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The relative role of AGB stars and SNe as the first cosmic dust polluters

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Abstract. Far infrared and sub-millimeter observations of quasars and normal star forming galaxies at $z > 6$ have revealed the presence of large amounts of dust. At such high redshifts, the inferred $10^7 - 10^9 M_\odot$ masses of dust must have formed in less than one billion years. Explaining this rapid chemical evolution is a challenge for both observations and theoretical models. Here we discuss the relative role of the two main stellar sources, AGB stars and SNe, in early dust enrichment, in light of new theoretical dust yields for AGB stars.

Key words. stars: AGB – supernovae: general

1. Introduction

Thermal emission associated to large amounts ($\geq 10^8 M_\odot$) of cool/warm dust has been revealed in a wide sample of $z \geq 5$ bright quasars hosted in sturburst ($\geq 100 M_\odot$/yr) galaxies (see Gallerani et al. 2017, for a review).

In addition, 10^7 up to few $10^8 M_\odot$ of dust explain the continuum emission observed in more common, star forming (few to few tens $M_\odot$/yr), galaxies back to redshift $z = 7.5$ (see Mancini et al. 2015, 2016, for data collection and references).

These observations unveil chemically evolved systems, signature of a rapid metals and dust pollution of the interstellar medium (ISM) in galaxies at early cosmic epochs. Here we discuss the role of the main stellar dust sources, i.e. asymptotic giant branch (AGB) stars and supernovae (SNe) in this rapid enrichment.

2. Stellar dust sources

Dust production in core-collapse SNe ejecta is often advocated to explain the origin of dust in the early Universe (e.g. Morgan & Edmunds 2003), because of the short progenitor stars, $(10 - 40)M_\odot$, lifetime, $\tau_* < 10$ Myr (Padovani & Matteucci 1993), with respect to intermediate-mass stars, $(1 - 9)M_\odot$. However, observations show that the effective SN dust yields are still highly uncertain, varying from SN to SN. In addition, extreme conditions for SN-dust formation/evolution (e.g. 100% dust condensation efficiency, no destruction due to the reverse or forward shocks) must be assumed to reproduce the observed $\sim 10^8 M_\odot$ (e.g. Dwek et al. 2007).

The (longer) stellar lifetime argument, does not necessarily implies that intermediate-mass stars did not contribute to dust production at early cosmic epochs. The contribution of AGB stars to high redshift dust production may be as important as that of SNe (Valiante et al. 2009).

The lifetime of $> 3M_\odot$ stars is < 300Myr (Padovani & Matteucci 1993) quite shorter than 1 Gyr (the age of the Universe $z \sim 6$). In addition, $(1-9)M_\odot$ stars are generally more numerous than $(10-40)M_\odot$ stars (see Fig. 1). Assuming a Larson IMF with $m_{\rm ch} = 0.35M_\odot$, $\sim 17\%$ ($\sim 40\%$ for a Chabrier IMF) of the stars will evolve through the AGB phase, while only $\sim 0.8\%$ ($\sim 14\%$) will end their lives as core-collapse SNe. Even assuming a top-heavy IMF (e.g. with $m_{\rm ch} = 10M_\odot$) the fraction of AGB (SNe) stars is $\sim 50(40)\%$[1].

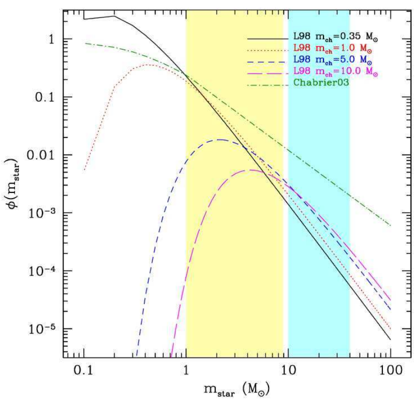

Fig. 1. Initial mass function from Chabrier (2003, dot-dashed) and Larson (1998) with $m_{\rm ch} = 0.35M_\odot$ (solid), $1M_\odot$ (dotted) $5M_\odot$ (dashed) and $10M_\odot$ (long-dashed). The yellow and cyan regions depict the AGB and core-collapse SNe progenitor mass ranges, respectively.

3. The cosmic dust yield: AGB vs SNe

The relative contribution of AGB stars to the total dust budget, depends on the galaxy star formation history (SFH) and IMF, but also on mass- and metallicity- dependent stellar dust yields, more than on cosmic time (see e.g. Valiante et al. 2009, 2011). Therefore, the adopted SN and AGB stars yields (i.e. the mass of metals and dust produced by a star) play a crucial role in determining the relative contribution of the two main stellar dust sources. In the next section we discuss how this contribution depends on the adopted stellar yields.

3.1. The role of SN yields

To investigate the role of SN dust yields we vary the SN dust condensation efficiency δ_{SNII} while the AGB yields are fixed. Fig. 2 shows the total dust mass as a function of time for a single burst of star formation, by using a detailed chemical evolution model with dust (Gioannini et al. 2017).

We explore three δ_{SNII}, which reflect different dust destruction efficiencies of the reverse shock. The highest δ_{SNII} reproduces observations in historical SN remnants (highest solid curve), whereas the lowest case assumes that ~10% of dust survives (lowest curve), similar to what found by Bianchi & Schneider (2007). Along the curves, different colors represent the fraction of dust from AGB relative to total (AGB + SN). AGB-driven dust production is $> 50\%$ already at early times for both the lowest and medium value of δ_{SNII}. On the other hand, the highest δ_{SNII} leads to a larger contribution by SNe ($\sim 80\%$). In the same Figure, we also show the death rate of SN and AGB stars. The vertical solid line indicates the onset of the galactic wind which halts the star formation. After the wind, SNe are no longer formed and AGB stars are the only dust source.

