PHOTOMETRIC REDSHIFTS OF SUBMILLIMETER GALAXIES

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ABSTRACT

We use the photometric redshift method of Chakrabarti & McKee to infer photometric redshifts of submillimeter galaxies with far-IR (FIR) Herschel data obtained as part of the PACS Evolutionary Probe program. For the sample with spectroscopic redshifts, we demonstrate the validity of this method over a large range of redshifts (4 ≳ z ≳ 0.3) and luminosities, finding an average accuracy in (1 + zphot)/(1 + zspec) of 10%. Thus, this method is more accurate than other FIR photometric redshift methods. This method is different from typical FIR photometric methods in deriving redshifts from the light-to-gas mass (L/M) ratio of infrared-bright galaxies inferred from the FIR spectral energy distribution, rather than dust temperatures. To assess the dependence of our photometric redshift method on the data in this sample, we contrast the average accuracy of our method when we use PACS data, versus SPIRE data, versus both PACS and SPIRE data. We also discuss potential selection effects that may affect the Herschel sample. Once the redshift is derived, we can determine physical properties of infrared-bright galaxies, including the temperature variation within the dust envelope, luminosity, mass, and surface density. We use data from the GOODS-S field to calculate the star formation rate density (SFRD) of submillimeter bright sources detected by AzTEC and PACS. The AzTEC–PACS sources, which have a threshold 850 μm flux ≳5 mJy, contribute 15% of the SFRD from all ultraluminous infrared galaxies (LIR ≳ 1012 L⊙), and 3% of the total SFRD at z ∼ 2.

Key words: galaxies: distances and redshifts – galaxies: evolution – galaxies: high-redshift – galaxies: luminosity function, mass function – galaxies: photometry – galaxies: starburst

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1. INTRODUCTION

Much of the energy emitted by the universe in its infancy was from dust-enshrouded luminous galaxies. The Herschel Space Telescope has opened a new window into this epoch, yielding unprecedented sensitivity in the far-infrared (FIR; Pilbratt et al. 2010), where dusty galaxies emit most of their radiation. The FIR spectral energy distribution (SED) allows us to probe the physical conditions of dusty sources. Chakrabarti & McKee (2005; henceforth CM05) developed an analytic means of self-consistently solving the radiative transfer equation for spherically symmetric, centrally heated dusty sources. They derived a simple and intuitive form for the emergent SED envelopes from the observed FIR SED. Chakrabarti & McKee (2008; henceforth by CM08 we refer to the paper and by “CM” we refer to CM08’s photometric redshift method) applied the method of CM05 to fit observed FIR SEDs of ultraluminous infrared galaxies (ULIRGs) and submillimeter galaxies (SMGs) and showed that accurate photometric redshifts could be inferred from derivation of the light-to-gas mass (L/M) ratio.

CM08 demonstrated the accuracy of their method with a sample of SMGs with FIR data from Kovacs et al. (2006). This was the only FIR sample of SMGs available at the time, which constituted a sub-sample of the bright SMGs studied by Chapman et al. (2005). The new PACS (Poglitsch et al. 2010) observations of SMGs (Magnelli et al. 2012) provide an ideal sample for testing the CM method on a larger and more diverse sample. SMGs are high-redshift galaxies (z ≳ 0.3) classified on the basis of their submillimeter (sub-mm) flux. “Classical” SMGs have F850,m ≳ 5 mJy, which corresponds to a luminosity of ∼3 × 1012 L⊙ at z ∼ 2. ULIRGs are generally taken to refer to galaxies emitting ∼1012 L⊙ in the infrared (Soifer et al. 1984). CM08 had noted that local ULIRGs have higher L/M values than their high-redshift cousins, a point that we discuss further in Section 3. The galaxies in the Magnelli sample cover four blank fields (Great Observatories Origins Deep Survey-North (GOODS-N), South (GOODS-S), Cosmological evolution survey (COSMOS), and Lockman Hole (LH)) as well as a number of lensing clusters. They span a range in luminosities from 7 × 1013 L⊙ ≳ L ≳ 5 × 1011 L⊙, and redshifts between ∼0.3 and 5. Many of these sources have spectroscopic redshifts. Thus, this sample is diverse enough (Magnelli et al. 2011) to yield a very robust measure of the accuracy of the CM photometric redshift method. This is an important test, as photometric redshifts will be crucial for analyzing the vast bulk of the observations expected from Herschel. Having derived photometric redshifts, we then calculate the star formation rate density (SFRD) of sources detected by AzTEC and PACS as a function of redshift in the GOODS-S field, which is homogeneously covered in the sub-mm down to the classical SMG threshold (F850,μm > 5 mJy). We contrast the accuracy of our photometric redshift method when we use PACS data versus SPIRE data, versus both PACS and SPIRE data. We also discuss potential selection effects that may affect the Herschel sample.
On the basis of IRAS' observations, Sanders et al. (1988) suggested that local ULIRGs may be produced by the merger of gas-rich spirals. The development of hydrodynamical codes that adequately model the collision of gas-rich spirals and the subsequent starburst that results from a violent merger (Springel et al. 2005) made it possible to test this suggestion, which had been anticipated early on by Toomre & Toomre (1972). The infrared emission of ULIRGs and SMGs during their life cycles was subsequently calculated using three-dimensional self-consistent radiative transfer calculations through the time outputs of smoothed particle hydrodynamics simulations of merging spirals with central active galactic nuclei (AGNs; Chakrabarti et al. 2007, 2008; Chakrabarti & Whitney 2009). These calculations reproduced empirically derived correlations, such as the correlation between the ratio of the 25 μm to 60 μm fluxes and energetically active AGN (de Grijs et al. 1985; Chakrabarti et al. 2007). Chakrabarti et al. (2008) reproduced the clustering of sources in Spitzer IRAC color–color plots (Lacy et al. 2004), and explained that it was due to the prevalence of the starburst phase in the time evolution of these sources. SMGs formed during these simulations have diverse properties (Hayward et al. 2012) and constitute a heterogeneous group. However, the simulations analyzed in these papers were not cosmological simulations, but rather simulated binary mergers of gas-rich systems with central black holes that yield high star formation and accretion rates onto the central AGN (Springel et al. 2005). Thus, the number density of the SMG population as a function of redshift could not be derived. (See, however, Hayward et al. 2011b for a phenomenological derivation of the number density of SMGs in this context.) Recently, Dave et al. (2010) performed hydrodynamical cosmological simulations and identified SMGs as the most rapidly star forming systems that match the observationally determined stellar mass function of SMGs. In these simulations, SMGs sit at the centers of large potential wells, and accrete gas-rich satellites, but are not typically undergoing major mergers. However, Magrani et al. (2010, 2012) noted that their high star formation rates for the bright SMGs (SFR ~ 1000 M⊙ yr−1) are difficult to reconcile with Dave et al.’s (2010) simulations that produce SMGs with star formation rates lower by ~3 than what is inferred observationally. Thus, models of SMGs cannot yet fully account for their contribution to the cosmic stellar mass assembly.

