Sub-millimeter Flux as Probe for Molecular Mass in high-z Galaxies

Lichen Liang * **Robert Feldmann** * **and the FIRE team**

*Institute for Computational Science, University of Zurich

Measurements of molecular gas in galaxies provide essential constraints for galaxy evolution models. Recent long wavelength observations of the thermal dust continuum suggest that the Rayleigh-Jeans (RJ) tail can be used as a time-efficient quantitive probe of the dust and ISM mass in high-z galaxies. We use high-resolution cosmological simulations from the Feedback in Realistic Environment (FIRE) project [1] to analyze the dust emission of galaxies with a broad range of masses at the Cosmic Noon ($z \sim 2-3$). Our simulations (MassiveFIRE) explicitly include various forms of stellar feedback, and they reproduce the stellar masses and star formation rates of high-z galaxies in agreement with observations. Using radiative transfer (RT) modeling we show that broadband sub-millimeter (sub-mm) flux and molecular gas mass are tightly correlated and that the overall normalization and slope are in quantitative agreement with observations. Our result supports the empirical approach of using sub-mm flux as a proxy for molecular gas content in high-z galaxies. Additional analyses regarding the scatter of the relation and its extension to fainter sub-mm fluxes will be presented. Future observations with ALMA may probe these regimes and lead to improved physical models of gas inflow and dust growth in high redshift galaxies.

sub-millimeter | radiative transfer | high-z ISM

Molecular gas is a key component of the ISM affecting the physics of galaxy and star formation. Traditionally, CO line emission has been used to measure molecular gas masses. In recent years, there have been emerging effort to use RJ tail of dust thermal emission to probe the dust and ISM mass in high-z galaxies, as an alternative to the CO method. This approach is time-efficient and powerful for observations of high-z objects owing to the "negative K-correction" effect.

The dust continuum is typically optically thin at sub-mm and resembles a "modified blackbody" spectra. The flux density is expected to follow the scaling [2]

$$S_\nu \propto \kappa_\mathrm{D}(\nu) T_\mathrm{D} \nu^2 \frac{M_\mathrm{D}}{d_\mathrm{L}^2} \qquad [1]$$

where κ_D, T_D and d_L represent the opacity of dust grain, the mass-weighted temperature, and the luminosity distance from the source, respectively. M_D can thus be estimated by measuring the sub-mm flux density. And M_ISM can in turn be derived given an observationally-constrained gas-to-dust ratio. Scoville et al. (2016) carried out a calibration study using a compilation of low-z SF galaxies as well as $z \sim 2$ SMGs having both CO and sub-mm measurements. They find that the ratio of $L_{850\mu m}$ to the H_2 mass depends weakly on $L_{850\mu m}$ and shows only mild evolution with redshift.

We apply 3D RT modelling to a set of cosmological zoom-in galaxies extracted from the MassiveFIRE suite [3, 4] to reproduce the sub-mm flux of high-z galaxies and compare it with the data. The simulations explicitly include various forms of stellar feedback, resulting in galaxies in reasonable agreement with observations. And the high fidelity and resolution of the simulations allows us to resolve the complex gas and dust geometry in the ISM, on the scales of tens of parsecs.

We produce the full (continuum) SED from UV to sub-mm wavelengths using the RT code SKIRT[1] at the post-processing stage. Scattering, absorption and emission processes are included. We assume a constant dust-to-metal mass ratio in the ISM, and a fixed dust grain size function and PDR model. Our sample includes 2 SMGs and over 10 faint SMGs ($S_{850} = 0.1 \sim 1$ mJy) at $z = 2$. The brightest system has stellar mass $M_* \sim 5 \times 10^{11} M_\odot$ and a SFR $\sim 350\ M_\odot \mathrm{yr}^{-1}$.

Main findings:

(i) In general, the simulated data of the brightest $z = 2$ galaxies in our sample is in good agreement with observations of SMGs (see Fig.1). The scaling of $L_{850\mu m}/M_{\mathrm{H2}}$ to $L_{850\mu m}$ extends to fainter luminosity and shows only mild redshift evolution from $z = 4$ to $z = 2$. These regimes may be probed by future observations with ALMA.

(ii) The scatter of $L_{850\mu m}/M_{\mathrm{H2}}$ in our simulated galaxies, however, appears to be smaller than the observational data. We find that this scatter is largely driven by the variance of the dust-to-gas (H_2) ratio in the simulations, which can be impacted by the dust physics and chemistry in the ISM and feedback prescriptions.

(iii) The simulations reproduce the observed trend that dust temperature increases with IR luminosity and with redshift. On the other hand, the dust-to-H_2 ratio declines with redshift. This reflects that galaxies at higher redshift are more H_2-rich while their ISM is poorer in metals (dust). The evolution of T_D and dust-to-H_2 mass ratio largely offset each other, leading to only a weak evolution of the $L_{850\mu m}$ ratio across the redshift range of interest (see Fig.1).

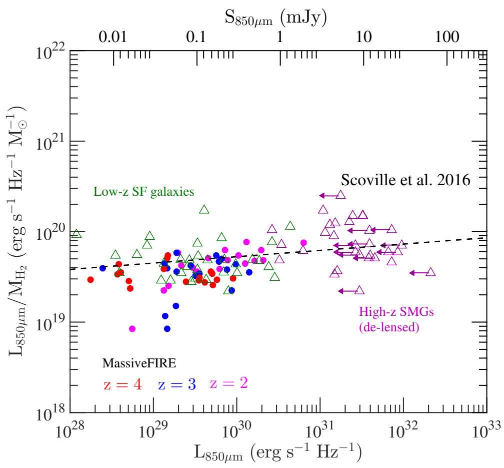

Fig. 1. $L_{850\mu m}/M_{\mathrm{H2}}$ vs. $L_{850\mu m}$. The observed data of low-z ULIRGs and star-forming galaxies are shown as green triangles while the $z = 2$ SMGs are shown as magenta triangles. The filled red, blue and magenta circles show the results of the simulated sample at $z = 4$, $z = 3$ and $z = 2$, respectively.

1. Hopkins P. F., Kereš D., Oorbe J., Faucher-Giguère C.-A., Quataert E., Murray N., Bullock J. S., 2014, MNRAS, 445, 581
2. Scoville N., et al., 2016, ApJ, 820, 83
3. Feldmann R., Hopkins P. F., Quataert E., Faucher-Giguère C.-A., Kereš D., 2016, MNRAS, 458, L14
4. Feldmann R., Quataert E., Hopkins P. F., Faucher-Giguère C.-A., Kereš D., 2017, MNRAS, 470, 1050

Reserved for Publication Footnotes