

Life Cycle of Dust in the Magellanic Clouds and the Milky Way

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To a great extent, our understanding of the life cycle of dust is based on the observational and theoretical studies of the Milky Way and the Magellanic Clouds, which will be the topic of this contribution. Over past years, a large volume of observations with unprecedented spatial resolution has been accumulated for the Milky Way. It permits investigations of different stages of the life cycle of dust, from its formation in stellar sources to destruction in star-forming regions and supernovae shocks. Observations of dust emission, extinction, and interstellar element depletions in the solar neighbourhood yield the most accurate constraints for interstellar dust models providing a reference for studies of dust content in extragalactic systems. However, global spatial studies of the circumstellar and interstellar dust are complicated in the Milky Way disk because of high extinction, confusion along the line of sight and large uncertainties in distances. In contrast, the favourable location in the sky and the proximity of the Magellanic Clouds allow detailed multi-wavelength studies of the dust-forming stellar populations and the investigation of variations of the interstellar grain properties for the entire galaxies. They enable the first comparison between the global stardust production rates from theoretical calculations and those from observations, which confirm discrepancy between accumulated stardust mass and observed interstellar dust mass – “the missing dust-source” problem. Modelling of the life cycle of dust in the Large Magellanic Cloud showed that dust growth by mantle accretion in the ISM, a major dust source in the Milky Way, can also be responsible for the existing dust mass in the LMC. We will present comparison of the dust input from different sources to the dust budgets of the Milky Way and the Magellanic Clouds, which reveals how the role of these dust sources depends on metallicity.

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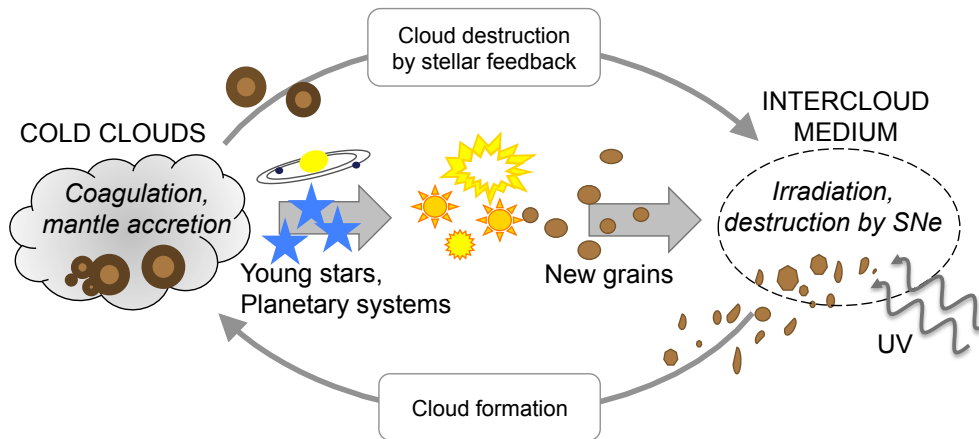


Figure 1: Schematic representation of the gas and dust cycle between clouds, intercloud medium, and stars. The main processes affecting grains in the ISM are shown (see explanation in the text).

1. Introduction

Our understanding of the nature and origin of interstellar dust is to great extent based on the observational and theoretical studies in the solar neighbourhood. It provides a testing ground for various dust models. Their development has been stimulated over the past decades by increasing power of observational facilities and advances in laboratory studies of cosmic dust analogues. Dust models constrained by high-resolution observations (e.g., IR and microwave dust emission, interstellar extinction, scattering, polarisation, and interstellar element depletions) in diffuse regions of the local Milky Way have been successfully applied to investigate the dust content in many extragalactic systems (e.g., [13, 84, 11] and many others). The properties of dust grains inferred from the diffuse regions are however not universal. It has been long recognised that the dust-to-gas ratio, chemical composition, size distribution, and solid-state structure of dust grains vary substantially across galactic environments (molecular clouds, hot gas, stellar outflows, and young stellar objects) [12, 14, 26]. These variations reflect evolutionary changes which grains experience during their life cycle in the ISM.

A simplified scheme of the life cycle of interstellar dust is shown in Fig. 1. Dust formation occurs at condensation temperatures in cooling outflows of evolved stars and expanding supernova ejecta through nucleation (formation of nm-sized molecule aggregates) and following grain growth to sub- μm sizes [24]. When stellar ejecta are mixed with the ambient ISM, newly condensed stardust grains become part of the interstellar dust population. In the diffuse phase, grains undergo various processing: ultraviolet (UV) irradiation, hydrogenation, and destructive processes resulting from grain-grain and gas-grain interactions in the interstellar shocks (melting, sputtering, vaporization, and shattering). The interstellar dust takes part in the matter cycle between dense and diffuse clouds and intercloud medium governed by the processes of star formation and energetic stellar feedback. The average lifetime of dust against destruction in the ISM (a few 10^8 yr) is longer than the timescale of formation of molecular clouds and their disruption (a few 10^7 yr). Grains therefore cycle multiple times between these phases before they are completely destroyed.

In the dense clouds, grains are subject to grain growth by accretion of gas-phase species and coagulation, the processes which are responsible for large observed variations in the shape of the extinction curve [19, 34]. Various dust processing across the ISM phases is reflected in the increase of interstellar element depletions with the gas density and decrease in the shocked gas observed in different sightlines [39, 68, 38]. There is a direct evidence that a fraction of stardust grains ends their interstellar journey being incorporated in material forming new stars and protoplanetary disks. Stardust grains from the molecular cloud formed our solar system which survived its formation can be found as presolar grains in meteorites and analysed in laboratory (e.g., [10, 55]). Anomalous isotopic element ratios in these grains bear signatures of the nucleosynthesis of their parent stars permitting identification of their origin. The ratio of presolar grains of different origins derived in the laboratory can be used as a constraint on efficiency of dust production by stellar sources [82].

