Uncovering Early Galaxy Evolution in the ALMA and JWST Era
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The Far-Infrared emission of the first (z ∼ 6) massive galaxies

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Abstract. The first massive galaxies (z ∼ 6) have (1) very high energy density due to their small diameters and extreme luminosities in young stars and (2) interstellar dust relatively deficient in carbon compared with silicates. Both of these attributes should raise their interstellar dust temperatures compared with lower redshift galaxies. Not only is this temperature trend observed, but the high-z spectral energy distributions (SEDs) are very broad due to very warm dust. As a result total infrared luminosities – and star formation rates – at the highest redshifts estimated by fitting blackbodies to submm- and mm-wave observations can be low by a factor of ∼2.

Keywords. galaxies: high-redshift – evolution – infrared: galaxies

1. Introduction

Theoretical models predict that the dust in high redshift galaxies ($z \gtrsim 5$) should be significantly warmer than that in galaxies at modest redshift ($z \lesssim 4$) (De Rossi *et al.* (2018); Ma *et al.* (2019)). The higher temperatures are predicted to result from the compact sizes (diameters of $1-2$ kpc) containing huge luminosities from young stars ($\sim 10^{13} L_\odot$), combined with the relatively silicate-rich composition of the dust with poor radiative efficiency at long far infrared wavelengths. We show that the available observations confirm these predictions. In addition, the broader SEDs (i.e., more radiation in the 10 - 40 μm range) at very high z can result in underestimates of the total infrared luminosities of these galaxies, by a factor of ∼2 if the estimates are based on fitting a modified blackbody ($\beta = 1.6$) to submm- and mm-wave measurements. Without taking correct account of the non-blackbody nature of the SEDs, the interpretation of the ALMA measurements will underestimate the star formation rates in these galaxies substantially.

2. Galaxy FIR SEDs at z = 3 and 6

Figure 1 shows the average far-infrared SED of luminous galaxies at $z \sim 3$ as represented by the best-fitting template (De Rossi *et al.* (2018)). The units are νf_ν, to indicate directly relative luminosity in logarithmic wavelength intervals. We have shown the average behavior of these galaxies as a fitted template because showing the full data (42 individual galaxies, multiple results from stacks that total several hundreds of galaxies) would be complex; see De Rossi *et al.* (2018) for these details. We have fitted this template with a modified blackbody with T = 34K and $\beta = 1.6$, reflecting common practice

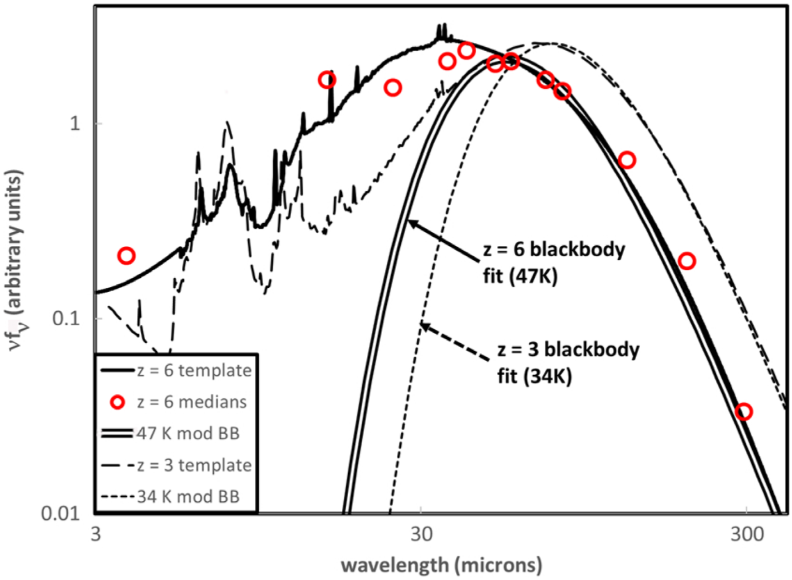

Figure 1. Average far infrared SEDs of galaxies at z ∼ 3 (dashed line) and z ∼ 6 (solid line). The open red circles are medians of the observations of galaxies with $5 \leqslant z < 7$; SEDs and medians from De Rossi *et al.* (2018). Modified blackbodies ($\beta = 1.6$) have been fitted to the parts of the SEDs accessible to ALMA, with a temperature of 34K for z = 3 and 47K for z = 6.

with submm- and mm-wave observations. Over the range of rest wavelengths probed at, e.g., 850μm observed (i.e., for $z < 4$, wavelengths $\geqslant 170$ μm), the correspondence is nearly perfect. However, at wavelengths < 50 μm, the emission from the galaxies substantially exceeds this fit and estimates of the total infrared luminosity based on the blackbody fit will be too small by a significant amount.

Figure 1 also includes (1) median relative flux densities vs. wavelength for galaxies at $5 \leqslant z < 7$; (2) the best-fitting template for these galaxies; and (3) a modified blackbody fit to the template. The medians include those in De Rossi *et al.* (2018) plus one that was missed (Strandet *et al.* (2017)), for a total of 19 (7 from the South Pole Telescope, 12 from other sources). The number of galaxies with useful measurements at rest $\lambda < 30\mu$m is small, hence the scatter, but nonetheless, the figure demonstrates that the template, based on the SED of the local galaxy Haro 11, is a reasonably good representation. The modified blackbody fit is at 47K, $\beta = 1.6$. Again, it is an excellent fit over the range of rest wavelengths accessible with ALMA at 850 μm ($\lambda \geqslant 40\mu$m), but only captures about half of the luminosity. The lower temperature blackbody that fits the data at $z \sim 3$ is clearly not a reasonable fit to the $z \sim 6$ points, and the equivalent temperature of the higher redshift galaxies would be pushed even higher with a metric that accounted for its broader SED caused by a larger contribution by very warm dust.

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