Atmospheric Composition, Mass Loss and Circumstellar Envelopes of AGB Stars at Different Metallicities

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ABSTRACT. The interplay between nucleosynthesis and mass loss in low mass stars during AGB phases is outlined, discussing the appearance at the photosphere and the subsequent ejection into the circumstellar environment of C and newly synthesized heavy elements. We focus on some observational constraints providing insight on key stellar parameters; they come either from high resolution spectroscopy at optical wavelengths, or from spectrophotometric IR data derived by the IRAS and ISO databases. We then compare these constraints with model predictions for the photospheric composition and for the circumstellar radiative transfer, showing how such comparisons can be used to achieve a better knowledge of AGB masses, of their classification, and of their mass loss.

1. Introduction

Low mass stars (LMS, hereafter those of $M \leq 3-4 \, M_\odot$) and intermediate mass stars (IMS, hereafter those with $4 \leq M/M_\odot \leq 8$), in their late evolutionary stages populate the so-called Asymptotic Giant Branch (AGB) of the H-R diagram. Here they undergo radial pulsations in various modes, which trigger an intense mass loss, responsible for the creation of a circumstellar envelope of gas and dust (see e.g. Habing 1996). This envelope is often opaque to visible photons coming from the central star, due to dust grains condensing above the stellar extended atmosphere; it is nonetheless a source of thermal infrared (IR) radiation, especially longward of 8-10 μm (see e.g. Busso et al. 1996). For this reason, and for the optical properties of silicates, amorphous carbon and silicon carbide (SiC), which are among the main constituents of circumstellar grains, these mid-IR wavelengths offer important diagnostic tools to investigate the physical and chemical composition of dusty circumstellar environments around AGB stars (Willems & De Jong 1988; van der Veen & Habing 1988; Waters et al. 1998).

The formation of such environments derives primarily from the pulsational behavior of the central variable star (either of Mira or Semiregular type), which controls the mass loss mechanism (Wood et al. 1999). This last is also linked to the chemical mix
established in the stellar convective envelope, and in particular to the C/O abundance ratio, which determines the type of dust grains that can be formed (Sharp & Wasserburg 1995). In its turn, the photospheric composition depends on the initial mass $M_i$ of the star, on the efficiency of mixing mechanisms carrying nucleosynthesis products to the surface, and on the strength of mass loss (Gallino et al. 1998; Busso et al. 1999). These parameters set strong limits on the creation of a carbon star (i.e. a star having $C/O \geq 1$ in the photosphere) from an O-rich M-type giant entering the AGB phase. The C enrichment of the convective envelope is the consequence of a mixing process known as third dredge up (hereafter TDU). It occurs repeatedly in advanced AGB phases, after thermal instabilities (or thermal pulses, hereafter TP) leading to sudden, explosive ignition of the He-burning shell, which interrupts the normal power release by H burning. During such TPs, convection spreads over the whole layer separating the two nuclear shells (hereafter called He intershell, according to Busso et al. 1999) and this guarantees a complete mixing of He-burning nucleosynthesis products over these intermediate stellar zones. It is for this reason that TDU episodes can bring newly formed carbon and neutron-rich elements to the stellar surface (for a general introduction to these phenomena see Iben & Renzini 1983; Busso et al. 1999).

Recently, updated stellar models (Straniero et al. 1997) suggested that, for Galactic disk metallicities, only stars above a minimum limit (which, for their choice of the mixing mechanism and of mass loss, was about 1.5 $M_\odot$) can undergo a sufficient number of TDU episodes to drive an increase of the C/O abundance ratio (by number) above unity. On the other hand, AGB stars with $M_i \geq 4-5 M_\odot$ experience partial H burning at the base of the convective envelope (Hot Bottom Burning, or HBB, see e.g. Frost et al. 1998; Lattanzio, this conference). This consumes the newly produced C, preventing the star from becoming carbon rich, at least for most part of its AGB phase. As a result, C stars are probably formed, in the disk of the Galaxy, over a quite narrow mass range (from about 1.5 up to perhaps 3 $M_\odot$). The indications outlined above are roughly confirmed by the observational evidence that C stars of various populations are always of low initial mass (Frogel et al. 1990). More massive AGB stars appear to be enriched in Li, and generally do not seem to evolve beyond the class S (Smith & Lambert 1989). O-rich envelopes are therefore expected around very different objects, either of very low mass ($M \leq 1.5 M_\odot$) or rather massive ($M \geq 3-4 M_\odot$), and can be in different stages of their AGB evolution. This is directly reflected in the larger variety of O-rich envelopes, compared to the rather uniform properties of C-rich ones (Marengo et al. 1999, 2000a).

