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Vindicating single-*T* modified blackbody fits to *Herschel* SEDs★ *(Research Note)*

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ABSTRACT

I show here that the bulk of the dust mass in a galaxy can be equivalently estimated from i) the full spectral energy distribution of dust emission, using the approach of Draine & Li (2007, ApJ, 657, 810) that includes a distribution of dust grains and a range of interstellar radiation field intensities; ii) the emission in the wavelength range 100 μm $\leq \lambda \leq$ 500 μm (covered by the *Herschel* Space Observatory), by fitting a simpler single-temperature modified blackbody to the data. Recent claims to the contrary should be interpreted as a caveat in the simpler fits to use an absorption cross section which is consistent both in the normalization and in the spectral index β with that of the full dust model. I also show that the dust mass does not depend significantly on the choice of β, if both the dust mass and the absorption cross section are derived with the same assumption on β.

Key words. dust, extinction – radiation mechanisms: thermal – infrared: ISM – infrared: galaxies – submillimeter: ISM – submillimeter: galaxies

1. Introduction

A full coverage of the spectral energy distribution (SED) of dust emission in galaxies has recently become available, thanks mainly to the *Spitzer* Space Telescope (Werner et al. 2004) and to the *Herschel* Space Observatory (Pilbratt et al. 2010). Dust emission models can now extract a wealth of information on the dust composition, grain sizes, and intensity of the dust heating sources from the infrared observations. One such model is that of Draine & Li (2007, hereafter, DL07), which has been successful in reproducing both the global (Draine et al. 2007; Dale et al. 2012, hereafter, D12) and the resolved SEDs (Aniano et al. 2012).

A general result of the modelling is that emission for $\lambda \geq$ 100 μm predominantly comes from dust heated at thermal equilibrium by a mean interstellar radiation field (ISRF) and that this dust component constitutes the bulk of the dust mass in a galaxy (≈98−99%; Draine et al. 2007, D12). If all dust grains share the same size and composition, this emission is equivalent to emission of a single-temperature modified blackbody (MBB), i.e. a blackbody multiplied by the dust absorption cross section. For a dust model including grains of different sizes and compositions, and thus different absorption cross sections, the SED could be broader than for an MBB, because different grains attain a range of thermal equilibrium temperatures. Thus, the mass obtained by fitting an MBB with an average absorption cross section to the observed SED could in principle be biased with respect to the one derived with the DL07 approach, using the full dust grain model. Nevertheless, when fitting *Herschel* data at $\lambda \geq$ 100 μm for a sample of Virgo Cluster galaxies from the HeViCS programme (Davies et al. 2012), Magrini et al. (2011) find that MBB dust masses are within ≈10% of DL07 masses, proving that the SED broadening due to the individual grain temperatures is minimal.

Using the same spectral range for the SEDs of galaxies in the *Herschel* KINGFISH sample (Kennicutt et al. 2011), D12 instead claim that the MBB approach can underestimate the dust mass by up to a factor two, because "single blackbody curves do not capture the full range of dust temperatures inherent to any galaxy".

Starting from the D12 dataset, in this note I derive the MBB dust masses independently. I confirm the results of Magrini et al. (2011) (Sect. 2). I also show that a meaningful derivation of the dust mass can be obtained only if the same spectral index is used both in the MBB fitting and in the derivation of the absorption cross section (Sect. 3). Conclusions are drawn in Sect. 4.

2. Dust masses from modified blackbody fits

D12 measured the flux densities of the KINGFISH galaxies observed by *Herschel* with the PACS instrument at 70, 100, and 160 μm (Poglitsch et al. 2010), and the SPIRE instrument at 250, 350, and 500 μm (Griffin et al. 2010). After complementing the *Herschel* observations with available infrared observations at shorter wavelengths, they derived various parameters characterizing the dust emission, including the dust mass, by using the DL07 approach. Here I use their photometry for the five *Herschel* bands with $\lambda \geq$ 100 μm, and derive the MBB dust mass for the objects detected in all five bands (56 objects out of 61). The distances of the galaxies are taken from Kennicutt et al. (2011).

