Far-infrared spectral energy distribution fitting for galaxies near and far

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ABSTRACT

Spectral energy distribution (SED) fitting in the far-infrared (FIR) is greatly limited by a dearth of data and an excess of free parameters – from galaxies’ dust composition, temperature, mass, orientation, opacity, to heating from active galactic nuclei (AGN). This paper presents a simple FIR SED fitting technique joining a modified, single dust temperature greybody, representing the reprocessed starburst emission in the whole galaxy, to a mid-infrared (MIR) power law, which approximates hot-dust emission from AGN heating or clumpy, hot starbursting regions. This FIR SED can be used to measure IR luminosities, dust temperatures and dust masses for both local and high-z galaxies with three to 10+ FIR photometric measurements. While the fitting technique does not model emission from polycyclic aromatic hydrocarbons (PAHs) in the MIR, the impact of PAH features on integrated FIR properties is negligible when compared to the bulk emission at longer wavelengths.

This fitting method is compared to IR template SEDs in the literature using photometric data on 65 local luminous and ultraluminous infrared galaxies, (U)LIRGs. Despite relying only on 2–4 free parameters, the coupled greybody/power-law SED fitting described here produces better fits to photometric measurements than best-fitting literature template SEDs (with residuals a factor of ~2 lower). A mean emissivity index of $\beta = 1.60 \pm 0.38$ and MIR power-law slope of $\alpha = 2.0 \pm 0.5$ is measured; the former agrees with the widely presumed emissivity index of $\beta = 1.5$ and the latter is indicative of an optically thin dust medium with a shallow radial density profile, $\approx r^{-1/2}$. Adopting characteristic dust temperature as the inverse wavelength where the SED peaks, dust temperatures $\sim 25$–45 K are measured for local (U)LIRGs, $\sim 5$–15 K colder than previous estimates using only simple greybodies. This comparative study highlights the impact of SED fitting assumptions on the measurement of physical properties such as IR luminosity (and thereby IR-based star formation rate), dust temperature and dust mass, for both local and high-redshift galaxies.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: starburst – infrared: galaxies.

1 INTRODUCTION

Modelling galaxies’ multiwavelength emission has become a sophisticated effort of extragalactic astronomy. Spectral energy distribution (SED) templates, generated by modelling galaxies’ stellar populations and radiation, are used prolifically to derive stellar masses, extinction corrections and stellar ages using broad-band photometry from the rest-frame ultraviolet (UV) to infrared (IR) wavelengths. They are also commonly used to constrain redshifts photometrically (e.g. Bolzonella, Miralles & Pelló 2000). The population synthesis-generated SEDs used to fit short-wavelength data ($\lambda \leq 8 \mu m$) are complex (Bruzual & Charlot 2003; Maraston 2005). They depend on the initial mass function (IMF; Salpeter 1955; Kroupa 2001; Chabrier 2003), metallicity, stellar age and starbursting time-scale – duration, frequency and strength. Although this gives rise to many free parameters in the models, the slew of broad-band filters in the optical and near-IR (NIR) make this detailed SED fitting possible, even with the effects of dust obscuration/attenuation taken into account (e.g. Calzetti, Kinney & Storchi-Bergmann 1994; Calzetti 2001). Follow-up spectral observations in the optical and NIR often confirm good fits to broad-band photometry and accurate stellar population modelling.

The dawn of new IR observing facilities – from the Herschel Space Observatory, the Atacama Large Millimeter Array (ALMA), to the Submillimetre Common-User Bolometer Array 2 (SCUBA-2) instrument on the James Clerk Maxwell Telescope (JCMT) – has triggered a wave of interest in extending the use of these template SED libraries to the far-IR (FIR; $\sim 8$–1000 $\mu$m rest frame),
for example, in generating FIR photometric redshift estimates (Roseboom et al. 2012). Unfortunately, modelling the dust emission from galaxies is just as complex in the FIR as it is in the optical since free parameters include dust composition, dust grain type, galaxy structure, orientation, active galactic nuclei (AGN) heating, emissivity and optical depth. However, in contrast to the optical and NIR, FIR observations are plagued with a dearth of data. Where there might be 10–20 broad-bands in the optical/NIR, there are at most ~8 bands in the FIR (most galaxies having data in three bands or less), all of which suffers from the increased beam size of single-dish FIR observations, thus increasing uncertainty on measured flux.

Nevertheless, detailed radiative transfer models and empirical template libraries have been devised in recent years to model the dust IR emission of stars, molecular clouds and starburst galaxies over a wide range of bolometric luminosities (Silva et al. 1998; Chary & Elbaz 2001; Dale et al. 2001; Abel & Wandelt 2002; Dale & Helou 2002; Draine & Li 2007; Siebenmorgen & Krügel 2007). These models are then often used as a basis on which to measure the fundamental parameters of observed starburst galaxies with constrained photometric measurements, both at low redshift (e.g. Armus et al. 2009; Chapin, Hughes & Arctaga 2009; Rieke et al. 2009; U et al., in preparation) and at high redshift (e.g. Blain et al. 2002; Chapman et al. 2004; Pope et al. 2008; Swinbank et al. 2010). Particularly for galaxies with high star formation rates (SFRs), the ‘UV chimney’ argument (Neufeld 1991) can be used to relate the modelled dust and molecular cloud structure back to the Lyγ escape fraction; Lyγ suffers from less attenuation than UV continuum photons despite very large reservoirs of dust and gas.

This paper investigates the use of these FIR template SEDs to determine fundamental galaxy properties such as IR luminosity, LIR, characteristic dust temperature, T_dust, and dust mass, M_dust. Section 2 presents a simple method for representing galaxies’ FIR emission as a coupled modified greybody plus a mid-IR (MIR) power law, which can constrain these fundamental IR-derived properties quite well for a wide range of galaxies. Section 3 compares these fits to the SED template fits of Chary & Elbaz (2001), Dale & Helou (2002) and Siebenmorgen & Krügel (2007), using the photometry of local luminous infrared galaxies and ultraluminous infrared galaxies (LIRGs/ULIRGs) from U et al. (in preparation). Section 4 discusses derived quantities of FIR SED fits and Section 5 concludes. Throughout, a Λ cold dark matter cosmology with H_0 = 71 km s^{-1} Mpc^{-1} and Ω_m = 0.27 is assumed (Hinshaw et al. 2009).