In this paper we briefly recall recent nucleosynthesis models for TP-AGB stars, and sketch the gross properties of their stellar winds and their envelopes. This is done in section 2. The interplay between theoretical modeling and observations of different nature at different wavelengths is then illustrated in section 3, with special attention to optical high resolution spectroscopy and to infrared spectrophotometry. Preliminary conclusions are then drawn in section 4.

2. Modeling AGB evolution, nucleosynthesis and mass loss

Understanding the consequences that the intense winds from AGB stars have on the chemical and dynamical evolution of the interstellar medium (ISM) would require a
complete modeling of the physical processes that, from an evolved red giant, ultimately lead to the formation of a planetary nebula and a white dwarf. One has to deal with the mass return from the star to the ISM, and with the modifications in the composition of such materials induced by He-intershell nucleosynthesis and by envelope mixing through TDU. One has also to understand how mass loss mechanisms work and are related to the stellar pulsational properties, and how the gas and dust components of the circumstellar envelopes are formed and evolve in time. No one of these processes is completely understood, but for most of them large improvements have been obtained in recent years. We sketch a very rough picture of them in the next subsections.

2.1. Nucleosynthesis in the He intershell

The main consequences of He burning occurring in the He intershell of TP-AGB stars is the production of $^{12}$C through the $3\alpha$ process, and the synthesis of neutron-rich elements, which is induced by the neutron release from $(\alpha,n)$ reactions.

It has been ascertained in the last two decades (see review in Busso et al. 1999) that the most efficient neutron source in AGB stars of low mass is the reaction $^{13}$C$(\alpha,n)^{16}$O, despite the difficulty of accounting for the formation of $^{13}$C in He-rich layers of the stellar structure.

After a thermal instability, the envelope convection extends downward, reaching regions previously affected by convective mixing in the thermal pulse, so that the hydrogen-rich and the helium- and carbon-rich zones are put in contact, leaving a sharp H/He discontinuity. This is in general expected to yield some form of mixing at the interface (Gallino et al. 1988), though suitable mechanisms are not normally modeled in stellar codes. Semiconvection and chemical diffusion of hydrogen into the He intershell were considered by Iben & Renzini (1982), and by Hollowell & Iben (1988), as occurring in the long post-flash dip where hydrogen burning is inactive. The effectiveness of diffusive mixing, however, is difficult to quantify (Iben & Renzini 1983). A second possibility is offered by hydrodynamical simulations of overshooting, i.e. of mixing processes that proceed beyond the formal border defined by the Schwarzschild’s criterion (Herwig et al. 1997). Another way is offered by rotational shear (Langer et al. 1998). In any case, the outcome of such phenomena is expected to be the penetration of a small amount of protons into the C-rich zone; at H-shell re-ignition, the protons are captured by $^{12}$C in a pocket that becomes enriched in $^{13}$C and (partly) in $^{14}$N (Käppeler et al. 1990; Gallino et al. 1993). In the absence of a self-consistent model, in recent years the consequences of these phenomena have been studied through extensive parameterizations, in which the mass involved in the $^{13}$C pocket and the resulting $^{13}$C and $^{14}$N profiles are allowed to vary over large intervals, constrained only by the rates of H-burning reactions (Gallino et al. 1998; Travaglio et al. 2001; Busso et al. 2001). As discussed by those authors, comparing the results of the ensuing $s$-processing with observations is a tool for constraining a posteriori the $^{13}$C-pocket parameters.

