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Modelling dust production from AGB stars: open challenges, uncertainties and new discoveries

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Abstract. The description of dust production by asymptotic giant branch stars (AGB) is matter of interest for a wide part of the astronomical community. In the light of this, the number of studies focused on this topic rapidly increased in the last decade. Latest releases of hydrodynamical models provide a deep insight of wind structure and mass loss process. On the other hand new generations of models able to couple a detailed description of the AGB evolution with a dust growth model allow the estimation of the amount of dust formed in the winds of these stars, with a special look at its dependence on AGB evolution properties. Nevertheless, several uncertainties connected with the AGB modelling still affect the global description of dust condensation process. In this contribution we discuss latest progresses, possible constrains and upcoming improvements expected on this side.

Key words. Stars: abundances – Stars: AGB and post-AGB. ISM: abundances, dust

1. Introduction

Dust represents an essential ingredients of the formation and evolution of different structure in the Universe. Among several dust sources, low and intermediate mass stars play a crucial role as main polluters of both gas and dust. After the exhaustion of helium in the core, stars with mass in the range $1 \leq M/M_{\odot} \leq 8$ evolve towards higher luminosities and lower temperatures, climbing the so called asymptotic giant branch (AGB). During this phase stars lose almost entirely their envelope made of gas contaminate by the internal nucleosynthesis, forming a dense and cold wind where conditions for dust condensation are suitable. This part of the star life is extremely rapid compared to the previous evolutionary phases ($\sim$ 1% of the time spent in the main sequence). Nevertheless, it is experienced by the great majority of the stars and represents a crucial step for the evolution of the environment where these stars form. For these reasons AGB stars represent a fundamental stone of the life cycle of the Universe, where they provide a notable contribution in terms of gas and dust since the early epoch of formation of the first structure (e.g. Valiante et al. 2009, 2011, and Valiante et al. contribution in this volume). Challenging improvements have been achieved studying deeply the process of dust formation in the circumstellar envelope (CSE) of AGBs. They represent a fundamental step to develop a more reliable description of still poorly known processes active in this phase (e.g. mass loss). Furthermore it is crucial to understand the real contribution of these stars in the gas and dust budget of their host environments.

2. Process of dust formation

The dust production process in AGB stars is determined by two fundamental ingredients: chemical and thermodynamical conditions that characterise the wind. The first one is determined by several complex processes active inside the star (e.g. Herwig 2005, Lugaro et al. contribution in this volume). Among the others two main processes have a strong impact on the surface chemistry of these stars: third dredge up and hot bottom burning. The first one consist in a series of dredge up episodes that touch the region contaminated by the results of the 3α nucleosynthesis, bringing to the surface a significant amount of carbon. Repeated episodes of third dredge up (TDU) increase the C/O ratio at the surface that can eventually become greater than one; this is the case of lower masses ($1 < M/M_{\odot} < 4$) in particular. AGB stars with initial mass above 3–$4M_{\odot}$[1] reach high temperatures ($> 40MK$) at the base of the convective envelope, activating the proton capture nucleosynthesis called hot bottom burning (HBB). This nucleosynthesis has a strong physical and chemical impact on more massive stars. The main effect (the one on which we are more interested for the dust production process) is the destruction of carbon that avoids the achievement of the carbon star stage.

The imprint of these two processes on the surface chemistry is crucial to determine the kind of dust produced. The extremely stable CO molecule leaves free to condense only the element in excess between carbon and oxygen. This leads to a dichotomy in the species expected to condense in O-rich and carbon stars. In first case the main dust species are silicates and alumina dust (Tielens et al. 1998) while solid carbon and silicon carbide are the most abundant compound in carbon stars (Groenewegen et al. 1998). On the thermodynamical side, dust condensation process requires high density to ensure collisions between particles and at the same time temperatures below the stability thresholds of each dust species. When these conditions are satisfied the growth of dust grains on seed nuclei present in the wind occurs. The process that leads to the achievement of favourable thermodynamical conditions is still poorly understood. Probably, shock waves induced by periodic pulsations that affect the AGB evolution, levitate the atmosphere out to few stellar radii, forming a cold and dense layer suitable for dust condensation. The formation of dust in the CSE determines the enhancement of the optical depth of the wind. If the amount and the optical properties of dust particles formed are high enough, the radiation pressure from the central object on the grains can accelerate the wind beyond the escape velocity. If these conditions for "dusty-driven" wind are satisfied, then the interstellar medium is enriched with dust and gas.

[1] The limit in mass for the activation of the HBB depends on the description adopted for the convection. More efficient convection models lead to lower limit in mass.