Under the assumption that all dust grains share a single temperature T_d and that the dust distribution is optically thin, the mass of dust M_d can be estimated by fitting the observed flux densities f_ν to an MBB,

$$f_\nu = \frac{M_\mathrm{d}}{D^2}\, \kappa_\mathrm{abs}\, B_\nu(T_\mathrm{d}), \quad (1)$$

★ *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

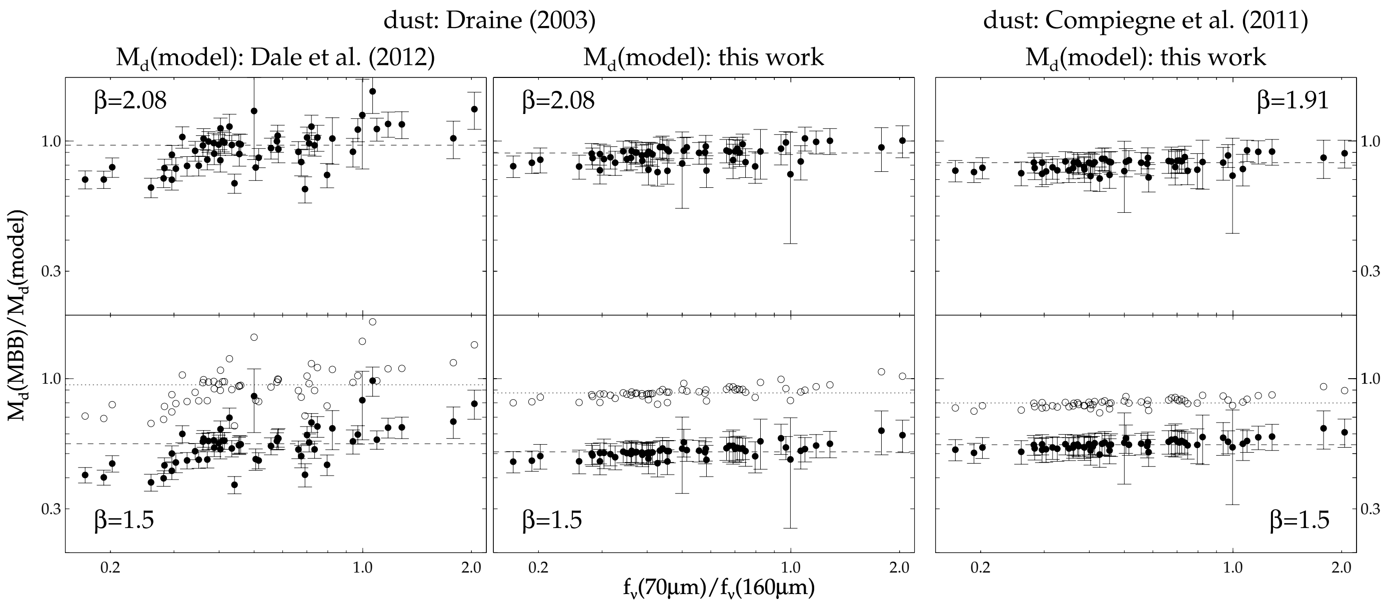

Fig. 1. Ratio between dust masses derived from MBB fits to the 100−500 μm SEDs of KINGFISH galaxies, M_d(MBB), and those obtained using a dust emission model, M_d(model). In the *left panels*, M_d(model) is obtained by D12 applying the DL07 method to the whole dust SED. In the *central panels*, M_d(model) comes from a simplified application of the DL07 approach to just the *Herschel* 100−500 μm SED; the same in the *right panels*, but using the dust properties from C11 (see text for details). In the *top panels*, M_d(MBB) is derived using a power-law fit to the dust absorption cross section from D03 (*left and center*) and from C11 (*right*). In the *bottom panels*, the spectral index is changed from the fitted value to $\beta = 1.5$. Dashed lines show the median value of the ratios. Open circles (and the dotted line) refer to the case for $\beta = 1.5$ after correcting the κ_{abs} normalization (see Sect. 3 for details).

where D is the distance of the object, $B_\nu(T_d)$ the Planck function, and κ_{abs} the grain absorption cross section per unit mass (a quantity sometimes referred to as *emissivity*). A power law was assumed for κ_{abs},

$$\kappa_{abs} = \kappa_{abs}(\lambda_0) \times \left(\frac{\lambda_0}{\lambda}\right)^\beta. \quad (2)$$

