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Dust formation in the winds of low metallities AGBs and implications for cosmic dust enrichment

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Abstract. We have calculated the dust formed around AGB and super-AGB stars of metallicity $Z = 3 \times 10^{-4}$, the lowest metallicity for which dust production by low and intermediate mass stars has been considered so far. This study complements previous investigations that were limited to metallicities $Z = 10^{-3}$ and $Z=8 \times 10^{-3}$. Stellar evolution is followed by means of a full integration of the equations of stellar structure, allowing to describe self–consistently the Hot Bottom Burning phenomenon. Our results imply that at these low initial metallicities, the production of dust is strongly suppressed, suggesting that in cosmic environments with metallicities $Z < 5\times 10^{-3}\ Z_{\odot}$ dust enrichment is entirely dominated by Supernovae.

Key words. Stars: abundances – Galaxy: formation – Galaxy: globular clusters – Stars: evolution

1. Introduction

The importance of intermediate mass stars in the asymptotic giant branch (AGB) and super asymptotic giant branch (super-AGB) phases as source of cosmic dust is currently a highly debated topic. Recent chemical evolutionary models (Valiante et al. 2009, 2011) have shown that AGB stars give important contributions to dust enrichment even at early cosmic epochs, when traditionally core-collapse supernovae (CCSNe) have been proposed as the main source of dust (Todini & Ferrara 2001; Nozawa et al. 2003; Bianchi & Schneider 2007; Dwek 2007). AGB and super-AGB stars are efficient polluters of the interstellar medium, because they release into their surroundings the whole convective envelope, before beginning the cooling to the White Dwarf stage. The gas ejected does not necessarily reflect the original chemistry, because two mechanisms may alter substantially their surface chemical composition: Hot Bottom Burning (HBB) and Third Dredge–Up (TDU). HBB is active in massive AGBs, and consists in the ignition of proton-capture nucleosynthesis at the bottom of the convective envelope; it is activated when the temperature of this region reaches $\sim 5\times 10^7$ K. TDU consists in the inwards penetration of the envelope after each thermal pulse (TP); the bottom of the surface convection zone may reach regions processed by 3α nucleosynthesis, enriched in carbon and oxygen.

The modification of the surface chemistry produced by HBB and TDU are different. TDU is accompanied by the increase in the surface abundance of carbon, and, to a smaller extent, of oxygen. The effects of HBB reflect proton-capture nucleosynthesis, and thus depend on the temperature at which HBB occurs. For temperatures below $\sim 8\times 10^7$K the main effect is the production of nitrogen at the expenses of carbon, whereas at higher temperatures oxygen destruction also occurs.

Due to the greater mass-loss rates experienced, and the cool temperatures in their expanded, low–density envelopes, the winds of AGBs are a favourable site for dust production, via condensation of gas molecules into solid grains. The investigations by Ferrarotti & Gail (2001, 2002, 2006) set the theoretical framework to model dust-formation in expanding AGB winds, and showed how the formation of carbonaceous species (essentially solid carbon and SiC) and silicates (olivine, pyroxene, quartz) depends on the surface chemistry of AGBs, particularly on the C/O ratio. These works are based on a synthetic description of the AGB phase, where core mass, temperature at the bottom of the convective zone, extension of TDU, are all imposed a priori, based on observational calibration. This approach has the clear advantage of allowing one to follow the whole AGB evolution with small computational efforts; the intrinsic limit of this description is that HBB cannot be described self–consistently. In our previous investigations (Ventura et al. 2012a,b, hereafter Paper I and Paper II, respectively) we presented new models where the AGB evolution was calculated by means of the integration of the whole stellar structure. We also extended the calculations to the super-AGB regime, ignored in previous works. Our analysis showed that the kind of dust formed around AGBs depends on the initial mass of the star: models with $M\geq 3\ M_\odot$, whose surface chemistry is dominated by HBB, produce silicates, whereas their lower mass counterparts produce carbon–type dust. These investigations also showed an interesting trend with metallicity: in higher–Z models the production of silicates is favoured, not only by the greater amount of silicon available in the envelope, but also because the HBB experienced is weaker, thus inhibiting the possibility of surface oxygen destruction.

2. The models

The stellar models presented in this work have an initial metallicity $Z = 3\times 10^{-4}$. The mixture is assumed to be α–enhanced, with $[\alpha/Fe]=+0.4$. This corresponds to an iron content [Fe/H]=-2 dex. The evolutionary sequences were calculated by means of the ATON stellar evolution code, in the version described in Ventura et al. (1998).

The range of masses involved is limited to $M\leq 7.5\ M_\odot$, because more massive objects undergo core–collapse SN type II explosion, thus not experiencing any AGB phase[1]. The evolutionary models were followed from the early pre–main–sequence phase, until the phase where almost all the external envelope is consumed. Models with masses below 2.5 $M_\odot$ develop a degenerate helium core while ascending the red giant branch, and undergo the helium flash

Dust grains are assumed to form via condensation of gas molecules in the wind of AGBs. The description of this process requires

[1] This limit is indeed partly dependent on the assumption of some extra mixing from the border of the convective core during the Main Sequence phase. If overshooting is neglected, the highest mass not undergoing SNII explosion is $\sim 9.5\ M_\odot$

knowledge of the evolution of the main physical and chemical properties of the central object, and a model for the thermodynamical and chemical structure of the wind. We address the interested reader to Ventura et al. (2012a) for a whole description of the stellar and wind modeling.