Using our method to derive photometric redshifts from the FIR SED of dusty sources detected by AzTEC and PACS in the GOODS-S field and present their SFRD as a function of redshift. We discuss future work and present caveats in Section 5, and conclude in Section 6.

2. PHOTOMETRIC REDSHIFTS: THEORY

2.1. SEDs of Dusty Sources

In CM05, we formulated an analytic solution for the FIR SEDs of spherically symmetric, homogeneous dusty sources with a central source of radiation. We considered envelopes that emit most of their radiation at wavelengths longer than 30 μm, and are sufficiently opaque that emission from the dust destruction front does not significantly influence the FIR SED. We defined characteristic parameters, Rch and Tch, that are analogous to the Rosseland photospheric radius and temperature, respectively, such that

\[ L = 4\pi \tilde{R}_c^2 \sigma T_{ch}^4 \]  

where \( \sigma = 5.67 \times 10^{-5} \text{erg cm}^{-2} \text{s}^{-1} \text{K}^{-4} \) is the Stefan–Boltzmann constant. \( \tilde{L} \) is a number of the order of unity that allows for better agreement with the numerical solutions and is relevant for very extended atmospheres, which have \( \tilde{R}_c \gg 1 \), reflecting the effective increase in emitting area. We find that

\[ \tilde{L} = 1.6 \tilde{R}_c^{0.1} \]  

is accurate to within ~10% for dusty envelopes with density scaling as \( \rho \propto r^{-2} \) with \( 1 \lesssim \kappa_\rho \lesssim 2 \), and \( \tilde{R}_c \equiv R_c/R_{ch} \). Here, \( R_c \) is the outer radius of the dust envelope; our relations apply for \( \tilde{R}_c > 1 \).

We assume that the characteristic frequency close to which the dust envelope emits most of its radiation, \( \nu_{\text{ch}} \), is within the frequency range where the opacity is approximately a power law:

\[ \kappa_\nu = \kappa_{\nu_0} (\nu/\nu_0)^\beta (30 \mu\text{m} \lesssim \lambda \lesssim 1 \text{ mm}) \]  

with \( \beta = 2 \) (Weingartner & Draine 2001). For \( \nu_0 = 3 \text{ THz} \), corresponding to \( \lambda_0 = 100 \mu\text{m} \) (fiducial values chosen for convenience), we adopt an opacity per unit mass of gas of

\[ \kappa_{100\mu\text{m}} = 0.548 \delta \text{ cm}^2 \text{ g}^{-1} \]  

For \( \delta = 1 \), this is twice the value given by the Weingartner & Draine (2001) model for dust in the diffuse interstellar medium since we assume that grains in star-forming regions have ice mantles that double the FIR opacity. The WD01 opacity is based on a gas-to-dust mass ratio of \( M/M_d = 105.1 \); since the ice mantles most likely have a different opacity per unit mass than the WD01 grains, we do not attempt to infer the dust mass in the sources. Deviations from solar metallicity, or from the assumed dust model, can be taken into account by choosing a different value for \( \delta \).

The SED variable \( \tilde{R}_c \) measures the extent of the dust envelope probed by the far-IR SED, which is reflected in the shape of the SED: very opaque envelopes have \( \tilde{R}_c \sim 1 \) (close to a blackbody), whereas less dense envelopes can have \( \tilde{R}_c \gg 1 \) (very broad SED). We model the emergent spectrum by assuming that the emission in each frequency channel comes
from a shell of thickness $\Delta r_m(v)$ centered at a radius $r_m(v)$, with a source function $\left(2h\nu v^3/c^2\right) \exp(-h\nu/kT(\tilde{r}_m))$ located at an optical depth $\tau_v(\tilde{r}_m)$:

$$F_v \propto \left(\frac{2h\nu^3}{c^2}\right) \kappa_v \tilde{v}^3(k_v - 1)^2 r_m^{-k_v} \Delta r_m \times \exp\left[-\frac{h\nu}{kT(\tilde{r}_m)} - \tau_v(\tilde{r}_m)\right],$$

where the optical depth $\tau_v$ from $r$ to the surface of the cloud is

$$\tau_v = \kappa_v(\tilde{r}^{-k_v+1} - \tilde{R}_c^{-k_v+1}).$$

Equation (5) (CM05) is the analytic expression that we fit to the observed SEDs, where the quantities $\tilde{v} \equiv v/v_{ch}$, $\tilde{r}_m \equiv r_m(v)/r_{ch}$, and $\theta_{ch} = R_{ch}/D_A$, where $D_A$ is the angular diameter distance of the source. The characteristic frequency $v_{ch} \equiv kT_{ch}/h$, and the quantity $\Delta r_m$ is a function of the SED variables $T_{ch}$ and $R_c$. Thus, given three photometric data points, we can fit for the unknowns $T_{ch}$, $R_c$, and $\theta_{ch}$ in Equation (5).