Fits were performed using the procedure of Magrini et al. (2011): since the flux densities of D12 are not colour-corrected, the MBB was integrated over the the PACS and SPIRE filter response functions before comparing it to the data. For SPIRE, the filter response functions for extended sources were selected. The MPFIT IDL χ^2 minimization routines were used (Markwardt 2009). Recently, concern has been raised about the use of standard χ^2 minimizations techniques when fitting MBBs to observed SED, with biases arising when both T_d and β are derived, resulting in a spurious T_d-β anticorrelation that might (or might not) conceal real grain properties (see e.g. Kelly et al. 2012). However, in this work I always keep β fixed and only derive M_d and T_d, in analogy to the other works I compare it with. Results from the fit were checked with a bootstrapping technique, by fitting one hundred random representations of each SED (each compatible with the original photometry, within its error). The mean and standard deviations for M_d and T_d obtained with the bootstrapping were almost the same as those obtained by fitting the observed SED with MPFIT. For the photometric errors provided by D12, the relative errors obtained by the fit on M_d and T_d are, on average, 8 and 2%, respectively.

Since the DL07 emission model used by D12 is based on Draine's (2003; hereafter, D03) model for Milky Way (MW) dust, an appropriate choice for κ_{abs} is the absorption cross section of the latter, averaged over the the grain size distribution and composition. The $R_V = 3.1$ MW dust model[1] absorption cross section for 70 μm < λ < 700 μm is well fitted by Eq. (2) with

$$\kappa_{abs}(250\,\mu m) = 4.0 \text{ cm}^2 \text{ g}^{-1}, \quad \beta = 2.08. \quad (3)$$

The ratio between the dust masses obtained with the two methods is shown in Fig. 1 (upper-left panel). As in the analogous Fig. 9 of D12, the ratio is plotted versus the 70 μm-to-160 μm flux density ratio. The dust mass obtained by fitting an MBB to the 100 μm ≤ λ ≤ 500 μm data is quite close to what is obtained with the DL07 model. The median ratio is 0.96 [2]. In a number of *Herschel* papers (see e.g. Magrini et al. 2011; Davies et al. 2012; Fritz et al. 2012; Smith et al. 2012)

$$\kappa_{abs}(350\,\mu m) = 1.92 \text{ cm}^2 \text{ g}^{-1}, \quad \beta = 2$$

was used, where the normalization at 350 μm comes from the the averaged absorption cross section of the MW D03 model. The median ratio obtained using these values is 0.95, almost the same as obtained using the fit of Eq. (3).

D12 claims that the dust masses derived with a $\beta = 2$ MBB fit are underestimated, on average, by 25% (though it appears that they have included the 70 μm flux density in the fits, which I do not use here). However, they adopted $\kappa_{abs}(250\ \mu m) = 4.8\,\text{cm}^2\,\text{g}^{-1}$, a value 20% higher than for the more recent

[1] The averaged absorption cross section for this model is available at http://www.astro.princeton.edu/~draine/dust/dustmix.html. Further updates to the model parameters (DL07; Aniano et al. 2012) did not change the mean dust absorption cross section substantially for the wavelength range considered here (Draine, priv. comm.).

[2] If the tabulated D03 averaged cross section is used, the ratio becomes 0.98. In addition to this, if the D12 masses are corrected for the fraction of dust that is heated by higher intensity radiation fields (as given by the γ parameter provided by D12) and does not contribute significantly to the emission at $\lambda \geq 100\,\mu$m, the median ratio rises to 1.0.

D03 model (i.e. they underestimated the MBB masses by 20%). If they had used a cross section consistent with the dust model used within their implementation of the DL07 method, their result would have been in line with what I find here.

The dispersion of the mass ratios is 0.18. As can be seen from Fig. 1, this is higher than the error on the ratio, whose mean is 0.12 (estimated using the error from the fits for individual MBB masses, and assuming the same errors for the DL07 masses, which were not provided). The large scatter is related to the intrinsic differences of the two methods. The masses from D12 were derived using additional fluxes, not just the five *Herschel* datapoints, with emission from dust heated by the mean ISRF constrained by shorter wavelength observations also. The dust absorption cross section also depends, though slightly for the *Herschel* wavelength range, on the fraction of the dust mass in the form of polycyclic aromatic hydrocarbons (PAHs), which is the parameter $q_{\rm PAH}$ that is a result of D12 fits.

