Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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AGB stars and the cosmic dust cycle

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Abstract. Theoretical and observational studies of dust condensed in outflows of AGB stars have substantially advanced the understanding of dust mixture from individual stars. This detailed information incorporated in models of the lifecycle of interstellar grains provides a flexible tool to study the contribution of AGB stars to the galactic dust budget. The role of these stars in dust production depends on the morphological type and age of galaxy. While AGB stars are sub-dominant dust sources in evolved systems as the Milky Way, the observed relation between the dust-to-gas ratio and metallicity suggests that the dust input in young dwarf galaxies with $7 \lesssim 12 + \log(\mathrm{O/H}) \lesssim 8$ can be dominated by the AGB stars. In application to post-starburst and early-type galaxies, the models for stardust evolution in combination with modern infrared observations give insights in the origin of their high dust content and its implications for their evolutionary scenarios.

Keywords. stars: AGB and post-AGB, dust, extinction, galaxies: evolution

1. Introduction

Cooling envelopes of thermally-pulsing AGB stars are known sites for efficient dust condensation. Presolar grains with isotopic signatures of AGB stars found in meteorites indicate that dust from these stars is transported to the ISM and survives in harsh interstellar environment for $100 - 1000$ Myr. Spectroscopic analysis of circumstellar envelopes of oxygen- and carbon-rich AGB stars reveal significant amounts of silicate and carbonaceous grains, respectively, which are thought to be the main dust components in the ISM. AGB stars are therefore considered important sources of interstellar dust, but their actual contribution to the galactic dust budget has remained unclear.

The input of AGB stars to the dust budget depends on (i) their mass and metallicity distributions and (ii) stellar dust yields, i.e. the amount of dust produced by stars during their entire AGB evolution. The former is determined by galactic evolution, namely, by the scenario of galaxy formation and evolution, matter cycle between gas and stars and attendant enrichment of the ISM with heavy elements. These processes are implemented in the models of galactic chemical evolution that follow enrichment history of the ISM and, correspondingly, initial chemical composition of subsequent generations of low- and intermediate-mass stars. The predictive power of these models is significantly enhanced by including a dust evolution model (Dwek 1998). Such models provide a simple, but powerful tool to study populations of AGB stars, their contribution to the interstellar dust budget and evolution of stardust grains in the ISM of galaxies (Gail *et al.* 2009).

Stellar dust yields are the key ingredient of galactic chemical evolution models with dust. The past two decades brought significant progress in the modelling of dust condensation in winds of low- and intermediate-mass stars. Condensation models for winds with carbon and oxygen chemistry were combined with stellar evolution models by Ferrarotti & Gail (2006), who produced the first stellar mass- and metallicity-dependent dust yields. Dust yields are implemented in the models of chemical evolution in a similar way as stellar

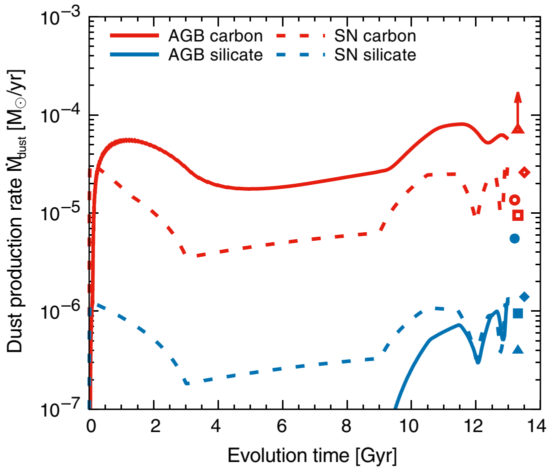

Figure 1. The dust production rate for carbon and silicate dust from AGB stars (red and blue lines, respectively) in the LMC as a function of evolution time. Dust input rate from type II SNe is shown with dashed line for comparison. Red and blue symbols indicate the values for C- and O-rich dust production rates derived from observations (Matsuura *et al.* 2009; Boyer *et al.* 2012; Riebel *et al.* 2012; Srinivasan *et al.* 2009). Adapted from Zhukovska & Henning (2013a).

nucleosynthesis yields, with the difference that dust species can be destroyed in the ISM by SN blast waves and star formation.