Despite the wealth of high-resolution observations in the local galactic environment, there is a number of obstacles in exploration of the entire life cycle of dust in the Milky Way. Our location in the galactic disk, high extinction in the disk, uncertainties in distances and confusion along the line-of-sight hamper global studies of interstellar and circumstellar dust. These complications can be resolved for our neighbouring dwarf galaxies, the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC). Their structure, kinematics, composition, distances and histories have been studied observationally in great detail by ground-based and space observatories over past decades [78]. Moreover, their dust-forming stellar populations and the interstellar dust emission have been mapped from 3.6 to 500 μm for the entire galaxies with *Spitzer* Space Science Telescope (SAGE survey) and *Herschel* Magellanic Survey (HERITAGE) [53, 29, 54]. Another advantage is that the distances to the LMC (50 kpc) and the SMC (61 kpc) have been determined with high accuracy down to $\sim 3\%$ [60, 30]. They are located far enough away that the same distances can be assumed for all stars and interstellar gas clouds for intrinsic brightness determinations. In addition, the metallicities of the LMC ($0.3\text{--}0.5Z_{\odot}$) and the SMC ($0.2Z_{\odot}$) [65] permit investigation of the lifecycle of dust at subsolar metallicities. Comparison of circumstellar dust in the SMC, the LMC and Milky Way gives a valuable insight into the metallicity dependence of dust formation process [29, 53]. With their enhanced star formation rates, low metallicities and high gas fractions [31, 32], the Clouds represent a template for the conditions for grain evolution in star forming galaxies at high redshifts [47, 74]. The subsolar metallicity in the Clouds implies a lower interstellar dust content compared to the Milky Way, which in turn affects the physical conditions in the ISM. The mean free path of UV photons from massive stars is longer and intensity of the interstellar radiation field is therefore higher than in the local Milky Way. The molecular gas fractions in the LMC (~ 0.1) and SMC ($\sim 0.05 - 0.10$) are therefore several times lower than that in the Milky Way ([46, 54] and references therein).

Some aspects of the lifecycle of interstellar dust in the Milky Way and Magellanic Clouds are covered in other contributions of this volume and we will refer to them where needed. This review will briefly describe the model of the lifecycle of dust and implementation of the main destruction and production processes and their relevant timescales in Sect. 2. Section 3 will focus on the dust input from AGB stars and type II SNe. We will discuss constraints on the stellar dust yields provided by the local Milky Way and metallicity dependence of the dust mixture from AGB stars by the Galactic disk. In the context of the global contribution of stars to the dust budget, theoretical and observational efforts to determine the dust production rates by AGB stars in the Magellanic

Clouds will be presented. Finally, the total contribution of stars to the interstellar dust budgets in the Milky Way and the Magellanic Clouds will be discussed in Sect. 4.

2. Models of the life cycle of dust in the ISM

Dwek and Scalo [16] proposed a model of the life cycle of refractory grains in the solar neighbourhood that captures main dust formation and destruction processes operating in the ISM (Fig. 1). This model is based on the chemical evolution model of the Galaxy, therefore it also accounts for the dependence of dust content on global galactic evolution processes such as star formation, and galactic in- and outflows. Other advantages of this approach is that it naturally includes element abundance constraints for the interstellar dust mixture, and allows to study variations of its amount and chemical composition. These quantities can be estimated from observations and compared with model predictions for the present day. Since the original work [16], the models of the life cycle of grains in the ISM have been further developed to include multiphase structure of the ISM [33, 82], individual evolution of stardust grains of different origins [82, 25], variations in grain size distribution (see [34] in this volume) and applied for the Milky Way disk and galaxies of different morphological types in the local Universe [17, 7, 83] and high redshifts [75, 61, 21]. Majority of models considers evolution of two species: silicate and carbonaceous grains. This dust mixture consists of the most abundant refractory elements (Mg, Si, Fe, O, and C) and satisfies the main observational constraints in the solar neighbourhood such as dust extinction, emission and element abundances (e.g., [84]).

2.1 Stellar dust production

The global production rate of stardust of kind i is determined from the dust and gas chemical evolution models by integration over stellar mass range ending their life at instant t

$$\dot{M}_{i,d}(t) = m_{\text{av}}^{-1} \int_{m_l}^{m_u} \phi(m) \psi(t - \tau(m, Z)) Y_{i,d}(m, Z) dm, \quad (2.1)$$

where $\phi(m)$ is the initial stellar mass function (IMF), $m_{\text{av}} = \int m \phi(m) dm$ is the average stellar mass, $\tau(m, Z)$ is the stellar lifetime, $\psi(t - \tau(m, Z))$ is the star formation rate at the instant of birth of a star with the initial mass m and metallicity Z in units $M_{\odot} \text{yr}^{-1}$, here Z is the metallicity of the ISM at the instant of birth of a star determined by galactic chemical evolution. $Y_{i,d}(m, Z)$ is the dust yield, i.e. the total mass of dust of kind i returned to the ISM by a star over its evolution. Mass- and metallicity-dependent dust yields are the central quantities for calculations of the total dust input from stars. The local Milky Way and the Magellanic Clouds provide complementary tests for the dust yields from both AGB stars and type II SNe as discussed in Sect. 3.

2.2 Dust evolution in the ISM

The change of mass of dust species of type i per unit time is

$$\frac{dM_{i,d}}{dt} = \dot{M}_{i,d}(t) + G_i - \frac{M_{i,d}}{\tau_{i,\text{SN}}} - \frac{M_{i,d}}{\tau_{i,\text{SF}}} + \dot{M}_{i,d}^{\text{inf}} - \dot{M}_{i,d}^{\text{out}}, \quad (2.2)$$

where the terms on the right side of the equation are the dust injection rate from stars given by Eq. (2.1), the dust growth rate by accretion in the ISM, the dust destruction rates by SNe and star

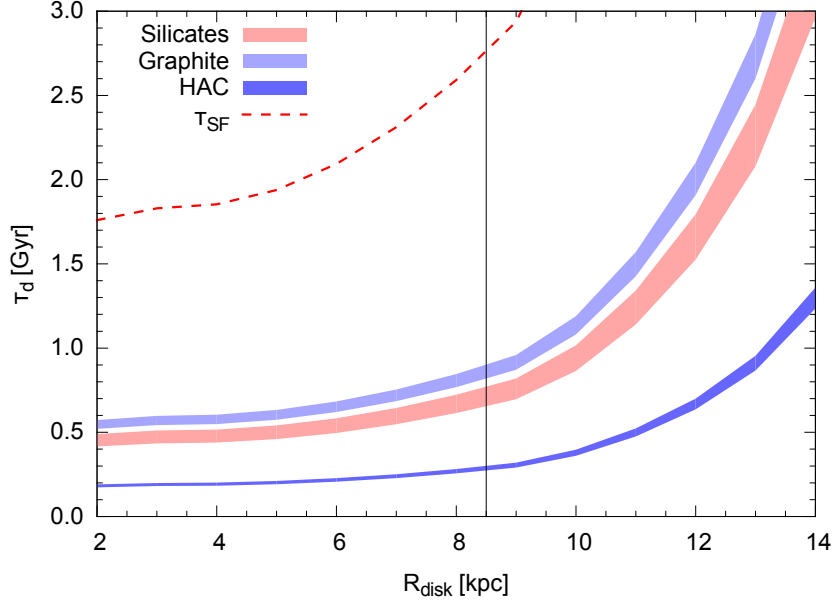


Figure 2: Radial variations of the lifetimes of silicate (light red shaded area) and carbonaceous (graphite and HAC, light and dark blue areas, respectively) grains against destruction by SNe and star formation (dashed red line) in the present Milky Way disk. The vertical line marks the position of the solar system. The data are taken from [79].

formation, and two last terms denote an increase of the dust mass due to infall of matter from outside and decrease due to galactic outflows from the galaxy.