Indeed if these differences are removed, the scatter is reduced. This was tested by deriving DL07 masses with the simplified approach of using the emission models[3] for dust heated by a single intensity of the ISRF alone (as defined by the U parameter in DL07, a scale factor with respect to the local Galactic ISRF from Mathis et al. 1983); and those computed for only the $R_{\rm V} = 3.1$ MW dust model (i.e. $q_{\rm PAH} = 4.68\%$; DL07). As in the full DL07 approach, emission templates for different intensites were convolved with the filter response functions, but only for the five *Herschel* datapoints considered for the MBB fits. SED fits were produced by minimizing χ^2 over the provided U grid and over $M_{\rm d}$, and errors on the two quantities were computed with the same bootstrapping technique used for MBBs. This confirmed that the errors on $M_{\rm d}$ are similar for both the MBB and DL07 approach, as assumed earlier in this section. The results of the fits are compatible with those of the full analysis in D12, though the Us found here are generally lower than their equivalent $U_{\rm min}$ (a distribution of Us is used in the full approach, the dust heated by $U_{\rm min}$ being responsible for most of the FIR peak). As a consequence, the DL07 masses derived here are higher, but only by ∼10%, the median ratio is lower, 0.9, and the scatter is reduced to 0.07, of the same order of magnitude as the error (Fig. 1, upper middle panel; the ratio is computed using the same MBB masses of top left-hand panel). This result is identical to the tests we did in Magrini et al. (2011).

The DL07 approach can be used with any dust grain model. As a further test, I use it here with the MW dust model by Compiègne et al. (2011, hereafter, C11), which basically differs from the D03 model in the use of optical properties for amorphous carbon. Using the DustEM code described in that paper[4], I have computed the emission for a grid of U values, and derived the dust masses as described in the previous paragraph. DustEM also provides the mean absorption cross section of the dust distribution, which can be fitted with Eq. (2) and

$$\kappa_{\rm abs}(250\,\mu{\rm m}) = 5.1\ {\rm cm}^2\ {\rm g}^{-1}, \quad \beta = 1.91. \tag{4}$$

As a result of the different $\kappa_{\rm abs}$, dust masses derived using the simplified, DL07 approach with the C11 model are a factor 0.73 the corresponding masses using D03. When MBB masses are computed using Eq. (4), the median ratio between MBB and DL07 masses for the C11 model is 0.82, with a scatter of 0.05 [5] (Fig. 1, upper right panel).

[3] The original DL07 models are available at http://www.astro.princeton.edu/~draine/dust/irem.html

[4] Available at http://www.ias.u-psud.fr/DUSTEM/

[5] It raises to 0.84 if the tabulated absorption cross section is used.

Thus, provided that an appropriate $\kappa_{\rm abs}$ is used, MBB fits can retrieve the dust mass within at most 20% of what more complex models including a distribution of dust grains (and temperatures) can. This difference is smaller than the current uncertainties in MW $\kappa_{\rm abs}$ models themselves. Finally, it is worth noting that for some objects, SEDs are well fitted by neither an MBB nor a DL07 model (D12).

3. MBB dust masses vs. β

D12 also made MBB fits allowing β to vary. For most of the objects, they find $\beta \approx 1.5$. The analysis of *Herschel* colours of galaxies does suggest that $1 \lesssim \beta \lesssim 2$ (see e.g Boselli et al. 2012; Auld et al. 2013). Keeping the same cross section normalization, D12 find that dust masses can be severely underestimated. Indeed, if I use the normalizations of Eqs. (3) and (4) together with $\beta = 1.5$ in Eq. (2), the median ratio between MBB and DL07 masses reduces to 0.55, 0.51, and 0.54 for the three comparisons in Fig. 1 (see the lower panels, filled symbols). This is due to the change in the fitted $T_{\rm d}$, whose median value rises from ≈20 K for $\beta = 2.08$ and 21 K for $\beta = 1.91$ to ≈24 for $\beta = 1.5$ (for a fixed normalization of $\kappa_{\rm abs}$, a smaller amount of hotter dust can reproduce the observed fluxes).

Despite it being common practice, it is however not justified to use $\kappa_{\rm abs}(\lambda_0)$ from a dust model (which has a proper spectral index, close to $\beta = 2$ for both models considered here) and then assume a different spectral index. This inconsistency leads to the puzzling result that the dust-mass estimate can vary with the wavelength chosen for the normalization: for the case of $\beta = 1.5$, adopting the model cross section at 500 μm results in dust masses that are 50% to 30% higher than those obtained with the 250 μm normalization of Eqs. (3) and (4), respectively. The difference comes simply from $(500/250)^{(\beta-1.5)}$, the fitted temperature being independent of the choice for the normalization. A similar remark is made by Skibba et al. (2011), who fitted KINGFISH SEDs from *Spitzer* and SPIRE using $\beta = 1.5$ and $\kappa_{\rm abs}(500\ \mu{\rm m})$ from D03. However, they inexplicably conclude that their normalization results in a mass that is a factor three higher than when $\kappa_{\rm abs}(250\ \mu{\rm m})$ is used. The temperatures from Skibba et al. (2011) are systematically higher than those obtained here for $\beta = 1.5$, and the dust masses, when corrected to the distances and normalization used here, are lower by a factor 2.7. A similar discrepancy is also noted by Galametz et al. (2012) and imputed to the use of 70 μm *Spitzer* data, which is contaminated by emission from stochastically heated grains.