This analytic form for the SED is easily understood as a dust envelope with photospheric radius $R_{ch}$ emitting most of its radiation at $v_{ch}$ (close to the peak frequency of the SED). Each frequency channel emanates from radius $r_m(v)$ with thickness $\Delta r_m$: the high frequency photons must also contend with the opacity of the dust envelope relative to their point of origin and the Wien cutoff. CM05 and CM08 have given expressions for the characteristic emission radii of different frequency channels—Rayleigh–Jeans: $h\nu/kT \ll 1$, intermediate: $h\nu \sim kT$, and high-frequency: $h\nu/kT \gg 1$, $\tau > 1$, which comes from the outer parts of the envelope, close to the photosphere, and regions that mediate an effective tug of war between the opacity and temperature gradient of the envelope, respectively. The characteristic emission radius $r_m(v)$ was self consistently determined in CM05 by the requirement that the integrated luminosity equal the total luminosity. The break frequency of the SED is the frequency at which the character of the emission switches from being dominated by hotter photons coming from close to the photosphere to colder photons that come from the outer regions of the envelope. It is given by (CM08):

$$v_{\text{break}} = 6.35 \times 10^9 \left(\frac{100}{R_c}\right)^{0.4} T_{ch} \frac{1+z}{1+z} \text{ Hz.} \quad (7)$$

For average values of $T_{ch} \sim 100$ K and $\tilde{R}_c \sim 300$, galaxies at $z \sim 2$ would have a break wavelength of $\sim 2$ mm. We have determined (by successively removing long wavelength data points of local ULIRGs and fitting the SEDs) that if the lowest frequency data point is more than a factor of two higher than the break frequency, then the shape of the entire SED (including the transition to intermediate frequencies) cannot be clearly determined. In such cases, we adopt a median value of $\tilde{R}_c$ ($\tilde{R}_c = 300$) that is determined by fitting to the sample that has both spectroscopic redshifts and long wavelength millimeter (mm) data, and at least three data points with $S/N > 3$ (with the latter being a requirement for all the sources we fit).

Once the SED variables $T_{ch}$ and $\tilde{R}_c$ are determined, we can solve for the source parameters of the dust envelope, i.e., the light-to-mass ratio $(L/M)$ and the surface density ($\Sigma$), using the following equations, which may be inferred from Equations (51) and (52) in CM05:

$$\frac{L}{M} = 1.6 \left(\frac{3 - k_{\rho}}{k_{\rho} - 1}\right) \kappa_{v_{ch}} \left[\frac{\sigma_{ch}^4}{T_{ch}^0}\right] \tilde{R}_c^{k_{\rho} - 2.9} \left[\frac{L_\odot}{M_\odot}\right], \quad (8)$$

$$\Sigma = \frac{4(k_{\rho} - 1)}{(3 - k_{\rho})} \kappa_{v_{ch}} \left(\frac{T_0}{T_{ch}}\right) \tilde{R}_c^{k_{\rho} - (k_{\rho} - 1)} \left[\text{g cm}^{-2}\right], \quad (9)$$

where $kT_0 \equiv h\nu_{v_{ch}}$. Motivated by CM08’s fits to the SEDs of ULIRGs and SMGs and their comparison with other observational estimates (Downes & Solomon 1998), we adopt $k_{\rho} = 2$.

2.2. Inferring the Redshift

The parameters we infer, $L/M\delta$ and $\Sigma\delta$, depend on redshift through the dependence of frequency on redshift. We can express the redshift dependence of these parameters in a very simple manner. Since the luminosity of a dust envelope satisfies $L \approx R^2 T^4$ and the inferred mass is $M \propto \Sigma R^2$, we have:

$$\frac{L}{M} \propto T^4 \frac{1}{\Sigma \delta} \quad (10)$$

(CM08). The redshift dependence of the surface density, $\Sigma\delta$, follows from noting that the optical depth at the observed frequency must match that at the emitted frequency, since $\tau_v$ determines the shape of the SED, which is invariant: $\kappa(T_{ch})\Sigma_{\text{obs}}\delta_{\text{obs}} = \kappa(T_{\text{rest}})\Sigma_{\text{rest}}\delta_{\text{rest}}$, so that $\Sigma_{\text{obs}}/\Sigma_{\text{rest}} = (T_{\text{rest}}/T_{\text{obs}})^{\beta} = (1+z)^{\beta}$. Since $T_{\text{obs}} = T_{\text{rest}}/(1+z)$, it follows that (CM08):

$$\left(\frac{L}{M\delta}\right)_{\text{obs}} = \left(\frac{L}{M\delta}\right)_{\text{rest}} (1+z)^{-(4+\beta)}. \quad (11)$$

