Challenges in Panchromatic Modelling with Next Generation Facilities
Proceedings IAU Symposium No. 341, 2018
M. Boquien, E. Lusso, C. Gruppioni & P. Tissera, eds.

doi:10.1017/S1743921319002096

Dust mass and dust production efficiencies on the redshift frontier

Hiroyuki Hirashita[1], Denis Burgarella[2] and Rychard J. Bouwens[3]

[1]Institute of Astronomy and Astrophysics, Academia Sinica, Astronomy-Mathematics Building, AS/NTU No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan
email: hirashita@asiaa.sinica.edu.tw

[2]Aix-Marseille Université, CNRS, LAM, UMR 7326, 13388 Marseille, France

[3]Leiden Observatory, Leiden University, NL-2300 RA Leiden, Netherlands

Abstract. In order to clarify the dust production in the early Universe, we constrain the dust mass in high-redshift ($z \gtrsim 5$) galaxies using the upper limits obtained by ALMA. We perform fitting to the rest-frame UV–far-infrared spectral energy distribution (SED) of a giant Lyα emitter, Himiko, at $z = 6.6$ and a composite SED of $z > 5$ Lyman break galaxies (LBGs). For Himiko, we obtain a high dust temperature > 70 K. This high dust temperature puts a strong upper limit on the total dust mass $M_{\rm d} \lesssim 2 \times 10^6$ M$_\odot$, and the dust mass produced per supernova (SN) $m_{\rm d,SN} \lesssim 0.1$ M$_\odot$. Such a low $m_{\rm d,SN}$ suggests significant loss of dust by reverse shock destruction or outflow. For the LBG sample, we only obtain an upper limit for $m_{\rm d,SN}$ as $\sim$2 M$_\odot$. This clarifies the importance of observing UV-bright objects (like Himiko) to constrain the dust production by SNe.

Keywords. dust, dust extinction, galaxy evolution, high redshift, ISM, far infrared

1. Introduction

Dust plays an important role in various aspects of galaxy evolution. In particular, dust absorbs and scatters stellar light and reemits it into far-infrared (FIR) wavelengths. Therefore, dust dramatically modifies the observed spectral energy distributions (SEDs) of galaxies (e.g., Takeuchi *et al.* 2005). Dust extinction could be estimated to match the SED at ultraviolet (UV) and optical wavelengths with a given stellar intrinsic SED. Because the stellar radiation energy absorbed by dust is emitted in the FIR, the total FIR emission constrains the total dust extinction as well. This energy balance between dust absorption and emission is the key to understand the effect of dust extinction on the SED shape ranging from UV to FIR.

Recently, it has become possible to investigate the dust production and evolution in high-z galaxies. The most sensitive dust search at high z is possible by the Atacama Large Millimeter/submillimeter Array (ALMA). The highest-z galaxies for which the dust emission is detected by ALMA are located at $z > 7$ (e.g., Watson *et al.* 2015). The high sensitivity of ALMA enables us to constrain the dust enrichment processes in those galaxies (Mancini *et al.* 2015; Wang *et al.* 2017). However, dust continuum has not been detected for most Lyman break galaxies (LBGs) at $z \gtrsim 6$ (e.g., Bouwens *et al.* 2016, hereafter B16).

Ouchi *et al.* (2013) observed a Lyα-emitting gas blob "Himiko" at $z = 6.6$ using ALMA. Hirashita *et al.* (2014) developed a method to constrain the dust mass formed per SN based on Ouchi *et al.* (2013)'s result. However, they treated the UV and FIR SEDs separately. As mentioned above, the SEDs in those two wavelength ranges are tightly