2 SED FITTING TECHNIQUES

2.1 Coupled greybody/power-law fitting

2.1.1 Method

Deriving the fundamental physical properties of IR-luminous galaxies can be as simple as assuming an isotropically emitting blackbody. This is represented as the Planck function, B_ν(T) (e.g. in units of erg s^{-1} cm^{-2} Å^{-1}), and is only dependent on dust temperature T. However, if the variation in opacity (e.g. assuming a screen of dust without scattering) and source emissivity is accounted for (the fact that very few sources are perfectly non-reflective), the flux density at rest-frame frequency ν is then represented by a modified blackbody (i.e. ‘greybody’) of the form

\[ S(ν) \propto (1 - e^{-ν/β}) B_ν(T) = \frac{(1 - e^{-ν/β}) ν^β}{e^{ν/β T} - 1}, \]

where S(ν) is in units of erg s^{-1} cm^{-2} Hz^{-1} or Jy. Optical depth is τ(ν) and fitted as τ(ν) = (ν/ν_0)^β, where ν_0 is the frequency where optical depth equals unity (Draine 2006) and β represents emissivity, or the spectral emissivity index. See Kovács et al. (2010) for a thorough discussion of the impact on β. The value of β is largely assumed to be 1.5 (and usually ranges 1–2; Hildebrand 1983), although this could be a result of the original wavelengths for which data were gathered on local starbursting samples (Dunne & Eales 2001). Some recent work points to a wider range of β values between 1 and 2.5 (e.g. Casey et al. 2011; Chapin et al. 2011). The theoretically expected value of ν_0 is 3 THz (i.e. λ_0 = 100 μm), although this value is unconstrained by data (see discussion in Conley et al. 2011). In the optically thin case, the term (1 − e^{-ν/β}) reduces to ν^β, and the flux density simplifies to

\[ S_0(ν) \propto ν^β \frac{B_ν(T)}{e^{ν/κ T} - 1}. \]

The normal range of dust temperatures expected for a galaxy’s interstellar medium (ISM) heated only by star formation ranges ~20–60 K. When fitted to a greybody (as in equation 1 or 2), most galaxies have a notable flux density excess at wavelengths shortward of ~50 μm (see Fig. 1, panels A and B). This MIR excess is due to a combination of hotter dust subcomponents (where dust is more compact) or dust heated by an AGN, and an optically thin medium by which the higher frequency radiation can escape. The disconnect between the observed MIR luminosities and the predicted Wein-tail luminosities has been studied for quite some time; a quite thorough discussion of dust clouds’ opacity, radial density distributions and dust mass coefficients (κ, α) impact on observed SED is given in Scoville & Kwan (1976); note in particular the difference between optically thin and optically thick models in the NIR and MIR regimes.

Non-thermal emission from polycyclic aromatic hydrocarbons (PAHs) in starburst galaxies or silicate absorption at 9.7 μm can contribute to the SED shape in this regime as well; however, their net effect on integrated IR luminosity, differing from a simple MIR power law, is <10 per cent in most cases (See Section 2.2). While the hot-dust component might be made up of several subcomponents of different warm temperatures, the cold-dust modified greybody still dominates the bulk of the total IR emission when integrated. The net sum is an SED which can be approximated as a power law in the MIR, with intensity dropping with decreasing wavelength, and a single-temperature greybody fit in the FIR. The greybody dominates at wavelengths >50 μm, whereas the MIR power law dominates at wavelengths <50 μm. This can be analytically approximated as

\[ S(λ) = N_{bb} \left( \frac{1 - e^{-λ/(λ_0 β)}}{e^{λ/(κ T)} - 1} \right)^3 + N_μ λ^α e^{-(λ/λ_κ)^β}, \]

where S(λ) is in units of Jy, T is the galaxy’s characteristic ‘cold’ dust temperature (in other words, the dust temperature dominating most of the IR luminosity and dust mass), λ_0 is the wavelength at which optical depth is unity (taken here to be fixed at λ_0 = 200 μm as in Conley et al. 2011), β represents the emissivity, α represents the slope of the MIR power-law component and λ_κ is the wavelength where the MIR power law turns over and no longer dominates the emission. This simplifies to

\[ S_0(λ) = N_{bb,0} \left( \frac{1}{e^{λ/(κ T)} - 1} \right)^3 + N_μ λ^α e^{-(λ/λ_κ)^β}, \]

in the optically thin case. Note that several works have recognized the utility of adding MIR power-law components to simple
Figure 1. Illustration of FIR SED fitting techniques using the example local galaxy UGC 02369. Panel (A) highlights the four IRAS-band photometric points in black (the more recent FIR photometric measurements in grey). The original computed FIR luminosity for this source was computed via equation (5). The original dust temperature for the source (Perault 1987) was found by fitting a single-temperature greybody with fixed $\beta = 1.5$ to the IRAS bands (magenta; the same best-fitting SED assuming optically thin conditions is shown in dashed magenta). Panel (B) shows a slightly improved SED fit, with a single-temperature greybody fit to all of the FIR photometric bands. Emissivity, $\beta$, is added as a free parameter (black) and measured as $\beta = 0.5$, which is similar to adding a very cold greybody component to the warm component dominating the emission, both with fixed $\beta = 1.5$ (e.g. 60- and 15-K SED shown). Both the fits in panels (A) and (B) have MIR excesses and are poor fits to a single-temperature greybody. Panel (C) shows an improved fit, using four temperature greybodies with fixed $\beta = 1.5$. The fit to the data is much better than (A) or (B), although the number of free parameters shoots up to nine. Panel (D) illustrates the SED fitting technique described in Section 2.1, a composite MIR power law plus cold-dust single-temperature greybody. The MIR power law is a good approximation for the composite of warm dust giving rise to the MIR excess. All fits here assume general-opacity conditions; in the optically thin case, the fits alter slightly, but produce the same $L_{\text{IR}}$ and $T_{\text{dust}}$ to within $\sim 1$ per cent.

greybody fits (e.g. Younger et al. 2009) but tend to fit the two components separately: first the greybody followed by the MIR power law. Coupling the two together and fitting simultaneously makes it possible for a more accurate fit to be made to systems with fewer FIR photometric data points.

