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) that includes a distribution of dust grains and a range of interstellar radiation field intensities; ii) the emission in the wavelength range $100\mu m \leq \lambda \leq 500\mu m$ (covered by the Herschel Space Observatory), by fitting to the data a simpler single temperature modified blackbody. Recent claims on the contrary (Dale et al. 2012) should be interpreted as a caveat to use in the simpler fits an absorption cross section which is consistent both in the normalization and in the spectral index $\beta$ with that of the full dust model. I also show that the dust mass does not depend significantly on the choice of $\beta$, if both the dust mass and the absorption cross section are derived with the same assumption on $\beta$.

Key words. dust, extinction - radiation mechanisms: thermal - infrared, submillimeter: ISM, 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 from the infrared observations a wealth of information on the dust composition, grain sizes and intensity of the dust heating sources. 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 $\lambda \geq 100\mu m$ 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 ($\approx 98-99\%$; Draine et al. 2007, D12). If all dust grains share the same size and composition, this emission is equivalent to that 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 that of a MBB, because different grains attain a range of thermal equilibrium temperatures. Thus, the mass obtained by fitting to the observed SED a MBB with an average absorption cross section could in principle be biased with respect to that derived with the DL07 approach, using the full dust grain model. Nevertheless Magrini et al. (2011), fitting Herschel data at $\lambda \geq 100\mu m$ for a sample of Virgo Cluster galaxies from the HeViCS programme (Davies et al. 2012), found that MBB dust masses are within $\approx 10\%$ 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 claimed 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 independently the MBB dust masses. 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$\mu m$ (Poglitsch et al. 2010), and the SPIRE instrument at 250, 350 and 500$\mu m$ (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 $\lambda \geq 100\mu m$, and derive the MBB dust mass for the objects detected in all five bands (56 objects out of 61). The distances of the galaxies is 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 $f_\nu$ to a MBB,

$$f_\nu = \frac{M_d}{D^2} \kappa_{abs} B_\nu(T_d),$$  

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

$$\kappa_{\text{abs}} = \kappa_{\text{abs}(0)} \times \left( \frac{\lambda}{\lambda_0} \right)^{\beta}.$$  \hspace{1cm} (2)

Fits were performed using the procedure of Magrini et al. (2011): since the flux densities of D12 are not color-corrected, the MBB was integrated over the PACS and SPIRE filter response functions before comparing it to the data; for SPIRE, the filter response functions for extended sources was selected. The MPFIT IDL $\chi^2$ minimization routines were used (Markwardt 2009). Recently, concern has been raised on the use of standard $\chi^2$ minimization techniques when fitting MBBs to observed SED, with biases arising when both $T_d$ and $\beta$ are derived, resulting in a spurious $T_d$-$\beta$ anticorrelation that might (or might not) conceal real grain properties (see e.g. Kelly et al. 2012). However, in this work I always keep $\beta$ fixed and only derive $M_d$ and $T_d$, in analogy to the other works I compare with. Results from the fit where 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 $\kappa_{\text{abs}}$ is the absorption cross section of the latter, averaged over the grain size distribution and composition. The $R_V = 3.1$ MW dust model\(^1\) absorption cross section for $70 \mu m < \lambda < 700 \mu m$ is well fitted by Eq. 2 with $\kappa_{\text{abs}}(250 \mu m) = 4.0 \text{ cm}^2 \text{ g}^{-1}$, $\beta = 2.08$.

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$\mu m$-to-160$\mu m$ flux density ratio. The dust mass obtained by fitting a MBB to the 100$\mu m \leq \lambda \leq 500\mu m$ data is quite close to that obtained with the DL07 model. The median ratio is 0.96\(^2\).

D12 claimed 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$\mu m$ flux density in the fits, which I don’t use here). However, they adopted $\kappa_{\text{abs}}(250 \mu m) = 4.8 \text{ cm}^2 \text{ g}^{-1}$, a value 20% higher than that of the more recent D03’s 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.

Fig. 1. Ratio between dust masses derived from MBB fits to the 100-500$\mu m$ 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$\mu m$ 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 $\kappa_{\text{abs}}$ normalization (see Sect. 3 for details).

\(^1\) 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 substantially the mean dust absorption cross section for the wavelength range considered here (Draine, private communication).