The mass of interstellar dust in a galaxy estimated from observations can be compared with the model predictions for grains from AGB stars that survived until the present time. This allows to study the role of AGB stars in the dust and gas recycling (Sect. 2), which in turn can be used to discern galactic evolution scenarios (Sect. 3). A direct comparison of the dust production rates by AGB stars is only possible for a handful of galaxies, for which these rates have been measured observationally for the entire population of dust-forming stars (Sect. 2). In the following we consider applications of dust evolution models for galaxies of various morphological types.

2. Dwarf galaxies

2.1. *Lessons from the Large Magellanic Cloud*

Stardust evolution models for the solar neighborhood find that AGB stars dominate the dust input to the galactic budget only during the early epoch, seeding the ISM with dust grains for the subsequent dust growth by accretion in the ISM (Dwek 1998; Zhukovska *et al.* 2008). This theoretical prediction cannot be directly verified for the Galaxy, since high extinction in the Galactic disk prevents measurements of the dust input rates from all AGB stars. This difficulty is alleviated for the Large and Small Magellanic Clouds (LMC and SMC), the closest dwarf galaxies, whose positions and proximity permitted the first census of their dust-forming stellar population carried out in the *Spitzer* Legacy Program "Surveying the Agents of Galaxy Evolution" (SAGE) (Meixner *et al.* 2006).

SAGE-LMC program resulted in the first observational estimates of the dust production rates in a galaxy (Matsuura *et al.* 2009; Boyer *et al.* 2012; Riebel *et al.* 2012; Srinivasan *et al.* 2009). Zhukovska & Henning (2013a) compare the dust production rate from observations to the theoretically calculated rates based on dust evolution models with AGB stellar populations.

This first comparison allowed to test stellar evolution prescription for the AGB phase used in the calculations of stellar yields and rule out the models with excessive hot bottom burning. Figure 1 shows the time variations of production rates for carbon and silicate

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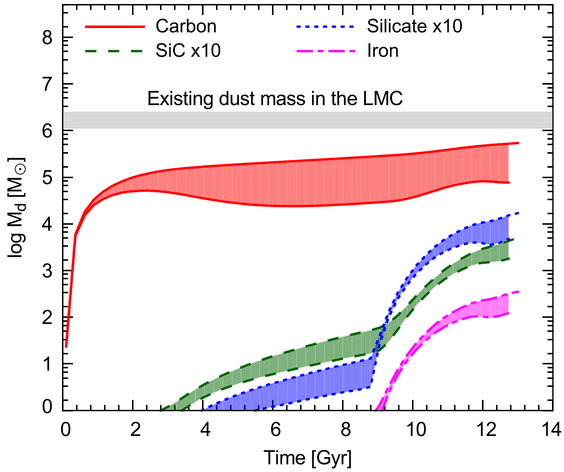

Figure 2. Time evolution of the dust mass ejected by AGB stars over the LMC history for carbonaceous, silicate, SiC, and iron grains. The upper and lower borders of shaded areas show the values with and without destruction, respectively. The grey rectangle indicates the present interstellar dust mass. Adapted from Zhukovska & Henning (2013a).

dust by AGB stars together with the corresponding values from observations plotted for the present time. Dust input from SNe is sub-dominant in the LMC. The results are shown for the dust yields from Ferrarotti & Gail (2006) providing the best match to observations.

Unlike for type II SNe, amount of oxygen-rich dust condensed in winds of AGB stars strongly depends on the stellar metallicity. The rates of O-rich dust production have approached the present-day levels only during the last 3 Gyr owing to the dust supply from stars formed from the gas enriched by the recent burst of star formation.

The total dust mass from AGB stars produced in the LMC during the entire galactic evolution is 8×10^4 $M_\odot$ and 5×10^5 $M_\odot$ with and without destruction in the ISM, respectively (Fig. 2). Even without destruction the accumulated dust mass from AGB stars is lower than the total dust mass in the LMC, $(1.1 - 2.5) \times 10^6$ $M_\odot$. This corroborates the discrepancy between the amount of interstellar dust in the Milky Way and the total dust mass from AGB stars. This is so-called "missing dust problem" is resolved by adding additional dust mass growth in the ISM by accretion of gas-phase species. This discrepancy decreases at subsolar metallicities in the outer Galactic disk and LMC, owing to the longer timescales of dust growth in the ISM (Zhukovska & Henning 2013b).