Fig. 1 illustrates this SED fitting technique relative to single-temperature greybody fits (as in equation 1) for an example local LIRG, UGC02369. This highlights the inconsistency of single-temperature greybodies with FIR photometry of real galaxies and the usefulness of an SED fitting technique which simultaneously fits the cold-dust, long-wavelength greybody and MIR excess power-law component.

Another common way to consider the ‘warm dust’ components is as a continuous power-law distribution of temperature components, e.g. $dM/dT \propto T^{-\gamma}$, as described in Kovács et al. (2010). The index $\gamma$ effectively represents $\alpha$; the values $\gamma = 7.2$ and 6.7 (both assumed in the Kovács et al. 2010, analysis for different samples) correspond to $\alpha$ values of $\approx 2.9$ and 2.6, respectively. Kovács et al. (2010) point out that $\gamma \approx 6.5–7.5$ is expected for sources in a diffuse, star-forming medium and $\gamma \approx 4–5$ for a dense medium from the heating source (e.g. a dusty torus around an AGN). The flux density function is then given as $S_{\nu}(T) = (\gamma - 1)T^{\gamma - 1} \int_{\nu=\infty}^\nu S_{\nu,T}(T)^{\gamma - 1} d\nu$. This integral must be solved numerically, but leads to an SED of shape similar to those produced by equations (3) and (4), particularly equation (3). The differences between the temperature power-law integral fit and the analytic approximation in equation (3) is that the latter provides a bit more flexibility in that the relationship between normalization factors can be adjusted. The former has a clear, robust motivation, but is also a computationally expensive algorithm. As photometry for IR sources improves and spectroscopy becomes more widely available, a minority of galaxies will likely have unusual SED shapes not well described by $dM/dT \propto T^{-\gamma}$, in which case a more general form of equation (3) might be appropriate.

Note that another popular IR SED fitting method joins a greybody to an MIR power law using a piecewise technique (Blain et al. 2002; Blain, Barnard & Chapman 2003), where the transition point between greybody and power law is defined by $d\alpha/d\lambda(S) = \alpha$, i.e. the gradients are equal. This is the most straightforward way of
generating SEDs of the desired shape (Fig. 1, panel D). In many instances, this method might be preferred over this paper’s fitting techniques (e.g. when generating hypothetical SEDs for testing selection, or generating fits for galaxies with only one FIR photometric point). However, one disadvantage of this method is its piecemeal nature, making it difficult to fit data across the whole IR range simultaneously and quantify the errors on each parameter. Having an analytic approximation for this functional form (e.g. equations 3 and 4) makes error propagation and multiple data point fitting much more straightforward.

2.1.2 Adjusting the 2–4 free parameters

There are six total parameters in this fit: the greybody normalization \( N_{\text{bb}} \), power-law normalization \( N_{\text{pl}} \), greybody temperature \( T \), emissivity index \( \beta \), MIR power-law slope \( \alpha \) and MIR turnover wavelength \( \lambda_c \). Since the turnover wavelength of the MIR power law would depend on the turnover point of the cold-dust greybody component and \( N_{\text{pl}} \) determines the flux scaling of the power-law term relative to the greybody, neither parameter should not be considered ‘free’ in the sense of the other four. Both \( \lambda_c \) and \( N_{\text{pl}} \) are tied to the best-fitting values of \( N_{\text{bb}} \), \( T \) and \( \alpha \) such that the total SED resembles both the Kovács et al. (2010) power-law temperature distribution SED and the Blain et al. (2003) piecewise matched-gradient SED.

The turnover wavelength, \( \lambda_c \) is set to 3/4 the wavelength where the gradient of the greybody is \( \alpha \), as in Blain et al. \( \lambda_c \) is both a function of \( \alpha \), \( T \) and the adopted opacity model, and can be approximated as \( \lambda_c = [T \times (a_1 + a_2 \alpha)]^{-1} \) (optically thin) and \( \lambda_c = [(b_1 + b_2 \alpha)^{-2} + (b_3 + b_4 \alpha) \times T]^{-1} \) (general opacity). The values of the coefficients are given in Table 1. Note that a factor of 3/4 is incorporated so that the juncture of the power law and greybody is most smooth (i.e. it does not have a physical interpretation, although is related to the falloff rate of \( e^{-\lambda_c \alpha} \)). The coefficient of the power-law term, \( N_{\text{pl}} \), is tied to the normalization of the greybody term and solves the condition \( N_{\text{bb}} \lambda_c^\alpha = S_b(\lambda_c) \), where \( S_b \) is given by equation (1) or (2). Having fixed these two parameters reduces the number of free parameters to 2–4.