Iben (1975) showed that, in IMS, the temperature at the base of the convective pulses reaches values as high as $T = 3.5 \times 10^8$ K, and that under such conditions the $^{22}$Ne$(\alpha,n)^{25}$Mg reaction could produce relevant neutron fluxes for the $s$ process. The presence of a remarkable concentration of $^{22}$Ne is due to the previous operation of the
chain $^{14}$N($\alpha$,γ)$^{18}$F(β+$\nu$)$^{18}$O(γ)$^{22}$Ne, starting from $^{14}$N left behind by H-shell burning. However, an efficient activation of the $^{22}$Ne source would imply an enhancement of $^{25}$Mg in the material carried to the surface by TDU, while in current AGB stars the photospheric isotopic mix of Mg is nearly solar (Clegg et al. 1979). Moreover, the neutron flux induced by the $^{22}$Ne($\alpha$,n)$^{25}$Mg source produces a high neutron density (up to values in excess of $10^{11}$ n/cm$^3$ in IMS), and this strongly modifies the operation of several reaction branchings, leading in particular to a strong overproduction of neutron-rich isotopes like $^{86}$Kr, $^{87}$Rb, $^{96}$Zr. Observations of most AGB stars reveal instead (Lambert et al. 1995), from the relative abundances of Zr isotopes and from the Rb/Sr ratio, that the neutron density occurring in the He intershell cannot be so high. These observational results, together with the analysis of the s-process contributions to heavy elements from Sr to Pb in the Solar System (the so-called main component) provide strong evidence that s nuclei beyond Sr are mainly produced by AGB stars of low mass. Indeed, below about 3 $M_\odot$ the temperature in the convective pulses does not exceed $T = 3 \times 10^6$ K, the $^{22}$Ne source is only marginally activated, and the production of nuclei on the neutron-rich side of reaction branchings can be limited. For a detailed analysis of the operation of the $^{22}$Ne source in LMS, and of its implications for the solar system main component see Arlandini et al. (1999). An important result of nucleosynthesis models in AGB stars is that, for suitable choices of the parameters in the $^{13}$C pocket (and in particular of the abundance ratio $^{13}$C/$^{56}$Fe between the neutron producer and the main heavy seed for s processing) the solar system distribution of s elements can be very well reproduced.

2.2. Radiative and chemical properties of circumstellar envelopes

Mass loss ejects the C- and s-enriched external layers of the star into the surrounding environment, creating large and cool circumstellar envelopes, where a solid particulate easily forms. Mid infrared wavelengths are the ideal spectral region where to study such circumstellar dust. The presence of broad features in the opacity of grains commonly formed in the extended atmospheres of giant stars allows in principle a precise identification of the mineralogical species by analyzing the 10 μm spectra. The temperature gradients in circumstellar envelopes, with dust in equilibrium with the environmental radiation field, are such that the bulk of the thermal radiation from grains is emitted in the 10 μm region. Since the optical thickness of many circumstellar envelopes, especially around the most evolved AGB stars, is high enough to make them completely opaque at visible wavelengths, mid-IR is the only accessible spectral window for probing the central regions of these systems. For basic reasons the IRAS database has been widely used for the development of diagnostic tools able to probe the chemical and physical status of circumstellar envelopes from their infrared emission. This approach, however, is limited by the low spatial and spectral resolution of IRAS data, and by the impossibility to make repeated observations of variable stars. Even though a few sources have been re-observed recently by ISO, these issues have not been completely resolved, due to the short duration of the mission, to serious calibration problems and to the still inadequate spatial resolution. These limitations confirm the need for ground-based high-resolution facilities, like Keck, VLT and LBT.

Together with the optical dust properties, another very uncertain parameter con-
trolling the formation of circumstellar envelopes is the total mass loss rate. It is often modeled through the Reimers (1975)’s wind formula, adopted also in the nucleosynthesis models discussed so far (section 2):

\[ \frac{dM}{dt} = 4 \times 10^{-13} \eta \times \frac{RL}{M} M_\odot/yr \] (1)

where \( \eta \) is a fudge factor between 0.3 and 3 and \( M, L, \) and \( R \) are the luminosity, mass and radius of the star, measured in solar units. This mass loss formula is insufficient to describe the highest wind rates, and is sometimes substituted by the alternative (Salpeter, 1974):

\[ \frac{dM}{dt} = 2 \times 10^{-8} \tau_V \frac{L}{v_e} M_\odot/yr \] (2)

where \( \tau_V \) is the optical depth due to dust at visible wavelengths, \( v_e \) is the ejection velocity in km/sec and \( L \) is the luminosity in solar units. The relation (2) assumes that the mechanism of ejection is due to radiation pressure on dust grains. Many modifications of it have been presented over the last 10 years or so, all subject to the unavoidable uncertainties of the limited observational basis (see Habing 1996 for a review). More reliable constraints from infrared observations are therefore strongly needed.

With the above situation in mind, we have tried here to get information on the type of mass loss expected for different sources and to achieve criteria for classifying newly discovered infrared AGB stars (unobservable in the optical bands) as being C-rich or O-rich. This is done through a comparison of circumstellar radiative transfer modeling with mid-IR colors derived from the IRAS and ISO databases, and with mass loss determinations from radio wavelengths.