\(^2\) In a number of Herschel papers (see e.g. Magrini et al. 2011; Davies et al. 2012; Smith et al. 2012), it was used $\kappa_{\text{abs}}(350 \mu m) = 1.92 \text{ cm}^2 \text{ g}^{-1}$, $\beta = 2$, where the normalization at 350$\mu m$ is the value for the $R_V = 3.1$ Milky Way (MW) averaged dust absorption cross section from D03. The median ratio obtained using these values is 0.95, almost the same of that obtained using the fit of Eq. 3. When the exact, tabulated, averaged cross section from D03’s model is used, the ratio becomes 0.98. It is to be noted that I consider here the full dust mass obtained by D12. If, in addition to the use of the tabulated values, I correct for the fraction of dust that is heated by higher intensity radiation fields (as given by the $\gamma$ 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.
The dispersion of the mass ratios is 0.18. As it 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 depend, though slightly for the Herschel wavelength range, on the fraction of the dust mass in the form of polycyclic aromatic hydrocarbons (PAHs), the parameter \( q_{\text{PAH}} \) which is a result of D12 fits.

Indeed if these differences are removed, the scatter is reduced. This was tested deriving DL07 masses using a simplified approach: I have used the emission models\(^3\) for dust heated by a single intensity of the ISRF only (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 the \( R_{\text{eff}} = 3.1 \) MW dust model only (i.e. \( q_{\text{PAH}} = 4.68\% \); DL07). As in the full DL07 approach, emission templates for different intensities 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 \( \chi^2 \) over the provided \( U \) grid and over \( M_d \), and errors on the two quantities were computed with the same bootstrapping technique used for MBBs. This confirmed that the errors on \( M_d \) 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 \( U \) found here are generally lower than their equivalent \( U_{\text{min}} \) (a distribution of \( U \) is used in the full approach, the dust heated by \( U_{\text{min}} \) being responsible for most of the FIR peak).

As a consequence, the DL07 masses derived here are larger, but only by \( \sim 10\% \), the median ratio is smaller, 0.9, and the scatter is reduced to 0.07, of the same order of the error (Fig. 1, upper-middle panel; the ratio is computed using the same MBB masses of top-left 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 D03’s 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

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

As a results of the different \( \kappa_{\text{abs}} \), 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).

Thus, provided that an appropriate \( \kappa_{\text{abs}} \) 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 the \( \kappa_{\text{abs}} \) models themselves. Finally, it is worth noting that for some objects SEDs are well fitted by neither a MBB, nor a DL07 model (D12).

### 3. MBB dust masses vs \( \beta \)

D12 also made MBB fits allowing \( \beta \) to vary. For most of the objects, they find \( \beta = 1.5 \). The analysis of Herschel colors of galaxies does suggest that \( 1 \leq \beta \leq 2 \) (see e.g. Boselli et al. 2012; Auld et al. 2012). Keeping the same cross section normalization, D12 find that dust masses can be severely underestimated. Indeed, if I use the normalization of Eq. 3 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 comparison in Fig. 1 (see the lower panels, filled symbols). This is due to the change in the fitted \( T_d \), whose median value raises from \( \approx 20K \) for \( \beta = 2.08 \) and \( 21K \) for \( \beta = 1.91 \) to \( \approx 24 \) for \( \beta = 1.5 \) (for a fixed normalization of \( \kappa_{\text{abs}} \), a smaller amount of hotter dust can reproduce the observed fluxes).

Despite it being common practice, it is however not justified to use \( \kappa_{\text{abs}}(\lambda_0) \) 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\(\mu m \) results in dust masses that are 50% to 30% higher than those obtained with the 250\(\mu m \) normalization of Eq. 3 and 4, respectively. The difference simply comes from (500/250)\(^{\beta-1} \), the fitted temperature being independent of the choice for the normalization. A similar remark was made by Skibba et al. (2011), which fitted KINGFISH SEDs from Spitzer and SPIRE using \( \beta = 1.5 \) and \( \kappa_{\text{abs}}(500\mu m) \) from D03. However, they inexcusably concluded that their normalization results in a mass that is a factor 3 higher than when \( \kappa_{\text{abs}}(250\mu m) \) 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 was also noted by Galametz et al. (2012) and imputed to the use of 70\(\mu m \) 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 \( \beta \). This could come from a galaxy whose SED behaves as a MBB with the chosen \( \beta \), 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 done by James et al. 2002); or from a dust model for the MW grains in which the materials cross sections follow the chosen spectral behavior (provided that those materials are able to predict consistently both the MW extinction curve and the FIR/submm emission).