We can now use Equation (11), setting $\beta = 2$ (WD01), to infer the redshift of a dusty galaxy from its observed value of $L/M\delta$, which we have shown can be derived from the FIR SED analytically (CM08):

$$1 + z_{\text{inf}} = \left[\frac{\langle L/M\delta \rangle}{L/M\delta_{\text{obs}}}\right]^{1/6}, \quad (12)$$

where $\langle L/M\delta \rangle$ is the typical value in the Herschel sample; since $L/M\delta$ can range over an order of magnitude, we use the geometric mean. Note that $L$ is the luminosity derived from fitting to the mm—FIR SED. A simple way to understand why our method yields a more accurate redshift than estimating it from the temperature (or peak of the SED) is as follows. Our inference of the redshift is proportional to $L/M^{1/6}$. Alternately, inferring the redshift from fitting a blackbody function to the SED and estimating a temperature from the shift of the peak of the SED is proportional to the temperature itself (i.e., to the template rest wavelength temperature assumed). It follows from Equation (8) that $L/M \propto T_{ch}^6 \tilde{R}_c^{-1}$ (for $k_{\rho} = 2$ and $\beta = 2$). The parameters ($T_{ch}$ and $\tilde{R}_c$) are correlated inversely for a given luminosity (from Equation (1)), leading to a smaller range in $L/M^{1/6}$ than in the temperature itself, and therefore a more accurate redshift. This is the case when $\tilde{R}_c$ can be independently determined, which can be done when there is sufficient information on the shape of the SED, as we discuss in Section 4. As in CM08, we define the accuracy of the redshift determination as:

$$A \equiv \max(1+z, 1+z_{\text{inf}})/\min(1+z, 1+z_{\text{inf}}). \quad (13)$$
3. OBSERVATIONS

In this study, we use deep PACS 70, 100, and 160 μm observations provided by the Herschel Space Observatory\textsuperscript{7} as part of the PACS Evolutionary Probe (PEP\textsuperscript{8}) guaranteed time key program (Lutz et al. 2011). We also use SPIRE data at 250, 350, and 500 μm of sources that have spectroscopic redshifts, as reported by Magnelli et al. (2012). We use data from the following fields: GOODS-N and GOODS-S fields, LH field, COSMOS field, and the lensed fields A2218, A1835, A2219, A2390, MS1054, CL0024, and MS045. The sample with spectroscopic redshifts is taken from and fully described in Magnelli et al. (2012).

The first aim of this paper is to test the CM FIR photometric redshift method on a large and more diverse sample than studied by CM08. To calibrate and test this photometric redshift method, we use data of SMGs with robust spectroscopic estimates from Magnelli et al. (2012). To assess the possible dependence of the accuracy of our photometric redshift method on the usage of PACS data, we also use SPIRE data for this sample, and report the average accuracies when we use PACS versus SPIRE, versus both PACS and SPIRE data. In this assessment of the photometric redshift method, we restrict our study to the sample of SMGs that have spectroscopic redshifts and available PACS and/or SPIRE flux densities, sub-mm/or mm fluxes. We have tested our photometric redshift method here on ~40 SMGs with spectroscopic redshifts that have PACS and/or SPIRE data, and sub-mm (850 μm, 870 μm) and/or mm (1.1 mm) data (Magnelli et al. 2012). While MIPS 24 μm data is available for this sample, we do not use the data in our SED fits as our model does not include physical effects that may contribute to the shorter wavelength emission (such as a clumpy geometry, distributed sources of luminosity, or a disk-like structure), and hence is unlikely to be applicable for $k_{\text{rest}} \lesssim 30 \mu m$. As in CM08, we restrict our SED fitting to sources that have at least three photometric data points with $S/N > 3$ in the mm–FIR range. This does mean that in some cases we cannot assess the accuracy of our method with PACS or SPIRE data alone (due to having too few data points of sufficient accuracy in the mm–FIR rest-frame wavelength region). However, including both PACS and SPIRE data is sufficient and gives us a larger sample to test the method on.

Magnelli et al. (2012) have discussed the selection effects of Herschel observations in detail, and conclude that the sample is representative of the high infrared luminosity ($L_{\text{IR}} \gtrsim 10^{12.5} L_\odot$) SMG population. We briefly review the main points here. The SMGs in the spectroscopic sample of Magnelli et al. (2012) have (sub)mm, MIPS, PACS and SPIRE detections as well as radio (1.4 GHz) observations needed for any spectroscopic follow up (sub-mm positions with their 15 arcsec beams are not accurate enough, so using the FIR/radio correlation, sub-mm sources are associated with their radio counterparts that have accurate positions within 1 arcsec). These observations introduce different selection biases that need to be characterized. By using a Kolmogorov–Smirnov analysis, Magnelli et al. (2012) verify that the radio and sub-mm flux of SMGs with spectroscopic redshifts is consistent with the parent sample of SMGs with radio counterparts. The MIPS 24 μm data correspond to selection limits that are several times lower in infrared luminosities, up to $z \sim 3–4$, than that introduced by radio observations, and as such do not represent a significant selection effect. The PACS and SPIRE selection effects are redshift dependent. The PACS observations are slightly biased toward galaxies with hotter dust while SPIRE observations are biased toward cooler dust. In GOODS-N (which has the deepest sub-mm observations), the selection bias due to PACS/SPIRE observations is comparable to that introduced due to sub-mm and radio observations. Magnelli et al. (2012) find that the PACS/SPIRE detection rate of SMGs with robust spectroscopic redshifts is comparable to that introduced due to sub-mm and radio observations. We note that this finding is confirmed by the very high PACS/SPIRE detection rate (73%) of SMGs with spectroscopic redshifts (i.e., SMGs with radio identifications).

Magnelli et al. (2012) also show that the redshift distribution of the spectroscopic sample with PACS/SPIRE detections is consistent with the entire SMG sample with robust redshift estimates. The median redshift of this sample is $z = 2.4$, which is consistent with the median redshift of the entire SMG sample (Chapman et al. 2004). We show further in Section 4.2 that the redshift distribution of galaxies in GOODS-S, where we additionally use galaxies that do not have spectroscopic redshifts, is consistent with the redshift distribution of the spectroscopic sample.