2.2.1 Dust destruction in the ISM

Dust grains are efficiently destroyed by SN blast waves predominantly in the warm neutral/ionised phase of the interstellar medium through inertial sputtering for shock velocities in the range of 50-150 km/s and through thermal sputtering at higher shock velocities [40, 41]. The global lifetime of dust grains against destruction by SN shocks τ_{SN} can be expressed in terms of the amount of interstellar gas cleared of dust by a single SN m_{cl} [52]:

$$\tau_{\text{SN}} = \frac{M_{\text{gas}}}{m_{\text{cl}} f_{\text{SN}} R_{\text{SN}}}, \quad (2.3)$$

where M_{gas} is the mass of gas in the galaxy, R_{SN} is the net SN rate, and f_{SN} is the fraction of all SNe that destroy dust in ISM. f_{SN} accounts for massive stars which end their life above the galactic gaseous disk and do not interact with dust. Additionally, the total SN rate is reduced due to correlated SNe exploding in existing superbubbles created by previous SNe in the cluster and constituting at least 75% of all Galactic SNe [36]. The expansion velocity of the supershell created by the multiple SNe of the cluster is below the limit for dust destruction. f_{SN} estimated from observations has similar values for the Milky Way and the LMC, 0.35 and 0.3, respectively [52, 83]. m_{cl} is calculated for a given SN shock structure and depends on the properties of dust material, grain size distribution and density of the ambient ISM [40]. The m_{cl} values of $1300 M_{\odot}$

and $1600 M_{\odot}$ for graphite and silicates, respectively, derived for the solar neighbourhood, are similar to the estimates in the LMC [83].

For the Milky Way, Equation (2.3) yields the average destruction timescales of 4×10^8 yr and 6×10^8 yr, for silicate and graphitic dust, respectively [40]. If carbonaceous grains are assumed to be in form of hydrogenated amorphous carbon (HAC), their lifetime is shortened by a factor of three [69]. The lifetime of the polycyclic aromatic hydrocarbon (PAH) molecules, another interstellar dust component, is even shorter, $1.4 - 1.6 \times 10^8$ yr [56]. Efficient dust destruction by SN blast waves is supported by observations of dust emission from SN remnants. Modeling of the spectral energy distributions from regions in front of and behind shock front of the Puppis A supernova remnant reveals that the PAHs are completely destroyed in the swept-up ISM, along with nearly 25% of the mass of graphite and silicate dust grains on the timescale of 80 yr [1]. Dust lifetimes are not the same throughout the Galactic disk due to slower chemical evolution in the outer regions compared to the inner disk, as indicated by the at least 10 times lower star formation rate and radial metallicity gradient. Figure 2 shows the radial variations of the lifetimes for silicate and carbonaceous dust in the Galactic disk calculated using the gas mass and SN rate per unit surface area from the galactic chemical evolution model in Eq. (2.3). The life cycle of grains is more than 6 times faster in the inner Galaxy compared to the outer disk as seen in Fig. 2 [79].

The grain lifetimes derived from Eq. (2.3) for the LMC are equal to 0.8 Gyr for silicate and 1 Gyr for graphitic grains [83]. This is somewhat longer than for the solar neighbourhood, see Fig. 2 for comparison. Using $M_g = 5.7 \times 10^8$ yr and $R_{\text{SN}} = 2.9 \times 10^{-3}$ yr $^{-1}$ for the SMC and adopting for m_{cl} and f_{SN} the same values as for the LMC [83], one yields values of the dust lifetimes of 0.4 and 0.5 Gyr, for silicate and graphitic dust, respectively, which are close to those in the Milky Way. Note that there are large uncertainties in estimates of the global galactic lifetimes from Eq. (2.3) related to uncertainties in the observational estimates of gas masses and SN rates [44]. Additionally, the local values of the lifetime of grains against destruction can deviate from the average value, in particular, in the regions that actively form stars. Star formation histories of the LMC and the SMC reveal that such regions are nonuniformly distributed both temporarily and morphologically in these galaxies [31, 32]. The spatial distribution of the dust-to-gas ratio in the LMC derived with *Herschel* and *Spitzer* IR dust emission maps combined with CO and HI observations indeed show large variations [26].

Interstellar dust is also destroyed in the process of star formation on the timescale τ_{SF} determined by the ratio of the gas mass to the star formation rate. Its variation with the Milky Way radius are also shown in Fig. 2. The value of $\tau_{\text{SF}} \sim 2.5$ Gyr estimated for the solar neighborhood is somewhat lower than 3.1 Gyr estimated for the LMC [83]. The SMC has higher gas fraction and lower star formation rate than the LMC and Milky Way, therefore $\tau_{\text{SF}} \gtrsim 10$ Gyr in the SMC is longer than in these galaxies.

2.2.2 Dust growth in the ISM

Many works have found that additional dust growth by accretion of gas-phase species on existing grain surfaces in the ISM is required to explain high levels of element depletions in the ISM (e.g., [16, 17, 82, 15, 38] and references therein). Nevertheless, the details of these process are not well-understood. Observational evidence that amorphous silicate and carbonaceous dust reside as two distinct populations seems to imply that the growth process should be selective: Si,

Fe, Mg and O atoms should preferentially stick to the silicate grain surfaces and C atoms to the carbonaceous dust surfaces, in contrast to what is expected for low-temperature condensates. [15] suggested that selective growth could occur in the diffuse ISM in the presence of UV photons. In this scenario, the UV irradiation helps to rearrange chemical bonds to form amorphous silicates, as Si, Mg, Fe, O atoms are adsorbed on the silicate grain surface, and remove C atoms by the UV photoexcitation. Similarly, carbon dust could grow by addition of impinging C atoms, while other species arriving on the carbon dust surface are removed by the UV photons [15]. Recently, a new detailed model of the life cycle of carbonaceous grains have been proposed, in which carbon dust in the form of hydrogenated amorphous carbon grows (re-forms) by accretion in the diffuse outer regions of dense molecular clouds (see [42] and [43] for recent reviews). For silicate grains, the growth mechanism is less clear. Recent experiments on low-temperature condensation has demonstrated that the formation of solid SiO is possible at a low temperature without energy barrier [45, 23]. Since SiO is the main building block of astronomical silicates, this finding is an essential step forward to understanding of the formation of more complex silicates.