For a proper mass estimate, one would need an absorption cross section derived consistently with the assumption made on β. This could come from a galaxy whose SED behaves as an MBB with the chosen β, provided the dust mass can be derived with sufficient accuracy independently of the SED itself (for example using the mass of metals as a proxy, as in James et al. 2002), or from a dust model for the MW grains in which the materials cross sections follow the chosen spectral behaviour (provided that those materials are able to consistently predict both the MW extinction curve and the FIR/submm emission).

As a numerical experiment, I show here what a different choice of β could imply in the derivation of the absorption cross section from the MW SED. C11 derived the FIR/submm surface brightness for the diffuse high Galactic latitude medium (DHGL, with latitude $|b| > 15°$) normalized to the hydrogen column density, $I_\nu/N_{\rm H}$. They provide *Herschel* surface brightnesses for the DHGL by convolving their COBE-FIRAS spectrum with the PACS (160 μm) and SPIRE (extended emission) filter response functions. They also provide the COBE-DIRBE 100 μm

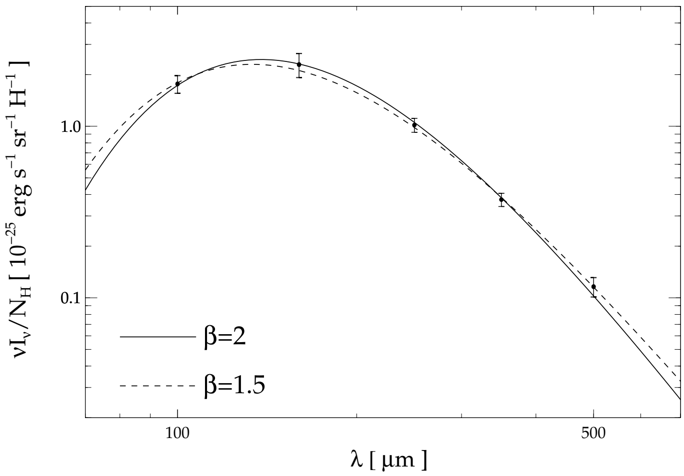

Fig. 2. MBB fits to the DHGL emission.

surface brightness, which I converted to PACS (100 μm) by multiplying it by 1.1 to take the different filter widths into account. This dataset is thus analogous to what I used in Sect. 2 to derive dust masses.

For a dust grain of temperature T_d^{MW} emitting as an MBB with a power-law absorption cross section (i.e. the same assumptions as in Sect. 2), the normalization of the cross section can be derived by fitting

$$\frac{I_\nu}{N_H} = \frac{\tau_{abs}}{N_H} B_\nu\left(T_d^{MW}\right), \tag{5}$$

where

$$\frac{\tau_{abs}}{N_H} = \kappa_{abs}\, m_H\, (D/G)_{MW} = \frac{\tau_{abs}(\lambda_0)}{N_H} \times \left(\frac{\lambda_0}{\lambda}\right)^\beta. \tag{6}$$

The absorption cross section per H atom, τ_{abs}/N_H, can be converted into the cross section per unit dust mass of Eq. (2) by dividing it for the hydrogen nucleon mass m_H and the MW dust-to-gas mass ratio $(D/G)_{MW}$.