Table 1. Adopted best-fitting SED equation and measured parameters based on the GOALS sample. The measurement of \( \beta \) is based on 48 out of the 65 galaxies which have 850–1.1 mm data, while the measurement of \( \alpha \) is based on the full sample of 65 (U)LIRGs.

| Emissivity                  | \( \beta \) | 1.60 ± 0.38       |
|----------------------------|------------|-------------------|
| Mid-IR power-law slope     | \( \alpha \) | 2.0 ± 0.5         |
| Wavelength where opacity is unity | \( \lambda_0 \) | \( \equiv 200 \mu \text{m} \) |
| Power-law turnover wavelength | \( \lambda_c \) | \( \equiv 3/4 L(\alpha, T) \) |
| where \( L(\alpha, T) = [(b_1 + b_2 \alpha)^{-2} + (b_3 + b_4 \alpha) \times T]^{-1} \) |            |
| b_1                        | 26.68      |
| b_2                        | 6.246      |
| b_3                        | 1.905 \( \times 10^{-4} \) |
| b_4                        | 7.243 \( \times 10^{-5} \) |
| Normalization of power-law term | \( N_{\text{pl}} \) | \( \equiv N_{\text{bb}} \times (1-e^{-\lambda_c \alpha})^{\alpha-1} \) |
| Characteristic dust temperature \((\neq T)\) | \( T_d \) | \( 1/\lambda_{\text{peak}} \) |

Depending on the amount of FIR photometric data available, further constraints can be made to reduce the number of free parameters in the fit described in equation (3) or (4) from four \( (N_{\text{bb}}, \alpha, \beta \) and \( \alpha \)) to two \( (N_{\text{bb}} \) and \( T \)). The number of free parameters should never exceed the number of independent data points minus one. The emissivity \( \beta \) varies from 1 to 2.5 in the literature for individual sources, although the vast majority of works assume a fixed value of \( \beta = 1.5 \) (Chapman et al. 2005; Pope et al. 2006; Casey et al. 2009, among others). Varying \( \beta \) does not have a very significant impact on FIR luminosity or dust temperature, but does have a strong impact on the slope of the Rayleigh–Jeans tail at rest-frame \( \lambda \geq 200 \mu \text{m} \). If there are >3 independent photometric points at \( \lambda \geq 200 \mu \text{m} \), then \( \beta \) can be constrained with the fit; otherwise, the fixed value of \( \beta = 1.5 \) is suggested. The MIR power-law slope can be constrained similarly; if >3 photometric points are available at rest-frame \( \lambda \leq 70 \mu \text{m} \), then \( \alpha \) can be measured. Otherwise, a fixed value of \( \alpha = 2.0 \) is consistent with most sources and is directly comparable to the MIR portion of SED templates presented in the next section. Typical values of \( \alpha \) range from 0.5 (nearly flat, consistent with quite a bit of warm dust) to 5.5 (very steep, consistent with very little warm dust). Note that the values of \( \alpha < 1 \) lead to a divergent luminosity in the NIR, so some additional cut-off should be placed at short wavelengths to avoid a non-physical interpretation.

2.1.3 Defining \( L_{\text{IR}} \) and \( T_{\text{dust}} \)

The normalization of the fits is governed by the IR luminosity, \( L_{\text{IR}} \), whose integration limits have varied throughout the literature. \( L_{\text{IR}} \) is intended to represent the bulk of a galaxy’s dust emission. For galaxies which are very IR-bright \( (L_{\text{IR}} > 10^{11} L_\odot) \), \( L_{\text{IR}} \) is a proxy for bolometric luminosity. \( L_{\text{IR}} \) is most often taken from 8 to 1000 \( \mu \text{m} \) (e.g. Kennicutt 1998), \( L_{\text{IR}} \) also goes by different names in the literature: \( L_{\text{IR}} \) (‘total IR’) or \( L_{\text{IR}} \) (‘FIR’). and can be integrated from 3 to 1100 \( \mu \text{m} \) (e.g. Chapman et al. 2003, 40 to 120 \( \mu \text{m} \) (e.g. Younger et al. 2009) or 40 to 1000 \( \mu \text{m} \) (e.g. Conley et al. 2011). The rest of the paper uses the standard 8–1000 \( \mu \text{m} \) integration limits for the sake of consistency with most of the literature; however, if only the cold-dust, star formation dominated IR luminosity is desired, more appropriate limits would be 40–1000 \( \mu \text{m} \).

In the initial years of characterizing IRAS-detected IR-luminous galaxies, the integrated IR flux was approximated by

\[
F_{\text{IR}(8-1000)} = 1.26 \times 10^{-14} \times (2.58 \times f_{50} + f_{100})
\]

in \( \text{W m}^{-2} \) (and where flux densities, \( f \), are given in Jy, see the review in Sanders & Mirabel 1996). Including all IRAS bands and integrating over a wider wavelength range, 8–1000 \( \mu \text{m} \), this becomes

\[
F_{\text{IR}(8-1000)} = 1.8 \times 10^{-14} \times (13.48 f_{12} + 5.16 f_{25} + 2.58 f_{50} + f_{100})
\]

Luminosities are then \( L_{\text{IR}} = 4\pi D_d^2 F_{\text{IR}} \). Section 3 discusses the accuracy of this widely accepted luminosity approximation to the U et al. sample.

Note also that the dust temperature \( T \) as given in equations (1)–(4) represents the intrinsic galaxy temperature, which is different from the inverse ‘peak wavelength’ temperature as measured by Wein’s displacement law, i.e. \( \lambda_{\text{max}} = b/T_d \) (where \( b = 2.898 \times 10^{10} \text{ K} \)), which only applies to perfect blackbodies. Fig. 2 shows the intrinsic dust temperature \( T \) against the peak wavelength dust temperature \( T_{\text{d}} \) for the above formulations. Fig. 2 also shows \( T_d \) against IRAS colour, log \( (S_{50}/S_{100}) \), for equations (1)–(4) and the IR template SEDs discussed in the next section.