Dust evolution models usually assume that the dust growth occurs by collisions of gas-phase species with surfaces of existing grains at dense ISM phase. The corresponding equation for the change of condensation degree of a dust-forming species of kind i in a dense cloud is

$$\frac{df_i}{dt} = \frac{f_i(1-f_i)}{\tau_{i,\text{acc}}}, \quad (2.4)$$

where $\tau_{i,\text{acc}}$ is the the accretion timescale. It is the key quantity for dust growth, which depends on the properties of the grain solid material, grain size distribution, and the physical conditions in the gas:

$$\tau_{i,\text{acc}}^{-1} = \frac{3\alpha_i A_i m_{\text{amu}}}{\rho_{i,c} v_{i,c}} \cdot \frac{1}{\langle a_i \rangle} \cdot v_{i,\text{th}} n_{\text{H}} \cdot \varepsilon_i, \quad (2.5)$$

where α_i is the sticking efficiency to the grain surface, A_i is the atomic weight of one formula unit of the dust species, $\rho_{i,c}$ is the density and $v_{i,c}$ is the number of atoms of the key element contained in the formula unit of the condensed phase, $\langle a_i \rangle$ is the average grain radius determined by the grain size distribution, $v_{i,\text{th}}$ is the thermal speed of the growth species, n_{H} is the number density of H nuclei, and ε_i is the element abundance of the key species.

Several approaches to calculate the dust production rate by growth in the ISM have been suggested in the literature. One can directly use Eq. (2.4) to calculate the dust production rate G_i as suggested in [17]. Other approaches explicitly account for the dust growth occurring at high densities in molecular clouds, which are characterised by the lifetime τ_{cl} and the total mass fraction X_{cl} (e.g., [35, 82]). The dust production rate can be expressed as [82]

$$G_{j,d} = \frac{1}{\tau_{\text{exch,eff}}} \left[f_{j,\text{ret}} M_{j,d,\text{max}} - M_{j,d} \right], \quad (2.6)$$

where $\tau_{\text{exch,eff}} = \tau_{\text{cl}}(1 - X_{\text{cl}})/X_{\text{cl}}$ is the effective exchange time required to cycle all ISM through clouds, $f_{j,\text{ret}}$ is the condensation degree for growth species of kind j after cloud dispersal, $M_{j,d,\text{max}}$ is the maximum possible dust mass assuming complete condensation, $M_{j,d}$ is the current average dust mass.

The dust growth timescale is inversely proportional to the abundance of the key species. It is therefore very inefficient in metal-poor environment until the metallicity in the ISM reaches some

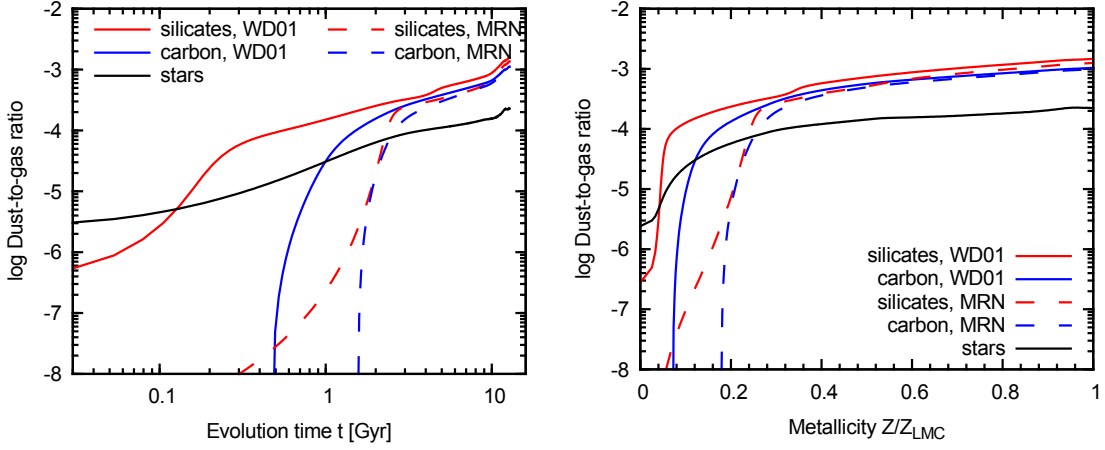


Figure 3: Evolution of the dust-to-gas ratio in the LMC calculated with two grain size distributions: a simple power law from [48] (MRN, dashed lines) and a more complex distribution from [77] (WD01, solid lines), as a function of time and metallicity (left and right panels, respectively). The dust-to-gas ratio is shown for the interstellar silicate and graphitic grains (red and blue lines, respectively) and for the stardust component (silicate+graphite, black line).

critical value [79, 82, 81, 2]. In the local Milky Way, the critical metallicity for the dust growth was reached within the first few 100 Myr evolution. In metal-poor dwarf galaxies, the growth is slower and it may take up to roughly ~ 1 Gyr, for the dust growth to become important [80]. The grain size distribution in the Magellanic Clouds is characterised by a larger abundance of small grains (a larger grain surface area) compared to the Milky Way [77], which can somewhat mitigate the effect of their low metallicities on the growth timescale, accordingly to Eq. 2.5. In order to illustrate the effect of the grain size distribution on the dust content of a galaxy, we perform calculations of the dust evolution in the LMC with two different size distributions: the standard power law (MRN) commonly used for dust in the local diffuse ISM [48] and a more complex size distribution derived from fitting of the average extinction curve in the LMC [77]. The resulting dust-to-gas ratios are shown for the silicate and carbon dust as a function of evolution time and metallicity in Fig. 3. Time evolution of the dust-to-gas ratio is indeed sensitive to the assumed grain size distribution, but only during the first 2 Gyr corresponding to the metallicity of 0.0025. After dust production by stars and by growth in the ISM reaches the balance with dust destruction in the ISM, the average dust abundances in the ISM weakly depend on the grain size distribution.