We can conclude that AGB stars rapidly pollute the ISM with dust, although their relative contribution depends on the assumed dust

[1] All IMFs are normalized to the same mass spectrum $(0.1-100)M_\odot$.

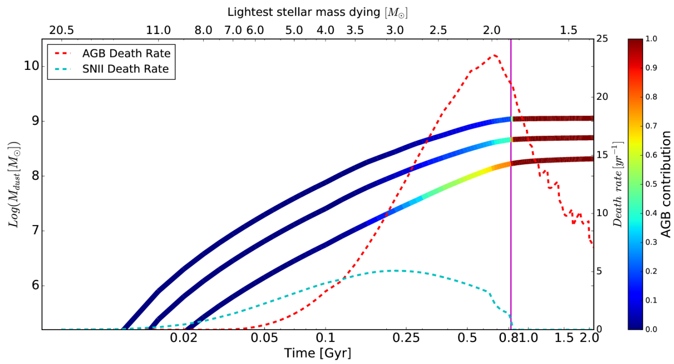

Fig. 2. Dust mass evolution during the initial phases of a starburst galaxy (solid lines) by varying δ_{SNII} from the highest value (upper curve) to the lowest one (lower curve). The colorbar indicates the contribution of AGB stars. Cyan and red dashed lines represent the death rate of AGB and Type II SNe, respectively. The vertical magenta line marks the onset of the galactic wind.

yields. We will investigate this issue in a future work, as new and complete grids of SN dust yields will be available soon (Marassi et al. in prep.).

3.2. The role of AGB yields

In this section, we investigate the role of AGB dust yields, fixing SN dust yields according to the Bianchi & Schneider (2007) model[2]. We first test the grids from the Heidelberg group models (e.g. Zhukovska et al. 2008, and references therein). In these models the AGB total dust yields (i.e. the sum of all the different dust species) show a little dependence on the stellar metallicity.

However, recently, new AGB yields have been computed by Ventura et al. (2012, 2014); Di Criscienzo et al. (2013); Dell'Agli et al. (2017), based on full evolutionary computations (ATON models), which instead show a clear trend with metallicity. The total dust mass, produced by $> 2\,M_{\odot}$ stars, increases with increasing metallicity (see e.g. Dell'Agli et al. 2017, for a detailed discussion). This implies that the relative role of AGB stars with respect to SNe will depend not only on the stellar mass (and thus on the IMF) but also strongly on metallicity, as shown in Fig. 3. For an instantaneous burst of star formation and a Larson IMF with $m_{\rm ch} = 0.35 M_{\odot}$, AGB stars contribute to $\sim 50\%$ of the total dust yield in ~ 300 Myr, independently of metallicity (upper panels), if the AGB yield grids from the Heidelberg group are adopted. According to the ATON models results, this fraction is reduced to less than 30% in low metallicity environments, with AGB stars becoming the dominant stellar dust factory after ~ 500 Myr from the onset of star formation when $Z > 0.2 Z_{\odot}$.

4. Conclusions

Observations of high-z QSOs and galaxies indicate that dust enrichment can be fast, providing masses as high as $(10^7 - 10^9)\,M_{\odot}$ in less than 1 Gyr.

The contribution of AGB stars as cosmic dust polluters depends on mass- and metallicity- dependent yields. In light of the new ATON AGB theoretical yields, the contribution of AGB stars can dominate the dust budget at $300 - 500$ Myr, when $Z > 0.2 Z_{\odot}$.

It is worth noting that, recent theoretical studies pointed out that stardust nucleation may be not efficient enough to account for the high-z dust masses. An additional contribution

[2] We consider the case in which $< 10\%$ of dust survives the passage of the reverse shock, providing results in broad agreement with observations (see Schneider et al. 2014).

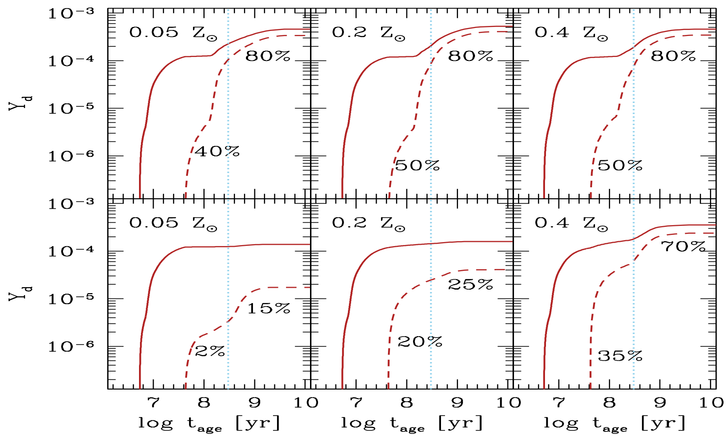

Fig. 3. The cosmic dust yield, i.e. the total dust mass produced by stars per unit stellar mass formed in a instantaneous burst of star formation. The panels are for $Z = 0.05, 0.2$ and $0.4 Z_{\odot}$ with a Larson IMF with $m_{\rm ch} = 0.35 M_{\odot}$). Curves show AGB+SNe (solid) and AGB only (dotted) dust yields. Percentages are the integrated AGB contribution at $t_{\rm age} < 300$ Myr (vertical line) and 10 Gyr. Upper and lower panels are for the Heidelberg group and ATON AGB models, respectively.

(e.g. grain growth in molecular clouds) is required, even in normal galaxies (e.g. Valiante et al. 2011; Pipino et al. 2011; Rowlands et al. 2014; Mancini et al. 2015, 2016).

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