Molecular Gas, Dust, and Star Formation in Galaxies
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Evolution of ISM Contents of Massive Galaxies from z = 2 to 0.3

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Abstract. The mass of ISM in high redshift Galaxies is a major determinant of their morphology, star formation activity and how they will evolve to low redshift. Measurement of the CO lines at z > 0.5 are time consuming, even with the sensitivity of ALMA, and the derived ISM masses are subject to uncertainty in the CO-to-H_2 conversion factor. Here I describe a much faster technique—measuring the long wavelength Rayleigh-Jeans dust emission using the spectacular continuum sensitivity of ALMA. Using a metallicity-dependent gas-to-dust abundance ratio derived from studies of low-z galaxies, one then obtains the ISM mass. Initial results from our ALMA Cycle-0 observations are presented for a small sample of stellar-mass selected galaxies in COSMOS. This technique will enable measurement of 100's of galaxies at high-z with observations of typically ∼10 min per galaxy.

Keywords. ISM: dust — ISM: molecules — ISM: evolution

1. Long Wavelength Dust Continuum as a Mass Tracer

The FIR-submm emission from galaxies is dominated by dust reradiation of the luminosity from young stars and active galactic nuclei (AGN), absorbed at shorter wavelengths. The luminosity at the peak of the FIR is thus often used to estimate the luminosity of obscured star formation. Equally important (but not often stressed) is the fact that the long-wavelength, Rayleigh-Jeans (RJ) tail of dust emission is nearly always optically thin. This RJ emission thus **provides a direct probe of the dust (and hence ISM) masses** – provided the dust emissivity per unit mass and the dust-to-gas abundance ratio can be constrained. Fortunately, both of these are well established from theory (Draine and Li 2007) and from observations of nearby galaxies (e.g. Draine *et al.* 2007; Galametz *et al.* 2011).

On the optically thin, Rayleigh-Jeans tail of the IR emission, the observed flux density is given by :

$$F_{\nu} = \kappa_{\nu} T_{\rm dust} \nu^2 M_{\rm dust} (1+z)/(4\pi d_l^2) \tag{1.1}$$

where $T_{\rm dust}$ is the temperature of the emitting dust grains, κ_{ν} is the dust opacity per unit mass, $M_{\rm dust}$ is the total mass of dust and d_L is the source distance. In nearby, normal star-forming galaxies, the majority of the dust is at $\sim 20 \rightarrow 25$K, and even in the most vigorous starbursts like Arp 220 the FIR/submm emission is dominated by dust at temperatures $\leqslant 45$K. Thus the expected variations in $T_{\rm dust}$ have less than a factor 2 effect on the observed flux. The rest of the terms in Eq. 1 can be calibrated from submm observations of nearby galaxies. In selecting local galaxies on which to base this empirical approach, it is vital that both the submm fluxes and ISM masses are global values (or at least refer to the same areas in the galaxies). For nearby galaxies this can be a problem due to their large sizes. As a reliability check on the submm measurements we have required two long wavelength flux measurements which yield reasonable spectral indexes β (e.g. between 450 and 850μm). Our local galaxy sample includes SCUBA data for 12 galaxies