3. Dust production by stellar sources

Low- and intermediate-mass stars ($m_* \lesssim 8 M_\odot$) at asymptotic giant branch (AGB) and massive stars ($m_* \gtrsim 8 M_\odot$) after the final SN explosion become the main stellar factories of dust, but their importance for the dust content of galaxies is a long-standing debate. The local Milky Way and the Magellanic Clouds offer unique complementary constraints for the models of the life cycle of dust permitting to ascertain the net dust input from stellar sources to the galactic dust budget. The star formation histories and chemical evolution of these galactic systems were extensively studied

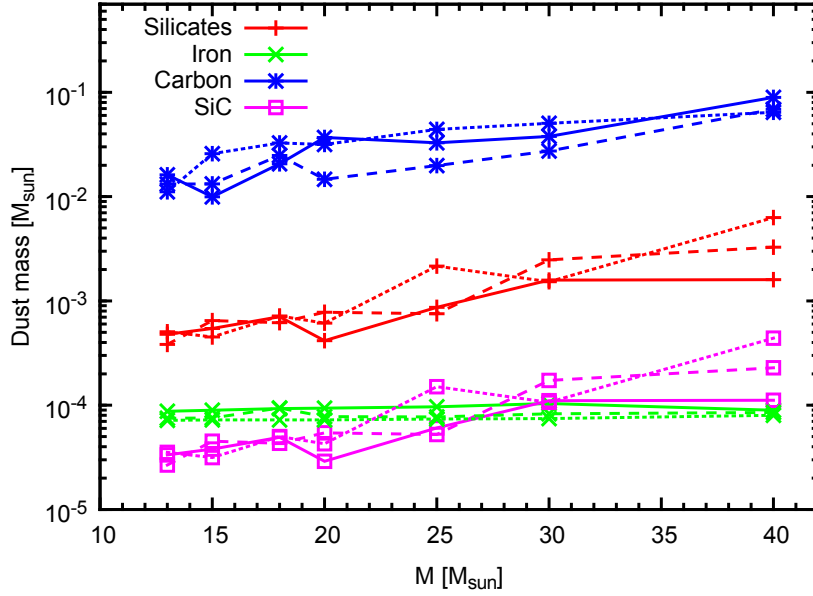


Figure 4: Dust masses returned by type II SNe as a function of progenitor mass calculated with the fixed condensation efficiencies for silicate, SiC, and carbon dust derived in [79, 82] using models of dust evolution in the solar neighbourhood. The solid, dashed and dotted lines correspond to the progenitor metallicities of 0.02, 0.004 and 0, respectively.

in many observational works (e.g., [3, 31, 32, 8, 9], and references therein) providing a reliable basis for the dust evolution models described in the preceding section. In the following we will summarise recent advances in theoretical and observational studies of the contributions of stellar sources to the dust budget in the solar neighborhood, Milky Way disk and Magellanic Clouds.

3.1 Role of type II SNe in dust production

Hot debates about efficiencies¹ of dust condensation in ejecta of core-collapse SNe have been revived with recent discoveries of copious dust masses in objects in the early Universe. Given that type II SNe produce heavy elements on a short timescale, they are potentially the primary source of dust at high redshifts [22]. SN remnants in the Milky Way and Magellanic Clouds are subjects of many observational studies of dust formation in SNe stimulated by new windows into far-IR wavelength range opened by *Herschel* Space Telescope and into sub-/millimetre by ALMA. Analysis of the IR dust emission in a few available data for SN remnants yields low values of condensation efficiencies in type II SNe of $10^{-4} - 10^{-3}$ (e.g., [63, 64, 71], see [28] in this volume for a review). Recent far-IR and millimetre observations of historical SN remnants Cassiopeia A and Crab Nebulae revealed larger dust masses of 0.1-0.7 M_{\odot} hidden in the cold component [50, 27, 28]. These discoveries do not however necessary imply that core-collapse SNe are the main dust factories in galaxies, since it is unclear what fraction of these grains will survive destruction in reverse shocks of SN remnants. Numerical simulations indicate that a large fraction up to 100%

¹Efficiency or degree of condensation is defined as a ratio of the mass of refractory elements condensed into dust to their total mass in ejecta.

Table 1: Global production rates of C-rich and O-rich dust from various stellar sources in the solar neighbourhood in units $M_{\odot} \text{ kpc}^{-2} \text{ Myr}^{-1}$

Stellar source	Dwek 1998 [17]	Tielens et al. 2005 [72]	Zhukovska et al [82]
C-rich dust, AGB stars	2.8	3	1.0
O-rich dust, AGB stars	3.7	5	0.4
C-rich dust, SNe II	1.5	<2	0.7
O-rich dust, SNe II	7.0	<10	0.01
Type Ia SNe	3.5	<2	0.002
Wolf-Rayet stars	0.02	<0.06	-
Novae	<0.003	<0.3	-

of freshly condensed dust can be destroyed by the reverse shock [66, 67, 5]. Moreover, if one SN destroys dust in $1300 - 1600 M_{\odot}$ of gas as discussed in Sect. 2.2.1, it has to produce a similar dust amount of about $13 - 16 M_{\odot}$, assuming a dust-to-gas ratio of 1%, for the positive net input. Reducing this value to account that not all SNe destroy dust results in the dust masses of $4.6 - 5.6 M_{\odot}$ per SN, which by far exceeds the largest estimates from observations.

Dust formation in SNe can be studied not only by observations and modelling of SN remnants, but also by analysis of actual SN grains extracted from meteorites in laboratory. These stardust grains, or so-called presolar grains, are fossils of the material which formed the solar system 4.56 Gyr ago. Their origins are identified by anomalous isotopic element ratios bearing nucleosynthesis signatures of their parent stars. Meteoritic data provide information about the relative abundances of stardust grains from AGB stars and SNe at instant of the solar system formation. It allows to constrain dust input from SNe by varying condensation efficiencies in SNe for the adopted dust yields for AGB stars to match the values derived from meteoritic data with those predicted by the models of dust evolution [82]. This methods yields the condensation efficiencies of 0.15 for carbonaceous grains, 10^{-3} for silicates and 10^{-4} for SiC [79, 82]. The corresponding dust masses are shown in Fig. 4 as a function of progenitor mass for metallicities $Z = 0, 0.004, \text{ and } 0.02$. For carbonaceous dust, the main dust species condensed in type II SNe, according to the available meteoritic data, the condensed mass varies from $\sim 10^{-2}$ to $0.1 M_{\odot}$, with a weak metallicity dependence. The lower values of dust mass compared with recent discoveries of cold dust in SN remnants [50, 27] may imply partial destruction of newly formed grains in the reverse shock. Low values of the condensation efficiencies in type II SNe are supported by the relation between the dust-to-gas ratio and metallicity derived from observations of a large sample of dwarf galaxies [80].

Table 1 shows the net dust production rates from core-collapse SNe in the solar neighbourhood for the present epoch estimated in several works. A large discrepancy between model predictions from [82] and from [17] and [72] is caused by the almost complete condensation of refractory elements in dust assumed in these works. The low condensation fraction of silicates inferred from meteoritic studies substantially reduces the total dust mass condensed in SN ejecta, so that AGB stars become the dominant stellar source of dust.