FIR colour is often taken as a proxy for dust temperature. Works in the literature vary the use of different fitting methods, some using IR
Figure 2. The left-hand panel shows a comparison of the $T$ temperature parameter of the fitted greybody against the ‘peak wavelength’ $T_d$, which is proportional to the inverse peak in $S_\nu$. This varies by fitting method mostly due to slight variations in adopted opacity, which shifts the SED peak slightly while keeping $L_B$ roughly constant. The right-hand panel shows a comparison of $T_d$, the ‘peak wavelength’ temperature, with $\text{IRAS } [60]–[100]$ colour, which has often been used as a proxy for dust temperature. Overplotted are various model template values, from Chary & Elbaz (2001), Dale & Helou (2002), Siebenmorgen & Krügel (2007) and Draine & Li (2007).

dust emission should clearly use template SEDs instead of simple greybody/power-law fits. However, in terms of the basic physical properties extracted from FIR SEDs – $L_B$, $T_{\text{dust}}$ and $M_{\text{dust}}$ – there is not a significant detriment to using the greybody/power-law fitting technique. The PAH emission lines at 7.7, 11.2 and 12.8 $\mu$m contribute to the integrated IR luminosity of the order of 5 per cent, although their contribution is often negated by the presence of the 9.7 $\mu$m absorption feature.

The MIR spectra of dusty starbursts have been shown to vary substantially at both low-$\zeta$ and high-$\zeta$ (Brandl et al. 2006; Pope et al. 2008; Menéndez-Delmestre et al. 2009). Without a direct MIR spectrum, it is impossible to know whether or not PAHs or absorption features are contributing significantly to broad-band photometric measurements. At certain rest-frame wavelengths, FIR photometric measurements are likely to deviate positively or negatively from an MIR power law (e.g. at $\sim8$ $\mu$m in the former case and 10 $\mu$m in the latter case). In those cases, IR template SEDs should be used to more accurately determine the structure of MIR emission.

3 SED COMPARISONS WITH DATA

Testing and comparing the different IR template SEDs from Section 2.2 and SED fitting methods from Section 2.1 requires a sample of well-constrained FIR-bright galaxies with accurate FIR photometric measurements. To date, the most extensively imaged IR galaxies – besides the handful of high-$\zeta$ brightly lensed sources (e.g. the ‘cosmic eyelash’; Swinbank et al. 2010) – are from the local IRAS-selected Revised Bright Galaxy Sample (RBGS; Sanders et al. 2003), particularly the subset which forms part of the Great-Origins All Sky LIRG Survey (GOALS; Armus et al. 2009). The revised standard-aperture photometry for 65 galaxies in the GOALS sample is summarized and presented in U et al. (in preparation) and used herein at rest-frame wavelengths 5–2000 $\mu$m.

Modified greybodies plus MIR power-law SEDs are fitted to data as described in Section 2.1, specifically to equation (3), taking both flux density uncertainties and non-detection upper limits into...
Figure 3. Example best-fitting SEDs to a subset of the GOALS sample, whose photometry is presented in U et al. (in preparation). Photometric data points are shown as red diamonds with uncertainties illustrated (sometimes smaller than the size of the data point). The best-fitting SED fit from equation (3) is shown in black, with the underlying greybody distribution shown as a dotted black line. The best-fitting Chary & Elbaz template SED is shown in magenta, Dale & Helou SED shown in green and Siebenmorgen & Krügel SED shown in orange. A ‘dummy SED’ is also constructed which linearly interpolates between data points in logλ–logSν space (dashed grey line). The 8–1000 and 40–1000 μm integration limits are marked as light grey vertical lines for reference.

The general-opacity fits are chosen for this local sample over the optically thin fits due to a subtle difference in the SED shape around rest-frame wavelengths ~20–40 μm.

For sources with more than three long-wavelength data points, β is kept as a free parameter; otherwise it is fixed to $\beta = 1.5$. MIR power-law slope $\alpha$ is allowed to vary since the number of short-wavelength points (<70 μm) is always more than three. The range of $\alpha$ values is found to vary between $\alpha = 0.5$ and 5.5. Dust temperature and luminosity are left to vary. Template IR SEDs from Section 2.2 are fitted to data with a $\chi^2$ minimization method, where the normalization (i.e. $N_{bb} \propto L_{IR}$) is a free parameter.

Fig. 3 shows several randomly selected examples of best-fitting SEDs for GOALS sources. The various best-fitting IR templates are coloured, while the fitted SED is shown in black. The underlying greybody function to the fitted SED is shown as a dotted line. Since >8 FIR photometric points exist for the GOALS sample, a dummy SED can also be constructed by linearly extrapolating between photometric points (shown in grey). While this is a rough approximation, the advantage of this extrapolation is that this dummy SED makes no intrinsic assumptions as to the SED shape. The subset of sources shown in Fig. 3 represents a wide variety of templates and fitted SEDs and is representative of the fits to the whole U et al. (in preparation) sample.

The residuals of the fits with respect to data are shown in Fig. 4. The residual is computed as the difference in logSν between the data points and the best-fitting SED at each of the following wavelengths: 12, 25, 60, 100 and 850 μm. Fig. 4 shows the distribution in the residuals at each wavelength for the U et al. GOALS sample for each fit. Black represents the residuals from the fitting method described in Section 2.1, and the residuals of the IR templates are coloured as in Fig. 3. At each wavelength, the mean and standard deviation of the residual distribution are given in the top left. At all wavelengths, the fitted SED from equation (3) is statistically a better fit to the data than any IR templates, despite having fewer free parameters than the SED templates; a summary of derived quantities from this fit is given in Table 1. However, some templates are more accurate than others; the Siebenmorgen & Krügel templates provide the best fit of the templates, significantly better than both Chary & Elbaz and Dale & Helou templates. However, all seem to suffer at short wavelengths where there is naturally no flexibility built into the models. This demonstrates that galaxies’ MIR properties are not tightly correlated with their FIR properties, as perhaps previously thought (since 24 μm is often used to infer $L_{IR}$, e.g. Le Floc’h et al. 2005, on Spitzer samples, among many others).

Another reason the Siebenmorgen & Krügel templates have lower residuals than the other two template libraries is that they contain more templates with which to compare the data. Even at the highest

1 An IDL function cmcirsed.pro, which can be used to fit an SED of the form in equation (3) or (4) to real data, is publicly available at www.ifa.hawaii.edu/~cmcasey/research.html. (This will be available on the research webpage of C. M. Casey upon any institution change).
luminosity end ($L_{IR} > 10^{11} L_\odot$), there are still 120 template models in the Siebenmorgen & Krügel (2007) library. In contrast, the Chary & Elbaz library contains 105 template SEDs and Dale & Helou contains 64 template SEDs.

