Dust production 0.7–1.5 billion years after the Big Bang

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Cosmic dust is an important component of the Universe, and its origin, especially at high redshifts, is still unknown. I present a simple but powerful method of assessing whether dust observed in a given galaxy could in principle have been formed by asymptotic giant branch (AGB) stars or supernovae (SNe). Using this method I show that for most of the galaxies with detected dust emission between $z = 4$ and $z = 7.5$ (1.5–0.7 billion years after the Big Bang) AGB stars are not numerous and efficient enough to be responsible for the measured dust masses. Supernovae could account for most of the dust, but only if all of them had efficiencies close to the maximal theoretically allowed value. This suggests that a different mechanism is responsible for dust production at high redshifts, and the most likely possibility is the grain growth in the interstellar medium.

1 Introduction

Cosmic dust is an important component of the Universe, because dust can be found in almost every galaxy, and because half of the energy ever emitted by stars has been absorbed by dust, as shown by the cosmic optical and infrared background (e.g. Hauser & Dwek 2001; Dole et al. 2006). Dust is known to be present at all cosmic epochs, and has been detected at redshifts as high as $z \sim 7.5$ (Watson et al. 2015).

The outstanding question is how dust is formed, and there are three most accepted options, which may all contribute to dust production depending on a galaxy’s type and redshift. Dust is known to be produced in the atmospheres of asymptotic giant branch (AGB) stars (Meixner et al. 2006; Matsuura et al. 2009, 2013; Sloan et al. 2009; Srinivasan et al. 2009; Boyer et al. 2011, 2012; Riebel et al. 2012), and theoretical works showed that the AGB dust production depends on a star’s mass and metallicity, reaching the maximum value of $\sim 0.04 M_\odot$ of dust per star (Morgan & Edmunds, 2003; Ferrarotti & Gail, 2006; Ventura et al. 2012; Nanni et al. 2013, 2014; Schneider et al. 2014). On the other hand some supernovae (SNe) were observed to produce a significant amounts of dust ($\sim 1 M_\odot$; Dunne et al. 2003, 2009; Morgan et al. 2003; Gomez et al. 2009; Matsuura et al. 2011; Indebetouw et al. 2014; Gomez et al. 2012; Temim & Dwek 2013), consistently with theoretical models (Todini & Ferrara 2001; Nozawa et al. 2003). However, such ‘maximum’ SN dust production has been claimed to be rare (Gallagher et al. 2012; Temim et al. 2012). Finally, it is possible that stellar sources only form small amount of dust, and the bulk of the dust mass accumulation happens thorough grain growth in the interstellar medium (ISM; Draine & Salpeter, 1979; Dwek & Scalo, 1980; Draine, 1990, 2009).

In the Milky Way and local galaxies most of the stardust (dust formed directly by stellar sources) has been attributed to AGB stars (Gehrz, 1989; Zhukovska & Henning, 1997).
The same has also been claimed for some high-redshift quasars (Valiante et al., 2009, 2011), but this is more controversial. On the other hand, based on the comparison of the measured dust masses with estimated number of dust-producing stars, most other works lean towards SNe as the most efficient dust producers, but with a significant contribution of the grain growth in the ISM (Dwek et al., 2007; Dwek & Cherchneff, 2011; Dwek et al., 2011, 2014, 2015; Michałowski et al., 2010c,b, 2015; Gall et al., 2011; Hjorth et al., 2014; Rowlands et al., 2014; Zavala et al., 2013). Direct evidence of SN-synthesised dust is scarce, as this was obtained only for three objects, based on their flat extinction curves: $z \sim 6.2$ quasar (Maiolino et al. 2004; Gallerani et al. 2010; but see Hjorth et al. 2013) and two GRB host galaxies at $z \sim 6.3$ (Stratta et al. 2007; but see Zafar et al. 2010, 2011) and $z \sim 5$ (Perley et al. 2010).

In this paper I present the method I developed to address the issue of dust production, and review the results obtained for galaxies between $z = 4$ and $z = 7.5$ (1.5–0.7 billion years after the Big Bang).

## 2 Sample selection

I discuss here the results based on galaxies at $z > 4$ for which dust emission has been detected. This includes submillimetre-selected galaxies at $4 < z < 5$ (discussed in Michałowski et al., 2010b), quasars at $5 < z < 6.5$ (discussed in Michałowski et al., 2010b) and dust-detected galaxies at $z > 6.3$: Herschel selected galaxy at $z \sim 6.34$ (Riechers et al., 2013), a quasar at $z \sim 7.1$ (Mortlock et al., 2011; Venemans et al., 2012) and a Lyman break galaxy at $z \sim 7.5$ (Watson et al., 2015).

Moreover, in order to obtain information on upper limits of the dust yield per star (see also Hirashita et al., 2014), I also analysed galaxies at $6.3 < z < 7.5$ for which dust emission has not been detected (Hu et al., 2002; Kanekar et al., 2013; Bradley et al., 2012; Schaerer et al., 2015; Ouchi et al., 2009, 2013; Iye et al., 2006; Ota et al., 2014; Finkelstein et al., 2013).

