Uncertainties in the submm SEDs of high- and low-z galaxies

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The importance of dust

Small interstellar dust grains (0.01–0.1μm) – that sparsely populate the ISM and make up a tiny fraction of the mass budget – play a huge role in galaxy formation and evolution due to their 'downconversion' of UV-light to IR/submm wavelengths.
Dust in distant galaxies

Submillimeter-selected galaxies: in the past decade submm/mm surveys have found a population of distant, highly dust-enshrouded IR-luminous starburst galaxies

- Forced the community to consider dust as an important component in the puzzle of galaxy formation and evolution

QSOs and HzRGs: in some cases targeted submm/mm observations have demonstrated the presence of vast amounts of extended, cold dust in these AGN-dominated systems
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Challenges

1) Detailed modeling of the FIR/mm SEDs of galaxies is highly non-trivial!
   - radiative transfer
   - large-scale geometry
   - dust grain sizes, multiple components, compositions and shapes

2) Poor frequency sampling of the FIR/mm SED. Typically less than a handful of photometry points – complicating even a simple modeling of the dust properties

3) Lack of spatially resolved dust emission on <1kpc, only exist for nearby sources
The modified black body law

Typical approach: assume a uniform grain population, the emission is well-approximated by a (modified) black body law:

\[ S_d(\nu) = N(\sigma_d/D_d^2)Q(\nu)B(\nu, T_d) \]

\[ Q(\nu) = 1 - \exp \left[ -\left(\frac{\nu}{\nu_c}\right)^\beta \right] \]

Some physical motivation for adding a dust opacity and not simply consider optically thin model

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Further challenges: When fitting to only a few data-points there is significant correlation between $T_d$ and $\beta$. Figure 3. An illustration of some of the issues involved in describing the SEDs of dusty galaxies. On the left is a probability contour plot that shows the $0.5 \times 10^{-3}$ and $5 \times 10^{-5}$ probability contours for a fit to an SED model defined by the variable parameters $\beta$ and $T_d$ with a fixed value of $\alpha = -1.95$, taking into account four SED datapoints for the galaxy NGC 958 as shown in the right-hand panel (Dunne and Eales, 2001). Note that 1 Jy = $10^{-26}$ Wm$^{-2}$ Hz$^{-1}$. Note that there is a very significant degeneracy in the fitted parameters. Adding additional data points with small errors close to the peak of the SED at 200 $\mu$m reduces the extent of the probability contours by about 50%, but they remain elongated in the same direction. Note that $\beta > 2$ is not expected physically. On the right the data are compared with fitted single-temperature SEDs. The solid line is the best fit to the data. The dashed lines correspond to SEDs from the ends of the probability 'banana' shown in the left-hand panel. Note that without the 450-$\mu$m point, the thick dashed curve describes the best-fit SED, which is defined by a significantly greater dust temperature. This SED is similar to that of a typical luminous IR galaxy, whereas the best fitting model with all four data points is much more like the SED of the Milky Way. Note that the shift in the best-fit model on adding 450-$\mu$m data is generally less significant than in this case.

The observed flux density distribution of galaxies in the far-IR and submm wavebands, which are sensitive to galaxies at low, moderate and high redshifts (Blain et al., 1999b; Trentham et al., 1999; Barnard and Blain, 2002). Using the $\epsilon_\nu B_\nu$ functional form, values of $\beta \simeq 1.5$ and $T_d \simeq 40$ K are required to provide a good description of the data, rather similar to the values derived for temperatures of individual low-redshift luminous dust galaxies in Dunne et al. (2000) and Lisenfeld et al. (2000), and for both the small number of high-redshift submm-selected galaxies with known redshifts and mid-IR spectral constraints (Ivison et al., 1998a, 2000a) and typical high-redshift QSOs (for example Benford et al., 1999). These temperatures are significantly less than those determined for the most extreme high-redshift galaxies (Lewis et al., 1998), and significantly greater than the $T_d = 17$ K inferred from the maps of the Milky Way made using the all-sky survey from the FIRAS instrument on the Cosmic Background Explorer (COBE) satellite in the early 1990's (Reach et al., 1995). Note that there are examples of moderate-redshift $15$ $T_d - \beta$ degeneracy in SED fits.
**T<sub>d</sub> dependence on β**

Despite the degeneracy between T<sub>d</sub> and β in SED fits there is empirical evidence for a real physical inverse relation between the two parameters. This may be used as a guide in parameter space when fitting SEDs.