This direct comparison between SED fitting and SED templates demonstrates that using IR templates will always provide a less accurate fit than simple greybody/power-law fitting. This is not meant to suggest that IR template SEDs are not of great use; on the contrary, they provide very good constraints on the relationships between FIR emission and PAH emission, and sources’ dust composition, which simple greybody fitting cannot do. However, if the purpose of FIR SED fitting is to measure a source’s FIR luminosity, dust temperature and dust mass accurately, this work demonstrates that direct fitting, as in Section 2.1, is the best.

3.1 Interpretation of best-fitting parameters

The U et al. (in preparation) sample has been used to constrain the mean SED parameters $\beta$, the spectral emissivity index and $\alpha$, the MIR power-law slope. How do we interpret the measurements $\beta = 1.60 \pm 0.38$ and $\alpha = 2.0 \pm 0.5$? Here I draw on the detailed discussions in Scoville & Kwan (1976).

The measured value of the emissivity index, $\beta$, is spot on its presumed value of $\approx 1.5$. Although not new information, this suggests that even the cold-dust component (dominating at $\lambda > 50$ µm) has a temperature gradient whereby the dust farthest from the luminous starburst is slightly colder, which deferentially boosts the flux density at the longest wavelengths. This boosting (above a simple blackbody) becomes enhanced when the density distribution falls off slowly, and with a steep density drop off, $\beta$ should increase and the FIR ‘slope’ should increase.

The MIR power-law slope, $\alpha$, probes the warmer, more compact dust and can be used to estimate the radial density profile. Our measurement of $\alpha = 2.0 \pm 0.5$ agrees with the earlier findings of $\alpha = 1.7–2.2$ from the analysis of IRAS and distant galaxies in Blain et al. (2002). Assuming there are sufficient hot dust grains near the interior and the dust is optically thin, $S_{\nu} \propto \nu^\alpha$ where $\alpha = 2.0 \pm 0.5$ translates to a density profile of $r^{-0.5 \pm 0.2}$, consistent with $r^{-1/2}$. In other words, the dust density profile is relatively flat and perhaps indicative of the diffuse nature of the dust around these starbursts, their distributions perhaps originating from the violent interacting nature within the galaxies.

4 DERIVED QUANTITIES

Section 3 used the GOALS sample (Armus et al. 2009; U et al., in preparation) to demonstrate that direct greybody/power-law SED fitting, as described in Section 2.1, is a more accurate fit to data than best-fitting IR SED template libraries from the literature. In this section, the derived quantities $L_{IR}$ (luminosity), $T_d$ (dust temperature) and $M_d$ (dust mass) are compared to see what can be expected using different SED fitting methods.

4.1 IR luminosity and star formation rates

The IR luminosity is most often integrated in the range 8–1000 µm, i.e. $L_{IR} = 4\pi D_e^2 \int_{\nu=8\mu m}^{\nu=1000} S_{\nu} d\nu$. The range 8–1000 µm encompasses some of the most prominent PAH emission features in addition to the greybody emission peak. The boundaries are still somewhat arbitrarily drawn, since 8 µm sits awkwardly on top of the 7.7 µm PAH emission feature, and 1000 µm splits the cold-dust greybody neither at its turnover point, where radio synchrotron emission begins to dominate, nor near the peak. On average, the cold-dust greybody component – thought to be exclusively heated by star formation processes – comprises 74 ± 11 per cent of $L_{IR(8–1000)}$, while warm AGN-heated dust and PAH emission components comprise 26 ± 11 per cent.

Fig. 5 shows the 8–1000 µm IR luminosities of the U et al. sample and luminosity residuals when contrasting methods. The $x$-axis is the IR luminosity as inferred by equation (6), also as summarized in Sanders & Mirabel (1996) and Armus et al. (2009). The whole RBGS sample is also included, refitting all luminosities using the method from Section 2.1 (due to limited long-wavelength photometry, $\beta = 1.5$ is fixed). Similarly, RBGS luminosities are compared to template SED-inferred luminosities. Both the fitted SEDs and template SEDs have lower IR luminosities than predicted using the RBGS equation (equation 6) by $\approx -0.02–0.04$ dex. Both Chary & Elbaz and Dale & Helou templates are 0.02 ± 0.07 dex lower in luminosity than IRAS predictions, while Siebenmorgen & Krügel templates are 0.03 ± 0.05 dex lower, and fitted SEDs are 0.04 ± 0.04 dex lower. These differences translate to luminosity
IRAS luminosities, 'IRAS luminosities', are measured as a linear combination of IRAS 12–100 μm flux densities, see equation (6) or Sanders & Mirabel (1996). Here IRAS luminosities are plotted against fitted luminosities from the direct fitting method (Section 2.1) and template SED libraries. The full RBGS sample of 625 sources from Sanders et al. (2003) is included, and luminosities are refitted using IRAS photometry alone and equation (3), fixing $\beta = 1.5$ (scatter is larger for this sample due to poorer photometric constraints). At the bottom are the residuals, luminosity against the difference in log $L_\mu$. All template libraries and fitted SEDs demonstrate that IRAS luminosities are overestimated by ~0.04 dex, or ~10 per cent.

Figure 5. The fitted RBGS IR luminosities, 'IRAS luminosities', are measured as a linear combination of IRAS 12–100 μm flux densities, see equation (6) or Sanders & Mirabel (1996). Here IRAS luminosities are plotted against fitted luminosities from the direct fitting method (Section 2.1) and template SED libraries. The full RBGS sample of 625 sources from Sanders et al. (2003) is included, and luminosities are refitted using IRAS photometry alone and equation (3), fixing $\beta = 1.5$ (scatter is larger for this sample due to poorer photometric constraints). At the bottom are the residuals, luminosity against the difference in log $L_\mu$. All template libraries and fitted SEDs demonstrate that IRAS luminosities are overestimated by ~0.04 dex, or ~10 per cent.