After assessing the photometric redshift accuracy, we apply the CM photometric method to a PACS-detected SMG sample of the GOODS-S field (i.e., without requiring any spectroscopic redshift estimate) and derive their SFRD, which is discussed in Section 4.2 below. This SMG sample corresponds to the AzTEC (1.1 mm) sample of the GOODS-S field presented in Scott et al. (2010) and which contains 41 sources detected with $S/N > 3.5$. This AzTEC sample is cross-matched with our PACS catalog using a matching radius of 9″. We find that 25/41 AzTEC sources are detected in our PACS catalog. We note that assuming a $S_{850\mu m}/S_{100\mu m}$ ratio of 2.1 (Scott et al. 2008; Austermann et al. 2010), the depth of the AzTEC survey converts into a 850 μm flux of 4.2 mJy. Using this sample of 25 galaxies, we derive the SFRD of AzTEC and PACS detected SMGs (i.e., down to ~1.2 mJy and ~2.4 mJy at 100 and 160 μm, respectively) that have 850 μm fluxes typical of “classical” SMGs ($F_{850\mu m} \gtrsim 5$ mJy). Our result on the SFRD is a lower limit due to the PACS non-detections of some of the “classical” SMGs in the GOODS-S field, and is uncertain due to the relatively small number of sources. In brief, we derived the SFRD of a sample of PACS-bright “classical” SMGs rather than the SFRD of the entire “classical” SMG population. As we discuss in Section 4.2, our derived SFRD for the AzTEC–PACS sample is in close agreement with that of other samples, and agrees most closely with the SFRD of mm-selected sources studied by Roseboom et al. (2012), which is unsurprising.

4. APPLICATION TO A SAMPLE OF HERSCHEL SOURCES

4.1. Photometric Redshifts

We first examine the sample with spectroscopic redshifts to verify the accuracy of the CM method. We consider three cases: including only PACS data, only SPIRE data, and both PACS and SPIRE data. All three cases include mm and/or sub-mm data. Some of the sources in this sample are lacking data points that are close to the break frequency of the SED. We note that the variation in the dust temperature when the SED is fit with a blackbody function is slightly larger than the variation of the

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\textsuperscript{7} Herschel is an ESA Space Observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

\textsuperscript{8} [http://www.mpe.mpg.de/fr/Research/PEP/index.php]
characteristic temperature when the SED is fit with our model. In some cases, as shown in Figure 1, we do have long wavelength data points that sample the break frequency of the SED. This allows us to improve the accuracy of our photometric redshift method (as it would allow us to independently fit for not only $T_{ch}$ but also $R_c$), and also provides a better determination of the mass of the envelope.

We first discuss our derived parameters and accuracy when including mm, sub-mm, and PACS data. The geometric mean of the $L/M$ values of the sample with spectroscopic redshifts is $30 L_\odot/M_\odot$, which is comparable to our determination for SMGs studied in CM08. This is the template $L/M$ value that we employ in deriving photometric redshifts here. CM08 had noted that the $L/M$ they derived for SMGs was a factor of two lower than local ULIRGs. The somewhat lower values of $L/M$ for SMGs relative to local ULIRGs found by CM08 is reflected in the lower dust temperatures found in high redshift infrared-bright galaxies (Symeonidis et al. 2011). Figure 1(a) depicts the accuracy of our method for sources in this sample with spectroscopic redshifts. The red filled circles mark the sources that have sufficient long-wavelength data, i.e., $v_{\text{min}} \lesssim 2 \times v_{\text{break}}$, to determine $R_c$ independently ($\sim$40% of the sources). The average accuracy for the entire sample is 1.095 and the standard deviation is 0.077. The corresponding numbers when the redshift is inferred by fitting a single temperature blackbody function to the SED are 1.2 and 0.2 respectively. Here, we have used a temperature of 60 K, finding that it yielded the maximal redshift accuracy when fitting with a blackbody function. Using a modified blackbody fit (with $\beta = 1.5$ as recommended by Gordon et al. 2010 and $T = 50$ K) yields similar accuracies as for a single temperature blackbody. The part of the sample with data at frequencies $\lesssim 2 \times v_{\text{break}}$ has an average accuracy of 1.07 and standard deviation of 0.075. The higher accuracy of the CM method is due to fitting for two parameters ($R_c$ and $T_{ch}$) to account for the influence of a range of temperatures on the FIR SED, along with the peak frequency of the SED. We can fit for both parameters independently when we have data for the long wavelength part of the SED, sampling close to the break frequency. For the sample that does not have sufficient long-wavelength data, we find a smaller dispersion of characteristic temperatures when we fit our functional form to the data than when we fit a single temperature blackbody, as our functional form is a better approximation to the real FIR SED. We attribute the slightly higher accuracy of the CM method for the sample with restricted data to the smaller dispersion in temperatures when we fit the data with our functional form.

Figure 1(b) depicts the accuracy when using mm, sub-mm, and SPIRE data. The average accuracy in this case is 1.09 (whether the break frequency is sampled or not). Fitting to mm, sub-mm, and SPIRE data leads to a lower limit on the characteristic temperature if the peak wavelength is not constrained. Fitting to SPIRE data also yields a lower limit on $R_c$, and thereby roughly comparable values of $L/M$ (and the inferred redshift) as when fitting to PACS data ($L/M \propto T_{ch}^{\beta} R_c^{-1}$ for $k_\alpha = 2$ and $\beta = 2$, i.e., from Equation (8)). At $z \lesssim 2$, SPIRE data alone are generally not sufficient to constrain the peak wavelength as it does not provide a data point shortward of the peak; as we discuss in the Appendix, SPIRE data do sample the peak of the SED for $z \gtrsim 4$ and for these cases the $1\sigma$ spread in the characteristic temperature is lower.