2.2. *Metal-poor dwarf galaxies*

Models of the lifecycle of cosmic dust predict that the dust content in young galactic systems originates from stellar sources, dust detected in high redshift galactic systems can therefore be injected by evolved stars. Unevolved, metal-poor local dwarf galaxies are considered templates for objects in the young Universe that can provide insights into the origin of their dust content.

Recent far-IR observations by the *Herschel* Space Observatory conducted within the Dwarf Galaxy Survey (DGS) have substantially improved estimates of the dust masses in the most metal-poor galaxies in the local Universe (Rémy-Ruyer *et al.* 2014). This study have for the first time established steepening of the relation between the dust-to-gas ratio (DGR) and the oxygen abundance log(O/H) at metallicities below 1/10 solar metallicity (Fig. 3). Large scatter of the DGR in the metallicity range $7.3 \lesssim 12 + \log(\mathrm{O/H}) \lesssim 8.4$ is another prominent feature of the observed relation. This implies that the fraction of

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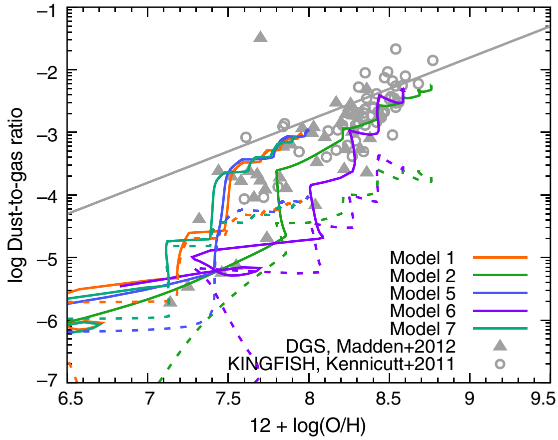

Figure 3. The dust-to-gas ratio as a function of oxygen abundance 12+log(O/H) in the ISM for dwarf galaxies with a wide range of model parameters from Table 1 in Zhukovska (2014) (solid lines). The dust-to-gas ratio for the case of AGB stars as the only dust sources is shown dashed lines. Triangles indicate the dust-to-gas ratios for dwarf galaxies from the Dwarf Galaxy Survey (DGS) and circles show the values of the KINGFISH sample for metal-rich galaxies, for comparison, estimated by Rémy-Ruyer *et al.* (2014). Straight grey line denotes the constant dust-to-metal ratio of 0.4, typical for spiral galaxies.

metals in dust in the DGS sources is generally lower and varies in a wider range than in spiral galaxies, characterised by the dust-to-metal ratio of $0.4 - 0.5$.

Because the DGS sample consists of galaxies with large spread in ages and metallicities, dust sources responsible for different trends in the observed DGR–metallicity relation can be studied by comparing it with DGR–metallicity evolutionary tracks for model galaxies (Zhukovska 2014). With a sufficiently large range of galactic parameters and star formation histories, the theoretical tracks with all dust sources included (AGB stars, type II SNe and ISM dust growth) cover the entire range in both DGR and log(O/H) values for dwarf galaxies (Fig. 3). Steps-like behaviour of the DGR is due to the bursty star formation histories, typical for dwarf galaxies. Theoretical tracks with dust production only by AGB stars overlap with the lower part of the observed DGR–metallicity relation, indicating the metallicity range of $7 \lesssim 12 + \log(\mathrm{O/H}) \lesssim 8$ in which AGB stars can dominate the dust production.

AGB stars are the major dust sources in dwarf galaxies during their initial evolution, up to 3 Gyr, before dust growth in the ISM takes over dust production. This is evident from the time variations of mass fraction of dust from AGB stars in the ISM of model galaxies (Fig. 4). The dips in the mass fractions mark bursts of star formation leading to the temporal increases of the SN dust production, while the fraction of AGB stardust increases up to 85% during post-burst evolution. The transition to the ISM-growth-mode of dust formation is indicated by the steep decrease in the mass fraction of AGB dust in all models. The star formation history is more important for this transition than metallicity: the higher is the star formation rate, the younger is the galactic age and the higher is the metallicity when the transition happens. In other words, galaxies with fewer star bursts of low intensity appear leftmost in Fig. 3 and rightmost in Fig. 4.

