CHARACTERIZATION OF AGB CIRCUMSTELLAR ENVELOPES BY MID-IR IMAGING

M. MARENGO\textsuperscript{1}, G. CANIL\textsuperscript{2}

\textsuperscript{1}SISSA/ISAS Int. School for Advanced Studies, I-34014, Trieste, Italy
\textsuperscript{2}Istituto di Fisica Generale - Università di Torino, Italy

ABSTRACT.
This paper reviews the observations, made with the mid-IR camera TIRCAM of a sample of O-rich and C-rich circumstellar envelopes, around AGB and post-AGB stars. The main envelope chemical composition, evolutionary stage and mass loss are characterized by mid-IR photometry and color. Physical parameters of the circumstellar environment are derived from fitting mid-IR data by means of radiative transfer modelling, using recent compilations for dust opacities. The chemical composition of the dust in the observed envelopes is discussed, and informations on dust grain evolution processes are inferred from a comparison of model and observed spectra.

1. Introduction
Intermediate and low mass stars (1-8 M\textsubscript{\odot}) in the Asymptotic Giant Branch (AGB) stage undergo processes of intense mass loss which lead to the formation of circumstellar envelopes (CSE) of gas and dust. The CSE composition depends on the metal abundance of the AGB star external layers: C-rich envelopes (characterized by a [C]/[O] ratio greater than 1) are associated to carbon stars, enriched of C as a consequence of mixing processes (third dredge-up) during thermal pulses at the end of AGB phase, while O-rich envelopes (having [C]/[O] < 1) mainly exist around stars of M spectral type. The transition between O-rich and C-rich envelopes is related to the extent of the third dredge-up experienced by the star and is possible only for an intermediate mass range: according to recent calculations (Straniero et al., 1995) a minimum core mass of 0.6 M\textsubscript{\odot} is necessary to start the dredge-up, and thus only stars more massive than \sim 1.5 M\textsubscript{\odot} will become C-rich; the occurrence of C burning at the base of the convective envelope (Hot Bottom Burning) for stars of mass roughly greater than \sim 5 M\textsubscript{\odot} (Boothroyd and Sackmann, 1992; Lattanzio, 1995) will destroy the newly dredged-up carbon, thus preventing them to become C-rich.

It is usually held that the oxygen excess in O-rich envelopes locks all carbon atoms in CO and allows the formation of silicate dust grains, which are globally responsible for a broad emission/absorption band at 9.7 \mu m, and an emission feature at \sim 20 \mu m (Pégourié and Papoular, 1985). On the other hand, an excess of carbon would form dust rich in graphite and/or amorphous carbon, with small but significant impurities of SiC (detectable at 11.3 \mu m) and perhaps Polycyclic Aromatic Hydrocarbons (PAH, Léger and
Puget, 1984; Puget and Léger, 1989), which would give rise to broad emission features at 3.3, 6.2, 7.7, 8.6 and 11.3 μm. Despite the low dust to gas ratio (about 1% or less), the dust in the circumstellar envelope is the main responsible for the mid- and far-IR excess observed in AGB systems. For this reason, the 10 μm atmospheric window is particularly suitable for the observation of dust emissions from AGB circumstellar envelopes, with the purpose of chemically and physically characterize these sources, even for the most evolved systems (in the post-AGB phase) not visible at optical wavelength, because of the large dust extinction.

In this paper we show how ground-based mid-IR observations can be used for the purpose of chemical and evolutionary classification of AGB objects. In Section 2 the results of observations with the mid-IR camera TIRCAM, of a sample of O-rich and C-rich AGB and post-AGB sources are presented. The data are compared with space (IRAS) and radio (CO) observations in order to correlate mid-IR colors with mass loss rates. In Section 3 the observational data are fitted with simple numerical modelling, and the main physical parameters are derived for the observed sources. Finally, in Section 4 the main results obtained with this technique are summarized, and possible future developments are discussed.

2. Mid-IR Observations of AGB Circumstellar Envelopes

The IRAS Point Source Catalogue (1985) provides the main source of data on mid-IR observations for AGB stars and circumstellar envelopes. The IRAS color-color diagram [12]-[25] versus [25]-[60] allows discrimination of AGB sources, that are distributed in separate regions of the diagram, according to their [C]/[O] ratio, variability (many AGB stars are well studied Mira variables) and infrared excess (van der Venn and Habing, 1988).

