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 ~ 70 K for consistency with the ALMA upper limit. This high dust temperature puts a strong upper limit on the total dust mass (2×10^6 $M_\odot$), 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 2×10^7 $M_\odot$ and $m_\mathrm{d} \sim 0.3$ $M_\odot$. 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 2×10^6 $M_\odot$ for a typical LBG at $z > 5$, but this only puts an upper limit for m_d as ~ 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.