Various estimates of dust production rates (DPR) from SNe in the Magellanic Clouds are given in Table 2. Models of dust evolution with the conservative condensation efficiencies from [79]

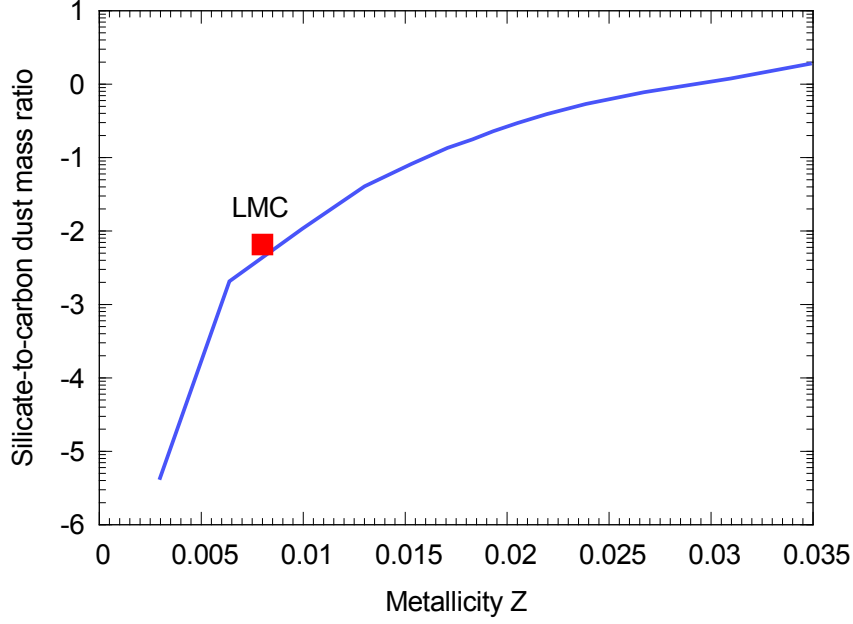


Figure 5: Silicate-to-carbon dust mass ratio in interstellar grain population from AGB stars as a function of present-day metallicity in the Galactic disk (solid line) and LMC (red square). The data for the figure are adopted from the dust evolution models for the Milky Way and for the LMC [79, 83].

indicate that dust input in the LMC is also dominated by AGB stars. The DPR for carbonaceous and silicate dust are $4.5 \times 10^{-5} M_{\odot} \text{yr}^{-1}$ and $0.2 \times 10^{-5} M_{\odot} \text{yr}^{-1}$, respectively. Recent estimates based on the SN rates and the condensed dust mass per SN determined by observations yield values of $(0.7 - 400) \times 10^{-5}$ for the LMC and $(0.1 - 110) \times 10^{-5} M_{\odot} \text{yr}^{-1}$ for the SMC [6, 51]. Large uncertainties in these estimates are caused by existing controversies in the dust masses derived from observations varying from $10^{-4} M_{\odot}$ to $0.5 M_{\odot}$ [50].

3.2 Dust input from AGB stars

Theoretical estimates of the net dust input from low- and intermediate-mass stars strongly depend on the adopted dust yields [83]. Mass- and metallicity-dependent dust yields for AGB stars are derived from the state-of-the-art numerical calculations combining extensive models for condensation of the multicomponent dust mixture in stellar winds with stellar evolution models, for the first time, performed by [18]. Stellar evolution prescription for the central star is essential for the amount and composition of the condensed dust as it determines the variations of the chemical surface composition during stellar evolution along the AGB and thus the chemistry of the wind. Recently, a number of new model calculations have been published in the literature, which differ mainly in the approaches to stellar evolution modelling (for details see [57, 76] and references therein). In the following we will discuss the stardust injection rates from AGB stars in the solar neighbourhood and their comparison with presolar grain studies, variations of stellar dust production in the Galactic disk, and the net dust input from stars in the Magellanic Clouds, from observational and theoretical perspective.

3.2.1 Solar neighbourhood

The rates at which AGB stars enrich the local ISM with new C- and O-rich dust estimated by several authors [17, 72, 82] are listed in Table 1. The main reason for the large differences between the values in Table 1 is [17, 72] assumed the almost complete condensation of refractory elements in AGB ejecta, while [82] employed the dust yields based on theoretical models [18] predicting incomplete condensation. According to the model calculations from [82], the dust input from AGB stars is dominated by carbon-rich dust, which is injected into the ISM at the rate of $1 M_{\odot} \text{kpc}^{-2} \text{Myr}^{-1}$. This is 2.5 times higher than the production rate for silicate dust [82].

Over the years, the efforts of the meteoritic science community on analysis of anomalous isotopic ratios in presolar dust grains has accumulated a wealth of data on the masses and metallicities of their parent stars. With the models of dust evolution combined with m - and Z -dependent yields one can determine the stellar population of AGB stars that contribute to the stardust inventory at the instant of the solar system formation. Comparison of the mass and metallicity distribution of parent AGB stars inferred by presolar grain studies with those predicted by the models provides a valuable test for the evolutionary dust models [25]. The authors find good agreement between the predictions from the dust model and the results from laboratory studies of the isotopic compositions of presolar SiC grains. The majority of these grains originates from AGB stars with masses from about 1.5 to 3–4 M_{\odot} and of roughly solar metallicity [25]. Only a small fraction of SiC grains are from stars with metallicity lower than about $0.5Z_{\odot}$. The predicted mass distribution of AGB stars that contributed O-rich dust is essentially bimodal, with similar contributions from stars in the ranges 1.3–2.5 and 4–8 M_{\odot} of about solar or slightly subsolar metallicities. The meteoritic data indicate that a large fraction of O-rich dust indeed comes from AGB stars with masses from about 1 to 2.5 M_{\odot} . However, presolar grains with isotopic anomalies of hot-bottom burning characterising massive AGB stars are completely missing from the presolar grain inventory [25]. This puzzling discrepancy remains to be understood.

3.2.2 Milky Way disk

Presence of the galactic radial metallicity gradient allows to investigate how the population of AGB stars and their dust production depend on metallicity. The radial distribution of evolved stars derived from IR data from IRAS and later from AKARI space missions has a flat profile for carbon-rich stars and exponential distribution for oxygen-rich stars [37, 73]. This is in a good agreement with the radial distributions of C- and O-rich dust from AGB stars predicted by the model of the life cycle of grains in the Milky Way [79].