3. Modelling AGB dust production

In the last decades several groups have been focused in addressing the complex task of modelling the process described above. Several works and great efforts have been spent to provide a full hydrodynamical description of the wind and dust formation process, focused on the comprehension of the mechanism responsible for the acceleration of the wind and the mass loss process. Coupling radiative transfer with pulsations and induced shocks, these models describe the complex interaction between radiation and dust grains. For carbon stars, photon scattering on large carbon grains may increase radiative pressure and boost wind acceleration (Mattsson et al. 2011). Stellar parameter space have been explored using a numerical radiation hydrodynamic model of atmospheres, including a detailed description of dust formation and frequency-dependent radiative transfer. A clear dependence of mass-loss rates and wind speeds on the choice of stellar temperature, mass, luminosity and the abundance of available carbon was found (Mattsson et al. 2010). The path was not so straightforward for the oxygen-rich stars, where the identification of the species responsible for the acceleration of the wind are not well univocally identified. Several studies have been focused on this point in the last years, finding that the best species capable of accelerating the wind by photon scattering on large grains are iron free silicates (Bladh et al. 2012, 2013, 2015). Recently, the Al_2O_3 dust species have been included in the wind description oxygen-rich stars, found to condense close to the stellar surface (2 stellar radii or less), prior to silicate condensation (e.g. Karovicova et al. 2013; Dell'Agli et al. 2014a). This requires high transparency of the grains in the visual and near-IR region to avoid destruction by radiative heating (Höfner et al. 2016).

A different approach has been developed in order to provide a quantitative estimate of the amount of dust returned to the interstellar medium. A pioneering work has been done by Ferrarotti & Gail (2006), where a simple scheme for the description of the wind dynamic and dust formation has been applied to synthetic models of AGB evolution. It considers an isotropic expanding wind integrating the equations of momentum and mass conservation to describe the velocity and density profiles. Growth and destruction coefficients describes the changes of grain sizes. The integration of the amount of dust produced during the enitre AGB phase provides yields of dust that have been used for several years, as essential ingredient of galaxies evolution modelling at low and high redshift (e.g. Zhukovska et al. 2008; Valiante et al. 2009, 2011).

Even if this description represents a simplified version of a more complex phenomena and it is not able to predict mass-loss rates expected for AGB stars, it is an extremely robust and feasible way to couple dust formation with stellar evolution models. In the last years the Rome's group applied for the first time the Ferrarotti & Gail scheme to AGB models computed self consistently with the ATON code for stellar evolution (Ventura et al. 2012a,b; Di Criscienzo et al. 2013; Ventura et al. 2014; Dell'Agli et al. 2017). This has represented an essential step forward to understand better the dependence of dust production on fundamental processes like TDU or HBB and on their efficiency. Covering a wide range of masses ($1 \leq M/M_{\odot} \leq 8$) and metallicities ($3 \times 10^{-4} \leq Z \leq 0.018$) they found that the amount of dust produced by low mass stars ($< 4M_{\odot}$) is dominated by solid carbon, with a total amount of dust produced during the entire AGB phase between $10^{-3} - 10^{-2} M_{\odot}$. In more massive stars ($< 4M_{\odot}$) silicates are the most abundant species produced and the amount of dust increase with the initial mass and metallicity of the star.

The same scheme has been applied by the Padua's group to the COLIBRI models for the AGB phase which couples a synthetic module with the numerical solution of the atmosphere and complete envelope model, down to the bottom of the H-burning shell (Nanni et al. 2013, 2014). They compute dust production models at several metallicities, considering also super solar cases (Z=0.04, 0.06), exploring alternative case for the condensation temperature of silicates.

While a detailed description of the wind is missing in both the cases, the dust yields produced are quite robust. Variations on the free parameters considered in the dust modelling (e.g. initial velocity of the wind, density of the initial seeds) have a smaller effect respect to the uncertainties of the stellar evolution modelling (e.g. Ventura et al. 2014). It can be seen in the comparison between the different results to understand the effects of the different description of the AGB evolution on the dust yields.

In Figure 1 we can compare the amount of carbon (left) and silicates (right) dust expected to be produced during the AGB phase by the two descriptions (ATON and COLIBRI) at different metallicities. First of all it is evident that the range of masses involved in the production of the different species is different in the two models. The range of masses expected to form silicate dust is larger in the ATON's models respect to the COLIBRI. This is because the more efficient description of the convection

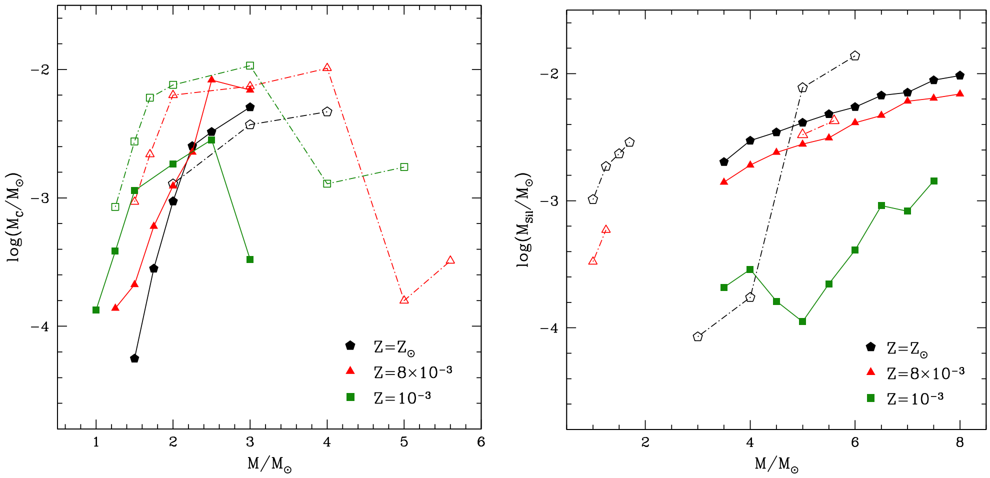

Fig. 1. The mass of solid carbon (left panel) and silicates (right panel) produced by AGB stars of different mass at different metallicities. The results from COLIBRI and ATON code are shown with open and full points respectively.