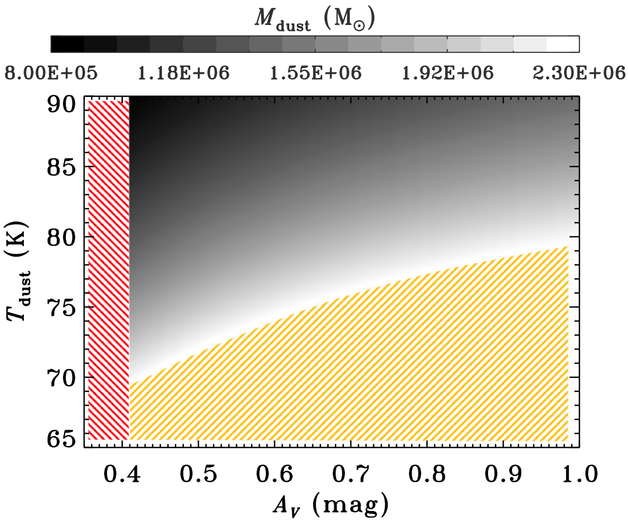

Figure 1. Dust mass derived from parameter set (A_V, T_d) for Himiko. The dust mass corresponding to (A_V, T_d) is shown by the gray scale, and the level of dust mass is shown in the bar on the top. The dust mass is only shown in the area where the SED fitting is successful. The yellow shaded area is the region where the mm flux exceeds the ALMA upper limit, while the red shaded area is the region where we do not obtain a satisfactory fit to the rest UV–optical data (i.e. reduced $\chi^2 \geqslant 3$).

related through dust absorption and reemission. It would be interesting to reexamine the above constraint on the SN dust production by treating those two wavelength ranges consistently with a single SED model.

2. SED fitting

We adopted Himiko at $z = 6.6$ to constrain the dust mass. We also composed a stacked SED using the 78 LBGs at $z \geqslant 5$ in B16. For the SED fitting, we use CIGALE (Noll *et al.* 2009; Boquien *et al.* 2019). The details of the method including the adopted parameters for the SED fitting are described in Hirashita *et al.* (2017). The varied parameters are the extinction in the V band (A_V), the dust temperature (T_d), the extinction of the old population relative to that of the young population (η) and the attenuation curve slope (δ). We minimize χ^2 to obtain the stellar mass (M_*). We only extract the solution which satisfies reduced $\chi^2 < 3$ and the ALMA upper limit. We adopt roughly a constant star formation history with a mean stellar age of 200 Myr. The fitting results below broadly hold as long as we have the present star formation activity. From the FIR dust emission, we obtain the total dust mass, M_d. The obtained dust mass depends on the assumed mass absorption coefficient; thus, we considered some variations in the dust species (unless otherwise states, we show the results for silicate).

First, we perform the SED fitting to Himiko with $\eta = 0$ and $\delta = -1.1$ (these parameters give the most conservative constraint for T_d). For a given set of parameters (A_V, T_d), we obtain the dust mass. In Fig. 1, we show the obtained dust mass at each point on the (A_V, T_d) plane by the gray scale. We only show the dust mass in the area of (A_V, T_d) where the fitting is satisfactory.

Next, we apply the same fitting procedure as above to the B16 LBG sample. Because the ALMA upper limit flux relative to the UV flux is higher than that of Himiko, the constraint on the parameters is weaker.

https://doi.org/10.1017/S1743921319002096 Published online by Cambridge University Press

3. Constraint on dust production

The most probable sources of dust at high redshift are SNe. The obtained dust mass above are used to derive the dust mass produced per SN. We constrain the dust mass formed in a single SN by using the upper limit of $M_{\rm d}$ obtained above. If we assume that all the dust originates from dust condensation in SN ejecta, we can estimate the dust mass ejected from a single SN, $m_{\rm d,SN}$ as

$$m_{\rm d,SN} = \frac{M_{\rm d}}{(1 - f_{\rm dest})N_{\rm SN}}, \tag{3.1}$$

where $f_{\rm dest}$ is the fraction of dust destroyed by SN shocks in the ISM, and $N_{\rm SN}$ is the total number of SNe. We estimate $N_{\rm SN}$ from the number of massive ($> 8\ {\rm M}_\odot$) stars obtained by the SED fitting, while we evaluate $f_{\rm dest} = 0.5$ based on a dust evolution model including shock destruction in the ISM (Hirashita *et al.* 2014).