IRAS Low Resolution Spectra (1986) show the emission/absorption features in the mid-IR spectra (in the range \( \lambda = 7.7-22.6 \ \mu m \)) for about 4,000 AGB sources. An automatic classification for each LRS spectra is given, based on spectrometric data alone. The LRS classification consists of a two number code; the first (main class) is related to the spectral index \( \beta \) of the LRS (assuming \( F_\lambda \propto \lambda^\beta \)), the second is a measure of the feature strength in the LRS, when present (the 9.8 μm silicate band for O-rich envelopes, and the SiC feature at 11.4 μm for C-rich envelopes). The relevant LRS codes for AGB objects are the main classes 2n and 3n for O-rich sources (with the silicate band in emission and absorption, respectively) and 4n for the C-rich class. Post-AGB objects fall in the main classes 6n and 7n (characterized by very large infrared excess), corresponding to “blue spectra” classes 2n and 3n respectively. No “red” equivalent to the 4n class was found in the IRAS LRS database. Finally, sources of both O-rich and C-rich types may fall in the 1n class, where sources with featureless spectra are grouped.

The LRS classification can in principle solve the problem of chemical and evolutionary characterization of all AGB envelopes. In fact the reduced number of sources for which the LRS code is given (some important bright AGB stars are missing for technical reasons, like the Mira prototype o Cet and the well known M star R Leo), and the uncertainties in the classification of intermediate objects like S-stars (not discriminated from O-rich envelopes with weak silicates emission feature, see Figure 1) advice to suggest
for a different method of classification suitable for a larger sample of sources.

2.1. TIRCAM Observations

The development of solid state pixel imaging arrays, sensitive to mid-IR radiation, has in recent years made possible direct detection of AGB circumstellar envelopes from ground based telescopes in the 10 μm wavelength range.

Observations of obscured AGB stars in the Magellanic Clouds have been performed by Zijlstra et al. (1995) using ESO TIMMI imaging mid-IR camera. They selected six sources from a wide sample of candidate AGB stars for 10 μm photometry in the standard N filter, and in two narrow band filters centered at 9.8 and 11.3 μm. From comparison with near-IR and millimetric (CO) data they derived criteria for the sources classification, and for deriving mass loss rates.

In Busso et al. (1995a) a sample of 16 bright low mass galactic AGB stars was selected for imaging with the mid-IR camera TIRCAM (see Persi et al., 1994) mounted either at the TIRGO 1.5-m Italian IR telescope at Gornergrat (Switzerland) or at the
TABLE I

The TIRCAM sample sources; sources labelled with * are post-AGB.

<table>
<thead>
<tr>
<th>#</th>
<th>Source</th>
<th>Class</th>
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<th>IRAS</th>
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<td>02168–0312</td>
</tr>
<tr>
<td>2</td>
<td>CRL 618a</td>
<td>C-rich</td>
<td>62</td>
<td>04395+3601</td>
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<tr>
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<td>O-rich</td>
<td>—</td>
<td>09448+1139</td>
</tr>
<tr>
<td>6</td>
<td>CW Leo</td>
<td>C-rich</td>
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<td>W And</td>
<td>S-star</td>
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2.1-m telescope of the Observatorio Astronomico Nacional (Mexico) at San Pedro Martir (SPM). The optical system of the camera is designed to have, at the detector (10x64 pixels Si:As array) position, a scale of 1.23″/pix and 1.38″/pix at the two telescopes, respectively. The used photometric system consists of four 10% band filters centered at 8.8 (continuum+PAH?), 9.8 (silicates), 11.7 (SiC+PAH?) and 12.5 (continuum+PAH?) micron respectively.

The observations were made in “background limited” conditions, using a chopping and beam switching technique, and the data reduction was performed as described in Busso et al. (1995a). The photometric calibration was achieved using two standard bright red stars (α Tau and α Boo) and gave, for the observed sources, a nominal error (1σ) of ~ 0.1 mag., with a S/N ratio generally larger than 10.

