prevent the use of classic methods, such as transits and radial velocity curves, to identify binary companions. Nevertheless, the detection of ultraviolet (UV) emission excesses orders of magnitude higher than the expected for AGBs [14] is an effective method to identify binary candidates. In some cases, it has been also detected an unexpected X-ray emission, see e.g. [16, 10]. These high energy emissions are expected to be produced by a stellar companion and/or by the presence of an accretion discs.

In this talk, first, I summarise the main results from our study of the molecular gas envelope of UV emitting AGBs (uvAGBs) based on CO emission lines observations. Second, I show a brief review of our current work in the analysis of their dust emission. Finally, I display some highlights of our study of the X-ray driven molecular gas chemistry.

2 CO emission lines study of the CSEs of uvAGBs

In this section, we summarise the main results from our recently published paper [2], aimed at the first characterisation of the gas properties of the circumstellar envelopes of uvAGBs as a class and compare them with those derived from previous CO-based studies performed over larger samples of AGBs.

We observed the ^{12}CO(J=1-0) and ^{12}CO(J=2-1) rotational transitions in a sample of 29 uvAGBs with the IRAM-30m radio telescope. We measured the main parameters of these lines and estimated the expansion velocity ($3\mathrm{km\,s^{-1}} < V_{\mathrm{exp}} < 13\mathrm{km\,s^{-1}}$), excitation temperature ($5\mathrm{K} < T_{\mathrm{ex}} < 25\mathrm{K}$) and the mass-loss rates ($10^{-8} M_{\odot}\, yr^{-1} < \dot{M} < 10^{-5} M_{\odot}\, yr^{-1}$) with the rotational diagram method. We derived some additional parameters such as the CO envelope sizes ($5 \times 10^{15}\mathrm{cm} < R_{\mathrm{CO}} < 2 \times 10^{17}\mathrm{cm}$) following additional prescriptions, see [2]. We also explored different trends between these envelope parameters and multi-wavelength fluxes, specially those from the far infrared and UV. We found a significant anti-correlation between CO emission and UV fluxes.

Our estimated CSE parameters (V_{exp}, M and $\dot{M}$) align with previous studies of large AGB samples and support the dust-driven wind model, We did not require alternative mass-loss mechanisms to explain these envelope parameters and future high spatial resolution observations are needed to further study the uvAGB winds.

One important result is that the correlation between CO line intensities and 60μm fluxes, a classical gas/dust indicator, is lower for our sample of uvAGBs than for the generic samples of AGBs from [12]. Our sample of uvAGBs have a trend more similar to that found by [6] for pre-PNe, which are more evolved systems. This difference in the CO to infrared emission might be related to photodissociation of the molecular gas leaded by the UV/X-ray emission.

3 Dust envelope characterisation with SED modelling

In this ongoing work, we characterise the dust envelope component in the same sample of uvAGBs. This analysis is performed by modelling the Spectral Energy Distributions

(SEDs) with the 1D-radiative transfer code DUSTY [8]. For this purpose, we gathered three kinds of archival data: (i) photometric fluxes obtained from general catalogues and surveys (e.g. *IRAS*, 2MASS), (ii) archival optical (*Gaia*) and infrared (*IRAS*/*ISO*) spectra and (iii) archival *HERSCHEL*/PACS images from which we extracted the photometric fluxes and radial brightness profiles. We compare the observed SEDs and PACS radial profiles with those created by DUSTY under the assumption of a central source surrounded by spherical dust layers.

The photospheric emission (input spectra of the central source) was modelled with the COMARCS stellar atmosphere library developed by [3, 4]. We assume standard dust chemical composition according to the respective chemical types. The size of the grains is described by the standard Mathis-Rumpl-Nordsieck (MRN) distribution [11].

The best fit model for each source is found by minimizing a χ^2 function depending on four parameters: the temperature in the inner radius ($T_{\rm inner}$), the density power-law index ($\rho \propto r^{-n}$), the radial optical depth at 0.55μm (τ), and the ratio of the outer to the inner radius of the circumstellar envelope (i.e. the size of the envelope, Y).

Fig. 1 shows an example of SED modelling for the C-rich AGB T Dra. The model correctly recreates the photometry and most of the infrared spectra, including the SiC dust feature at $\sim 11\mu$m, validating that the model reproduces adequately the main dust properties.