3. The results

We find that for this low metallicity in the high–mass domain, with $M \geq 3\ M_\odot$, strong HBB prevents the formation of carbon stars. The scarcity of silicon in the wind and the strong destruction of the surface oxygen in the most massive models lead to a negligible formation of silicates, not sufficient to accelerate the wind via radiation pressure on dust grains. Dust production is limited to the formation of solid carbon grains around low–mass stars, with initial mass $M \leq 2.5\ M_\odot$. The results depend on the way TDU is modelled, but as far as a minimum abundance of carbon of the order of $X_C \sim 0.005$ is reached in the surface layers, the results are approximately independent of the extent of TDU. This is a consequence of the balance between greater carbon abundances reached by models experiencing the deepest dredge–up and their lower core masses, that lead to smaller mass-loss rate.
Under these conditions, the carbon dust produced is $2 \times 10^{-4}\ M_\odot < M < 6 \times 10^{-4}\ M_\odot$ with grains radii in the range $0.08\ \mu$ m $< a_C < 0.12$ μ m.

Compared to higher metallicity models, low–mass stars with $M \sim$ 1-1.5 $M_\odot$ produce more dust because they reach more easily the carbon–star stage. Conversely, for $M > 1.5\ M_\odot$ higher Z models produce dust more efficiently, owing to their cooler surface layers.
These results can be extrapolated to even more metal–poor AGBs. No dust is expected in the high–mass domain, dominated by HBB, because of the scarcity of silicon available. At low Z's HBB is present even in low–mass stars, below 2 $M_\odot$. Although it is not sufficiently strong to burn oxygen, still it destroys part of the carbon accumulated by TDU. The scarcity of carbon in the envelope prevents the formation of carbon grains, if not in small quantities.

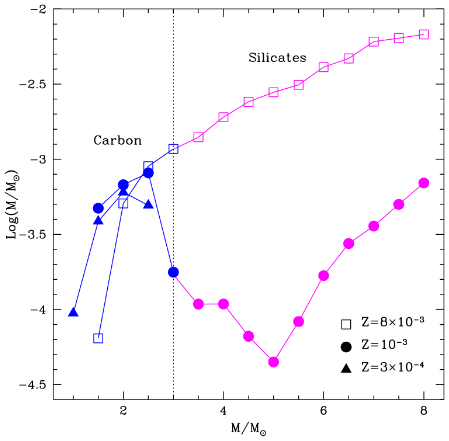

Fig. 1. The mass of dust produced by AGB models of different initial mass, at various metallicities. Full points indicate results for $Z = 10^{-3}$ published in paper I, open squares refer to the $Z = 8 \times 10^{-3}$ metallicity presented in paper II, whereas full triangles refer to the present investigation. The models in the low–mass regime were calculated by assuming an extra mixing ζ=0.002 from the convective shell which forms during each TP. The thin, dotted line separates models producing silicates from those producing carbon dust.

4. Implication for cosmic dust enricment

These results have interesting implications for the contribution of AGB stars to dust enrichment. The grid of stellar models that we have presented in paper I, II and in the present study, suggest that for $Z = 8 \times 10^{-3} = 0.4\ Z_\odot$, the metallicity of the Large Magellanic Cloud (LMC), AGB stars can contribute to dust enrichment of the ISM on relatively short timescales, $\approx$ 40 Myr, comparable to the evolutionary time of a 8 $M_\odot$ star. According to our results, the enrichment is initially limited to silicate dust, and carbon dust is released on longer timescales, t > 300 Myr, comparable to the evolutionary time of a 3 $M_\odot$ star. For initial metallicities in the range $3 \times 10^{-4} < Z \leq 10^{-3}$ or $0.015\ Z_\odot < Z \leq 0.05\ Z_\odot$, the production of silicates by the most massive AGB stars is strongly suppressed and low-mass stars can mostly contribute to carbon dust enrichment when t > 300Myr.

It is important to stress that these results and the dependence of the predicted AGB and super-AGB dust yields on the initial stellar metallicity reflect the complex evolution of these stars and can not be appreciated when synthetic stellar models are adopted. Indeed, our results partly contradict previous claims that AGB stars can always contribute to carbon dust enrichment, independently of their initial mass and metallicity, at least in the metallicity range, 5×10^{-2} $Z_\odot \leq Z \leq 1$ $Z_\odot$ (Ferrarotti & Gail 2006; Zhukovska et al. 2008).

More importantly, our study suggests that the dust yields computed for stars with initial metallicity of $Z \sim 10^{-2}$ $Z_\odot$ can not be extrapolated to lower metallicity as the contribution of AGB stars to dust enrichment can be safely neglected when the metallicity of the stars is Z ¡ 10^{-4} (5×10^{-3} $Z_\odot$). Hence, our results imply that at these low metallicities, supernovae are left as the only viable stellar dust sources (Todini & Ferrara 2001; Nozawa et al. 2003, 2007; Bianchi & Schneider 2007).

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