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Dust from AGBs: understanding the Spitzer observations of evolved stars in the Large Magellanic Cloud

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Abstract. Asymptotic Giant Branch (AGB) stars represent one of the main stellar sources for production of dust in the Universe. We provide a description of the formation and growth of dust particles in the circumstellar envelope of AGBs, starting from detailed calculations of the AGB evolutionary phase. We use stellar population synthesis to interpret the Spitzer observations of dusty AGBs in the Large Magellanic Cloud (LMC). Our results show that carbon-rich and oxygen-rich stars evolve into different and separated regions of the observational diagrams obtained with the Spitzer bands. This allows a straight comparison with the spectroscopically confirmed samples of AGBs in the LMC present in the literature. The overall impact of AGBs on the dust production rate in the LMC is also discussed.

Key words. stars: AGB and post-AGB – stars: dust production

1. Introduction

In recent years, the crucial role played by low- and intermediate-mass stars ($1M_\odot \leq M \leq 8M_\odot$) during the Asymptotic Giant Branch (AGB, Herwig 2005) phase has been explored in relation to many different important fields of modern astrophysics. This stems from the complicated physics of their interiors, which makes them a valuable laboratory for stellar evolution theories, and from their importance in the formation and evolution of their host systems in the Local Universe, as well as at high redshift (Romano et al. 2010, Valiante et al. 2011). During their evolution, while they are increasing their luminosity, AGB stars are subjected to high mass-loss rate which provokes the entirely loss of their envelope, via a cold and dense wind, which is a suitable environment for condensation of gas molecules into dust (Gail & Sedlmayr 1999). The mechanism of dust production favours the acceleration of the wind and consequently the pollution of the interstellar medium (ISM). The yields of dust and gas produced by AGB stars are strictly dependent on the efficiency of two physical processes that influence the variation of the surface chemical composition: third dredge up (TDU) and hot bottom burning (HBB) (Ventura et al. 2014). Even though many steps forward have been done so far, AGB modelling requires a great computation effort and the description of complex physical processes. In particular, the mass-loss and convection mechanisms, still poorly known. An important opportunity to calibrate AGB modeling is now given by the large body of observational data of AGB stars in the Magellanic Clouds (MCs), which represent an excellent astrophysical laboratory to study the AGB evolutionary phase and the relative dust production, owing to the known distances and proximity of the sources observed.

In this work we present our recent results on the comparison between the current AGB+dust modelling (Ventura et al. 2014) and the *Spitzer* observations of AGB stars (Reibel et al. 2012) in the Large Magellanic Cloud (LMC; Reibel et al. 2012). This analysis allows to characterize the AGB population of the LMC in terms of initial mass, formation epoch and dust production. This provides useful hints on the evolution of this galaxy, e.g., the overall star formation history and the metal enrichment process, which are relevant to determine the metallicity distribution of the stars observed. The same analysis was recently extended by Dell'Agli et al. (2015b) to the Small Magellanic Cloud. The nice agreement found with the observations increased the reliability of the theoretical description here presented. It also offers the possibility of a direct comparison among the histories of star formation of the two galaxies.

