Challenges in Panchromatic Modelling with Next Generation Facilities
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Systematic errors in dust mass fits: The role of dust opacity

Lapo Fanciullo[1], **Francisca Kemper**[1], **Sundar Srinivasan**[2], **Peter Scicluna**[1] **and James M. Simpson**[1]

[1]Academia Sinica Institute of Astronomy and Astrophysics,
11F of AS/NTU Astronomy-Mathematics Building, No.1, Sec. 4,
Roosevelt Rd, Taipei 10617, Taiwan, R.O.C.
email: lfanciullo@asiaa.sinica.edu.tw

[2]Instituto de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México,
Antigua Carretera a Pátzcuaro # 8701 Ex-Hda. San José de la Huerta,
Morelia, Michoacán. México. C.P.58089

Abstract. The estimation of interstellar dust masses is an important pursuit in our understanding of both local and early Universe – see e.g. the "dust budget crisis". One of the most used methods of estimating dust masses – dust emission fitting – requires an estimate of the dust opacity at far-infrared and submillimeter wavelengths, but in most models this quantity is based on extrapolation rather than on actual measurements. It is becoming more and more evident that the opacity in typical dust models differs from that of dust analogs measured in the lab, meaning that astronomical dust mass estimations may need to be revised. To estimate the systematic errors introduced by this mismatch, we calculated dust emission for a model where dust far-infrared opacity is the same as that measured in lab samples, then we fit the synthetic emission with a typical (modified blackbody) dust model. Our results show that, if interstellar dust is indeed similar to the lab dust analogs, most fits may overestimate dust masses by as much as an order of magnitude.

Keywords. methods: laboratory, methods: numerical, ISM: dust, infrared: ISM, submillimeter

1. Context and motivation

Interstellar dust is an important contributor to the spectral energy distribution (SED) of galaxies, which it dominates – through thermal emission – at far infrared (FIR) and submillimeter (submm) wavelengths. Determining interstellar dust masses provides important constraints on galactic and cosmic evolution, as exemplified by the "dust budget crisis": too much dust is observed at high redshift to have formed in the wind of evolved stars, which are the main contributors to dust in the local Universe; dust from supernovae or grain growth in the interstellar medium are usually invoked to solve the discrepancy (see Rowlands *et al.* (2014); Watson *et al.* (2015) and refs. therein). Similar issues are encountered in nearby galaxies, such as the Magellanic Clouds (e.g., Srinivasan *et al.* 2016).

One of the most common methods for estimating dust masses is to fit the dust FIR/submm SED – normally in the form of multi-wavelength photometry – with a modified blackbody (MBB) model (Casey 2012). For an optically thin, pointlike (unresolved) source, the SED follows

$$I_\nu(\lambda) \propto M_d\ \kappa(\lambda)\ B_\nu(T_d), \tag{1.1}$$

where M_d is the dust mass, T_d the temperature, and the opacity $\kappa(\lambda)$ is in units of $cm^2\ g^{-1}$. The opacity is usually approximated as a power law $\kappa(\lambda) = \kappa_0\ (\lambda/\lambda_0)^\beta$ with a value of β variable between 1.0 and 2.5, but often $\sim$1.5−2 (e.g., Clements *et al.* 2018). Eq. 1.1 is usually valid for $\lambda > 50$ μm in the rest frame.

As is evident from eq. 1.1, there is a degeneracy between the fit-derived dust mass and the opacity $\kappa(\lambda)$. Dust mass estimations therefore require the dust FIR/submm in input. Many dust models use lab measurements on dust analogs (carbon, silicates) for the optical properties in the ultraviolet to mid-infrared range, but due to the sparsity of lab measurements for $\lambda > 100$ μm, FIR/submm opacity has traditionally been extrapolated from the optical properties at shorter wavelength. As FIR/submm lab measurements become more widespread, however, it is becoming clear that the long-wavelength opacity of dust analogs is more complex than previously thought. More specifically (e.g., Coupeaud *et al.* 2011; Demyk *et al.* 2017a,b):

- $\kappa(\lambda)$ often cannot be expressed as a simple power law;
- The $\kappa(\lambda)$ measured in the lab are generally higher – even by an order of magnitude – than the ones in typical dust models;
- For amorphous materials, $\kappa(\lambda)$ also depends on temperature and tends to increase with higher T.

If the optical properties of interstellar dust are close to those measured in the lab, there could be systematic errors in the dust masses derived from MBB fits. To test for this possibility we build synthetic observations of dust emission and fit them with a typical MBB model, then control whether the fit recovers the true value of the model input parameters.