Figure 1(c) depicts the accuracy when using mm, sub-mm, and PACS+SPIRE data. In this case, the average accuracy is 1.07. For $z \gtrsim 3$, we see that the accuracy when using PACS data alone is slightly less (Table 4) than using either SPIRE or PACS+SPIRE. We do not have a sufficiently large number of sources at high redshifts to statistically assess the improved accuracy when using PACS+SPIRE versus using either PACS or SPIRE. Such an improvement will likely become more significant for sources at high redshift, of which we do not have enough in our sample to make a statistical comparison. For the highest redshift sources, while we can determine photometric redshifts using SPIRE data or PACS+SPIRE data, we cannot do so with PACS data alone (due to having too few data with sufficient signal-to-noise ratio ($S/N$) in the rest-frame FIR region). The SPIRE-only case is of special practical importance, since many sub-mm galaxies have been detected in large areas of sky that have been covered with SPIRE but only to shallow levels with PACS, for example, in the H-Atlas program (Eales et al. 2010).
discussed above the accuracy in the inference of the redshift by fitting a single temperature blackbody. Another commonly used FIR redshift method employs the radio-sub-mm spectral index (Carilli & Yun 1999). This technique provides a gross indication of the redshift by using the variation of the radio-sub-mm spectral index as a function of redshift. The uncertainty in redshift for this method depends on the scatter of the spectral index for a given polynomial fit to the data. The uncertainty in redshift also depends on how well a given polynomial fits the data. The ±σ variation in the spectral index for the adopted polynomial fit in Carilli & Yun (1999) is ~1, with 30% of the galaxies in their sample falling outside this range. Thus, this method is less accurate than ours. Aretxaga et al. (2005) sample mock galaxy catalogs with an assumed evolutionary history to derive photometric redshifts from radio to FIR colors, finding a redshift accuracy of δz ~ 0.3 (rms dispersion about the line z_{phot} = z_{spec}). In terms of our metric (1 + z_{int})/(1 + z_{spec}) (where we take z_{int} to be the most probable photometric redshift), the average accuracy of the sample considered in Aretxaga et al. (2005) is 1.213 (the average accuracy of our sample is 1.12). Kovacs et al. (2006) suggest the use of the FIR–radio correlation as a photometric redshift estimator, in a manner similar to Carilli & Yun (1999). Roseboom et al. (2012) use radio, mm, and SPIRE data to find a comparable average accuracy (although the standard deviation in their estimates is greater). In summary, these photometric redshift methods (whether estimating the redshift from Monte Carlo sampling of mock catalogs, the radio-sub-mm spectral index, or from the dust temperature) yield comparable or generally poorer accuracy relative to our method.

We conclude therefore that our method yields reasonably accurate photometric redshifts for infrared-bright galaxies out to z ~ 5. As Magnelli et al. (2012) note, using mm, sub-mm, and PACS/SPIRE data leads to a bias at low infrared luminosities (L_{IR} < 10^{12.5} L_{⊙}) toward low redshift galaxies with colder dust (i.e., given the original selection at mm, sub-mm wavelengths). Our sample should be representative of the high luminosity (L_{IR} > 10^{12.5} L_{⊙}) population. It is likely that we may be missing low luminosity galaxies at high redshifts. A statistical determination of the accuracy of our method at higher redshifts (z > 3) is yet to be realized. Maximal accuracy and applicability of our method can be realized with the inclusion of PACS and SPIRE data, with long wavelength mm data sampling the break frequency, so that T_{eb} and ˜R are independently determined. The addition of near-IR data (Daddi et al. 2009) does improve the accuracy of photometric redshifts beyond what we are able to do here with FIR data alone. We should note though that our method does not require radio data, as is used in the estimates by Aretxaga et al. (2005), Carilli & Yun (1999), and Roseboom et al. (2012), or an optical identification, as is used by Daddi et al. (2009). This may be an advantage compared to other methods (those that use near-IR data) that achieve similar or better accuracy.

We list the average accuracy and standard deviation of our derived photometric redshifts when using mm, sub-mm, and PACS, SPIRE, and PACS+SPIRE data in Table 1. We also give these numbers for a restricted range of redshifts, from z = 1–2, z = 2–3, and z > 3 in Tables 2–4, respectively. In the Appendix, we discuss specific sources in the redshift range z ~ 1, z ~ 2, z ~ 3, z ~ 4, and z ~ 5 and derived parameter values when employing PACS, SPIRE, and PACS+SPIRE data.

4.2. Cosmic Star Formation History of AzTEC–PACS Sources in GOODS-S

Now that we have derived the photometric redshifts, we use them to calculate the SFRD for the PACS-selected SMG sample in the GOODS-S field. We focus on the GOODS-S field here as that field is homogeneously surveyed down to 5 mJy at 850 μm (thereby selecting “classical” SMGs), as discussed Section 3. The other fields (GOODS-N, LH, and COSMOS) are surveyed at different depths over parts of the field in the mm and sub-mm, and as such yield a more heterogeneous sample of galaxies than the GOODS-S field observations.

We convert our infrared luminosities to star formation rates using the relation presented in Kennicutt (1998), modified (by a factor of ~2; Portinari et al. 2004) to use the Chabrier initial mass function (IMF; Chabrier 2003), i.e., we take

$$SFR = \frac{L_{IR}}{1 \times 10^{10} L_{⊙}}.$$

The average star formation rate for galaxies with infrared luminosity in excess of $3 \times 10^{12} L_{⊙}$ is 700 $M_{⊙}$ yr$^{-1}$ for all of the fields we have studied here, including GOODS-S (this is consistent with the observed infrared luminosity function at $z ~ 2$, e.g., Wardlow et al. 2010). This is a factor of ~3 in excess of the average values found by Dave et al. (2010), and prior to Herschel observations the total infrared luminosity, and hence the star formation rate, of SMGs was indeed uncertain. However, recent Herschel observations which probe the rest-frame FIR peak of SMGs (Magnelli et al. 2012) do support the higher star formation rates of major merger models (Chakrabarti et al. 2008; Hayward et al. 2011a).