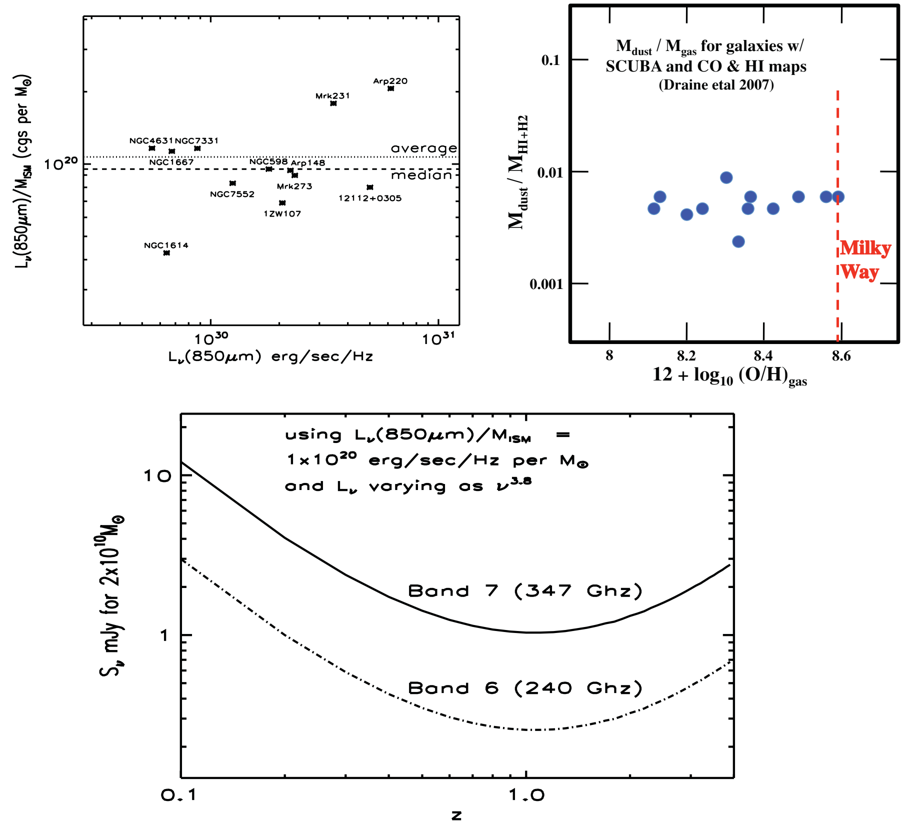

Figure 1. **Left upper panel** The ratio of L_ν at 850μm to M_{ISM} is shown for a sample of low z spiral and starburst galaxies from Dale *et al.* (2005) and Clements *et al.* (2010). The average and median values for the sample are shown by horizontal lines. **Right upper panel** shows dust-to-gas mass ratios derived by Draine *et al.* (2007) for galaxies from the SINGS nearby galaxy survey, selecting only those galaxies with both SCUBA 850 μm fluxes and complete maps of H_2 and HI gas. **Bottom panel** The expected Band 6 and Band 7 flux densities are shown for $M_{ISM} = 2 \times 10^{10} M_\odot$.

– 3 from the SINGS survey (Dale *et al.* 2005) and 9 from ULIRGs survey (Clements *et al.* 2010). The ULIRG sample is in fact probably most relevant since these galaxies are closer in IR luminosity to observed high redshift galaxies and very importantly, their emission is compact so we can be confident that the total 850μm flux and ISM masses encompass the same regions. The 850μm fluxes were converted to specific luminosity at 850μm ($L_{\nu(850)}$) and ratioed to the ISM masses (HI & H_2) (see Fig. 1-Left). Based on the data shown in Fig. 1-Left, we adopt a constant of proportionality between the 850μm specific luminosity and the ISM mass,

$$\alpha_{850} = \frac{L_{\nu_{850}}}{M_{ISM}} = 1 \times 10^{20} \text{ erg s}^{-1} \text{ Hz}^{-1} M_\odot{}^{-1}. \tag{1.2}$$

In order to predict the observed Band 7 fluxes for high redshift galaxies, it is necessary to know the spectral slope β (S_ν varying as ν^β) for the restframe RJ emission. Observed 450μm/850μm flux ratios on submm galaxies indicate β between 3 and 4. For most dust models the spectral index of the opacity is typically 1.5 to 2, implying β = 3.5 to 4 (adding in the index +2 for the RJ tail). Empirical fits to the observed long wavelength

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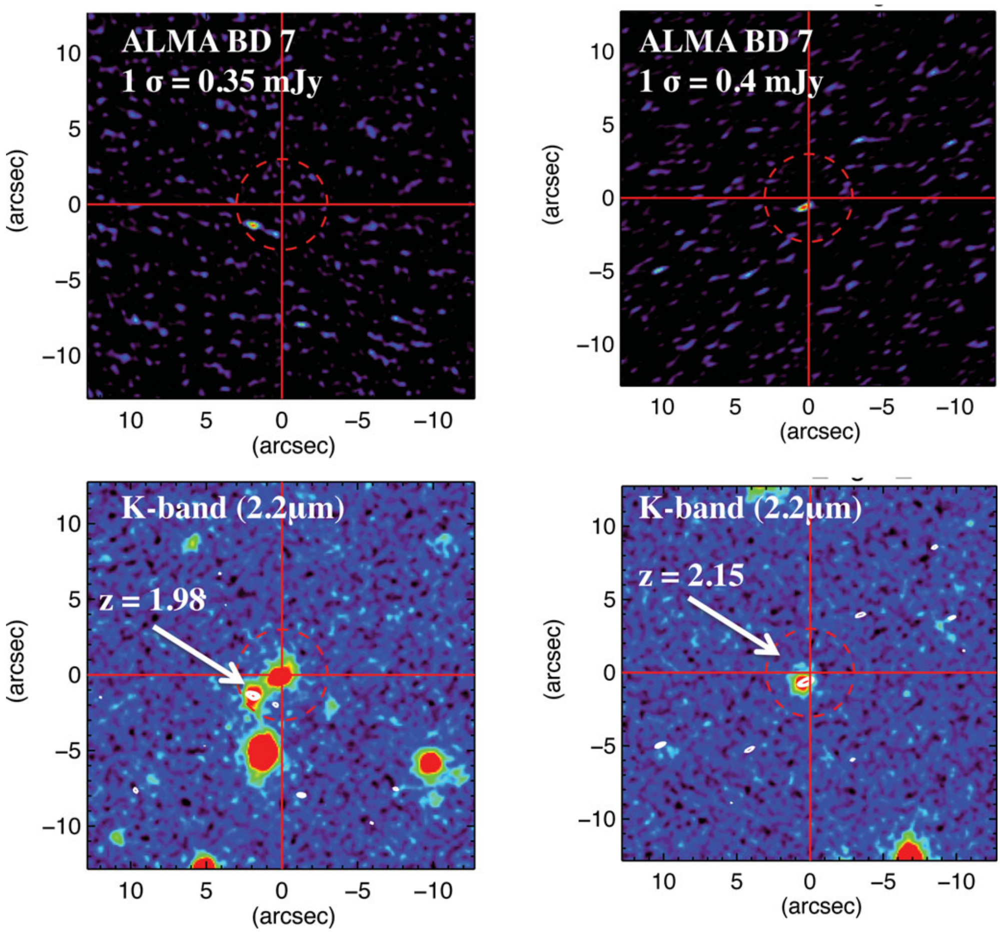