Note that the Kennicutt (1998) scaling relation between $L_{B(8–1000)}$ and SFR takes both the contribution of 'infrared cirrus' cold-dust emission and 'warm' dust around young star-forming regions into account and is generated using stellar synthesis models (Leitherer & Heckman 1995) for continuous bursts aged 10–100 Myr. Since the Kennicutt scaling is not determined as an empirical relation between, e.g. Hα SFR and $L_{B_{\mu}}$, there is no need to recalibrate it to correct for the overestimated $L_{B_{\mu}}$; however, the FIR SFRs of the local (U)LIRG sample should be revised to reflect the systematic offset.

Regardless of the systematic offset, IR-based SFRs are only accurate to ~10 per cent mostly due to the variation in MIR properties, likely not directly scaling to the galaxies’ SFRs, since complex processes dominate the MIR. Similarly, slight changes in any SED which impacts the MIR (e.g. changes in opacity assumptions, assumed $\alpha$ and PAH contributions) will impact the derived SFR. For this reason, it is worth emphasizing that the systematic offset is of minor significance. Also worth pointing out is that the range 8–1000 μm is not ideal to generate precise SFRs.

Ideally, one would extract the integrated luminosity from the cold-dust greybody component over all wavelengths where it dominates.

This can be estimated precisely if the fitting method in Section 2.1 is used, as the greybody component can then be constructed independently after fitting to a joint greybody and power law. However, to make fair comparisons with different SED fitting methods, the optimal alternative limits of integration should be taken as 40–1000 μm as in Conley et al. (2011). Longward of 40 μm, the cold-dust greybody dominates at all dust temperatures $<100$ K.

4.2 Dust temperature

Comparing dust temperatures between models first requires an understanding of the dust temperature convention for the original work on the U et al. (in preparation) GOALS sample objects. Dust temperatures were originally fitted in Pernault (1987) by fitting a single-temperature dust emissivity model ($\epsilon \propto \nu^{-\beta}$) to the flux in all four IRAS bands (briefly described in Sanders & Mirabel 1996). In other words, these dust temperatures are fitted to data ranging 12–100 μm to either equation (1) or (2). Assumptions made with regard to opacity are not stated; however, the impact on peak dust temperature is minimal. It could be that the dust temperature reported in Pernault (1987) is indeed $T$ taken from e.g. equation (2) rather than 'peak wavelength' dust temperature $T_d$, although it is unclear. Regardless, refitting greybodies of either form specified in equation (1) or (2) to only the four IRAS data points causes the dust temperatures $T_d$ to drop by ~10 K. This is shown in Fig. 6 (and is illustrated clearly in Fig. 1, panels A and B). The difference between dust temperatures of simple greybodies and greybodies which incorporate an MIR component has been known (see also the recent detailed discussion in Hayward et al. 2012), yet few works are explicitly clear on how their dust temperature measurements should be interpreted.

The Pernault/RBGS dust temperatures are also found to be significantly hotter than dust temperatures measured from the SED template libraries. However, any dust temperatures extracted from the template SEDs should be used with great caution, as the dust temperatures are quantized in all cases (as seen in the right-hand panel of Fig. 2). The Dale & Helou (2002) templates exhibit the

Figure 6. A comparison of dust temperatures from Pernault (1987), described also in Sanders & Mirabel (1996), against dust temperatures found using methods in Section 2.1 and from template SEDs. Colours and symbols are the same as in Fig. 5. In all cases, a single greybody fit of the form described in equation (1) or (2) (which was the method used in Pernault 1987) overestimates dust temperature by 10 K on average. Caution is necessary when using dust temperatures from template SEDs since they are quantized.
poorest constraints on dust temperature, as the templates only have two dust temperatures: \( T_d \approx 31 \) and \( \approx 51 \) K. The Chary & Elbaz (2001) templates have four different dust temperatures, at \( \approx 23, 32, 41 \) and 50 K. The Siebenmorgen & Krügel (2007) templates are quantized on yet finer scales, at 5 K increments between \( \sim 24 \) and 85 K; however, the fitted SEDs, as an analytic fit, are not quantized in \( T_d \). For this reason, any dust temperature-based results should be based on fits of the type described in Section 2.1, not on template SEDs in the literature.

4.3 Dust mass

Dust mass is related to IR flux density and dust temperature via

\[
S_\nu = \kappa_\nu B_\nu(T) M_d D_L^2 (1+z),
\]

where \( S_\nu \) is the flux density at frequency \( \nu \), \( \kappa_\nu \) is the dust mass absorption coefficient at \( \nu \), \( B_\nu(T) \) is the Planck function at temperature \( T \), \( M_d \) is the total dust mass and \( D_L \) is the luminosity distance. The fact that our sources are not perfect blackbodies is accounted for by the dust mass coefficient \( \kappa_\nu \) so that the greybody is effectively represented by the product \( \kappa_\nu B_\nu(T) \) and the sources’ luminosity at frequency \( \nu \) scales as \( S_\nu/B_\nu(T) \propto \nu^{-2} \). The dust mass is then

\[
M_d = \frac{S_\nu D_L^2}{\kappa_\nu B_\nu(T)(1+z)} \propto \frac{D_L^2}{\kappa_\nu \nu^2 (1+z)}.
\]

As Draine et al. (2007) point out, care should be taken when computing dust masses using measured dust temperatures since the thermal emission per unit dust mass at \( \lambda \) is \( \propto \exp(\lambda/\kappa T) - 1 \). At wavelengths \( \lambda \lesssim 360 \) \( \mu \)m, dust temperature has a profound effect on dust mass, since \( B_\nu(T) \) is very much dependent on \( T \) (so that a 4 K difference between 18 and 22 K results in a 150 per cent increase in \( M_d \)). At \( \lambda \gtrsim 450 \) \( \mu \)m, \( M_d \) is less sensitive to dust temperature. Note that the dust temperature used in equation (8) is the \( T \) from equation (3) and not the ‘peak wavelength’ dust temperature \( T_d \) characterizing the system as a whole.