## 3 Method

Dust masses for all galaxies were estimated with a spectral energy distribution (SED) modelling, either by a panchromatic treatment including all wavelengths, or by a grey-body fits, which usually required the dust temperature and emissivity index to be assumed.

Stellar masses of galaxies whose emission is dominated by star-formation were calculated from the SED modelling (the method described Michałowski et al., 2008, 2009, 2010a). The assumption of double-component star formation histories resulted in higher stellar masses (Michałowski et al., 2012, 2014), which led to more conservative results (more potential dust-producing stars).

For quasars optical/near-infrared emission contains no information about stellar populations, so stellar masses were obtained from dynamical ($M_{\text{dyn}}$) and gas ($M_{\text{gas}}$) masses measured from submillimetre lines (carbon monoxide or atomic carbon). Stellar masses were estimated as $M_{\text{star}} = M_{\text{dyn}} - M_{\text{gas}}$, or at least an upper limit could be set as $M_{\text{star}} < M_{\text{dyn}}$.

In a given galaxy the number of stars with masses between $M_0$ and $M_1$ in a stellar population with a range of masses between $M_{\text{min}}$ and $M_{\text{max}}$ can be calculated from
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stellar mass of this galaxy and the slope of the initial mass function (IMF; $\alpha$):

$$N(M_0 - M_1) = M_{\text{star}} \int_{M_0}^{M_1} M^{-\alpha} dM / \int_{M_{\text{min}}}^{M_{\text{max}}} M^{-\alpha} MdM,$$

(1)

where $(M_0, M_1) = (1, 8) M_\odot$ for AGB stars and $(8, 40) M_\odot$ for SNe, respectively. The lower limit for AGB stars may be adjusted to take into account only stars which had finished their main-sequence life at a given redshift (and had started producing dust), assuming that they were born shortly after the Big Bang. Hence, it was assumed to be $2.5 M_\odot$ at $4 < z < 6$, and $3 M_\odot$ at $z > 6$.

Finally, the average dust yield per star required to explain the observed dust masses is $M_{\text{dust}}/N(M_0-M_1)$. This dust yield can be expressed as $f \times (M_{\text{dust}}/M_{\text{star}})$, where $f = \int_{M_{\text{min}}}^{M_{\text{max}}} M^{-\alpha} MdM / \int_{M_0}^{M_1} M^{-\alpha} dM$. The compilation of the values of the factor $f$ for various types of stars and IMFs can be found in Table 2 of Michałowski (2015). The derived required dust yield can be compared with the theoretically allowed values to assess whether a given type of stars could be responsible for dust production in a given galaxy.

4 Results and Discussion

The analysis of submillimetre galaxies at $4 < z < 5$ (Michałowski et al., 2010c) resulted in the required yields per AGB star of $\sim 0.1 M_\odot$ (Fig. 1 of Michałowski et al., 2011). This is significantly above the theoretically allowed value, which rules out significant contribution of AGB stars to dust production in these objects. The required yields for SNe are $\sim 0.2$–$0.7 M_\odot$. Hence it is possible that SNe were responsible for dust production in these galaxies, but almost all SNe would need to be maximally efficient to account for the observed dust mass.

For $5 < z < 6.5$ quasars the constraints are even stronger. The required dust yields per AGB star are a few times $0.1 M_\odot$, and per SN are close to or exceeding $1 M_\odot$ (Fig. 1 of Michałowski et al., 2010b). We also demonstrated that even with the combined effort of AGB stars and SNe, it is difficult to explain the observed dust masses.

For the $z \sim 7.1$ quasar the situation is less conclusive as the required yields extend to values as low as $0.01 M_\odot$ per AGB star and $0.02 M_\odot$ per SN (Fig. 1 of Michałowski, 2015). This means that both populations might in principle be responsible for dust production. However, for star-forming galaxies at $z \sim 6.34$ and 7.5 the required yields per AGB stars are as high as $0.1$–$1 M_\odot$, and per SN above $1 M_\odot$. This implies that another mechanism must be responsible for dust production in these galaxies.

Grain growth in the ISM is the most likely alternative. This process is believed to be very fast with a timescale of a few tens of million years (Draine, 1990, 2009; Hirashita, 2000; Zhukovska et al., 2008), so it can be invoked even for galaxies observed a few hundred million years after the Big Bang.

5 Conclusions

I presented a method which is based on the comparison of the measured dust and stellar masses (the latter giving an estimate of the number of dust-producing stars) in order to assess the dust origin of high redshift galaxies. This was used to show that for most of the galaxies with detected dust emission between $z = 4$ and $z = 7.5$ (1.5–0.7 billion years after the Big Bang) AGB stars are not numerous and efficient.
enough to be responsible for the measured dust masses. Supernovae could account for most of the dust, but only if all of them had efficiencies close to the maximal theoretically allowed value. This suggests that a different mechanism is responsible for dust production at high redshifts, and the most likely possibility is the grain growth in the interstellar medium.

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