Using $\beta = 1.91$, the DHGL emission can be fitted[6] with $T_d^{MW} = 17.8 \pm 0.4$ K. At 250 μm, the absorption cross section is found to be $\tau_{abs}(250\,\mu m)/N_H = 0.84 \pm 0.09 \times 10^{-25}$ cm^2 H^{-1}. Assuming $(D/G)_{MW} \approx 0.01$, as can be estimated from the elemental depletion patterns in the diffuse MW gas (Draine 2011), it is $\kappa_{abs}(250\,\mu m) \approx 5.0$ cm^2 g^{-1}, a value close to that from C11 in Eq. (4). This is not surprising, since the dust model was made to fit the DHGL data and has a similar dust-to-gas ratio, $(D/G)_{MW} = 0.0102$. For $\beta = 2$, $T_d^{MW} = 17.4 \pm 0.4$ K and $\tau_{abs}(250\,\mu m)/N_H = 0.91 \pm 0.10 \times 10^{-25}$ cm^2 H^{-1} (Fig. 2), a value close to the original determination of Boulanger et al. (1996) on the COBE-FIRAS spectrum (though C11 correct for the contribution of ionized gas to the hydrogen column density, while Boulanger et al. only consider atomic gas). When $\beta = 2.08$, as for the D03 model, $T_d^{MW} = 17.1 \pm 0.4$ K and $\tau_{abs}(250\,\mu m)/N_H = 0.98 \pm 0.11 \times 10^{-25}$ cm^2 H^{-1}, which converts to $\kappa_{abs}(250\,\mu m) \approx 5.9$ cm^2 g^{-1}, a value 45% higher than that in Eq. (3). D03's model could still be reconciled with the data, if the ionized gas contributes more to the total hydrogen column density than what is assumed by C11. To be consistent with the mass determinations so far, I continue to use the absorption cross sections from Eqs. (3) and (4) but scale them according to the ratios of τ_{abs}/N_H obtained from the DHGL with different βs.

Using $\beta = 1.5$, the temperature rises to $T_d^{MW} = 19.7 \pm 0.5$ K, and the cross section reduces to $\tau_{abs}(250\,\mu m)/N_H = 0.57 \pm 0.06 \times 10^{-25}$ cm^2 H^{-1}, a factor 0.58 and 0.68 those for $\beta = 2.08$ and 1.91, respectively. Obviously, the change in β has the same effect on both the dust mass and cross section determination, since Eqs. (1) and (5) are formally identical.

When the normalizations of Eqs. (3) and (4) are corrected by those factors, the dust masses obtained using $\beta = 1.5$ become very close to those obtained using β fitted to the dust models (see the open symbols in the lower panels of Fig. 1, with median mass ratios of 0.94, 0.88, and 0.8 for the three panels, from left to right). Thus, as already noted in Bianchi et al. (1999), the dust mass estimate does not change significantly with β if both the absorption cross section and the dust mass are derived with the same β. Substituting Eqs. (2), (5) and (6) in Eq. (1), one finds that the dust mass of a galaxy depends on β only through the ratio

$$M_d \sim \frac{B_\nu(T_d^{MW})}{B_\nu(T_d)}.$$

For the wavelength and temperature ranges considered here, this ratio does not change significantly if the temperatures are derived using $\beta = 1.5$ or $\beta \approx 2$.

4. Conclusions

I have shown that, if the DL07 model of dust emission in galaxies is correct, a simple single-temperature MBB fit to the SED for $\lambda \geq 100\,\mu$m can reliably provide one of the parameters of the more complex approach, i.e. the dust mass. For this, it is necessary to ensure the consistency in dust emission properties between the two approaches: the absorption cross section used in the MBB needs to be the average over the grain size distribution and composition of the dust model used in DL07. This consistency is broken when a cross section normalization at a given wavelength is taken from, e.g., the D03 and C11 grain models (which have been derived with $\beta \approx 2$, implicitly coming from the adopted material properties) and used in conjunction with $\beta \not\approx 2$ in the MBB fits.

The need for consistency is illustrated by a numerical experiment: using either $\beta \approx 2$ or 1.5 to derive the absorption cross section from the MW SED for $100\,\mu m \leq \lambda \leq 500\,\mu m$, and the same β to derive the dust mass from the SED of galaxies (both under the assumption of a single-temperature MBB) results in dust masses that are almost independent of β. This might be true only for this limited range, which is still able to provide a reliable fit of the MW SED. For βs outside this range, the normalization of the absorption cross section must come from other sources.

Finally, I remind the reader that I have only considered the SED for $\lambda \geq 100\,\mu$m. Single-temperature MBB fits to datasets including flux densities at shorter wavelengths (i.e. with a large contribution from non-equilibrium emission), as well as two-temperature MBB fits, might result in further biases in deriving the dust mass, in addition to those discussed here (Aniano et al. 2012, in prep.).

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[6] Though βs between 1.5 and 2.1 produce plausible fits in the limited spectral range considered in this work, it is worth noting that the analysis of the full MW dust SED yields $\beta \approx 1.8 \pm 0.2$ (Planck Collaboration 2011).

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