Due to poor constraints on dust absorption coefficients and no data points longward of \( \sim 450 \) \( \mu \)m, dust masses for the GOALS sample were not reported until the work of U et al. (in preparation), who use the method described in this paper, equation (8), to calculate dust masses at 850 \( \mu \)m using a dust absorption coefficient of \( \kappa_{850} = 0.15 \) m\(^2\) kg\(^{-1}\) (Weingartner & Draine 2001; Dunne et al. 2003). Fig. 7 plots the galaxies’ dust masses against IR luminosity, which highlights two important facts. First, the calculation of dust mass is very sensitive to dust temperature, \( M_d \propto L_{IR} \). This highlights that dust mass should only be estimated when dust temperature is adequately constrained. The second noticeable detail of Fig. 7 is the lack of correlation between the two physical properties, \( L_{IR} \) and \( M_d \). The lack of correlation is a testament to how large amounts of dust can be formed quite quickly in starburst galaxies (in contrast, star-forming galaxies with much more moderate SFRs overall have dust masses several orders of magnitude smaller, \( < 10^{-2}-10^{-3} M_\odot \)).

4.4 Future improvements

The next decade will see great improvements in our understanding of dust emission in galaxies thanks to vast repositories of data from large field-of-view mapping bolometers and efficient follow-up with interferometric imaging. Facilities less limited by confusion noise (e.g. SCUBA-2 450-\( \mu \)m mapping on JCMT, and future 200–850 \( \mu \)m data from the Cornell–Caltech Atacama Telescope, CCAT) will make IR photometric measurements more accurate, precise and more numerous. Submillimeter spectrometers (e.g. like Z-Spec operated at the Caltech Submillimeter Observatory and Atacama Pathfinder Experiment, e.g. see Bradford et al. 2009, also those being designed for CCAT) will measure spectra for individual sources in the IR and submillimetre, providing crucial constraints on emissivity while also confirming redshifts through CO lines and assessing their contribution to continuum photometry (e.g. see Smail et al. 2011).

With this superb data, IR SED fits can be significantly refined. Better photometric constraints mean that more free parameters can be reintroduced into SED fitting, providing a more concrete physical context. What does the value of \( \beta \) imply for the distribution of cold dust? What does the value of \( \alpha \) imply for the radial dust distribution? Is there a wavelength regime where the assumption of a power-law distribution of warm dust temperatures does not hold, and is that in turn related to the dust distribution or presence of a luminous AGN? Are any galaxies better fitted with two independent greybodies than one, and does this indicate two distinct dust reservoirs not yet mixed?

Furthermore, interferometers like ALMA will make it routinely possible to resolve dust emission on kpc scales within distant galaxies (as the Submillimeter Array, SMA, has done for some local ULIRGs; Wilson et al. 2008). Spatial mapping of the dust distribution in multiple IR channels can then be used to assess the MIR power-law inferred dust distribution. Combined with resolved molecular gas maps obtained through CO emission, routine tests of the Schmidt–Kennicutt relation (Schmidt 1959; Kennicutt 1998) can be performed on a variety of galaxy types at different stages of their star formation histories.

A further refinement which can be made to SED fitting described in this paper is the introduction of PAH emission and Si absorption modelling on top of the suggested dust continuum. Given the wide variety of MIR properties for IR starbursts, this modelling is best
fitted independently from the MIR power-law dust continuum. This decoupling of the two will be possible with deep NIR and MIR data from the James Webb Space Telescope (JWST).

5 DISCUSSION AND CONCLUSIONS

The characterization of IR-bright galaxies has become increasingly important in recent years with the introduction of new MIR to FIR observing facilities, including Herschel Space Observatory and the ALMA. IR SED fitting techniques vary widely in the literature, from simple greybody fits to detailed dust emission modelling templates.

Section 2.1 has presented an SED fitting technique which can be used to fit a wide range of IR data, from sources which have only three IR photometric points to sources with >10 photometric points. These SED fits do not account for PAH emission in the MIR, although they produce accurate estimates to a source’s integrated IR luminosity, dust temperature and dust mass. The fitting technique is based on a single dust temperature greybody fit linked to a MIR power law, fitted simultaneously to data across ~5–2000 μm. Without inclusion of the MIR power law, dust temperatures are overestimated and the short-wavelength data (<50 μm) fit is likely very poor. From the measurement of the mean MIR power-law slope α, the dust radial density profile in most local (U)LIRGs is fairly shallow, \( \equiv^{-1/2} \). IDL code for the fitting procedure has been made publicly available.

This SED fitting procedure is contrasted with fits to IR template libraries generated through dust-grain modelling, including those of Chary & Elbaz (2001), Dale & Helou (2002) and Siebenmorgen & Krügel (2007). SED fit quality is categorized by goodness of fit to the GOALS local LIRG and ULIRG sample photometry reported in U et al. (in preparation). Since the GOALS sources are the most extensively surveyed IR galaxies to date, they provide a good test bed for SED fitting reliability. The SED templates and original formulation of luminosity for the RBGS sample do not fit the data as well as the fitting method described in Section 2.1, leading to overestimated IR luminosities by 10 per cent. Similarly, dust temperatures estimated for the original RBGS sample (Sanders et al. 2003) were overestimated by ~10 K, due to the different fitting methods used (single greybody versus single greybody plus MIR power law). Dust temperatures cannot be well constrained with SED templates because they are quantized and only peak at certain wavelengths corresponding to fixed dust temperatures. Clarification is offered on the calculation of dust mass, its dependence on dust temperature and the lack of correlation between dust mass and IR luminosity.

This comparative study should be useful to highlight some of the current problems facing FIR SED fitting techniques, and the details often overlooked in ambitious analyses of IR-galaxy population trends for galaxies both near and far.

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