For Himiko, we obtain a stringent upper limit of $M_{\rm d} < 2.1 \times 10^6\ {\rm M}_\odot$ (for silicate; 0.97–5 $\times 10^6\ {\rm M}_\odot$, depending on the dust species). Using $N_{\rm SN}$ obtained by the SED fitting, we obtain $m_{\rm d,SN} < 0.067\ {\rm M}_\odot$ (for silicate; 0.031–0.16 ${\rm M}_\odot$ depending on the dust species). For the LBG sample, we obtain $m_{\rm d,SN} < 2.3\ {\rm M}_\odot$. The upper limit of $m_{\rm d,SN}$ obtained for the LBGs is too large to put a useful constraint on the SN dust production theory. Thus, we concentrate on the upper limit obtained for Himiko.

4. Discussion

In the above, we suggested a high dust temperature for Himiko. Indeed, some studies have suggested that the dust temperatures in high-redshift star-forming galaxies are high (e.g., Ouchi *et al.* 1999). Our recent cosmological simulation results (Aoyama *et al.* 2019) also show that the dust temperatures become higher at higher redshifts. The high dust temperatures are most probably due to high interstellar radiation field: since galaxies become more dense and compact at higher redshift, the mean distance between dust and stars becomes shorter. Other theoretical estimates also show high dust temperatures at high redshift (Ferrara *et al.* 2017; Narayanan *et al.* 2018).

The upper limit for $m_{\rm d,SN}$ obtained for Himiko indicates either that reverse shock destruction in SNe is efficient because of high ambient medium density ($\gtrsim 10$ cm^{-3}) if we compare it with dust condensation calculations by Nozawa *et al.* (2007) (see also Bianchi & Schneider 2007). Alternatively, the dust may be lost by galactic winds, etc. This possibility is shown to occurs by Hou *et al.* (2017), based on a numerical simulation developed by Aoyama *et al.* (2017). They showed that dust can be transported into the circum-galactic space by SN feedback.

We assumed $\delta = -1.1$ for the steepness of the attenuation curve. This is as steep as the Small Magellanic Cloud extinction curve. However, as shown by Asano *et al.* (2014), the extinction curve is expected to be flat in the early phase of galaxy evolution when SNe are the dominant source of dust (see also Hou, Hirashita, & Michałowski 2016). If we adopt a flat attenuation curve, we need more dust extinction to explain the rest-frame UV SED, leading to a higher dust temperature. In this case, we expect that $m_{\rm d,SN}$ is even lower than that obtained above. Alternatively, we can consider a scenario in which SN dust production is not dominant any more, but dust growth in the ISM is already efficient. In this case, $m_{\rm d,SN}$ should be much smaller than the above, since only a limited fraction of dust originates from SNe. In summary, regardless of whether SNe are the dominant source of dust or not, the dust mass per SN is expected to be smaller than 0.1 ${\rm M}_\odot$, supporting efficient dust destruction within SNe through the so-called reverse-shock destruction.

5. Conclusion

We investigate the possibility of constraining the dust mass in high-redshift ($z > 5$) galaxies by applying SED fitting (CIGALE) to rest UV–optical photometric data and the ALMA upper limits. For Himiko, we obtain $T_{\rm d} > 70$ K and $M_{\rm d} < 2 \times 10^6$ $M_\odot$. Based on this value, the dust mass produced per SN is estimated as $\lesssim 0.1$ $M_\odot$. This low value indicates that dust once condensed is destroyed in the shocked region associated with the SN, or that dust is lost out of the main body of the galaxy.

Acknowledgement

HH is supported by the Ministry of Science and Technology grant, MOST 105-2112-M-001-027-MY3 and MOST 107-2923-M-001-003-MY3 (RFBR 18-52-52-006).