The chemical composition of the stardust population from AGB stars residing in the ISM is significantly more C-rich compared to the interstellar dust. The radial profile of the current mass ratio of silicate to carbonaceous interstellar grains of AGB origin is shown as a function of the ISM metallicity in the disk in Fig. 5. For comparison, the silicate-to-carbon dust mass ratio in the solar neighbourhood is about 1.7. The dust mixture from AGB stars approaches this values only in the inner Galaxy at galactocentric disk radii $R < 4 \text{ kpc}$ and $Z \gtrsim 2Z_{\odot}$. In most of the Galaxy, dust population from AGB stars remain C-rich. The silicate-to-carbon ratio in stardust grains of AGB origin depends non-linearly on metallicity and its slope decreases with Z . A steeper slope at lower metallicities in the outer disk partly results from the strong non-linear metallicity dependence

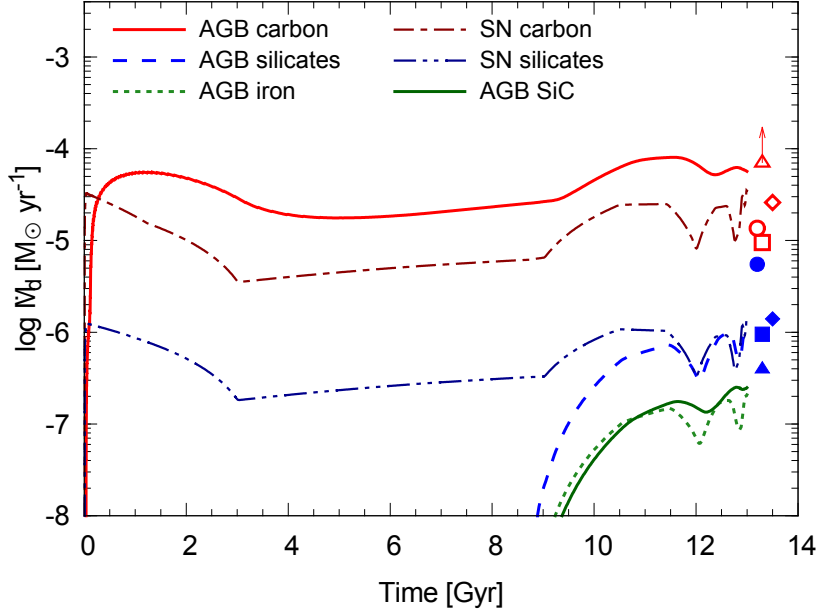


Figure 6: Time evolution of dust production rates by AGB stars for silicate, carbonaceous, SiC and iron dust and by type II SNe for silicates and carbonaceous dust in the LMC. Open and closed symbols show the current DPRs for carbon- and oxygen-rich dust, respectively, derived from IR observations ([49] - triangles, with an arrow marking an upper limit, [6] - squares, [62] - circles and [70] - diamonds). The data for the plot are taken from [83].

of dust condensation in stellar outflows. Additionally, the lifetimes of dust against destruction is longer in the outer disk permitting accumulation of grains from many generations of more metal-poor stars, which produce more carbon-rich dust.

3.2.3 Magellanic Clouds

Findings from the dust evolution models that stars contribute a minor fraction to the ISM dust reservoir in our galaxy cannot be checked directly with observations because of the large extinction in the galactic disk. The Magellanic Clouds are the first galaxies for which dust mass-loss rates have been measured from IR observations for the entire population of evolved stars. This became possible with the *Spitzer* Legacy Programs “Surveying the Agents of Galaxy Evolution in the LMC” (SAGE-LMC) that catalogued over 8 million IR sources [53] and the SAGE-SMC program that catalogues over 2 million IR sources in the SMC [29]. The Clouds thus offer a chance to compare the synthesised present population of AGB stars, and the net production rates and composition of circumstellar dust with observations.

The SAGE survey quantifies the dust mass-loss rates by detecting excess emission at 8 and 24 μm . Several methods and source classifications have been used to measure individual dust production rates (DPR) by evolved stars from SAGE-LMC data [49, 6, 62, 70]. Their results for carbon-rich and oxygen-rich AGB stars in the Magellanic Clouds together with theoretical predictions [83] are summarised in Table 2. One way to measure the dust mass-loss rates from AGB stars is by means of empirical relations between dust-mass loss rate and excess dust emission

Table 2: Global production rates of C-rich and O-rich dust from AGB stars and type II SNe in the Magellanic Clouds in units $M_{\odot} \text{yr}^{-1}$ derived by the dust evolution model in the LMC [83] and IR observations within SAGE-LMC and SAGE-SMC programs [70, 49, 6, 62, 51].

Type of dust, source	LMC <i>model</i>	LMC <i>observations</i>	SMC <i>observations</i>
AGB stars, C-rich dust	5.7×10^{-5}	$(0.95 - 4.3) \times 10^{-5}$	$(0.8 - 4) \times 10^{-6}$
AGB stars, O-rich dust	1.3×10^{-6}	$(0.95^a - 5.5) \times 10^{-6}$	$(0.08 - 3) \times 10^{-6}$
Type II supernovae	4.7×10^{-5b}	$(0.7 - 400) \times 10^{-5c}$	$(0.1 - 110) \times 10^{-5c}$

^a For the lower limit, we added the dust production rates from anomalous and regular O-rich AGB stars from [6].

^b The value includes the carbon dust injection rate of $4.5 \times 10^{-5} M_{\odot} \text{yr}^{-1}$ and silicate dust mass of $2.0 \times 10^{-6} M_{\odot} \text{yr}^{-1}$ [83].

^c The DPR by SNe is computed assuming that a SN produces $10^{-3} - 0.5 M_{\odot}$ of dust [6, 51].

in the mid-IR [70, 49, 6]. The DPR for the evolved stellar population in the LMC derived from the IR excess is dominated by a small number of highly evolved stars undergoing heavy mass-loss (extreme sources). Extreme AGB stars produce dust at the rate of $0.9 - 2.4 \times 10^{-5} M_{\odot} \text{yr}^{-1}$, this is about ten times faster than the DPR by low- and moderately-obscured AGB stars [70, 6]. [49] adopted a different empirical relation between IR excess and mass-loss rate and an alternative source classification separating C-rich from O-rich stars, which led them to a higher DPR of $\gtrsim 4 \times 10^{-5} M_{\odot} \text{yr}^{-1}$ for carbon-stars and a lower limit of $4 \times 10^{-7} M_{\odot} \text{yr}^{-1}$ for oxygen-rich stars. A more elaborate method to estimate the DPR of an AGB star involves fitting its spectral energy distribution with a pre-computed grid of radiative transfer models of evolved stars. Such Grid of Red Supergiant and Asymptotic Giant Branch Models (GRAMS) designed for C- and O-rich stars was applied to fit the multi-band photometry of ~ 30000 AGB and RSG stars in the LMC and measure their individual DPRs and bolometric luminosities [62]. This work managed to discriminate between O- and C-rich extreme stars based on the chemistry type of the best fit GRAM model. They confirm that majority of extreme stars (97%) are C-rich and they dominate the dust input from evolved stars (75% of total DPR). The models of the AGB dust populations in the LMC indicate that extreme stars are likely AGB stars in the super-wind evolutionary phase.