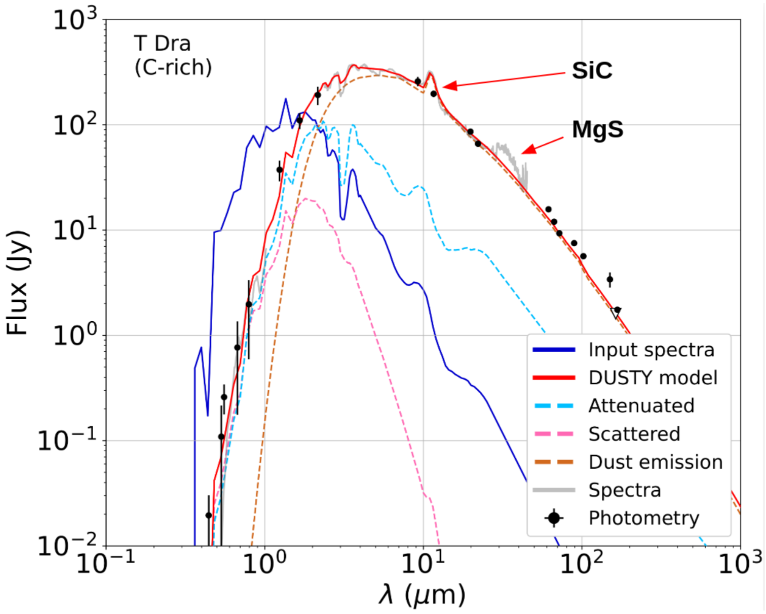

Figure 1: SED of the C-rich AGB T Dra. Black points are photometric data and grey curves archival spectra. Blue: input stellar spectra and red: DUSTY output spectra for the best-fit model ($T_{\rm inner}$=1200 K, n=2.05, τ=5.0 and Y=7 $\times$ 10^5). Red curve is divided in three components: Cyan: Attenuated input stellar spectra, pink: Dust scattered emission and brown: Dust Thermal emission.

Finally, a comparison between the gas ($10^{-2} - 10^{-5} M_\odot$) and dust masses ($10^{-3} - 10^{-6} M_\odot$)

derived from the modelling serves as a method to estimate the gas to dust ratio. We found an average gas to dust ratio of ∼20, which is an order of magnitude lower than for standard AGBs (∼160 and ∼400 for O-rich and C-rich respectively [9]), reinforcing the enhanced internal gas photodissociation hypothesis from [2].

4 X-ray induced molecular chemistry

We performed an exploratory study of the effects of an internal source of UV and X-ray emission in the molecular chemistry of the CSEs (Alonso-Hernández et al., in prep). We conducted a search for emission lines of HCO^+, an X-ray sensitive molecule, with the IRAM-30m radio telescope in two X-ray emitting AGB stars with previous CO line detections (T Dra and EY Hya). We additionally observed two uvAGBs (V Eri and VY UMa), which were not detected in X-rays, in order to empirically isolate the effects of X-rays and UV radiation. We have chosen one C-rich and one O-rich AGB star in each of these subsamples to compare the effects of these two radiations on envelopes with different chemistry.

We use the chemical kinetics model previously developed by [1]. We included the effects of an internal source of UV radiation, following the porosity formalism of [17], and, as a novelty, we introduced X-rays as an additional source of internal H_2 ionisation together with cosmic rays. Our model predicts the radial abundance profiles of the different molecules, which are expected to be produced under different ranges of the internal UV and X-ray luminosities and mass-loss rates.

Fig. 2 shows the HCO^+ radial abundance profile and the effects of the internal UV and X-ray emission. The HCO^+ is very sensitive to the X-ray emission, with an average enhancement of ~ 2 orders of magnitude throughout the envelope, whereas the internal UV emission does not produce a significant effect. This is related to the photodissociation and photoionisation energies of the hydrogen molecule (around 10 eV), which are larger than most UV photons and cannot be efficiently photodissociated or photoionisated by UV radiation. Therefore, the internal X-ray emission lead the production of the H_3^+ radical, enhancing HCO^+ abundance through the chemical reaction

$$H_3^+ + CO \rightarrow HCO^+ + H_2 \tag{1}$$

Fig. 3 shows the detected HCO^+ lines in T Dra, the C-rich AGB with X-ray emission. This molecular emission was detected in two observational campaigns, one in 2020 and the other in 2024, and shows variability of a factor $\sim 2-3$ in the line intensities. This variability was not identified in the rest of thermal lines detected in the same spectral scans (e.g. HCN, SiO, HNC, among other molecular species) and, therefore, seems to be real and likely related with a equivalent variability of the X-ray flux.