References

Aoyama, S., Hirashita, H., Lim, C.-F., Chang, Y.-Y., Wang, W.-H., Nagamine, K., Hou, K.-C., Shimizu, I., *et al.* 2019, *MNRAS*, in press (arXiv:1809.10416)
Aoyama, S., Hou, K.-C., Shimizu, I., Hirashita, H., Todoroki, K., Choi, J.-H., & Nagamine, K. 2017, *MNRAS*, 466, 105
Asano, R. S., Takeuchi, T. T., Hirashita, H., & Nozawa, T. 2014, *MNRAS*, 440, 134
Bianchi, R. & Schneider, R. 2007, *MNRAS*, 378, 973
Boquien, M., Burgarella, D., Roehlly, Y., Buat, V., Ciesla, L., Corre, D., Inoue, A. K., & Salas, H. 2019, *A&A*, 622, 603
Bouwens, R. J., Aravena, M., Decarli R. Walter, F., da Cunha, E., Labbé, I., Bauer, F. E., Bertoldi, F., *et al.* 2016, *ApJ*, 793, 115 (B16)
Ferrara, A., Hirashita, H., Ouchi, M., Fujimoto, S., *et al.* 2017, *MNRAS*, 471, 5018
Hirashita, H., Burgarella, D., & Bouwens, R.J. 2017, *MNRAS*, 472, 4587
Hirashita, H., Ferrara, A., Dayal, P., & Ouchi, M. 2014, *MNRAS*, 443, 1704
Hou, K.-C., Hirashita, H., & Michałowski, M. J. 2016, *PASJ*, 68, 94
Hou, K.-C., Hirashita, H., Nagamine, K., Aoyama, S., & Shimizu, I. 2017, *MNRAS*, 469, 870
Mancini, M., Schneider, R., Graziani, L., Valiante, R., Dayal, P., Maio, U., Ciardi, B., & Hunt, L. K. 2015, *MNRAS*, 451, L70
Narayanan, D., Davé, R., Johnson, B., Thompson, R., Conroy, C., & Geach, J. E. 2018, *MNRAS*, 474, 1718
Noll, S., Burgarella, D., Giovannoli, E., Buat, V., Marcillac, D., & Muñoz-Mateos, J. C. 2009, *A&A*, 507, 1793
Nozawa, T., Kozasa, T., Habe, A., Dwek, E., Umeda, H., Tominaga, N., Maeda, K., & Nomoto, K. 2007, *ApJ*, 666, 955
Ouchi, M., Ellis, R. Ono, Y., Nakanishi, K., Kohno, K., Momose, R., Kurono, Y., Ashby, M. L. N., *et al.* 2013, *ApJ*, 778, 102
Ouchi, M., Yamada, T., Kawai, H., & Ohta, K. 1999, *ApJ*, 517, L19
Takeuchi, T. T., Ishii, T. T., Nozawa T., Kozasa, T., & Hirashita, H. 2005, *MNRAS*, 362, 592
Wang, W.-C., Hirashita, H., & Hou, K.-C. 2017, *MNRAS*, 465, 3475
Watson, D., Christensen, L., Knudsen, K. K., Richard, J., Gallazzi, A., & Michałowski, M. J. 2015, *Nature*, 519, 327

Discussion

TOMO GOTO: Declining star formation histories might increase $M_{\rm dust}$?

HIROYUKI HIRASHITA: Declining star formation histories put a loose constraint on the dust mass, but as long as there is recent star formation activity as indicated by the strong Lyα emission, the resulting constraint on $M_{\rm dust}$ does not change much.

https://doi.org/10.1017/S1743921319002096 Published online by Cambridge University Press

Akio Inoue: The spectral energy distribution fit for Himiko shows the best solution with the SMC law. However the grain size distribution model shows that in the early phase, the grain size tends to be larger, suggesting a flatter extinction curve. Are these consistent?

Hiroyuki Hirashita: There is a tension between these two are separate results. The assumed steep extinction curve gives the most conservative constraint on the dust mass. This is why we assumed the SMC-like law in the spectral energy distribution fitting.

Ke-Jung Chen: How do you know the number of supernovas and the destruction fraction of the dust?

Hiroyuki Hirashita: We estimated the number of supernovae based on the spectral energy distribution fitting since the UV luminosity is proportional to the number of massive stars. The destruction fraction is derived from our dust evolution model separately.

Hiroshi Shibai: What happens if you do not assume uniformity?

Hiroyuki Hirashita: I expect only a little change in the obtained dust mass constraint because we still need significant extinction. However further tests would be useful for the geometry effect.