3. Galaxies with extreme environments

Recent detections of substantial dust amounts in massive galaxies with extreme environments such as post-starburst and early-type galaxies challenge their classical view as

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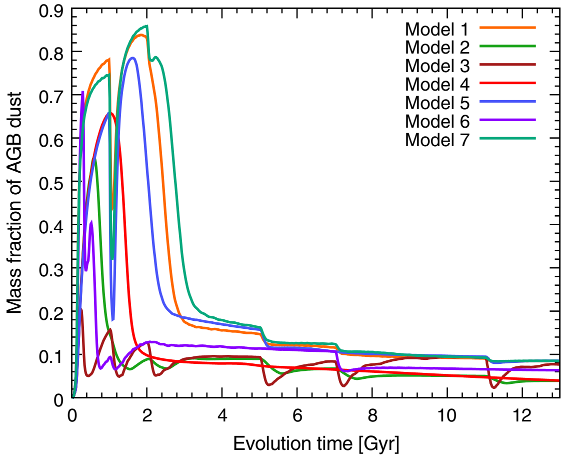

Figure 4. Mass fraction of dust from AGB stars as a function of evolution time (galactic age) for dwarf galaxy models from Zhukovska (2014).

dust- and gas-poor systems and raise questions about the origin and subsequent fate of this dust, which can be addressed with dust evolution models.

The optical spectra of post-starburst galaxies, designated also as E(K)+A galaxies, combine spectral characteristics of a young A-star population and old K-stars suggesting that they experienced a recent burst of star formation that was rapidly quenched several hundred Myr ago. In the traditional picture, post-starburst galaxies are dust- and gas-poor remnants of most violent mergers of gas-rich disks, rapidly transitioning to quiescent spheroids. This picture suggests that their ISM was expelled by the event that nearly truncated their star formation as a result of outflows from starburst or active galactic nuclei activity. The observed gas and dust reservoirs are then explained by replenishment of the ISM by ageing stellar populations. In order to test this scenario, Smercina *et al.* (2018) compare dust and gas masses measured observationally for a sample of 33 post-starburst galaxies with material ejected from a single stellar population (an instantaneous burst of star formation) as a function of its age. Figure 5 shows dust and molecular gas masses per unit burst stellar mass and theoretical curves for matter returned by AGB stars from a single stellar population with metallicity $Z = 0.02$. Since post-starbursts may be in the transition to early-type galaxies filled with hot gas, the models with grain destruction by thermal sputtering in a hot gas are also shown in Fig. 5.

Smercina *et al.* (2018) find that dust amounts in all post-starburst galaxies younger than 400 Myr can not be explained by condensation in stellar winds of AGB stars alone, suggesting that the ISM was not completely expelled by the quenching event and replenished by old stars. This conclusion is corroborated by higher masses of molecular gas in most sources than expected from stellar recycling alone (Fig. 5).

Dust-to-burst stellar mass ratios show a negative trend over three orders of magnitude with galactic age, similar to the models with thermal sputtering of grains in a hot gas on the shortest timescale of 50 Myr. This trend is explained by the higher dust destruction rates than the production rate by stars. For comparison, dust content in young dwarf galaxies increases with time and in spiral galaxies, dust destruction is balanced by formation processes leading to the constant average dust abundances. The dust-to-burst stellar mass ratios for post-starburst ages > 600 Myr are consistent with observations of dusty early-type galaxies ($M_{\rm d}/M_{*,\rm burst}$ of a few 10^{-5}), suggesting an ongoing transition to virialized early-type gas conditions.

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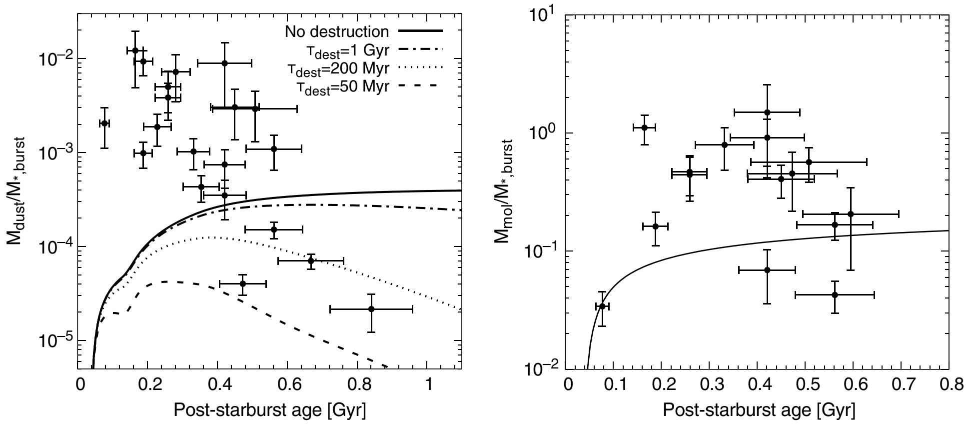