The sample of selected sources consists of 16 bright low mass AGB stars, with known $M$ (see Table I): 7 O-rich (M-type), 6 C-rich (N- and J-type), 1 S-star and 2 post-AGB (1 O-rich and 1 C-rich). Their location on the IRAS [12]-[25] versus [25]-[60] color-color diagram (Figure 2) is in general agreement with the LRS code and the chemical classification given in Loup et al., 1993). Note that the two post-AGB objects (one O-rich and one C-rich) are both in the same region of the diagram (IV), originally associated to evolved O-rich envelopes; this confirms that IRAS LRS and colors are not able to distinguish between evolved AGB envelopes of different chemical composition.

In Busso et al. (1995a) TIRCAM photometry is compared with IRAS LRS spectra (normalized to IRAS 12 μm flux), when available, for the observed sources; within the errors TIRCAM fluxes are able to reproduce the general features of mid-IR energy distribution: O-rich sources are dominated by the presence of 9.8 μm silicate feature,
Fig. 2. van der Veen and Habing (1986) IRAS color-color diagram for the observed TIRCAM AGB sources.

and show a steeper decrease in the continuum, while C-rich envelopes are characterized by a smoother $\lambda F_\lambda$.

2.2. Spectral Classification and Mass Loss Rates

A quantitative analysis of the differences in O-rich and C-rich mid-IR photometry is provided by colors in the TIRCAM filters. The color-color diagram in Figure 3 shows the distribution of the observed sources on the plane [8.8]-[12.5] vs [8.8]-[11.7], where the [8.8]-[12.5] color is mainly related to the continuum emission and the amount of infrared excess and the [8.8]-[11.7] color is more sensitive to the dust features. Despite the low statistics, the sources appear to be distributed in different regions: O-rich sources have [8.8]-[12.5] < 0 with a limited dispersion in the [8.8]-[11.7] color; C-rich sources have [8.8]-[12.5] > 0 and are widely dispersed in the [8.8]-[11.7] color; the post-AGB sources and the S-star have larger [8.8]-[12.5] color.

The chemical discrimination of the sources in the [8.8]-[12.5] color is probably due to the different location of silicate and carbon features, and is in agreement with the idea that the slope of the continuum spectra is correlated to the chemical composition of the
Fig. 3. TIRCAM [8.8]--[12.5] vs [8.8]--[11.7] color-color diagram for the observed sources.

dust. The larger mid-IR excess of the post-AGB sources and the S-star should indicate a larger mass loss, that can be related to the advanced evolution (as in the case of the post-AGB sources) or to episodes of enhanced mass loss (for the S-star W And). Note that the [8.8]--[11.7] color is essentially unaffected by the chemical characterization and the IR excess of the envelopes; the same is verified by the other colors in the TIRCAM photometric system. The only apparent correlation is with the [8.8]--[12.5] color.

In order to obtain a better discrimination of the sources, based on two independent parameters able to distinguish between the chemistry and the evolution of the envelopes, we tried to correlate the [8.8]--[12.5] color to the mass loss rates derived from CO data (from Loup et al., 1993). We tried a power-law relation based on the Salpeter mass loss formula where the dust optical depth is estimated through a flux ratio:

\[ \dot{M} = A \frac{L_4}{v_{15}} \left( \frac{F_{8.8}}{F_{12.5}} \right)^\alpha \ M_\odot/yr \]

The above formula is the extension in the mid-IR range of a similar relation for IRAS \( F_{12}/F_{25} \) flux ratio in van der Veen and Olofsson (1989); \( L_4 \) and \( v_{15} \) are the bolometric luminosity (in \( 10^4 \) \( L_\odot \) units) and wind velocity (in 15 km/s) for each source derived
Fig. 4. TIRCAM [8.8]-[12.5] color vs a logarithmic mass loss parameter for the observed sources: linear fits are derived for O-rich (+ S star) and C-rich sources separately.

from the Loup et al. (1993) database; the parameters $A$ and $\alpha$ are derived fitting the data. The result is shown in Figure 4.

Due to the characteristic of our sample, C-rich stars have a larger scatter in the mass loss parameter, while O-rich sources are grouped in a relatively small region of the diagram. This is probably due to the fact that, in average, O-rich stars in the sample should be less massive than C-rich ones, to prevent them undergoing the third dredge-up. A limited core mass will thus prevent large mass loss. The largest mass loss parameter belongs to the more evolved post-AGB stars, according with the hypothesis that the [8.8]-[12.5] color is a measure of increasing mass of dust, and is thus related to the time spent on the AGB (not linearly, if mass loss is not monotonic, as may be the case of the S-star). For C-rich stars a regression line can be found, and even a small IR excess corresponds to a large mass loss parameter, due to the lower opacity of carbonaceous grains, compared to silicates.