As a numerical experiment, I show here what a different choice of \( \beta \) 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 \(|b| > 15^\circ \) normalised to the hydrogen column density, \( I_s/N_H \)). They provide Herschel surface brightnesses for the DHGL by convolving their COBE-FIRAS spectrum with the PACS (160\(\mu m \)) and SPIRE (extended emission) filter response functions. They also provide the COBE-DIRBE 100\(\mu m \) surface brightness, which I converted to PACS (100\(\mu m \)) by multiplying it by 1.1 to take into account the different filter widths. This dataset is thus analogous to what I used in Sect. 2 to derive dust masses.

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\(^3\) The original DL07 models are available at: http://www.astro.princeton.edu/~draine/dust/direm.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.
For a dust grain of temperature $T_{d}^{MW}$ emitting as a 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

$$I_{\nu} \propto \frac{\tau_{abs}}{N_{H}} B_{\nu}(T_{d}^{MW}), \tag{5}$$

where

$$\frac{\tau_{abs}}{N_{H}} = \kappa_{abs} \frac{m_{H} (D/G)_{MW}}{N_{H}} = \frac{\tau_{abs}(\lambda_{0})}{\lambda_{0}^{\beta}} \times \frac{(\lambda_{0})^{\beta}}{\lambda}. \tag{6}$$

The absorption cross section per H atom, $\tau_{abs}/N_{H}$, can be converted into the cross section per unit dust mass of Eq. 2 by dividing it by 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\(\mu\)m, the absorption cross section is found to be $\tau_{abs}(250\mu m)/N_{H} = 0.84 \pm 0.09 \times 10^{-25} \text{ cm}^2 \text{ H}^{-1}$. Assuming $(D/G)_{MW} = 0.01$, as can be estimated from the elemental depletion patterns in the diffuse MW gas (Draine 2011), it is $\kappa_{abs}(250\mu m) = 5.0 \text{ cm}^2 \text{ g}^{-1}$, 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 $\tau_{abs}(250\mu m)/N_{H} = 0.91 \pm 0.10 \times 10^{-25} \text{ cm}^2 \text{ H}^{-1}$ (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 ionised gas to the hydrogen column density, while Boulanger et al. only consider atomic gas). When $\beta = 2.08$, as for D03’s model, $T_{d}^{MW} = 17.1 \pm 0.4 K$ and $\tau_{abs}(250\mu m)/N_{H} = 0.98 \pm 0.11 \times 10^{-25} \text{ cm}^2 \text{ H}^{-1}$, which converts to $\kappa_{abs}(250\mu m) = 5.9 \text{ cm}^2 \text{ g}^{-1}$, a value 45% higher than that in Eq. 3. The model could still be reconciled with the data, if the ionised gas contributes more to the total hydrogen column density than what assumed by C11. To be consistent with the mass determinations done so far, I continue to use the absorption cross sections from Eqs. 3 and 4 but scale them according to the ratios of $\tau_{abs}/N_{H}$ obtained from the DHGL with different $\beta$s.

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

When the normalizations of Eq. 3 and 4 are corrected by those factors, the dust masses obtained using $\beta = 1.5$ become very close to those obtained using $\beta$ 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 if $\beta$ if both the absorption cross section and the dust mass are derived with the same $\beta$. Substituting Eq. 2, 5 and 6 in Eq. 1, one finds that the dust mass of a galaxy depends on $\beta$ 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 provide in a reliable way 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 $\beta \neq 2$ 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 $\beta$ to derive the dust mass from the SED of galaxies (both under the assumption of a single temperature MBB) results in dust masses which are almost independent of $\beta$. This might be true only for this limited range, which is still able to provide a reliable fit of the MW SED. For $\beta$s 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 of non-equilibrium emission), as well as two temperature MBB fits, might result in further biases in the derivation of the dust mass, in addition to those discussed here (Aniano et al. 2012, Aniano et al. in preparation).

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