2. Methods

Our synthetic emission is calculated from eq. 1.1, using $\kappa(\lambda)$ values from lab measurements. We made a bibliographic search for lab-measured, temperature-dependent dust analog opacities in the FIR/submm. From Mennella *et al.* (1998); Coupeaud *et al.* (2011); Demyk *et al.* (2017a,b) we obtained the $\kappa(\lambda)$ for various types of amorphous carbon and amorphous silicates. The materials vary considerably in composition, grain structure and – for silicates – oxidation state of metals.

The final purpose of the project is to construct a dust model grid spanning a wide variety of dust compositions, temperature distributions and redshifts, to see how the fit results depend on these factors. In the present proceedings we limit ourselves to dust composed of 30% in mass amorphous carbon (material BE from Mennella *et al.* 1998) and 70% amorphous $Mg_{0.7}Fe_{0.3}SiO_3$ silicate (material E30R from Demyk *et al.* 2017b), close to the average composition for Milky Way dust (e.g. Compiègne *et al.* 2011). The grid spans six redshift values (0.00, 0.25, 0.50, 0.75, 1.00 and 1.50) and four dust temperatures (20, 30, 40 and 50 K). After creating the synthetic SEDs we convolved them with the SPIRE 250, 350 and 500 μm and the JCMT SCUBA2 850 μm filter profiles, to produce four-band photometry which we then fit with a MBB model.

The MBB fit used an opacity of the form κ_0 $(\lambda/\lambda_0)^\beta$ and left mass, temperature and β as free parameters. Following James *et al.* (2002) we used a value of $\kappa_0 = 0.7$ cm^2 g^{-1} at $\lambda_0 = 850$ μm. In the following, we call the fit-derived mass and temperature $M_{\rm fit}$ and $T_{\rm fit}$ respectively, to distinguish them from the values $M_{\rm d}$ and $T_{\rm d}$ used in the creation of the synthetic SED. The purpose of our analysis is to see whether $M_{\rm fit}$ ($T_{\rm fit}$) differs significantly from $M_{\rm d}$ ($T_{\rm d}$).

3. Fit results

The fit results are shown in Fig. 1. The best fit results are those for the temperature, $T_{\rm fit}$. The values of β show a large dispersion and are relatively low compared to the typical ISM values of $\sim$1.5−2, but they remain within the physically plausible range of

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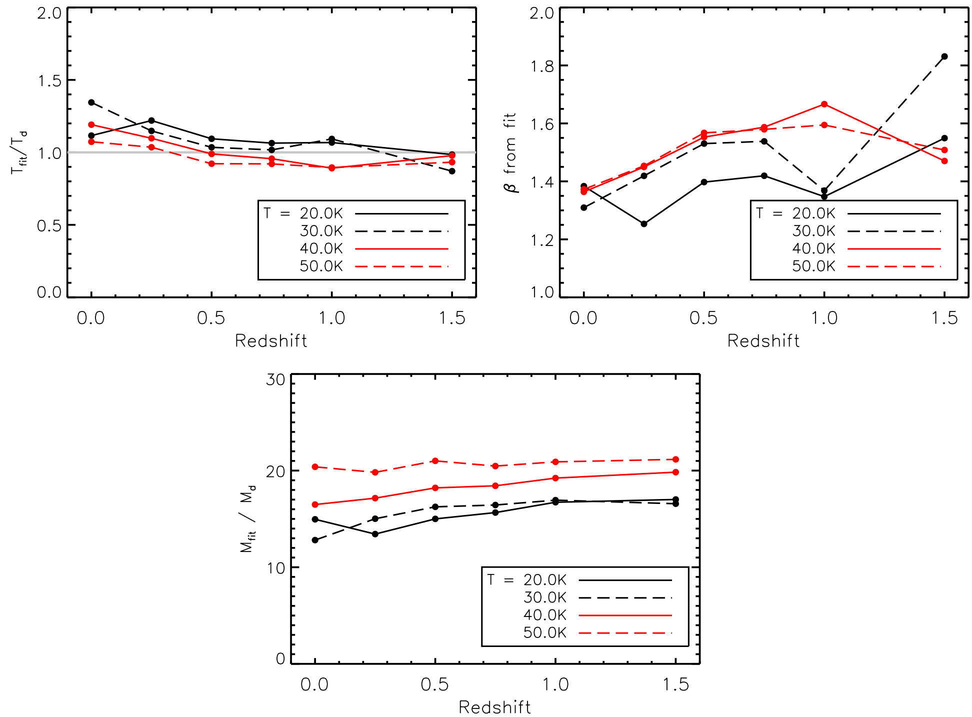

Figure 1. Parameter results from the MBB fit to synthetic photometry. Top left: T_{fit}/T_d, with a grey horizontal line showing $T_{fit}/T_d = 1$. Top right: β. Bottom: M_{fit}/M_d.