Figure 2 shows our derived SFRD (black symbols) over-plotted with the determination by Magnelli et al. (2011)
SFRD’s derived by Magnelli et al. (2011) using 24 μm and 70 μm data for ULIRGs and all galaxies, respectively. Note that the sample in Magnelli et al. (2011) is the SFRD for all galaxies at a given epoch and all ULIRGs, sources in these redshift bins. The green and yellow symbols depict the SFRD for all galaxies at a given epoch and all ULIRGs. We have derived the SFRD shown here (and corresponding infrared luminosity density) using the standard 1/V_max method (Schmidt 1968). The luminosity density is given by:

\[ \phi(z) \Delta z_j = \sum_{z_{j-1} < z < z_j} \frac{L_z}{V_{c,i}}. \]  

Here, \( V_{c,i} = \min[V(z_{\text{max,i})}, V(z_j)] - V(z_{j-1}) \), with \( V \) being the co-moving volume; \( i \) labels sources and \( j \) redshift bins, so that \( z_{\text{max,i}} \) is the maximum redshift at which source \( i \) would have been detected, \( \Delta z_j = z_j - z_{j-1} \), \( L_z \) is the luminosity of source \( i \), and \( z_j = 0.5(z_{j-1} + z_j) \). The star formation density in a redshift bin is then simply the luminosity density scaled by the conversion factor given by Kennicutt (1998), using the Chabrier IMF correction. Figure 3 depicts the redshift distribution of sources in GOODS-S. Our conclusions about the SFRD are uncertain due to the small number of sources, but as we discuss below, our SFRD for AzTEC–PACS sources is comparable to other work in the literature. The overall shape of the redshift distribution of sources in GOODS-S is also comparable to the spectroscopic sample presented by Magnelli et al. (2012). Spectroscopic follow-up of SMGs may miss some sources between 1.2 < z < 1.8, i.e., in the “redshift desert” (Magnelli et al. 2012).

We find that the sub-mm-bright PACs sources contribute 15% to the SFRD at \( z \sim 2 \) relative to ULIRGs (as determined in Magnelli et al. 2011), and 3% relative to the total SFRD at that epoch. These percentages are relative to the most probable value for the SFRD determined by Magnelli et al. (2011), with the spread in derived values indicated in Figure 2. For comparison, Magnelli et al. (2011) found that the ULIRG population contributes 17% to the total SFRD at \( z \sim 2 \). As discussed in Section 3, the sources we consider here have a 850 μm flux typical of “classical” SMGs (\( F_{850,\mu m} \gtrsim 5 \) mJy). However, given the relatively small number of sources (~30), we interpret our findings as yielding the SFRD of AzTEC–PACS sources in GOODS-S, rather than that of the SMG population.

It is worthwhile noting that there are systematic differences in the determination of the SFRD of SMGs using different surveys. For instance, radio-detected LABOCA Extended Chandra Deep Field South (ECDFS) SMGs in the ECDFS as studied by Wardlow et al. (2010) have a different redshift evolution and overall contribution to the SFRD than the sample studied by Chapman et al. (2005). Our results are comparable with the SFRD of mm-selected sources in the LH and GOODS-N fields calculated by Roseboom et al. (2012). Our determination of the SFRD of the AzTEC–PACS sources is a lower limit to the ULIRG population which are a less extreme version of infrared-bright galaxies and increasingly common at high redshifts (Wuyts et al. 2011). The shape of the SFRD of the AzTEC–PACS sources does not show a decline out to \( z \sim 4 \).

5. DISCUSSION

There are a few caveats worth mentioning, relating to the use of our method and astrophysical effects. If lensed galaxies are present in our sample, they would artificially boost the number counts of SMGs. Negrello et al. (2007) estimate the probability of lensing as a function of the sub-mm flux of a galaxy, which we can use to ascertain the likelihood of galaxies in our sample being lensed. They find a significant incidence of lensing (\( \gtrsim 50\% \)) for galaxies with 850 μm fluxes in excess of 40 mJy, but all our sources are well below this threshold. For known lensed galaxies, we have checked that our method works equally well on the lower luminosity SMGs in the A2218 lensed cluster. We conclude therefore that lensing is not a serious source of concern for this sample, i.e., the probability of galaxies being lensed in the fields we have studied is very low given their 850 μm flux. Moreover, we have checked that for known lensed galaxies in the A2218 lensing cluster, our method yields robust photometric redshifts.

Our simple model is designed to yield through SED-fitting the large-scale parameters of infrared-bright galaxies, namely, the mass, size, and luminosity once the redshift is determined using the CM photometric redshift method. We do not treat the effects on the SED of a clumpy dust envelope or distributed sources of luminosity. Although we do not treat the morphology of infrared-bright galaxies in detail, our derivation of the mass, size, luminosity, and density profile is in good agreement with observational determinations (CM08). The advantage of our model is that it incorporates a self-consistent range of dust temperatures in an analytic expression for the emitted luminosity, which we have shown can be applied to infrared-bright galaxies to robustly derive redshifts and large-scale source parameters that are accurate on average to ~10% out to \( z \sim 4 \).
6. CONCLUSION

1. We have applied the photometric redshift method of CM08 to Herschel data to demonstrate the accuracy of our method for a large and diverse sample of SMGs. We find average accuracies of 1.09 relative to spectroscopic redshifts, i.e., in \((1 + z_{\text{inf}})/(1 + z)\), from \(z = 1–2\) using PACS and SPIRE data; the average accuracy from \(z = 2–3\) is 1.06 using PACS and SPIRE data; and 1.11 for \(z > 3\) sources. We do not have a sufficiently large number of sources at \(z \gtrsim 3\) to provide a statistical assessment of the accuracy of our method at high redshifts. Our method is optimally applied to a sample that has both FIR and mm data, which would allow for the FIR peak and the long wavelength shape of the SED to be properly sampled.