2. Dust production

To calculate the dust produced by AGB stars, we coupled the description of the wind provided by the Heidelberg group (Ferrarotti & Gail, 2006) and the AGB modelling computed by means of the ATON code (Canuto& Mazzitelli, 1991). We calculated the dust produced by stars in the range of masses $1M_{\odot} \leq M \leq 8M_{\odot}$ and metallicities $10^{-3} \leq Z \leq 8\times10^{-3}$. Low mass stars (M$\leq 3M_{\odot}$), after several TDU episodes, eventually become carbon-rich stars. In these environments most of the dust is in the form of solid carbon particles, with size $0.1\mu m \leq a_C \leq 0.25\mu m$, formed at a distance $\sim 5R_*$ from the surface of the star. A smaller quantity of dust is under the form of SiC grains, with size $\sim 0.07\mu m$; the latter compound, more stable than carbon, forms in a more internal region, $\sim 2R_*$ away from the stellar surface. As shown in Fig. 1, the amount of carbon dust produced spans in the range $10^{-5}M_{\odot} - 10^{-3}M_{\odot}$. Models of higher mass produce more dust, because they experience more TDU events, thus reaching higher surface carbon content. No trend with metallicity is found, because the carbon transported to the surface is of primary origin, thus scarcely dependent on the initial content of metals. AGB stars of initial mass above $\sim 3M_{\odot}$ evolve as oxygen-rich objects during the whole AGB phase. This is due to the effects of HBB, activated when the temperature at the base of the envelope overcomes $\sim 40MK$, which favors a significant depletion of the surface carbon. In this environment the main species formed are silicates with dimension in the range 0.07-0.13 μm, at 5-10R_* form the stellar surface, and alumina dust, with smaller grain size (0.05-0.07 μm), in a more internal layer (1-3 R_*) (Dell'Agli et al 2014b). In this case, as shown in the right panel of Fig. 1, there is a significant dependence of the dust produced on both mass and metallicity. More massive stars experience stronger HBB, which favors larger rates of mass loss and winds of higher densities, thus increasing the growth rate of dust particles. As for metallicity, in stars with a larger content of metals there is more silicon available, which leads to the formation of higher quantities of silicates.

3. Evolutionary tracks in the Spitzer colors

From the results of the AGB+dust models we calculate the synthetic spectral energy distribution for various masses and metallicity, trac-

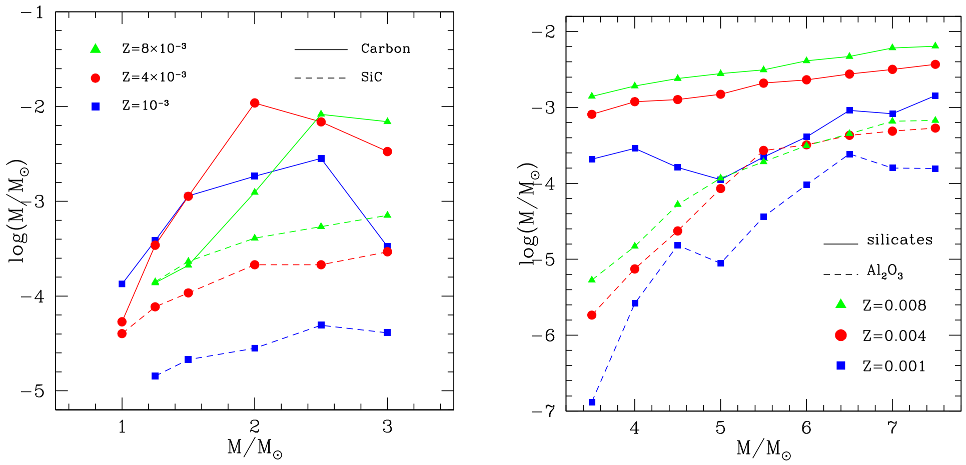

Fig. 1. Total mass formed during the AGB phase as a function of the initial mass and metallicity of the star. The species considered are SiC (dashed line) and solid carbon (solid line) for carbon stars (left panel) and silicates (solid line) and alumina dust (dashed line) for oxygen rich stars.

ing the variation of the emission in the infrared bands for several evolutionary stages during the AGB phase. The treatment of the radiation transfer was computed by means of DUSTY code. We focused our interest on the Spitzer bands [3.6], [4.5], [5.8], [8.0] and [24], with the final goal of comparing the theoretical evolution of AGB stars with the SAGE sample of AGB stars in the LMC.