We made a radiative transfer model to empirically infer the HCO^+ abundance in the two epochs and compare it with the chemical model. Our preliminary results are HCO^+ abundances of $1-3\times10^{-8}$ with respect to H_2, which is consistent with the X-ray model and significantly larger than the HCO^+ abundance expected in the absence of X-ray emission. A similar analysis was done for the rest of identified molecules. Preliminary results indicate

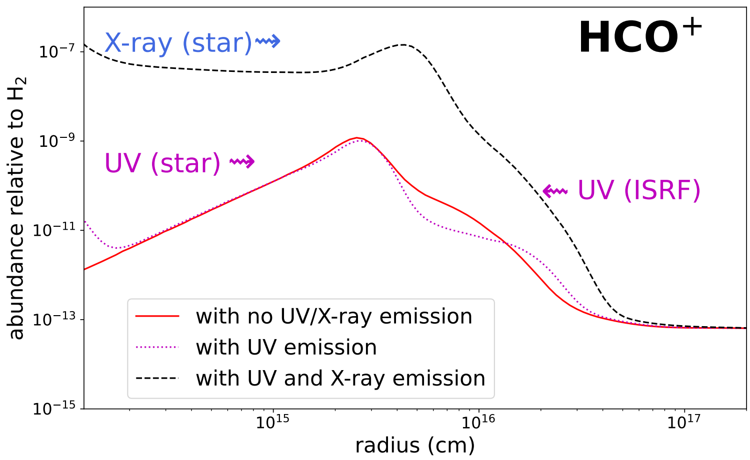

Figure 2: Comparison between the HCO^+ radial abundance profiles for three cases. Dashed black line: with internal UV and X-ray emission. Dotted purple line: with internal UV (only) emission. Solid red line: with no internal source or high-energy radiation. The envelope parameters used as input for the chemical model correspond to the C-rich AGB T Dra. The UV interstellar radiation field (ISRF) is also indicated as it dominates the abundance in the external regions of the envelope.

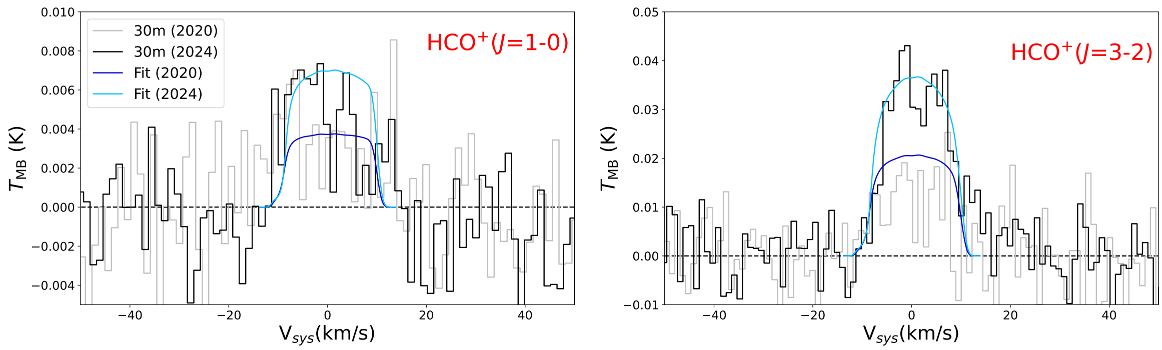

Figure 3: HCO^+(J=1-0) and HCO^+(J=3-2) lines. Grey: observed spectra in 2020, Black: observed spectra in 2024. Blue: fitted line to the observed spectra of 2020. Cyan: fitted line to the observed spectra of 2024.

additional X-ray-driven enhancements of the abundances of HNC and HC_3N, also leaded by H_3^+, although in a lesser degree than HCO^+.

5 Summary of the results

In this talk, I described the analysis carried out to characterise the CSEs of AGB with UV and X-ray emission, which are binary candidates. This analysis combined complementary observations (multi-wavelength photometry, far infrared images and sub-mm spectra) and different physical processes (radiative transfer in gas and dust as well as chemical kinematics), offering a complete picture of these particular systems.

We found that these internal sources of high energy radiation might be producing molecular photodissociation and photoionisation, leading to the decrease of CO in the inner regions of their envelopes and enhancing the abundance of some key molecules like HCO^+. Further analysis with high-spatial resolution observation are needed for a better characterisation of the geometry, density distribution and radial abundance of key molecules. These studies might shed light on how the interaction with the companion stars affects the dust-driven wind and mass-loss processes in AGB stars.

Acknowledgments

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