adopted by ATON models favours the activation of the HBB at lower initial masses. This leads to a wider range of masses where the production of silicates is expected. On the other hand the production of carbon dust is higher in the COLIBRI case where even 4-5 $M_{\odot}$ are expected to reach the carbon star stage (see Dell'Agli et al. 2017, for more details). These differences as well as the expected evolutionary times scales represents key points that can be tested in the comparison with the observations.

4. Observational constrains

Direct and useful application of the models described in the previous section was provided by Dell'Agli et al. (2014b) where the evolutionary tracks computed for the description of the AGB+dust evolution were calculated to be compared with the AGB population of the LMC observed by *Spitzer* (Riebel et al. 2012). This study were able to reproduce even the most obscured objects present in the sample, expected to be responsible for the majority of the dust production. From the population synthesis analysis computed for this galaxy (Dell'Agli et al. 2015a) the so called extreme AGB stars were found to produce more than half of the dust produced and that they are composed for 90% of carbon stars. The same approach of population synthesis have been adopted to study the AGB population of the SMC and to a dwarf galaxy of the Local Group Dell'Agli et al. (2015b, 2016). Nice agreement between models and observations have been found, providing also important feedback on the initial mass, metallicity and history of formation of the AGB stars observed.

Recently, Marigo et al. (2017) presented a new set of isochrones that take into account the description of the AGB+dust phase provided by the COLIBRI code. They will be useful for future study of different galaxies and are currently applied to the study of the SMC (see the contribution by Pastorelli et al. in this volume). Comparison between the results obtained in this work and the above mentioned study by Dell'Agli et al. (2015b) will be interesting to see the effects of the AGB description on the results derived from the population synthesis.

Other interesting comparisons made in this direction have been done by Ventura et al. (2015, 2016). In these works the results obtain for the evolutionary tracks computed with the AGB+dust ATON code, have been compared to the ones obtained applying the same scheme for the dust production and wind dynamics to the MONASH AGB models (Karakas 2010). The physical evolution of the two models are significantly different, predicting very different results for the surface chemistry, and the C/O ratio in particular, owing to their treatment of convection in the envelope and of convective boundaries during TDU. Nevertheless the properties of dust formed in their winds are surprisingly similar in the majority of the cases, apart from the most obscured final phases of carbon stars evolution. This analysis shows how this kind comparisons represent a valuable instrument to path the way for future observations able to constrain present uncertainties in the modelling.

On the side of the dust production modelling, which are the appropriate optical properties for each dust species are still matter of debate. They influence the shape of the spectral energy distribution and consequently the path traced by the models in the colour-colour diagrams of the infrared bands. To test the best description for these parameters, Nanni et al. (2016) explored several optical data sets provided in the literature for the carbon dust. The comparison with the AGB stars observed in the SMC is made in different bands (*J, H, K*, and the IRAC *Spitzer* bands). Their results indicate that better agreement between models and observations is achieved for smaller grains ($\sim$ 0.06–0.1 μm) and this behaviour is found for all the data set tested.

5. Ongoing improvements

Despite the important improvements made on several sides of the dust production modelling, the complexity of the AGB evolution and the processes involved in the CE require further endeavours to reach a description of the phenomena closer (as much as possible) to the reality. Several works are going towards this direction. Important efforts have been made to model the nucleation process which is in most of the cases omitted in the description of the dust formation. A study of the nucleation of the SiC seeds in carbon stars have been recently published by Gobrecht et al. (2017), finding energetically favourable clusters for (SiC)n up to a size of n=16 and that SiC dust formation is viable in the dense cooling atmospheric gas layers by addition of single SiC gas phase molecules. Concerning O-rich stars, Gobrecht et al. (2016) studied the synthesis of molecules and dust in the inner wind of the oxygen-rich Mira-type star IK Tau by considering the effects of periodic shocks induced by the stellar pulsation on the gas and by following the non-equilibrium chemistry in the shocked gas layers. They found clusters of alumina, Al_2O_3, are produced within 2 $R_\star$ and lead to a population of alumina grains close to the stellar surface; clusters of silicates (Mg_2SiO_4) form at larger radii ($r > 3\ R_\star$). Important step forward are in progress also on the front of the AGB+dust evolution models where thermal gas pressure and pulsation contributions have been included in the wind dynamic description. Preliminary results on the impact that they have on the grain sizes and total amount of dust expected are described in this volume by Mattsson & Ventura.

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