In Figure 2 we show the evolutionary tracks of the models in the [3.6]-[4.5] vs [5.8]-[8.0] and [8.0]-[24] vs [24] diagrams, overlapped to the AGB population from Riebel et al. (2012). In these planes we can distinguish four classes of stars: the obscured carbon stars (OCS), hot bottom burning stars (HBBS), finger stars (F) and a miscellaneous of carbon and oxygen stars (CMS). All the stars in this latter group are characterized by a low infrared excess: CMS stars are mainly low mass stars ($< 3M_{\odot}$) at the beginning of the carbon rich phase, with a low metallicity component. Finger stars, identified for the first time by Blum et al. (2006), are low-mass ($\leq 1.5M_{\odot}$) oxygen-rich stars, with $Z \geq 0.004$, in the previous phases to the C-stars stage. The production of silicates during this phase determines an infrared excess in the SED of the higher metallicity component, allowing the distinction of this group of stars from the CMS group. This effect is particularly evident in the [8.0]-[24] vs [24] plane. OCS and HBBS, even if they constitute only the $\sim$ 20% and $\sim$ 1% of the total sample, are responsible for almost the totality of the dust product by AGB stars in the LMC. For this reason in the next sections we will focus on these two classes of stars.

To provide a quantitative description of the AGB sample, we computed a synthetic population on the base of the evolutionary tracks and the star formation history provided by Harris & Zaritsky (2009).

3.1. Obscured carbon stars

The OCS are defined as the stars populating a diagonal band, with $0.2 < [3.6] - [4.5]$ and $0.2 < [5.6]-[8.0] < 1.6$ (see Fig. 3). According to our modelling, no oxygen-rich star is expected to evolve to this region; therefore, the

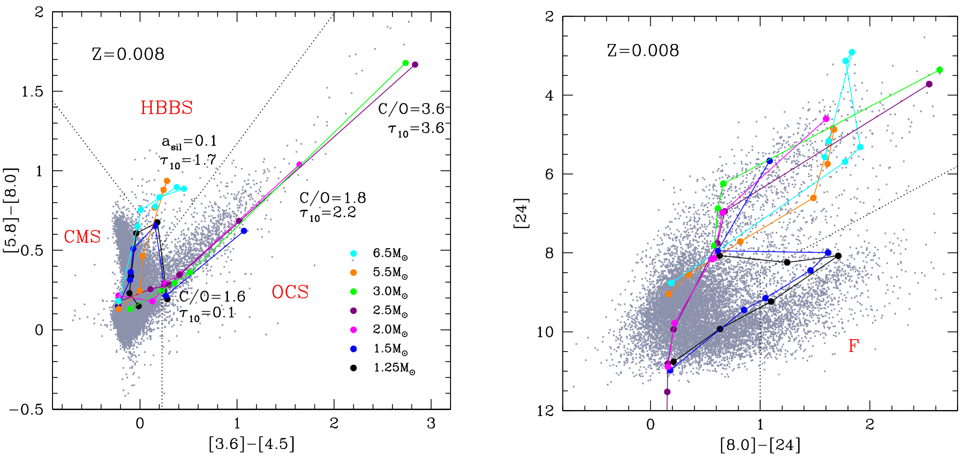

Fig. 2. Evolutionary tracks of AGB models of metallicity $Z = 8 \times 10^{-3}$ in the colour-colour ([3.6] − [4.5], [5.8] − [8.0]) (left panel) and colour-magnitude ([8.0] − [24], [24]) planes (right panel). The LMC AGB sample by Riebel et al. (2012) is also shown (grey points).

OCS group is entirely composed of carbon stars. The optical depth increases along this sequence in the range $0.01 < \tau_{10} < 3.5$, owing the higher and higher degree of obscuration reached by the stars, once they achieve the carbon star stage. This is because repeated TDU events favour a gradual increase in the surface carbon, which, in turn, makes grater quantities of carbon molecules available for condensation into dust.