Figure 5. *Left Panel.* Dust mass per unit burst stellar mass for the sample of post-starburst galaxies as a function of time since the burst (error bars). The four curves are the theoretical dust models for a single stellar population with metallicity $Z = 0.02$ without destruction (solid line) and with thermal sputtering on the timescale of 1 Gyr, 200 Myr and 50 Myr (dash-dot, dot, and dash lines, respectively) derived for various representative gas conditions in early-type galaxies. *Right Panel.* Molecular mass per unit burst stellar mass (error bars) also plotted as a function of time since the burst. The solid curve shows total injection of gas by a single stellar population. Adapted from Smercina *et al.* (2018).

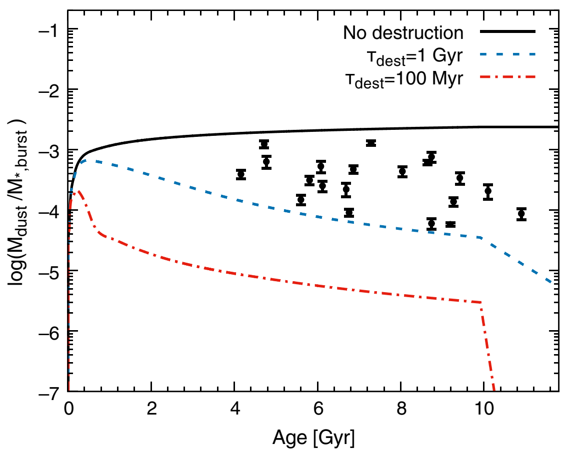

Figure 6. Dust mass per unit stellar mass in the sample of red-elliptical galaxies from Dariush *et al.* (2016) with metallicity $Z > 2.5\ Z_\odot$ plotted as a function of the mass-weighted age of their stellar populations (error bars). The three curves are the theoretical dust models for a single stellar population with metallicity $Z = 3\ Z_\odot$ without destruction (solid line) and with thermal sputtering on timescale of 1 Gyr and 100 Myr (dash and dash-dot lines, respectively).

Unexpectedly large dust reservoirs were recently detected in sub-millimetre bands in optically red early-type (red-E) galaxies at low-redshifts (Dariush *et al.* 2016). The origin of dust in these systems can be also probed by a simple stellar population model, neglecting the age spread of their old populations. Dust in early-type galaxies is traditionally believed to be formed in outflows of AGB stars. The total dust mass returned by a single stellar population is indeed larger than the dust quantities detected in red-E galaxies. However, dust from AGB stars cannot accumulate over extended time owing to efficient grain destruction by thermal sputtering in a hot gas, ubiquitous for early-type gas conditions (Fig. 6). Even for a low gas density of 10^{-4} cm^{-3} resulting in a long sputtering

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timescale of 1 Gyr, the models fail to reproduce the observed dust masses. The mismatch between the model predictions and the observed dust masses suggests an external origin (e.g. supplied through mergers or tidal interactions) or dust growth in the cold ISM of these early-type systems.

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Discussion

MAERCKER: In dwarf galaxies, the dust first comes from SNe and AGB stars and then from ISM growth. Would the ISM growth be possible without the first producing stardust? And does the type of ISM dust formed depend on the original stardust?

ZHUKOVSKA: The ISM growth requires seed particles providing initial surface, so stardust is required to initiate the growth. Yes, the type of ISM dust depends on the chemical composition of the original stardust. We assume selective growth, i.e. silicate dust grows on silicate grains and carbon on carbon grains, respectively. The growth rates depend on the abundances of these dust species in the ISM.