Figure 2. Postage stamps of the ALMA Band 7 continuum detections and 2.2μm images for two z = 2 galaxies detected in our Cycle0 COSMOS dust continuum project. The measured fluxes are 1.6 - 4.3 mJy.

SEDs give 3.5 to 4 (Clements *et al.* 2010) for local galaxies. For high z submm galaxies, the spectral index can be between 3.2 and 3.8 but in some cases the shorter wavelength point is getting close to the IR peak in the rest frame and therefore not strictly on the RJ tail.

Normalizing to $M_{ISM} = 2 \times 10^{10} M_{\odot}$ and adopting $\beta = 3.8$,

$$S_{\nu_{obs}} = \alpha_{850} \frac{M_{ISM}}{2 \times 10^{10} M_{\odot}} (1+z)^{4.8} \frac{\nu_{obs}}{350}^{3.8} \frac{1}{4\pi d_L^2} \tag{1.3}$$

$$S_{\nu_{obs}}(mJy) = 1.67 \frac{M_{ISM}}{2 \times 10^{10} M_{\odot}} (1+z)^{4.8} \frac{\nu_{obs}}{350}^{3.8} \frac{1}{d_L^2(Gpc)} \tag{1.4}$$

Fig. 1-Right shows the predicted continuum fluxes as a function of redshift for both Band 7 (347GHz) and Band 6 (240 GHz). (Band 3 is not plotted in the figure since the expected flux density is 28 times below that of Band 6.) The expected fluxes on Fig. 1 for z = 2 are ~1.7 and 0.3 mJy respectively for 2×10^{10} $M_{\odot}$. ALMA with 7.5 GHz BW in each polarization and 10 min of integration yields σ = 0.068 mJy at 345 GHz and

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$\sigma = 0.045$ mJy at 240 Ghz. It is thus clear that Band 7 is favored since the expected flux ratio is ~5:1 whereas the sensitivity ratio is less than 2:1.

Detecting the fiducial ISM mass of $2 \times 10^{10} M_{\odot}$ (1.7 mJy in Band 7) at 5σ requires only ~1 min of integration at Cycle-1 sensitivity. One can compare this with the time required to measure the same mass using the CO line, e.g. redshifted CO (3-2) in the Band 3. Using line fluxes from Tacconi *et al.* (2010), the average line flux averaged over a single resolution element of 300 km/s would be 0.28 mJy and **detecting this same mass in CO at 5σ would require ~3 hr at ALMA Cycle-1 sensitivity.**

Lastly, I address the issue of variation in the dust-to-gas ratio and its dependence on metallicity. Seventeen of the nearby SINGS survey galaxies have good total submm flux measurements (see Draine *et al.* 2007), as well as good measurements of the total molecular (H_2) and atomic (HI) gas masses. In Fig. 2, the derived dust-to-gas (H_2 + HI) mass ratios from Draine *et al.* (2007) are shown for galaxies having 850μm total flux measurements, for a range of spiral type (Sa to Sd) and as a function of mean metallicity. Fig. 1 shows that over a range of ~0.5 dex down in metallicity from the Milky Way, there is little evidence of variation in the dust-to-gas mass ratios. Hence, the scaling between RJ tail flux and ISM mass should remain valid over this metallicity range. [At even lower metallicity, the SINGS galaxies do not have total SCUBA 850 μm fluxes and the submm fluxes must be estimated from an overall SED fit using shorter wavelength observations; for these lower metallicity galaxies, there is evidence for a decrease in the dust-to-gas ratio (see Draine *et al.* 2007).]

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