Stars of initial mass in the range $1M_{\odot} \leq M \leq 3M_{\odot}$, formed $3 \times 10^8 - 3 \times 10^9$ years ago. The majority of OCS are the descendants of low-mass stars with masses $M \sim 1 - 2M_{\odot}$ at low–metallicity (Z below 4×10^{-3}), formed during the burst of SFH in the LMC that occurred ~ 2 Gyr ago (Harris & Zaritsky 2009). A smaller group of OCS (~ 10% of the total sample), formed during the peak in the SFH occurred $\sim 5 \times 10^8$ year ago, descending from stars with initial mass in the range $2M_{\odot} \leq M \leq 3M_{\odot}$ of higher metallicity ($Z \geq 4 \times 10^{-3}$). Though smaller in number, these more massive objects are the only stars expected to evolve redder than [3.6] − [4.5] > 1 (see left panel of Fig. 3). The reason for this is twofold: a) stars more massive than $\sim 2M_{\odot}$ experience a high number of TDU episodes, thus they accumulate great quantities of carbon in the surface regions, which reflects on a high-efficiency formation of solid carbon particles; b) the degree of obscuration reached by lower-Z models is smaller, because they evolve at larger surface temperatures, which causes the dusty layer to form at larger distances and smaller densities.

3.2. Hot bottom burning stars

The HBBS region is populated by a group of stars clustering around [3.6] - [4.5] ~ 0.2, [5.8] - [8.0] ~ 0.8, detached from the rest of the LMC AGB population. We interpret these sources as the descendants of massive AGBs, with initial mass $3.5M_{\odot} \leq M \leq 7.5M_{\odot}$, experiencing HBB at the base of the convective envelope and forming silicates and alumina dust. The occurrence and the strength of HBB is the key–quantity to determine the amount of silicates formed. The degree of obscuration is smaller than their C–rich counterparts (τ_{10} is

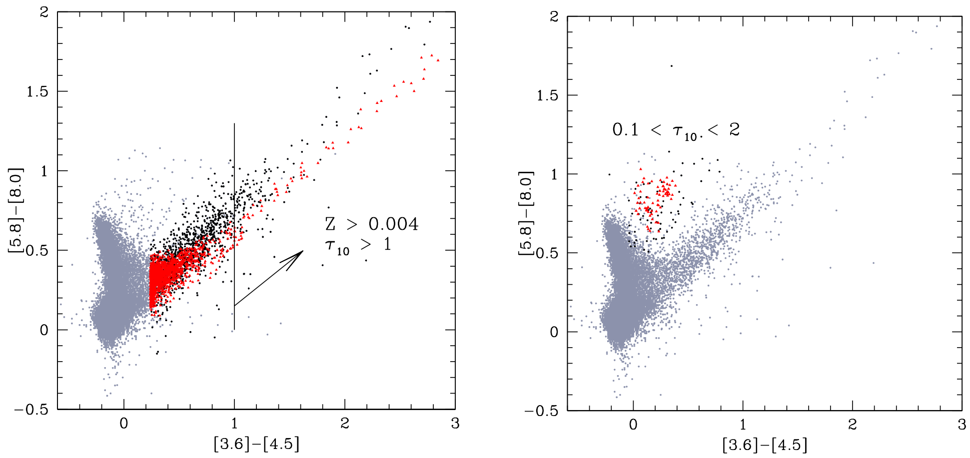

Fig. 3. The distribution of the OCS (left panel) and HBBS (right panel) samples in the colour-colour ([3.6]−[4.5], [5.8] − [8.0]). The whole sample of stars by Riebel et al. (2012) is shown with grey points; the black dots indicate the stars in the Riebel et al. (2012) sample that fall in the OCS (left) and HBBS (right) region. The red dots indicate results from synthetic modelling.

below 2 in all cases): this difference stems from the lower extinction coefficients of silicates compared to carbon dust and the much higher availability of carbon molecules in the envelope of carbon stars, compared to the abundance of silicon in the outer regions of oxygen–rich stars. The burst in the SFH in the LMC occurring $\sim 10^8$ years ago determines the formation of HBBS. They belong to the more metal–rich population, because of the small percentage of low–Z stars formed in these epochs (Harris & Zaritsky 2009). The paucity of objects in the HBBS region (they account for $\sim 1\%$ of the total sample) stems not only from the intrinsically small number of stars formed in the relevant range of mass, but also as a consequence of HBB, which produces a fast increase in the luminosity of the star, that, in turn, favours a rapid loss of the residual external mantle. Because of the dependence on the efficiency of the HBB, this group of stars is a suitable laboratory to test the convection efficiency (Ventura et al. 2015).

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