- Simple theoretical arguments favor a T<sub>d</sub>-β dependence:
  \[ T_d \propto \left( \frac{F}{\beta} \right)^{1/1+\beta} \]

- Laboratory experiments supports this

- Dependence could be due to a mix of dust populations. For example, β–1 have been found for grains covered in ice mantles formed in cold dust, whereas β–1 is more typical for small grains (which are more easily heated).

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**An empirical inverse T<sub>d</sub>-β relation** (Yang et al. 2006)

\[ T_d = \left( 9.86 \times 10^3 \right)^{1/[1.431 + \beta]} \]
IR-luminosities and dust masses

- Inferring the IR–luminosities and dust masses of galaxies is key to obtaining their starformation rates and evolutionary stage.

- Yet doing so means uncertainties in $T_0$ and $\beta$ translate into similar or bigger uncertainties on $L_\text{IR}$ and $M_d$.

$$L_\text{IR} = 4\pi D_L^2 \int \kappa_{\nu} \kappa_{\nu} \text{d}\nu$$
$$M_d = \frac{S_\nu D_L^2}{\kappa T_0 (T_0)}$$

$$\kappa_\nu = \frac{3Q_\nu}{4\alpha\rho}$$

Assumes spherical dust grains (a big if!)

- In general one should therefore be somewhat cautious about quoting dust masses of (high–z) galaxies with the utmost confidence, other than as a comparative measure to distinguish galaxies.
Increasing the redshift of a galaxy has the same effect on its measured submm colours as decreasing its dust temperature.

- Combine several submm-bands to derive $z$ and $T_d$ together.
- Strongest lever from 200–1000um.
- Large-format, multi-colour submm cameras (SCUBA-2, KIDS).
- Generous SED sampling combined with sophisticated phot-z techniques may ultimately provide unbiased redshift distribution.
Selection effects: cool vs. hot

- 850um-selected SMGs vs. optically faint, radio-selected galaxies (OFRGs - Chapman et al. 2006), not detected at 850um
- OFRGs a new population of hot ULIRGs at $z > 1$

- Submm observations of $z\sim1$–3 galaxies have a strong bias towards cool systems
- Our knowledge about the $z > 1$ ULIRG population is still incomplete
- Herschel, SCUBA-2 combined with deep radio observations will help remedy the situation
Obtaining robust FIR/submm SEDs is still extremely hard work – especially at high-$z$.

Better frequency sampling is needed on both sides of the dust peak.

As is spatially resolved observations in order to disentangle hot dust from cold dust.

This will result in much more accurate dust masses, IR luminosities, star formation rate etc, but is unlikely to shed much light on the microscopic properties of the dust (composition, shape etc).

Photometric redshifts based on submm colours as well as our ability to select high-$z$ dust-enshrouded galaxies an a Td-independent way is hampered by the the Td-$z$ degeneracy and the sensitivity limits on current submm cameras.

ALMA, Herschel, SCUBA-2 combined with up-coming radio facilities will drastically improve the situation.
Looking to the immediate future

SFR=10M_☉/yr

- cm: Star formation
- mm: (sub)mm
- Near-IR:

Local Example: The Antennae

- HST/WFPC2
- OVRO
- CSO/SHARC-2
- ISOCAM
- CO(2-1) Gas
- Warm dust
- Cold dust