Dust input from AGB stars during the LMC history has been recently investigated with a model of dust evolution and m - and Z -dependent dust yields [83]. The model dust mixture is dominated by carbonaceous grains ejected at the rate $0.2 - 1 \times 10^{-4} M_{\odot} \text{yr}^{-1}$ for the whole LMC evolution (Fig. 6). The production of silicate, iron and SiC dust is very inefficient until a burst of star formation commenced 4 Gyr ago, when it rapidly increased to its present level of $10^{-6} M_{\odot} \text{yr}^{-1}$. The silicate-to-carbon dust mass ratio in the stardust population from AGB stars in the LMC survived until the present day is also plotted for $Z_{\text{LMC}} = 0.008$ in Fig. 5. Despite the different star formation histories of the LMC and the Milky Way, the ratio in the LMC is only slightly higher than that at the Galactic radius with $Z = Z_{\text{LMC}}$. The injection rates for carbonaceous and silicate dust are commensurate with the values for C- and O-rich dust derived from the IR observations, within the scatter of various observational estimates (Fig. 6). Comparison of the parent stellar population of silicate and iron grains from AGB stars in the LMC and the local Milky Way reveals drastic differences stemming from the strong metallicity dependence. Most of silicate and iron grains originate

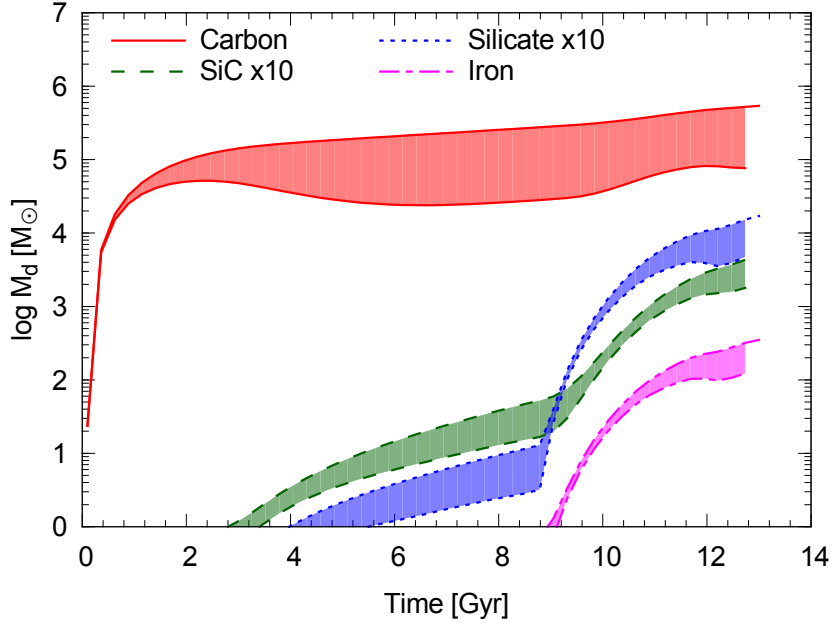


Figure 7: Time evolution of accumulated dust mass of dust species ejected by AGB stars over the LMC history. Lower and upper borders of shaded areas denote the calculations with and without destruction processes. The data for the plot are taken from [83].

from a small population of intermediate-mass stars consisting of only 4% of the total number of stars, whereas in the solar neighbourhood they originate from low-mass stars [83].

4. Can stellar sources reproduce the interstellar dust budget?

The models of the lifecycle of dust predict that AGB stars and type II SNe in the solar neighbourhood contribute only a minor fraction of roughly 3% to the interstellar dust budget [82]. Although the stardust fraction increases towards the outer disk, dust grown by accretion in the dense ISM dominates the interstellar dust population in the Milky Way [79]. While the value of stellar contribution may vary in different works (e.g., [79, 15, 16, 17]) depending on the adopted condensation efficiencies in stellar sources, they nevertheless agree that stardust grains constitute a minor fraction of the total dust mass in the Milky Way.

How does the contribution from stars change at subsolar metallicities? We can answer this question by comparing the dust mass accumulated over the LMC history predicted by the models, which have been verified with observations at the present time, and compare it with the existing dust mass in the ISM of $(1.1 - 2.5) \times 10^6 M_\odot$ as estimated from extinction and emission studies. Figure 7 shows time evolution of the total stardust masses for the main dust species from AGB stars in the LMC calculated for two limiting cases: with and without dust destruction in the ISM. The upper limit of the current dust mass from AGB stars of $5 \times 10^5 M_\odot$ is lower than the present interstellar dust mass. After 0.1 – 2 Gyr of evolution, the dust-to-gas ratio in the LMC is dominated by the ISM-grown dust, with AGB stars and SNe contributing about 10% (Fig. 3). This result confirms a large discrepancy between dust input from stars and the existing interstellar dust mass

in the LMC termed as “missing dust-mass problem” in [49]. Agreement between the models of the lifecycle of stardust grains in the LMC and observations on contribution of AGB stars to the dust mass budget implies that dust growth by accretion in the ISM, a major dust source in the solar neighbourhood, is also important at subsolar metallicities of the LMC [83].

The dust mass budget at the lower metallicity of the SMC has been studied observationally within the SAGE-SMC programs [6, 51]. AGB stars contribute only about 2% to the interstellar dust mass of $(0.29 - 1.1) \times 10^6 M_{\odot}$ in the SMC, estimated from IR and submillimeter imaging [6] and references therein). The star formation rate has increased by a factor of 4 during the last 12 Myr resulting in the higher relative SN rate in the SMC compared to the Milky Way and the LMC and, consequently, enhanced dust production by SNe. Considering upper and lower limits for SN dust production and destruction, [6] find that the interstellar dust can be accounted for solely by stellar sources if all SNe produce dust mass of at least $0.05 M_{\odot}$ and if most SNe explode in dense regions where much of the ISM dust is shielded from the shocks. This scenario is however not likely, since 20 – 25% of massive stars are ejected from their parent clusters and become runaway stars [59]. Travelling often at supersonic velocities, these stars end their life far away from their natal dense clouds and explode as isolated SNe in the warm or hot gas, which have much larger filling factors than molecular clouds. The question on whether destruction by the isolated SNe can balance dust input from type II SNe in the SMC can be answered in the future by dust evolution models. Generic models of dust evolution in late-type dwarf galaxies indicate that, despite the longer destruction timescales in gas-rich dwarf galaxies, the dust growth by accretion in the ISM does play an important role even in metal-poor galaxies [83]. The characteristic timescales on which this process becomes important in these galaxies are $\lesssim 1$ Gyr, which is longer than in the local Milky Way ($\lesssim 10^5$ yr), but significantly shorter than the age of old stellar populations in the SMC implying that the dust growth should be important in the SMC at present epoch.

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