This temptative criterium for the interpretation is in agreement with the idea of evolution ruled by the mass of the star: lower mass stars (i) will evolve with low mass loss rates up to the pre-PN phase, (iia) do not reach a core mass sufficient to dredge
up carbon and remain O-rich, or (iiib) the critical mass is reached only in advanced thermal pulses, limiting the carbon enrichment (S-stars), and (iii) are characterized by large IR excess despite moderate mass loss; more massive objects (i) can have larger mass loss rates, (ii) experience third dredge up becoming C-rich and (iii) evolve toward C-rich pre-PN. A larger sample of sources is necessary to confirm this interpretation and derive the fitting parameters for the two classes of sources; observations of the rare more massive AGB stars (which will undergo hot bottom burning) are necessary for the comprehension of the complete evolutionary frame.

3. Envelope Modelling

In order to derive from IR data the main physical parameters for the observed sources, we have developed a simple numerical code to compute non-grey radiative transfer equation through a spherically symmetric dust shell (see Busso et al., 1995b). The model allows, for a wide range of parameters, to derive the thermal structure for envelopes of different chemical composition (according to the used dust opacity) and thus the radial brightness distribution and emergent spectra. Fitting of observational data (near- and mid-IR) will provide an estimate of the optical depth of each envelope, directly related to the mass loss. The detailed study of the observed sources in the sample will be presented in a forthcoming paper (Marengo et al., 1996).

A self-consistent modelling of envelopes around evolved late-type stars, characterized by intense mass loss and stellar wind requires the coupling of radiative transfer with hydrodynamic equations of motion for two interacting fluids (gas and dust). Such approach has been undertaken by Ivezić and Elitzur (1995), and can successfully explain the observed mass loss rates assuming dust driven winds. They reproduced the IRAS colors for a large sample of AGB objects in all LRS classes, in the hypothesis of a steady state outflow due to constant stellar wind. More recently, models taking into account time dependent outflows have been developed to study the effect of sudden variations in the stellar parameters in connection with thermal pulses (e.g. Schönberner et al., communication at this workshop). Although this analysis is necessary to explain the latest stages of the AGB evolution, which lead to the formation of the planetary nebula, time variations in the mass loss (in the TP timescales) have negligible effects on the infrared properties of at least 95% of late-type stars in the IRAS sources (Ivezić and Elitzur).

In our model the dynamics of the envelope is totally neglected; the radial density profile (with steady mass loss) is fixed fitting IRAS LRS spectra for the observed sources. The other model parameters (the stellar effective temperature, the stellar radius and the inner and outer radius of the envelopes) are derived fitting the TIRCAM and IRAS fluxes, and the photometry in the near-IR.

3.1. Dust Opacities

For any given grain composition, the shape of the emergent spectra is only dependent on the flux averaged optical depth of the envelope, due to a scaling property of radiative transfer equation in spherical symmetry, first noted by Chan and Kwok (1990). The dust optical depth, for envelopes created by a steady mass loss \( n(r) \propto r^{-2} \) is only function
of the dust opacity $Q_\nu$.

Opacities are given by laboratory measurements and fits of observed spectra; for our model we adopted a “dirty silicates” model (Ossenkopf et al., 1992) for O-rich dust, and a mixture of amorphous carbon (Rouleau and Martin, 1991) and (\leq 10\%) SiC (Pégourié, 1988) for C-rich dust. We have not introduced PAH because they are mainly excited by UV radiation, and their contribution to the dust heating and the final spectra is low for C stars, at least if a hot star companion is not present (see Buss et al., 1991).

Our models are scaled on the optical depth at 10 $\mu$m; this parameter is proportional to the mass loss rate of the model: $\dot{M} = (16\pi/3)(\mu \rho_{da}/Q_{10})r_{10}R_1v_e$

3.2. Model Results

We obtained a self-consistent thermal structure and the emitted spectra for each source in the sample with available LRS. For large envelope radii, the radial temperature profile can be fitted with a power law $T(r) \propto r^{-\alpha}$, with $\alpha \approx 0.34$ for O-rich models and $\alpha \approx 0.40$ for C-rich models. This is in agreement with the formula derived by Harvey et al. (1991) for spherically symmetric dust clouds with dust opacity $Q_\nu \propto \lambda^{-\beta}$ ($\beta \approx 1$ for the Rouleau and Martin amorphous carbon, and $\approx 2$ for the Ossenkopf et al. silicates) and radial density profile $\rho(r) \propto r^{-2}$: $T_d(r) \propto r^{-2/(4+\beta)}$.