Fully bi-dimensional models dealing with complex envelope geometries (Lopez et al., 1995) can be applied only to a limited number of sources bright enough that their extended images can be observed at high S/N ratios, showing departures from spherical symmetry. For the sake of a general assessment of the problem on a statistically significant sample of AGB stars we have instead adopted the simpler scheme provided by the DUSTY code (Ivezić al. 1999). It gives 1-D radiative transfer modeling of stationary circumstellar envelopes in spherical symmetry. It is characterized by the following parameters: (1) the total optical depth \( \tau_V \) of the envelope, (2) the temperature \( T_1 \) at the inner boundary of the dust shell, (3) the shape of the spectral energy distribution of the central star, and (4) the optical properties of the dust. We have modeled a sample of AGB stars from the IRAS database assuming a blackbody curve at \( T = 2500 \) K for the stellar energy distribution, varying \( T_1 \) and \( \tau_V \) as free parameters, and adopting the optical properties of the dust from the current literature (see discussion in Marengo et al. 2000b).

3. Comparison with Observations

3.1. Photospheric abundances in AGB stars of different metallicity

At galactic disc metallicities the observed stars are \( s \) process- and carbon-enriched AGBs (both intrinsic and extrinsic, i.e. both single AGBs of classes MS-S-SC, and giants or
dwarfs of the Ba-star type, produced through mass exchange in a binary system, from a now evolved AGB primary). Among metal poor stars, s-process rich objects generally belong to the classes of CH- and Ba-stars, though an increasing role is played by newly available observations of post-AGB A-F-G supergiants (see e.g. Van Winckel & Reyniers 2000).

In Figure 1 we show our model predictions for the abundances of different elements in the material mixed to the surface during the AGB as a function of the initial [Fe/H] of the parent star. The curves refer to different choices for the concentration of $^{13}$C in the pocket; taking as a reference the case defined as 'standard' (ST) by Gallino et al. (1998), corresponding to $M(^{13}$C) $= 4 \times 10^{-6} \, M_{\odot}$, our models span the range from ST/16 to ST $\times$ 2. The predictions are expressed in terms of the logarithmic abundance ratio [hs/ls] between heavy (Ba, La, Nd, Sm) and light (Y, Zr) s elements (panel a), and of the abundances of Ba-peak elements with respect to iron, [hs/Fe] (panel b), following a scheme introduced by Luck & Bond (1991).

Figure 1a shows as most observations are in the range covered by models, which also reproduce the non linear behavior as a function of metallicity, according to which the [hs/ls] ratios are not a monotonic function of [Fe/H]. This is due to the fact that, decreasing the metallicity, the number of neutrons available per iron seed increases. Hence, the Ba-group elements first start to dominate over the Zr-group ones, leading to an increase in the ratio; but for very low concentrations of Fe the heaviest elements, and Pb in particular, become dominant, so that also the 'hs' elements (and the [hs/ls] ratio) decline (Travaglio et al. 2001, Busso et al. 2001). Reproducing not only the abundance ratios, but also the enhancements with respect to iron at the photosphere (Figure 1b).
then requires to find the exact dilution factor that the s-enriched material underwent through TDU. The sources that in Figure 1b lay below the curves simply require a further dilution with respect to the models, which refer to the end of the TP-AGB. This further dilution is due either to an evolutionary phase that precedes the end of the AGB, and has therefore not yet seen the complete sequence of TDU episodes, or to a further mass transfer to a companion, in binary Ba-like sources.

3.2. Constraints from Mid-IR on the carbon enrichment and mass loss

In analogy to what was done by Busso et al. (1996) and Marengo et al. (1997), we made a re-binning of the data from the IRAS Low Resolution Spectra (LRS) and from the ISO Short Wavelength Spectra (SWS) over simulated filters of 1 μm thickness, centered at 8.5, 9.8, 11.2 and 12.5 μm, similar to those available in most ground-based Mid-IR cameras, trying to establish relations between Mid-IR colors built through them, the properties of circumstellar chemistry (especially the distinction between C-rich and O-rich envelopes) and mass loss. The filters at 8.5 and 12.5μm define the limits of the 'N' band around 10μm, available from the ground: their color index is a measure of the slope of the flux in the continuum. The other two filters are centered on features characteristic of O-rich and C-rich dust, in order to permit a better discrimination. In this way we mimic the results that can be obtained with observational facilities in mid-IR from the Earth.