2. To assess the dependence of our photometric redshift method on the data in this sample, we contrast the average accuracy of our method when we use mm, sub-mm, and (a) PACS data versus (b) SPIRE data, versus (c) both PACS and SPIRE data. We find comparable average accuracies.

3. We also give the average values for the \(L/M\) ratios of SMGs in these samples, which is lower than that for local ULIRGs by a factor of two. Our average star formation rate is \(700 \ M_\odot \ yr^{-1}\) for galaxies with luminosities in excess of \(3 \times 10^{12} L_\odot\).

4. We estimate the SFRD of sub-mm-bright PACS sources in the GOODS-S field. These sources have an extrapolated 850 \(\mu\)m flux typical of classical SMGs, \(F_{850\mu m} \gtrsim 5 \ mJy\) (we extrapolated the sub-mm flux from AzTEC observations as discussed in Section 3). Our derivation of the SFRD is a lower limit, particularly at low redshifts (\(z < 1\)) where normal spirals (and secular processes or minor tidal interactions) drive the star formation history of the universe. These PACS sources contribute 15% to the SFRD relative to ULIRGs at \(z \sim 2\), and 3% relative to the total SFRD at that epoch that is produced by all galaxies. We find that there is no decline in the shape of the SFRD of the sub-mm-bright PACS sources in the GOODS-S field out to \(z \sim 4\).

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APPENDIX

FITTING TO PACS, SPIRE, AND PACS+SPIRE DATA FROM \(z = 1–5\)

We discuss specific sources in the redshift range from \(z = 1–5\) and our derived parameter values from fitting to the SED. We choose one source at \(z = 1, z = 2, z = 3, z = 4,\) and \(z = 5\) to illustrate the inference of parameters and their variation when we use mm, sub-mm, and PACS, SPIRE, and PACS+SPIRE data across this redshift range.
obtain a redshift accuracy of 1.05. When fitting to mm, sub-mm data, and PACS+SPIRE data, we can cleanly sample the peak of the SED ($T_{ch} = 114 \pm 0.6$). In this case, the redshift inference is accurate to 1.08. The derived PACS+SPIRE characteristic temperature is intermediate between the PACS-only and SPIRE-only cases, and closer in value to the PACS-only inference.

For the source at $z = 2.214$, shown in Figure 5, we find $T_{ch} = 124 \pm 3$, and a redshift accuracy of 1.01 when fitting to mm, sub-mm, and PACS data. When fitting to SPIRE data, we find $T_{ch} = 92 \pm 3$ and a redshift accuracy of 1.22. When fitting to all available data (PACS+SPIRE), we infer $T_{ch} = 117 \pm 1.5$ and a redshift accuracy of 1.01.

The SED of a $z = 3.38$ source is shown in Figure 6. When fitting to PACS data, we infer $T_{ch} = 153 \pm 8$ and a redshift accuracy of 1.26. When fitting to SPIRE data, we infer $T_{ch} = 145 \pm 14$ and a redshift accuracy of 1.21. When fitting to PACS+SPIRE data, we infer $T_{ch} = 152 \pm 4.6$ and a redshift accuracy of 1.2. This is a high luminosity, high $L/M$ source
(L \sim 1.5 \times 10^{13} L_\odot, \ L/M \sim 90), and in this case our method results in poorer accuracies than is typical.

The SED of a z = 4.055 source is shown in Figure 7. When fitting to mm and sub-mm data, we infer T_{ch} = 139 \pm 32, and a redshift accuracy of 1.1. PACS data was not available for this source, and in this case, the peak of the SED is not cleanly sampled. SPIRE data does cleanly sample the peak, and we infer T_{ch} = 109 \pm 7 and a redshift accuracy of 1.1. When fitting to PACS+SPIRE data, we infer T_{ch} = 109 \pm 7 and a redshift accuracy of 1.1.

The SED of a z = 5.31 source is shown in Figure 8. PACS data was not available for this source. The fit to mm and sub-mm data, we infer T_{ch} = 171 \pm 9 and a redshift accuracy of 1.1. In this case, this is the same as using all available data. In summary, we find that using mm, sub-mm and PACS data for z \lesssim 3 galaxies allows us to cleanly sample the peak of the SED. In these cases, we derive parameter values that are comparable to that inferred when using all the data for z \lesssim 3 galaxies. For z \sim 4 sources, as shown here, using SPIRE data allows us to cleanly sample the peak. For the z \sim 5 source in this sample, no PACS data was available, but we find a redshift accuracy that is comparable to our average accuracy using mm, sub-mm, and SPIRE data. However, due to the paucity of high redshift (z \gtrsim 4) sources in this sample, we cannot demonstrate the statistical viability of our photometric redshift method beyond z \sim 4.

Figure 7. SED of z = 4.055 source, fitting to (a) mm and sub-mm data only, (b) mm, sub-mm, and SPIRE.

(A color version of this figure is available in the online journal.)

Figure 8. SED of z = 5.31 source, fitting to mm, sub-mm data, and SPIRE data.

(A color version of this figure is available in the online journal.)

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