In Figure 5 we show the mid-IR spectra given by the model, superimposed on the IRAS LRS spectra, for the sources in Figure 1.

C-rich envelopes are well reproduced by the available opacities, except that the $\mathrm{SiC}$ feature is not completely accurate, perhaps due to the presence of other minor components (PAH ?).

In general, optically thick O-rich envelopes can be simulated fairly well with the given opacities, while our models are unable to account for sources with weaker silicate features (fitting the continuum, one obtains too strong a 9.8 $\mu$m feature). A way out of such difficulty could be considering a different geometry: Collison and Fix (1991), and Lopez et al. (1995) developed an axisymmetric model of circumstellar dust envelopes, in which the optical depth depends on the angle of the line of sight to the system axis. We notice however, that the model is unable to change the band intensity with respect to the slope of the continuum. Alternatively, Ivezic and Elitzur (1995) notice that the color of this class of sources are reproduced using a mixture of silicates (plus 20\% crystalline olivines) and amorphous carbon (in the ratio 1:4). Nevertheless, we object that the possibility of such a mixing is controversial; furthermore, the hypothesis is unattractive in that it requests the presence of a mixture only for sources of small optical depth, since the optically thick ones are well accounted for by our model.

An alternative way to obtain weak silicate features in O-rich envelopes without carbonaceous dust is to assume annealing and aging of the dust grains, as proposed by Nuth and Hecht (1990). On this basis Little-Marenin and Little (1990) classified the LRS spectra of Mira variables in the IRAS catalogue into a sequence based on the shape of the silicate feature around 10 $\mu$m, associated to different processes of grain formation, connected to the evolutionary age of the envelopes. Following Nuth and Hecht, grain condensation starts with oxidation of $\mathrm{SiO}$, $\mathrm{AlO}$ and $\mathrm{OH}$ in O-rich stellar winds, producing silicate dust characterized by weak silicate features and secondary
bands at 11-13 μm; full grown silicates with strong features condensate only later, and can be found in more evolved O-rich envelopes. In this view, our sources with weak silicate feature have to be associated to less evolved envelopes.

Testing Little-Marenin and Little predictions would require accurate opacities for silicate grains of different ages; our models for these sources have been obtained fitting only the photometric data and the continuum.

We obtain mass loss rates comparable with other estimates presented in Loup et al. (1993); the model parameters for the stars in the TIRCAM sample will be presented in a forthcoming paper.
4. Future Developments

Ground based mid-IR imaging and photometry has proven to be a powerful tool for chemical and physical characterization of dust component in AGB circumstellar envelopes, allowing discrimination between O-rich, C-rich and post-AGB sources. Color-color diagrams based on mid-IR observations give indications on mass loss history for AGB stars of different initial masses, and allow to estimate mass loss rates. The full characterization of the envelopes can be achieved coupling the observations with radiative transfer modelling of the envelopes, to derive the main physical parameters from IR data; this kind of analysis gives indications on the dust composition, the geometry of the dust shell and the processes of dust grain formation for sources of different chemical class or evolutionary stage.

The development of new mid-IR cameras with larger and more sensitive arrays will allow for spatial resolution of the envelopes, and thus provide the possibility of a direct test for the computed thermal radial profiles in different geometries; mid-IR spectra obtained with the spectrometer at the ESO TIMMI camera (see Käufel et al., 1992) would increase the quality of IRAS LRS data, making possible the discrimination of dust features associated to minor components.

Further contributes will come from the ISO mission, where a large part of the Stellar and Circumstellar Guaranteed Time Programme is devoted to the achievement of spectra (either with LWS and SWS spectrometer), photometry and images of AGB and post-AGB objects.

Finally, new envelope models will couple the dust component with the gaseous one, and will take into account the global dynamic of the system, allowing direct correlation between IR and CO data.

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References


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