1.0−2.5. The values of M_{fit} are by far the most problematic, since they overestimate the dust mass by a factor ∼15−20. The large value of M_{fit}/M_d is due mainly to the higher opacity of laboratory materials compared to the κ_0 values used in dust models. The ratio M_{fit}/M_d also depends on temperature, but in the range explored (20 − 50 K) the effect is minor compared to the baseline M_{fit}/M_d value.

We hypothesized that the low β might be due to our using the Mennella *et al.* (1998) carbon, which has a very shallow dependence of opacity on wavelength. To test this hypothesis we repeated the photometry synthesis and fit with a "carbon poor" model using the same materials, but now containing only 20% carbon. The results, shown in fig. 2, support our hypothesis since the carbon poor model has a higher β, comparable to the values typical of the ISM. Since carbon has a higher opacity than silicates, decreasing its opacity also has the effect of reducing M_{fit}/M_d; nonetheless, M_{fit} remains one order of magnitude larger than M_d, so our previous remarks remain qualitatively valid.

4. Astrophysical implications

If the composition of interstellar dust is close to the materials studied in the lab the implications of the high M_{fit}/M_d ratio are far-reaching, and dust mass estimates from SED fits may have to be reduced by an order of magnitude. This result alone, if confirmed, would solve the dust budget crisis. Since this is a preliminary study, there are some issues to be addressed before this finding's full significance can be assessed.

In our dust models, we used the $\kappa(\lambda)$ from the lab as-is, but dust opacity is influenced by the size and structure of grains. Lab samples are often in the form of porous aggregates, which have a higher FIR/submm opacity than an equivalent mass of compact grains (see e.g. discussion in Demyk *et al.* 2017b); the $\kappa(\lambda)$ measured in the lab may therefore be

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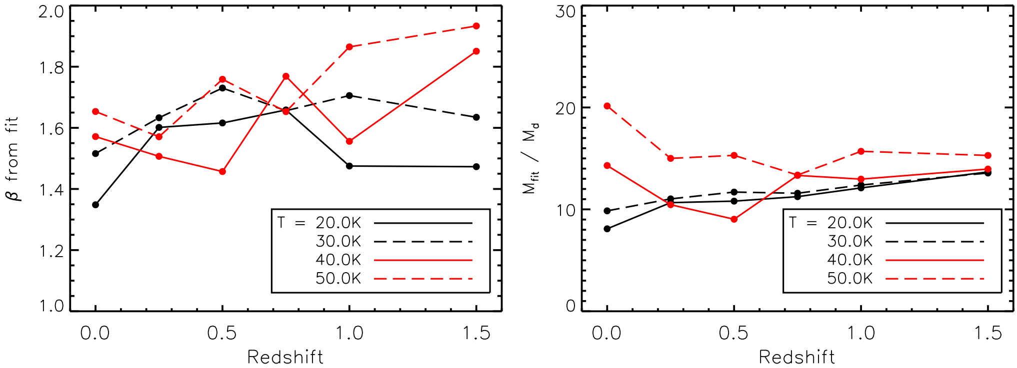

Figure 2. Fit results for the "carbon poor" model (see text). Left: β. Right: M_{fit}/M_d.

an overestimate. However, models show that aggregation tends to increase opacity by a factor $\sim$2 (Köhler *et al.* 2015; Demyk *et al.* 2017a,b), which falls short of explaining the difference between M_{fit} and M_d.

Another point to consider is that SED fitting is not the only dust mass tracer. Revised estimates of dust masses from FIR/submm fits will have to be checked for consistency against other tracers, such as elemental depletion in the gas phase (e.g., James *et al.* 2002).

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Discussion

Goto: Would adding shorter wavelengths ($\lambda < 250\,\mu$m) help because the wavelength dependence is different?

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Fanciullo: I plan to add shorter wavelengths in the future. However, I don't think it will make a large difference in my results. As you can see from my plots, we have a better fit at a high redshift (where the $\lambda = 250\,\mu$m band probes $\lambda \sim 100\,\mu$m in the rest frame) than at a low redshift. But while $T_{\rm fit}(z)$ and $B_{\rm fit}(z)$ show some dependence on z, $M_{\rm fit}(z)$ shows none (or a very weak one). This leads me to think that shorter-λ bands would give better constraints on T and β, but not M.

Galliano: You showed laboratory measured opacities of different materials, exhibiting a large scatter. But, how confident are you that these materials are actually those constituting interstellar grains? There could be a lower scatter in $\kappa(\lambda)$ if only a few of this candidate analogs were actually dominating the grain composition.

Fanciullo: We have indeed no guarantee that lab materials are the same as those constituting interstellar dust. However, no dust analog ever studied has shown FIR/submm opacity as low as those used in interstellar dust models. If we solve the mass fit problem by assuming that interstellar material are not the same as in the lab, we now have the issue of an unknown interstellar material with the same stoichiometry as silicates and carbon (as revealed by elemental depletions) but much lower (FIR/submm) opacity.