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Dust evolution in galaxies at $z > 7$

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Abstract. Recently huge amount of dust $M_{\rm dust} \simeq 10^{6-7}\,M_\odot$ in galaxies at $z = 7$–8 has been discovered by ALMA observations. The suggested timescale of the dust production was a few–several $\times\,10^8$ yr, while the stellar mass was several $\times\,10^9\,M_\odot$. This amount of dust cannot be easily explained only by a supply from supernovae if we consider the dust destruction by reverse shocks. We propose that these values can be consistently explained if we take into account the grain growth in the interstellar medium (ISM). This scenario successfully reproduces the evolution of the dust mass, as well as the SFR, and stellar mass simultaneously. We conclude that even at such an early epoch of the Universe, the dust grain growth in the ISM plays a significant role in galaxies.

Keywords. galaxies: evolution, galaxies: formation, dust, stars: formation

1. Introduction

Now the importance of dust in galaxy evolution is widely accepted. A large fraction of the star formation (SF) activity is significantly hidden by dust (up to $\geq 90\,\%$) during most of the history of the Universe (e.g., Takeuchi *et al.* 2005; Burgarella *et al.* 2013). Dust also plays an important role in the SF process itself, since it works as a catalyst of molecular formation which is needed to form stars in molecular clouds (e.g., Gould & Salpeter 1963). Then, a fundamental question arises: when dust started to form, and became important in the cosmic history? Recently, some authors discovered galaxies containing a huge dust mass at $z \sim 7$–8 (Watson *et al.* 2015; Laporte *et al.* 2017). The SFR of these galaxies was found to be only moderate ($\sim 10 - 20\,M_\odot{\rm yr}^{-1}$). This means that a galaxy of moderate SFR could already form such amount of dust at such an early epoch of the Universe. A natural explanation is desired if we develop a general theory of dust production in the early Universe. We propose a plausible explanation to solve this problem. We use $h = 0.7$, $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$ for the cosmological parameters throughout this article.

2. Asano Model

We have developed a theoretical framework of dust evolution in galaxies that is consistent with chemical evolution (Asano *et al.* 2013a,b, 2014; Nozawa *et al.* 2015: hereafter referred to as Asano model). Asano model takes into account the dust production in SNe and asymptotic giant branch (AGB) stars, grain destruction of dust by SN blast waves, grain growth in the ISM, and coagulation and shattering of grains. Among them, the dust supply from SNe and AGBs (stellar origin) and the grain growth play the central role to increase the net amount of dust. The strongly nonlinear behavior of dust mass is due to the onset of the grain growth Asano *et al.* (2013a,b). Asano *et al.* (2013a) discovered that the timing of the onset of grain growth is determined by metallicity, not the SF history. Asano model succeeded in reproducing the strong nonlinearity of the relation between metallicity and dust-to-gas mass ratio of local galaxies observed by *Herschel* (Rémy-Ruyer *et al.* 2014).

3. Results and Discussion

We calculated the dust amount based on Asano model using the Salpeter IMF with a mass range of $[0.1\,M_\odot–100\,M_\odot]$, and the SF timescale $\tau_{\rm SF} = 0.5$ Gyr and the initial gas mass $M_{\rm gas}(0) = 10^{10}\,M_\odot$. These values were not tuned to fit the data, but rather to demonstrate how naturally the data can be reproduced by the model. Other parameters are the same as those used in Asano *et al.* (2013b).

We first calculated the SFR and stellar mass evolution. We assumed a closed box and the Schmidt law with index $n = 1$. The SFR is approximately constant, and reproduces the observed SFR $\sim 20\,M_\odot\,{\rm yr}^{-1}$ in galaxies at $z \sim 8$. The stellar mass increases up to $\sim 10^8$ yr and converged to the initial gas mass because almost all the gas has turned into stars at this age of $\sim 10^8$ yr. If we use the cosmic age as a substitute of their ages, we obtain several $\times\,10^9\,M_\odot$. These model predictions are consistent with observations (Watson *et al.* 2015; Laporte *et al.* 2017).

Now we focus on the main subject of the observation, the dust mass of these galaxies. The most striking feature of the dust mass evolution is the sudden jump at around $\sim 3 \times 10^8$ yr. This is due to the onset of the dust grain growth in the ISM, turned on when the metallicity surpasses the critical metallicity $Z_{\rm cr}$ (Asano *et al.* 2013a,b). This feature was not recognized in previous works, where a linear relation was assumed (Guiderdoni *et al.* 1998). We stress that the relation between the metal and dust, and consequently that between the gas and dust is strongly nonlinear. This is in conflict with what very widely assumed and accepted. We also compare the prediction of Asano model for the dust-to-gas mass ratio (D/G ratio) with observations. Since the direct observation of the total gas mass is not available yet, as presented in Watson *et al.* (2015), we use the inversion of the Kennicutt–Schmidt (KS) law (e.g., Kennicutt & Evans 2012). Comparing the model predictions with observed values, we reach the conclusion that the grain growth in the ISM is indeed necessary to account for the huge amount of dust discovered in such a high redshift.

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