![Fig. 2. Mid-IR colors of O-rich envelopes. Curves are from models of the radiative transfer in the circumstellar envelope. Observed data are from IRAS.](image1)

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![Fig. 3. Mid-IR colors of C-rich envelopes. Curves are from models of the radiative transfer in the circumstellar envelope. Observed data are from IRAS.](image2)

Fig. 3. Mid-IR colors of C-rich envelopes. Curves are from models of the radiative transfer in the circumstellar envelope. Observed data are from IRAS.

Figures 2 and 3 show the color-color diagrams built in the way described above for a sample of AGB stars observed by IRAS, for which mass loss was estimated from radio wavelengths by Loup et al. (1993). In both cases we used as abscissa the color of the continuum, and as ordinate a color made using the most significant filter where O-rich and C-rich features can be observed. When put in this form, the behavior at Mid-IR wavelengths of O-rich and C-rich sources can be understood, when the observed data are compared to envelope modeling. The O-rich AGB stars are more dispersed over a
wide area in the plane, because the silicate feature can be either in absorption or in emission, depending on the physical parameters of the envelope. This is so because it is related to dust particles that can dominate the radiative properties of the environment. On the contrary, for C-rich dust SiC is a minor component, most dust particles being in the form of featureless amorphous carbon. Hence, the SiC feature is always in emission (optically thin) and moves the representative point by a moderate shift with respect to the black body line. Radiative models of the circumstellar envelope can explain the position of the points through different combinations of the main parameters. Repeating the exercise for different color combinations, an unambiguous separation of O-rich AGB stars from C-rich ones can be achieved, thus allowing optically unobserved, infrared AGB stars to be included in the statistics of C stars and M giants, and providing a first classification.

Fig. 4. Mass loss estimates from Loup et al. (1993) as a function of the [8.5]-[12.5] color for all AGB and post-AGB circumstellar envelopes of C-rich and O-rich sources. No trend appears.

Fig. 5. Mass loss estimates from Loup et al. as a function of the [8.5]-[12.5] color for a sample of C-rich Miras and SR variables from the ISO mission.

Figure 4 shows, for the same AGB stars, a mass-loss parameter (defined by Loup et al. 1993), plotted versus the color of the continuum. Data are dispersed and only a weak (if any) trend emerges. Definite relations between mass loss and colors of the dusty circumstellar envelopes are actually expected, and normally found, for certain AGB subclasses, like the Mira variables (see e.g. the line in Figure 4, deduced by Busso et al. 1996 from data taken with the Tircam and Camiras IR cameras). Such relations are clearly evident when K-[12] colors are constructed using near infrared (K-band) and IRAS (12 μm) filters (Guglielmo et al. 1998). However, the sample of figure 4 contains many different types of sources, among which semiregular and irregular (Lb-class) stars. Many such sources are known to show large variations in their mass loss rates over timescales of several decades (~ 100 yr, according to Marengo et al. 2000b). Such variations may result in a breakdown of the color - mass loss relation holding for the Mira variables. These last are indeed characterized by high mass loss rates rather constant in time. To have a more unbiased sample, we searched the ISO SWS database for known Miras (or Semiregulars with Mira-like pulsations) and made the same re-binning already
done for the IRAS data. Figure 5 shows as an example the result for C-rich sources. A correlation (of parabolic type) is rather evident, despite the still preliminary calibration available for SWS. We therefore tentatively conclude that correlations between colors and mass loss exist only for the AGB stars that are more efficiently losing mass, and that can sustain roughly constant mass loss rates for long periods of time.

4. Conclusions

We have shown how theoretical modeling of the photospheric composition in TP-AGB stars (deduced from nucleosynthesis calculations), and models of the radiative transfer in the circumstellar envelopes can be used to get information on physical properties of AGB stars in the Galaxy. The trend of AGB abundances as a function of the metallicity, and the fact that they can be accounted for by LMS models, confirm that most AGBs are of low mass. The analysis of abundances at the main s-process peaks then serves as a guideline in interpreting the complex trend revealed by s-process models at different metallicities. Most AGB stars are however invisible at optical wavelengths, and not subject to these observations. They can be studied only in the infrared. Here simple comparisons between spectrophotometric properties and circumstellar radiation transfer simulations can provide a number of physical parameters of the environment, thus helping our knowledge of stellar winds. They also provide a first classification, distinguishing O-rich from C-rich sources, and seem to indicate that only AGBs rather efficient in losing mass (all Miras and some Semiregulars) may sustain high mass loss rates for long periods of time, through mechanisms involving dust particles.

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