Dust masses of high-redshift galaxies from SED fitting and ALMA upper limits

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Dust production in the early Universe (at high $z$, where $z$ is the redshift) is the starting point of dust evolution. The early dust enrichment is considered to be dominated by dust condensation in supernovae (SNe). The dust mass in high-$z$ galaxies may reflect the efficiency of dust formation by SNe (or other sources). We aim at constraining the dust mass in high-$z$ (here, high $z$ means redshifts typically higher than 5) galaxies using the upper limits obtained by Atacama Large Millimetre/submillimetre Array (ALMA) in combination with the rest-frame UV–optical spectral energy distributions (SEDs). For SED fitting, because of degeneracy between dust extinction and stellar age, we focus on two extremes: continuous star formation (Model A) and instantaneous star formation (Model B). We apply these models to Himiko at $z = 6.6$ (as a representative UV-bright object) and a composite SED of Lyman break galaxies (LBGs). For Himiko, Model A requires a significant dust extinction, which leads to a dust temperature higher than $\sim 70$ K for consistency with the ALMA upper limit. This high dust temperature puts a strong upper limit on the total dust mass ($2 \times 10^6$ M$_\odot$), and the dust mass produced per SN, $m_d$, smaller than 0.1 M$_\odot$. Such a low $m_d$ suggests significant loss of dust by reverse shock destruction in SNe or outflow from the galaxy, and implies that SNe are not the dominant source of dust at high $z$. Model B allows dust mass $2 \times 10^7$ M$_\odot$ and $m_d \sim 0.3$ M$_\odot$. We could distinguish between Models A and B if we observe Himiko at wavelength shorter than 1.2 mm by ALMA. For the LBG sample, we obtain dust mass smaller than $2 \times 10^6$ M$_\odot$ for a typical LBG at $z > 5$, but this only puts an upper limit for $m_d$ as $\sim 2$ M$_\odot$. This weaker constraint for the LBGs than for Himiko is due to a much smaller number of SNe expected from their much lower UV luminosity. This clarifies the importance of observing UV-bright objects (like Himiko) to constrain the dust production by SNe.

We extend our analysis to a few high-$z$ LBGs in which dust emission has recently been detected by ALMA. We find that the dust temperatures are generally high ($\sim 40$–$50$ K), confirming that the high dust temperature derived above for Himiko is a common property for high-$z$ star-forming galaxies. We also discuss the similarity of the dust emission SED in those high-$z$ LBGs to that in nearby low-metallicity star-forming dwarf galaxies.